Reporting to the Convention on Biology Diversity: How are countries assessing and protecting their genetic diversity?

Sean Hoban[1], Catriona D. Campbell[2] , Jessica da Silva[3a,3b], Robert Ekblom[4], W. Chris Funk[5*^], Brittany A. Garner[6], José A. Godoy[7], Francine Kershaw[8], Anna J. MacDonald[2,9*^] , Joachim Mergeay[10a,10b*^], Melissa Minter[11], David O'Brien[12], Ivan Paz Vinas[13a,13b], Sarah K. Pearson[14], Sílvia Pérez-Espona[15a,15b], Kevin M. Potter[16], Isa-Rita M. Russo[17*], Gernot Segelbacher[18], Cristiano Vernesi[19], Margaret E. Hunter[20*^]

[1]Center for Tree Science, The Morton Arboretum, 4100 Illinois Rt 53, Lisle, USA, 60532, shoban@mortonarb.org, 001 630 719 2419

[2] Institute for Applied Ecology, University of Canberra, Canberra, ACT 2601, Australia, cat.campbell@canberra.edu.au, ORCID: 0000-0001-7983-1832

[3a]Biodiversity Research, Assessment and Monitoring Division, South African National Biodiversity Institute, Kirstenbosch Research Centre, Rhodes Drive, Private Bag X7 7735, Cape Town, South Africa, j.dasilva@sanbi.org.za, +27-21-799-8860, ORCID: 0000-0001-8385-1166

[3b]Centre for Ecological Genomics and Wildlife, University of Johannesburg, PO Box 524, Auckland
Park 2006, South Africa

[4] Department of Ecology and Genetics, Uppsala University, Uppsala, SE-75236, Sweden, robert.ekblom@ebc.uu.se, +46 18 471 6468, ORCID: 0000-0003-2222-1966

[5] Department of Biology, Graduate Degree Program in Ecology, Colorado State University, 1878 Campus Delivery, Fort Collins, CO 80523-1878, USA, Chris.Funk@colostate.edu, ORCID: 0000-0002-6466-3618

[6] Interdisciplinary Degree Program, The University of Montana, 32 Campus Dr., Missoula, MT, 59812, brittany.garner@umontana.edu, ORCID: 0000-0002-8122-5636

[7] Department of Integrative Ecology , Estación Biológica de Doñana (CSIC), Seville, E-41092, Spain, godoy@ebd.csic.es, +34 954466781, ORCID: 0000-0001-7502-9471

8 Natural Resources Defense Council, 40 West 20th Street, New York, NY, USA, 10011, fkershaw@nrdc.org, +1 917 450 0994

[9] The John Curtin School of Medical Research / Research School of Biology, The Australian National University, Acton, ACT 2601, Australia, anna.macdonald@anu.edu.au, ORCID: 0000-0003-2972-200X

[10a] Research Institute for Nature and Forest, Havenlaan 88, 1000 Brussels, joachim.mergeay@inbo.be

[10b] Aquatic Ecology, Evolution and Conservation, KULeuven, Charles Deberiotstraat 32, box 2439, 3000 Leuven Box 2439. +32499942942. Joachim.mergeay@inbo.be Orcid: 0000-0002-6504-0551

11 Leverhulme Centre for Anthropocene Biodiversity, Department of Biology, University of York, Wentworth Way, York, YO10 5DD, United Kingdom mm1874@york.ac.uk ORCID: 0000-0003-1580-7176

12 Scottish Natural Heritage, Great Glen House, Leachkin Road, Inverness, IV3 8NW, UK david.obrien@nature.scot ORCID: 0000-0001-7901-295X

[13a] Laboratoire Ecologie Fonctionnelle et Environnement, Université de Toulouse, UPS, CNRS,

INP, UMR-5245 ECOLAB, 118 route de Narbonne, Toulouse, France 31062, ivanpaz23@gmail.com; +33 534323946, ORCID ID: 0000-0002-0043-9289

[13b] Laboratoire Evolution & Diversité Biologique, CNRS, IRD, UPS, UMR-5174 EDB, 118 route de Narbonne, Toulouse, France 31062.

[14]College of Science and Engineering, Flinders University of South Australia, GPO Box 2100, Adelaide, South Australia, 5001, Australia, sarahkimpearson@gmail.com , +61 444 529 061, ORCID: 0000-0002-6895-7832

[15a] Royal (Dick) School of Veterinary Studies, The University of Edinburgh, Easter Bush Campus, Roslin, Midlothian, EH25 9RG, Scotland, United Kingdom, silvia.perez-espona@ed.ac.uk, ORCID 0000-0001-7098-4904

[15b] The Roslin Institute, The University of Edinburgh, Easter Bush Campus, Roslin, Midlothian, EH25 9RG, Scotland, United Kingdom, silvia.perez-espona@ed.ac.uk, ORCID 0000-0001-7098-4904

[16] Department of Forestry and Environmental Resources, North Carolina State University, 3041 Cornwallis Rd., Research Triangle Park, NC 27709, USA, kpotter@ncsu.edu, ORCID ID: 0000-0002-7330-5345

[17] Cardiff School of Biosciences, Sir Martin Evans Building, Cardiff University, Museum Avenue, Cardiff, CF10 3AX, United Kingdom, russoim@cardiff.ac.uk, +44 29 2087 6036, ORCID ID: 0000-0001-9504-3633

[18] Chair of Wildlife Ecology and Management, University Freiburg, Tennenbacher Str. 4, D-79106 Freiburg, gernot.segelbacher@wildlife.uni-freiburg.de ORCID: 0000-0002-8024-7008

[19] Forest Ecology and Biogeochemical Cycles Unit, Research and Innovation Centre-Fondazione Edmund Mach, San Michele all'Adige 38010 (TN), Italy, cristiano.vernesi@fmach.it, +39 331 6471339, ORCID 0000-0001-7534-5669

[20]U.S. Geological Survey, Wetland and Aquatic Research Center, 7920 NW 71st St, Gainesville, FL,
32653, USA mhunter@usgs.gov, 001 352 264 3484, ORCID: 0000-0002-4760-9302

* Conservation Genetics Specialist Group, International Union for Conservation of Nature (IUCN), 1196 Gland, Switzerland

^ Group on Earth Observation Biodiversity Observation Network

Abstract

Genetic diversity is critically important for all species- domesticated and wild- to adapt to environmental change, and for ecosystem resilience to extreme events. Nonetheless, assessment and monitoring of genetic diversity are often overlooked, and there are large knowledge and policy gaps regarding genetic biodiversity conservation. International agreements such as the Convention on Biological Diversity (CBD) have committed to conserve, and sustainably and equitably use, all levels of biodiversity- genes, species and ecosystems- in all parts of the planet. In this study, we present, to our knowledge, the first thorough assessment of consideration of genetic diversity by Parties to the CBD. We conducted a detailed, systematic analysis of a large representative sample of CBD 5th (submitted 2014) and 6th (submitted 2018) National Reports to quantitatively assess each country's actions, progress, values and indicators related to genetic diversity. The results highlighted that although the importance of

genetic diversity is recognised by most Parties to the CBD, and that recognition has increased over time, genetic targets mainly concerned genetic diversity within cultivated plants, farm animals, and crop wild relatives, with little focus on other wild species. Actions for conserving genetic diversity were primarily ex-situ facilities, as well as policy, rather than monitoring and intervention for maintaining genetic diversity in situ. The most commonly used indicators of genetic diversity status were the number of genetic resources in conservation facilities, number of threatened breeds and Red List Index, which are not well correlated to genetic erosion in most species- meaning that genetic change is not well monitored by currently used indicators. Analyses of genetic data observations, indigenous use and knowledge of genetic diversity, and strategies being developed and implemented to conserve genetic diversity are highly under-reported. Based on these findings we make several recommendations for the post-2020 CBD Biodiversity Framework, to facilitate improved awareness, assessment and monitoring, and consistent and complete reporting of progress, of genetic diversity in future National Reports.

Introduction

The biodiversity crisis is increasingly urgent as human activities threaten life-supporting ecosystems and natural resources (Galli et al. 2014). In response, most countries have signed on to international accords, such as the Convention on Biological Diversity (CBD), committing to taking action and regularly reporting on progress towards protecting biodiversity. Although biodiversity includes diversity of ecosystems, species and genes, the loss of genetic diversity (genetic and trait differences among individuals and populations within a species) has been relatively underappreciated for decades in both policy and practice, despite its importance (Vernesi et al. 2008, Laikre 2010, Laikre et al. 2010, Holderegger et al. 2019). Genetic diversity provides wild species with the potential to adapt to environmental change (Wernberg et al. 2018), reduces negative inbreeding effects, supports ecosystem structure, integrity and resilience (Lotze et al. 2011), and is the basis for species diversity. It provides society with a range of improvement options for plant and animal breeding to improve agriculture (Bhandari et al. 2017), forestry (Potter et al. 2017), fisheries (Houston et al. 2020) and other biodiversity-dependent industries, and forms the foundation for all other levels of variation (Hughes et al. 2008). Maintaining genetic diversity in domesticated species (e.g. breeds, landraces, and varieties) allows for cultivation/breeding under different environmental conditions and pressures such as pests and disease, which impact productivity (Hoffmann 2010).

Recent analyses show that genetic diversity has declined over the past century (Leigh et al. 2019), that genetically distinct populations are being lost, and that remaining genetic diversity is not well safeguarded *in situ* or *ex situ* (Khoury et al. 2019). Major drivers of genetic diversity loss include climate change, habitat fragmentation and destruction, and overharvest (resulting in small population sizes). In spite of this, biodiversity assessments and reports tend to focus on species-level diversity; within-species genetic variation assessments are limited due to perceived costs and lack of training and standard protocols. However, there are some examples of genetic diversity in biodiversity assessments (Hoban et al 2020; Santamaria and Mendez 2012).

The CBD was first put into force in 1992 following the Rio de Janeiro Earth Summit and is the premier instrument for guiding and measuring global biodiversity conservation, sustainable development, and equity. The CBD's signatory Parties committed to conserving all levels of biodiversity via 21 targets to be achieved by 2010 (CBD 2004), and a new set of 20 targets by 2020 (CBD 2010a). However, the wording of targets emphasized genetic diversity primarily for species of direct human use, especially agricultural ones. The 2010 genetic Target 3 focused on genetic diversity of "crops, livestock, and harvested species of trees, fish and wildlife and other valuable species" and the 2020 Target 13 focused on genetic diversity of "cultivated plants and farmed and domesticated animals and wild relatives, including other socio-economically and culturally valuable species" (CBD 2004; CBD 2010a). Other commitments such as the Global Strategy for Plant Conservation (GSPC) and UN Sustainable Development Goals (SDG) are also primarily related to genetic diversity within agricultural species. The focus of the targets likely influences how countries monitor, manage, and report on genetic diversity. Although genetic diversity is critical to agricultural innovations, resilience and food security, a primary focus on domesticated species could also result in genetic erosion in other species (semi-managed and wild species, including wild relatives of domesticated species) and consequent losses in a range of ecosystem services (Hoban et al 2020). The ongoing post-2020 planning by the CBD will set new goals, targets and indicators for 2030 and 2050; recent drafts of this framework still reflect lack of emphasis, ambition and clarity on genetic diversity conservation (Hoban et al. 2020).

National Reports were developed in 1995 to assess progress in the implementation of the CBD. Since 2000, signatory Parties have been required to submit National Reports every four years to report on their progress towards the CBD targets and on any related national targets that are implemented. These reports assist the Conference of Parties to consider the lessons learned during implementation of the Convention, identify gaps in capacity and analysis at different levels (national, regional, and global), and formulate appropriate requests and guidance to signatory Parties and other related bodies. Each reporting period has a particular set of guidelines e.g. the guidance differs slightly for each reporting period (see Methods and Discussion). Reports are typically compiled by government agencies, such as a Ministry of the Environment, and other relevant stakeholders (CBD website - https://www.cbd.int/reports/). In addition to progress towards CBD and national targets, the reports summarize the status of all levels of biodiversity, threats, advances in sustainable development, and inclusion of indigenous and local communities. Because of their periodic nature, global scope, and common template and guidelines for preparing the document, analyses of National Reports can help evaluate global progress in biodiversity conservation. Previously, National Reports have been analysed to assess: progress towards the implementation of the CBD targets (CBD 2014; Birdlife et al. 2016); national challenges in meeting CBD goals (Chandra & Idrisova 2011); indicators and knowledge gaps towards their use to achieve CBD targets (Bhatt et al 2019); women and gender equality (IUCN GGO 2016; GmbH 2018); success on the implementation of the GSPC (Paton & Lughada 2011); and progress towards protected area management effectiveness targets (Woodley et al. 2012; Coad et al. 2013). Most recently, 5th National Reports were critically assessed to evaluate the status of the natural world and actions needed to conserve

biodiversity and ecosystem services (IPBES 2019).

The consideration of genetic diversity, genetic approaches, or progress towards genetic diversity targets in National Reports has not yet been systematically analyzed. In fact, genetic diversity has been noted as one of the principal data gaps to assessing biodiversity progress (OECD 2019). In previous analyses of National Reports, genetic diversity was mentioned primarily in the context of conservation of genetic diversity of agricultural species for global food security (IPBES 2019; CBD 2014). Reference to the importance of conservation of genetic diversity of wild species, without a link to agricultural species, is rare (see CBD Secretariat 2007; OECD 2019). In the context of Aichi Target 16 (benefits and sharing of genetic resources), data gaps to monitor genetic diversity were also mentioned (Aguilar-Støen & Dhillion 2003). The scant analysis of genetic diversity in these reports may be due to challenges in using genetic information for measuring CBD target progress (Chandra & Idrisova 2011), and lack of metrics for monitoring genetic diversity (Bubb et al. 2011; Walpole et al. 2009; OECD 2019).

In this context, we systematically assessed the consideration of genetic diversity in a large representative sample of 5th and 6th CBD National Reports from 2014 and 2018, to gain a better understanding of how countries are assessing genetic diversity and its protection in agricultural and natural ecosystems. This analysis contributes to a general understanding of how genetic diversity is considered in global biodiversity assessments, following numerous calls to increase such consideration (Shafer et al. 2015; Taylor et al. 2017; Hoban et al. 2020; Laikre et al. 2020). It also provides a basis for suggesting improvements to future reporting on genetic diversity. Our specific aims were to analyze 5th and 6th National Reports to:

- Assess targets pertaining to genetic diversity, and which indicators (i.e., measures used to present a high level summary) are used to assess status (present state) and trends (change) in biodiversity
- Quantify the reporting of genetic diversity actions (e.g., management interventions, policy, funding, capacity building, training), threats (e.g., concerns or drivers of change such as habitat fragmentation), and values (e.g., utility or benefits)
- Quantify the frequency with which different types of species are mentioned in reference to genetic diversity
- Determine whether the variables we assess change across time (as genetic diversity data has become more affordable and is recognized as more important) and across socio-economic categories (due to funds available).

Methods

We reviewed 57 5th National Reports (NR) and 57 6th NR (9 in Spanish, 10 in French, and 38 in English) available prior to 1 July 2019 (see Supplemental Document A, Questionnaire Development) obtained from the CBD Clearinghouse (https://chm.cbd.int/). We evaluated reports using a structured questionnaire composed of standardized questions (hereafter “questionnaire”) developed over several review phases of both the protocol and the questionnaire in 2019. We devised the set of questions based on the CBD instructions to Parties on how to prepare their reports (https://www.cbd.int/reports/). We limited our questions

to thematic sections that were common between the 5th and 6th NRs (CBD 2010b, 2014). The list of questions and an explanation of how each question matches the CBD instructions is in the Supplemental Document B. Every question had a corresponding detailed set of instructions to help with consistent interpretation and completion of the questionnaire among reviewers.

The final questionnaire had 13 questions for each report. In this manuscript, we focus on 9 of these questions (Table 1), leaving the remainder to investigate in future manuscripts. This questionnaire was filled out by a set of experts (the authors of this manuscript) in population genetics and applied conservation genetics (hereafter "reviewers"), following a protocol similar to Pierson et al. (2016), Bhatt et al. (2019), and Chandra and Idrisova (2011). Each reviewer evaluated six to eight reports split between 5th and 6th NRs (with no reviewer evaluating both 5th and 6th reports from a single country). We allocated reports to reviewers to ensure that each had reports from multiple continents and differing levels of economic income (according to the IMF: see Nielsen 2011). In addition to reading the report "cover to cover," the reviewers also performed a keyword search, querying the document for 15 pre-determined genetic diversity-related keywords (in the relevant report language, see Supplemental Document A). After reading, highlighting and taking notes on each report, the reviewer completed the questionnaire (via a Google Form and then compiled in a .csv file).

Question from questionnaire	**Notes**
Is genetic diversity (e.g., genetic threats, genetics-related policy or gene conservation actions, essentially any genetic content) mentioned in the executive summary?	Reviewers chose from multiple categories representing genetic diversity (e.g., agrobiodiversity, population genetics, biotechnology)
Is the importance or utility of genetic diversity noted, and if yes, how?	Eleven categories and an "other" response were provided; reviewers could select as many as applicable
Is there a national-level target focused on "conserving/ maintaining genetic diversity," "genetic erosion," "genetic resources," "genetic loss," etc. (e.g., a national target similar to Aichi Target 13)?	Reviewers answered Yes or No; if Yes, they were asked to determine if the target applied to agricultural, socio-economically important, or all species
Is there a different national-level target that REFERS to "genetic diversity," "genetic erosion," "genetic resources," "genetic loss," or other genetics related terms or genetic data?	Reviewers were asked if genetic diversity is mentioned under Target 16* (access and benefits) or any other targets (and to specify which one)
What is the degree of progress reported regarding Aichi Target 13, or if Aichi progress is not reported, then progress on the national target corresponding to the Aichi Target 13, if one can be identified?	Reviewers selected one of 6 categories of progress; these categories were defined in Instructions to the 6th National Report, but not in the 5th National Report; thus, for the 5th National Report, reviewers were asked to select the closest applicable degree of progress

Is the STATUS** of genetic diversity reported on? Is the TREND of genetic diversity reported on?	Fifteen indicators (including eight previously recommended by the CBD) and an "other" response were provided for both status and trends; reviewers could select as many as applicable and categorized each as "qualitative" or "quantitative"; trends were also categorized as "increasing", "decreasing", or "no change"
Are there actions planned regarding genetic diversity or actions taken regarding genetic diversity, in or by this country?	Eleven categories of action and an "other" response were provided; reviewers could select as many as applicable and categorized each as "general" or "specific"
What genetic threats/ pressures/ drivers are reported- according to the report authors (potential or actual, measured or not)?	Eleven categories of threats and an "other" response were provided; reviewers could select as many as applicable
The reviewer should identify any mention of species, genera, or species groups that can be placed in one of the categories below, in the context of genetic diversity	For each mention of a species, the reviewer recorded the category (e.g., domesticated animal, species of concern, forestry, culturally important, etc.) and categorized the mention as relating to actions, status, threat, trend, or other

Table 1: The questions that reviewers answered for this study.
*Aichi Target 16 calls on countries to enact legislation implementing the Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization
**Status refers to a single time point while trend refers to either a change, or status at two time points, from which a change can be inferred.

We made a strong effort to standardize the review approach and to provide precise instructions and examples for reviewers. However, we acknowledge that each reviewer has a unique background, training, and expertise and there could be room for some level of interpretation in reviewing National Reports. To maximize standardization of questionnaire completion, we had several scoping phases to check agreement among reviewers and discussed disagreements as a group. Additionally, 15 reports (eight for 6th NR and seven for 5th NR) were reviewed independently by two reviewers to ensure consistency in interpretation (see Supplemental Document A, Agreement Among Reviewers).

All data were analyzed in R v3.6.3. To analyse the questionnaire responses, we first tabulated the number of reports with each potential answer. We compared the *proportion* of responses for each question between the 5th and 6th NRs using Fisher's exact tests (for example, we determined whether the proportions in each category of indicators, e.g. the relative length of each bar in Figure 1, differed between the reports). We also compared the mean *number* of responses recorded between the 5th and 6th NRs (for example the number of times that indicators were identified, the sum of the lengths of bars in Figure 1) using paired t-tests when data met the conditions of normality and Wilcoxon tests when not. Responses from low, medium, and high income countries (according to the IMF) were also compared; significance

was tested for 5th and 6th NRs separately and pooled together.

Results

Throughout the results section, differences between 5th and 6th National Reports (NR) are only reported if statistically significantly different. Briefly, no contingency tests for comparing whether the categories changed between the 5th and 6th NRs were significant (i.e., no temporal change in proportion of responses in each answer category). The t-tests for the number of responses are noted if significant. All *p* values (significant and not significant) are reported in Supplemental Document A, Table S2.

Genetic diversity in executive summary. A majority (82%) of countries contained an executive summary for the 5th NR. Of these, 60% mentioned genetic keywords relating to agrobiodiversity (e.g., gene banks, breeds, or varieties); 40% mentioned genetic studies, gene conservation actions, or genetic processes; and 34% mentioned biotechnology or access to and benefit sharing of genetic resources.

Values of genetic diversity. The most frequently noted values of genetic diversity included resilience to environmental or climate change (37% 5NR, 30% 6NR), increasing productivity in agriculture/ forestry/ fisheries (37% 5NR, 30% 6NR), developing new varieties in these sectors (26% 5NR, 25% 6NR), and adaptation to environmental change (26% 5NR, 23% 6NR, see Supplemental Document A Table S4). There were 34% more mentions of values of genetic diversity in the 5th NR compared to the 6th NR (p=0.04).

Genetic diversity targets wording and progress. Of the 57 countries reviewed, 70% and 79% referred to a national-level genetic diversity target in the 5th and 6th NRs, respectively. Many NRs (47% 5NR, 69% 6NR) mentioned other socio-economically important (e.g., not only agricultural) species relating to this genetic diversity target, while a smaller percentage included wording that could refer to species that do not have economic importance (21% 5NR, 38% 6NR). For target progress, the most commonly reported progress was “Some progress but insufficient” (57% 5NR, 44% 6NR), followed by “on track to achieve” (30% 5NR, 38% 6NR). Most countries also mentioned genetic diversity under Aichi Target 16, which regards access to and benefit-sharing of genetic resources (56% 5NR, 60% 6NR).

Genetic diversity in other targets. This question assessed the extent to which countries identify genetic diversity as a concern, tool, or opportunity in association with any target other than Targets 13 and 16 (topics such as human well-being, protected areas, education, science capacity, and mainstreaming biodiversity). The number of countries with references to genetics, associated with at least one Aichi target other than Targets 13 and 16, increased over time (19% 5NR, 49% 6NR), a significant increase of more than 2.5 times (p=0.001). In addition, the number of targets for which at least one country included a genetics-related reference increased over time. Genetics was mentioned at least once under 13 different ‘other’ Aichi targets in the 5th NR, but under 19 ‘other’ targets in the 6th NR, a significant increase (p=0.044) of almost 50%.

Several targets are of note. In the 6th NR, 16% of countries mentioned genetics in relation to both Targets 12 and 18, and 19% mentioned genetics for Target 19. Target 12 focuses on the prevention of threatened species extinction, 18 on the preservation and application of traditional knowledge relevant to conserving and sustainable use of biodiversity, and 19 on the improvement and application of knowledge relating to the value, functioning, and status of biodiversity. Only Target 8 (controlling pollution) had no reference to genetics by any country.

Indicators used for genetic diversity status and trends. The most commonly mentioned indicators of status were the number of genetic resources in conservation facilities (Fig. 1, and Supplemental Document A, Table S7), the number of plant genetic resources known/surveyed, and the Red List status. Note that these indicators are loosely, or not at all, connected to genetic diversity change. Meanwhile, the state of preservation of indigenous/local knowledge of genetic diversity was rarely reported, as were metrics from analysis of DNA/genetic markers.

Trends were mentioned half as often as status, and showed a mix of increasing, decreasing, and no change. A strong trend was only seen for "the genetic resources secured *ex situ*" which were typically reported as increasing (Supplemental Document A, Table S8)

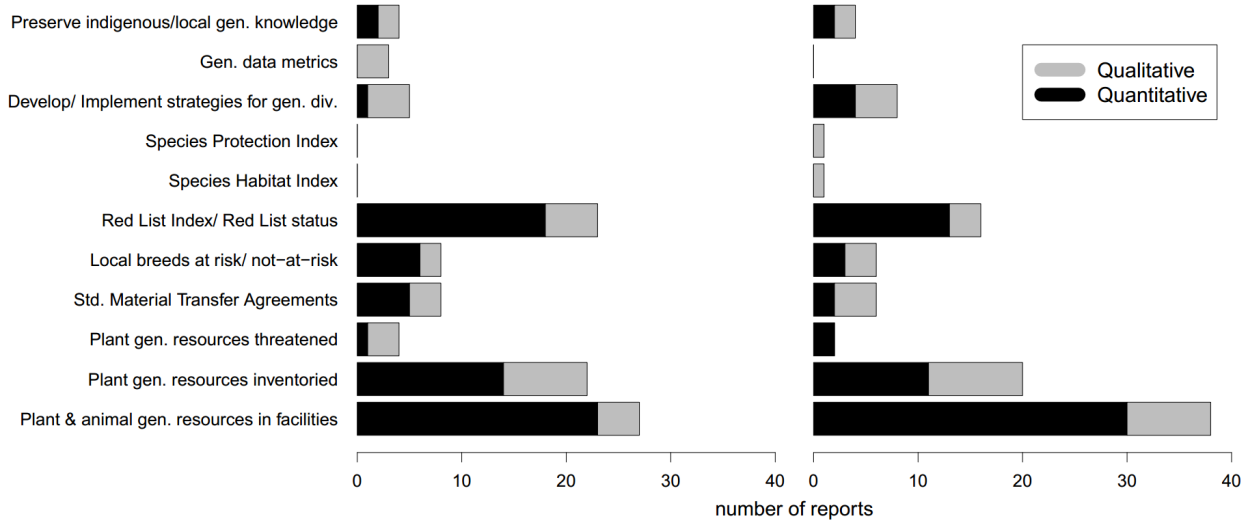

Figure 1: Number of 5th (left) and 6th (right) National Reports (NR) that include each indicator of genetic status with a Quantitative (numeric, such as a percentage) or Qualitative (descriptive, such as "high" or "low") value.

Actions. The most common genetic diversity actions (Fig. 2) were establishing seed banks, research agencies or breeding programs, and laws or policies. Single time point genetic studies and genetic monitoring were rare.

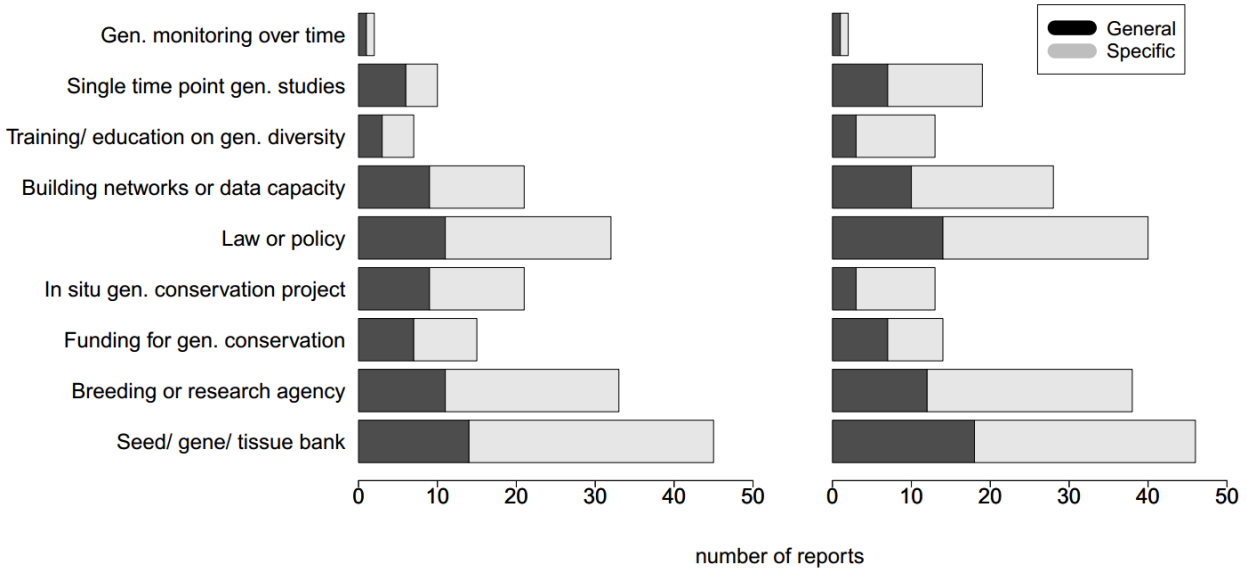

Figure 2: Number of 5th (left) and 6th (right) National Reports that report each type of genetic diversity action with General (e.g. non-specific action, black) or Specific (grey) information.

Threats. National Reports documented a variety of recognized threats to genetic diversity. The most common threats in the NRs were replacement of native varieties or breeds, habitat fragmentation, and climate or environmental change (Supplemental Document A, Table S9). Other typical conservation genetic concerns were also mentioned, including decrease in range size, overharvest, pests or other invasive species, small population problems, genetic modification, and hybridization. A higher number of threats were identified in the 5th NR than the 6th NR (p=0.02).

Species mentioned. The top three species types (Fig. 3 and Supplemental Document A, Table S11) mentioned were cultivated crops and farm animals (both >20% in both reports). These were followed closely by crop wild relatives, forestry species, and species of conservation concern (all >9% in both reports). There were few references to “other socio-economically important species” such as wild-harvested plant and animal species, species providing ecosystem services, and culturally valuable species (each <5% in both reports). There were few mentions of wild relatives of domesticated animals (4% both reports). Species were most frequently acknowledged in relation to “actions,” followed by mentions relating to “threat” or “status” of genetic diversity. References of species with respect to “change” in genetic diversity were rare.

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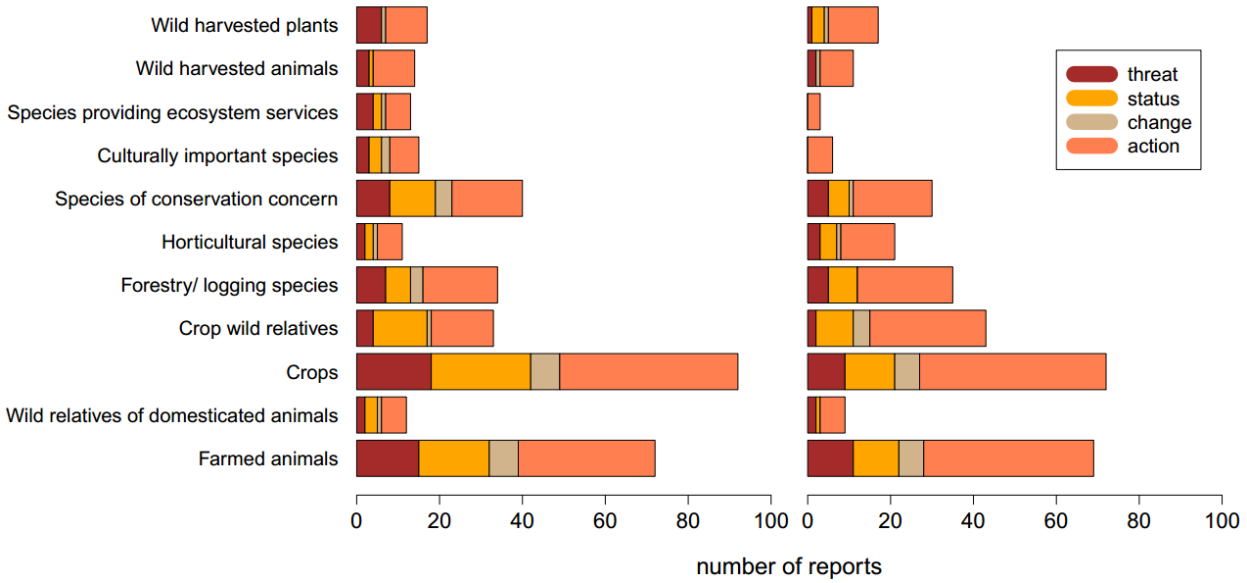

Figure 3: Number of mentions (x-axis) of each species type (y-axis) in four different contexts (whether the mention of the species' genetic diversity related to a threat, status, change, or action) for each report.

Differences related to income levels of countries. Differences in countries' responses according to their income level were tested for all questions. Differences were only observed in three areas: mentions of genetic diversity in relation to targets other than Aichi Targets 13 and 16, threats, and species types.

Low-income and middle-income countries were more likely than high-income countries to mention genetics in relation to genetic diversity targets, genetic resources targets, and in targets other than Aichi Targets 13 and 16, though none of these results were significant (see Supplemental Document A, Socioeconomic status).

There were no significant differences among income level categories in the number of mentions of threats, but there were significant differences in the proportion of categories of threat. Specifically, middle- and low-income countries' NRs had fewer mentions of small population size and habitat fragmentation as threats to genetic diversity, but more mentions of replacement of traditional varieties as a threat (significant only when 5th and 6th NRs are pooled, p=0.04).

As for species type, middle- and low-income countries had fewer mentions of species of conservation concern and species providing ecosystem services in their NRs, but had more mentions of horticultural species, compared to high income countries (only marginally significant when 5th and 6th NRs are pooled, p=0.08).

Discussion

Genetic diversity provides species with adaptive potential, and contributes to the resilience and functioning of ecosystems (Prieto et al. 2015; Raffard et al. 2019). The need to maintain genetic diversity to counter current global crises (climate, biodiversity loss, hunger) is well established (e.g. Di Falco & Perrings 2003; Spielman et al. 2004; Frankham 2005; Ehlers et al. 2008; Casadebaig et al. 2014; Sjöqvist & Kremp 2016). If countries are to design effective targets and interventions for this goal, they need to adequately report on genetic diversity. CBD National Reports are an essential information source, and reveal how countries value, monitor, and manage biodiversity (CBD 2000). For both the 5th and 6th CBD reports we found that most countries did mention the importance of genetic diversity. However, where status and actions relating to genetic diversity were reported, they primarily referred to agricultural species, and used indicators that are not well connected to genetic diversity status or change. There were also only minor differences in findings for the 5th vs. 6th Report, reflecting consistency over time. Below, we discuss the findings and how they point to improved future National Reports and genetic diversity Targets, indicators and capacity.

Genetic diversity Targets

Encouragingly, most countries have sufficient awareness of genetic diversity to include it in the Executive Summary and to have a genetic diversity National Target. Numerous benefits of genetic diversity were recognised, including maintaining ecosystem stability or services, food production, and pest/disease resistance. National Targets largely, but not always, focused on agricultural species, which aligns with how Aichi Targets 13 and 16 approach genetic diversity. The high (and increasing over time) number of reports linking genetic diversity to Target 12 (prevention of species' extinctions) may reflect increasing recognition of genetic diversity's role in supporting species survival (Booy et al. 2000; Frankham 2010; Sgrò et al. 2011). Meanwhile, references to genetic diversity in Targets 18 (recognition, respect and integration of "traditional knowledge, innovations and practices of indigenous and local communities") and 19 (improving and sharing scientific knowledge relating to biodiversity and its "values, functioning, status and trends, and the consequences of its loss") may reflect increasing recognition of the importance of indigenous and scientific knowledge of genetic diversity and/or genetic resources (Talaat et al. 2012).

Low- and middle-income countries were more likely than high-income countries to discuss genetic diversity in relation to targets other than Aichi Targets 13 and 16. This may reflect higher relative interest in knowledge transfer and greater recognition of traditional ecological knowledge by these countries (FAO 2009). Nonetheless, the importance of genetic diversity and the use of genetic tools are still rarely mentioned. We emphasize a need for increased knowledge of, capacity development, and access to genetic data for practical use (Recommendations 1 and 2 below). Scientists must ensure that assessments of genetic diversity should be effectively communicated to managers and policy makers (Peréz-Espona and ConGRESS 2017, Lundmark et al. 2019). It is also incumbent upon policy makers (in CBD and beyond) to explicitly state that genetic diversity is important for multiple targets in its reporting guidance, as recently mentioned for sustainable fisheries in the CBD draft monitoring framework (REF) (Recommendation 7).

Genetic diversity indicators

The number of genetic resources in conservation facilities, the number of plant genetic resources known/surveyed, and the Red List were commonly-mentioned indicators of the status of genetic diversity. These indicators are recommended by the CBD (CBD 2010c), but their prevalence probably also reflects data availability in existing national and international databases. The first two indicators also likely reflect Aichi Target 13's emphasis on agricultural species, and the importance of genetic resources for national food security (Esquinas-Alcázar 2005; Khoury et al. 2014). Despite their status as official genetic CBD indicators, they don't directly assess genetic diversity and are at best loosely connected to genetic change Hoban et al. (2020). Our reviews also highlight the need for consistent and appropriate terminology relating to genetic biodiversity (Recommendation 6). For example, the term "genetic resources" merely reflects that the material contains hereditary information (DNA) and can be propagated, but does not always pertain to within-species genetic diversity- sometimes it refers to species diversity. This and other terms are often used by reporting countries as a substitute for true genetic diversity monitoring.

Only 5% of countries referenced DNA-based studies (e.g. genetic statistics) or recorded indigenous and local knowledge of genetic diversity. This is likely because there are no official CBD indicators based on genetic markers or indigenous knowledge of genetic biodiversity (CBD 2010c). Further, Indicator uptake and reporting depend on availability of data on baselines and trends, as well as capacity (resources, technical expertise, and management) (Bubb 2013; Vanhove et al. 2017). Similarly, only 13% of countries reported measures to develop or implement strategies for minimizing genetic erosion, even though Target 13 calls for such strategies. One limiting factor may be that there is no available database on, or guidance on how to develop and apply, such strategies. Anecdotal reports of indigenous and local knowledge of genetic diversity occur in several reports (e.g. Antigua & Barbuda: "local communities are considered to be the first line of defence and will report instances of removing genetic diversity"; Myanmar: "hotspots of crop wild relatives identified through farmers"), suggesting that indicators are needed on this topic (Recommendation 3).

Our analysis follows previous assessments of the use of genetics in national and international conservation policy and reporting, including in species action plans, biodiversity legislation, etc. (Laikre 2010; Pierson et al. 2016). While genetic diversity often has relatively straightforward applications to management, it is more difficult to assess and report on genetic diversity change for policy (OECD 2019, SCB 2020), and consequently pragmatic substitutes for genetic diversity are sometimes used as Indicators. For example, the Montréal Process (an international forest sustainability framework) includes three "genetic diversity" indicators that focus on: species at risk of losing genetic variation; population levels of forest-associated species; and the status of on-site and off-site gene conservation efforts (Montréal Process 2015). Similarly, the Forest Europe sustainable forest framework includes a genetic diversity indicator that quantifies the area managed for the conservation and utilization of forest tree genetic resources (Ministerial Conference on the Protection of Forests in Europe 2015). Overall, the paucity of references to reliable indicators of genetic diversity shows that the scientific community needs to develop

affordable, standardized indicators that clearly track genetic change (Hoban et al. 2020; Laikre et al. 2020) (Recommendation 5).

Genetic diversity actions

The most common genetic diversity actions reported were *ex situ* strategies (seed banks, research agencies, breeding programs, laws, etc.). Less common, but still mentioned were *in situ* actions (developing *in situ* genetic conservation projects, single time point genetic studies). The lower frequency of these actions may reflect the same constraints on capacity, knowledge, and funding constraints previously mentioned. While *ex situ* actions, as well as laws and policies, are important to forestall the absolute loss of genetic diversity (Mastretta-Yanes et al. 2018; Hoban 2019), they cannot be relied upon exclusively, because only a limited representation of species and their genetic diversity can be maintained *ex situ* (Hoban 2019, Castañeda-Álvarez et al. 2016; Fant et al. 2016), and sustaining genetic diversity *in situ* is important to allow for natural processes such as adaptation to environmental change (Reusch et al. 2005; Sgrò et al. 2011; Smith et al. 2014). Further, while *ex situ* actions may help address one of the threats to genetic diversity frequently mentioned in National Reports (replacement of native varieties or breeds), they do not address two other major reported threats (habitat fragmentation and climate or environmental change). More analysis will be needed to explore linkages between actions and threats.

Despite their importance for conserving genetic diversity, genetic data (as indicators) and genetic monitoring (as an action) were mostly absent from the reports, even though genetic monitoring programs exist (e.g. trees across Europe: Aravanopoulos et al. 2015; Chinook salmon in California: Meek et al. 2016; European sturgeon in France: Roques et al. 2018; grey wolves in Switzerland: Dufresnes et al. 2019). These findings complement the observation by Pierson et al. (2016) that European countries rarely include genetic diversity data and monitoring in species recovery plans due to a lack of legislative requirements, as well as relatively limited input or involvement of geneticists (Taft et al. 2020). Also, assessing and reporting on change in genetic diversity typically requires standardized genetic monitoring across long-term (i.e., multi-decadal) time frames (Hoban et al. 2014; Le Cam et al. 2015; Mathieu-Bégné et al. 2019). Although such work is hindered by resources, capacity, funding cycles and strategic planning timeframes, it is vital- increased monitoring investment has the added benefit of increased competency and collaboration for managers and policy makers within and between countries. Overall, the limited number of long-term monitoring programs precludes our understanding of genetic diversity status and trends and undermines the goals of the CBD and other international commitments.

Types of species

References to genetic diversity in the CBD National Reports were biased towards certain categories of species. National Reports most commonly mentioned genetic diversity of cultivated crops and farm animals. Genetic diversity of crop wild relatives, forestry species, and species of conservation concern was discussed to a lesser degree, while there were few mentions of “other socio-economically important species” such as wild harvested species, species providing ecosystem services, and culturally valuable species. Trends in one

organismal group may be quite different from another (e.g. Outhwaite et al. 2020)- species groups for monitoring need to be discerned carefully using the best available scientific and local knowledge. There were limited mentions of genetic diversity in wild relatives of domesticated animals, possibly because the small number of domesticated animals means there are just fewer wild relatives. Our observations may reflect the relative emphasis of the Target 13 wording, as well as a focus on economic values. We support calls for the CBD to explicitly state the importance of maintaining genetic diversity of all species (Laikre et al. 2020), as agriculturally valuable species make up a small fraction of life on Earth (Recommendation 4).

Change over time

The relative *frequencies* in each category or response for all questions were not significantly different between 5th and 6th Reports. For example, reporting on "seed/tissue/gene banks" was the most frequent action in both Reports. This suggests that the focus and priorities of countries, regarding genetic diversity, have not shifted substantially over this four-year period (an admittedly short time for biodiversity). However, the total *number* of responses varied in some cases between 5th and 6th National Reports, e.g. the total numbers of actions identified.

First, the 6th Report contained significantly more mentions of genetic diversity topics under Targets not specifically focused on genetic diversity (i.e. Targets other than 13 and 16). Instructions did not ask countries to mention genetics with respect to other Targets in either report, so this increase may be attributable to increasing affordability of genetic tools and knowledge of genetic diversity, and to numerous calls for consideration of genetics in biodiversity policy (Pierson et al. 2016; Shafer et al. 2015; Taylor et al. 2017; Hoban et al. 2020; Laikre et al. 2020). Second, significantly more trends, values, and threats to genetic diversity were identified in 5th Reports (even though 6th Reports were longer). This could be because instructions for 5th National Reports provided more detail about these aspects (see Supplemental Document B). If this is true, it emphasizes strongly that the wording of CBD instructions (not just Targets) is extremely important for reporting (Recommendations 4, 6 and 7). An alternative explanation is decreased interest or expertise in genetic diversity in report writers over time.

We also note that Trends were reported less than half as often as Status- National Reports are seriously lacking in a clear temporal comparison of progress over time, as noted by (REF), further emphasizing a need for monitoring and reporting of genetic diversity (Recommendations 5 and 7).

Caveats

We acknowledge several methodological caveats. Although the CBD intended consistency for the 5th and 6th NRs to facilitate tracking progress (https://www.cbd.int/reports/guidelines/), the structure and format of the 6th NR are somewhat different. Therefore, in our study we focused on equivalent sections between the reports: status, threats, actions, obstacles, and progress towards the different biodiversity conservation targets (Supplemental Doc B). It is also very important to note that National Reports do not reflect all conservation actions or knowledge in a particular country, but are summaries of activities and progress, and might represent a country's

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priorities, as well as data availability. Genetic research may be poorly understood or known by some government officers involved in CBD reporting, or some officers may lack sufficient access to data or genetics expertise when preparing the reports. This means that there may be discrepancies between reported progress and actions, and actual progress within countries (i.e. some countries may have achieved more or less than they reported, see Recommendation 7). However, at this stage there is no comparable global data set that could be used to track how countries assess their genetic diversity, and despite these caveats, we were able to analyse data provided in National Reports and discuss patterns and trends in reporting.

Recommendations/ Conclusions

We close with recommendations for actions that may address issues we uncovered in our detailed survey of 114 National Reports. Our assessment suggests future improvements to the guidelines and format of National Reports, and to improved measures for assessing genetic diversity especially for the post-2020 CBD Biodiversity Framework.

Our results highlight that:

1. There is a need to increase awareness and knowledge of the essential role of genetic diversity in biodiversity, and of the benefits it brings to nature and people. Knowledge sharing should be encouraged through education, networking, and capacity building initiatives. Assessments of genetic diversity in agricultural and natural systems must be communicated to policy makers and conservation managers, and the effectiveness of such science-policy communication should be measured (e.g. Lundmark et al. 2019).
2. Better reporting on genetic diversity in wild species, including long-term monitoring to evaluate trends, is essential for effective biodiversity conservation. This must be practical for all countries, not simply those with highly-developed scientific infrastructure. Collaborations with geneticists would allow for guidance on cost-effective monitoring including sampling strategies and genetic markers.
3. There is a need for greater understanding of, and more reporting on, genetic diversity relating to traditional ecological knowledge. Databases and indicators for this area are needed.

We also discuss recommendations for CBD reporting, including NRs, post 2020. Signatory countries and the CBD Secretariat invest significant resources in designing, producing, and showcasing reports, so it is beneficial for reports to be informative to enable comparisons of progress over time.

4. Reporting on genetic diversity in ecologically and culturally important species, not just species associated with agriculture, is essential (Laikre et al 2020; Hoban et al 2020) to result in stable and resilient ecosystems. We recommend that the CBD requests discussion of targets, status, threats, and actions relating to genetic diversity in each category of species mentioned above (including culturally-important species, species providing ecosystem services, and species of conservation concern, Fig 3). This would increase the diversity of species represented in NRs.
5. We support recent suggestions to improve the CBD's 2020 zero draft genetic goals, action targets, and genetic diversity indicators including the measurement of effective

population size and changes to geographic range (Hoban et al. 2020; Laikre et al. 2020). Genetic diversity indicators must be easy to quantify but must also reliably reflect changes in genetic diversity and enable evaluation of actions taken to protect and restore genetic diversity.

6. We recommend that the CBD adopts improved and consistent terminology relating to genetic diversity and genetic methods. These should be communicated in the reporting instructions via glossaries, with examples, in all languages in which reports may be submitted (and more languages if possible). This should improve consistency in reporting, and awareness of genetics and its importance to conservation.
7. We suggest that amendments to the structure of NRs, and to their instructions, would provide greater guidance to countries on what to report and how, and would enable clearer comparisons of reporting on genetic diversity (and other metrics) among countries and over time. As one example, NR formatting could include lists of actions performed, or categories of species discussed, which can be "checked off" in the report. At the same time, to allow unstructured information, the CBD could encourage the inclusion of published reports and/or descriptions of case studies.

Implementing these recommendations in future CBD National Reports should increase reporting of indicators, actions, and progress towards the protection of genetic diversity in all species, as well as consideration of genetic diversity in other targets. The gaps that we demonstrate are also an opportunity for CBD to facilitate capacity building and international collaboration, and equip countries to monitor genetic diversity post-2020.

Lastly, to ensure recognition and protection of the fundamental role that genetic diversity has in biodiversity, conservation geneticists and managers should be included among scientific experts consulted in policy making and reporting. Reciprocally, conservation geneticists need to actively present their expertise at the science-policy interface, in order to effectively preserve that part of biodiversity so often forgotten.

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Glossary

- Action – an activity undertaken (or planned to be undertaken) by a country to make progress towards one or more targets, for example: development of policy; management intervention; training; implementation of a conservation program
- Aichi targets – a set of 20 targets agreed by the CBD to be achieved by 2020
- CBD – The Convention on Biological Diversity
- Genetic diversity – inherited genetic and trait differences among individuals and populations within a species
- Genetic erosion – a loss of genetic diversity
- Genetic resource – refers to genetic material of actual or potential value. Genetic material is any material of plant, animal, microbial or other origin containing functional units of heredity (CBD, Art 2). Animals, plants, micro-organisms and invertebrates which are used for Food, Agriculture and Forestry are called Genetic Resources. Together with the components which fulfill agri-ecological functions they are grouped under the concept Agrobiodiversity.
- GSPC – Global Strategy for Plant Conservation
- Indicator – a measure used to present a high level summary of biodiversity; we include in our questionnaire both "official" CBD indicators (REF) and other indicators

- National Reports – reports submitted by signatories (countries) to the CBD every 4 years to outline progress towards CBD and national targets: 5th Reports were submitted in 2014 and 6th Reports were submitted in 2018
- National targets - targets that each country sets for themselves: a national-level interpretation of the 20 CBD Aichi targets
- Progress – an assessment of whether a country considers itself as on track to meet a CBD or national target, for example: “on track to achieve”; “some progress but insufficient”; “moving away”
- SDG – Sustainable Development Goals
- Status – a measure of genetic diversity (or more frequently a proxy assumed to relate to it) at a single time point, e.g., the number of seeds in a seed bank at a given point in time.
- Target -
- Threat – a process or driver of change that is, or has potential to be, detrimental to genetic diversity
- Trend – a measure of change in status over a period of time, i.e. an observation that status has increased, decreased, or has not changed.
- Value – a perceived utility or benefit obtained from genetic diversity