



Policy analysis

Genetic diversity is considered important but interpreted narrowly in country reports to the Convention on Biological Diversity: Current actions and indicators are insufficient



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ABSTRACT

International agreements such as the Convention on Biological Diversity (CBD) have committed to conserve, and sustainably and equitably use, biodiversity. The CBD is a vital instrument for global conservation because it guides 195 countries and the European Union in setting priorities and allocating resources, and requires regular reporting on progress. However, the CBD and similar policy agreements have often neglected genetic diversity.

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Genetic monitoring
Target 13
Indicators

This is a critical gap because genetic diversity underlies adaptation to environmental change and ecosystem resilience. Here we aim to inform future policy, monitoring, and reporting efforts focused on limiting biodiversity loss by conducting the largest yet evaluation of how Parties to the CBD report on genetic diversity. A large, globally representative sample of 114 CBD National Reports was examined to assess reported actions, progress, values and indicators related to genetic diversity. Although the importance of genetic diversity is recognized by most Parties to the CBD, genetic diversity targets mainly addressed variation within crops and livestock (a small fraction of all species). Reported actions to conserve genetic diversity primarily concerned ex situ facilities and legislation, rather than monitoring and in situ intervention. The most commonly reported status indicators are not well correlated to maintaining genetic diversity. Lastly, few reports mentioned genetic monitoring using DNA data, indigenous use and knowledge of genetic diversity, or development of strategies to conserve genetic diversity. We make several recommendations for the post-2020 CBD Biodiversity Framework, and similar efforts such as IPBES, to improve awareness, assessment, and monitoring of genetic diversity, and facilitate consistent and complete reporting in the future.

1. Introduction

Actions to halt the biodiversity crisis are increasingly urgent as human activities threaten life-supporting ecosystems and natural resources (Galli et al., 2014). In response, most countries have signed international accords, such as the United Nations Convention on Biological Diversity (CBD, <https://www.cbd.int/>), committing to taking action and regularly reporting on progress towards protecting biodiversity. Although biodiversity includes diversity at the level of ecosystems, species, and DNA, 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 (Vernesi et al., 2008; Laikre, 2010; Holderegger et al., 2019).

Higher levels of genetic diversity reduce negative inbreeding effects in populations (Frankham, 2005), provide wild species with the potential to adapt to environmental change (Sgrò et al., 2011; Wernberg et al., 2018; Carroll et al., 2014), support community structure and ecosystem functions, integrity and resilience (Lotze et al., 2011; Raffard et al., 2019; Hughes et al., 2008), and are the basis for many of nature's contributions to people (Des Roches et al., 2021; Díaz et al., 2018; IPBES, 2019; Stange et al., 2021). Genetic diversity provides society with a range of options for plant and animal breeding to improve productivity and resilience in agriculture (Bhandari et al., 2017), forestry (Potter et al., 2017), fisheries (Houston et al., 2020) and other biodiversity-dependent sectors (e.g. medicine, engineering). Recent analyses show that genetic diversity has declined globally over the past century in wild populations (Leigh et al., 2019), that geographic ranges are shrinking, resulting in dramatic losses of genetically distinct populations for most species (Ceballos et al., 2017), and that remaining genetic diversity is not well safeguarded in situ or ex situ (Khoury et al., 2019; Hoban et al., 2020b). Major drivers of genetic diversity loss include climate change, habitat fragmentation and destruction, overharvest, and reduction of population sizes (IPBES, 2019; CBD, 2014; DiBattista, 2008; Aguilar et al., 2008; Pinsky and Palumbi, 2014; Schlaepfer et al., 2018). In spite of this, biodiversity assessments often exclude genetic diversity (Vernesi et al., 2008; Laikre et al., 2010; Pierson et al., 2016), with some exceptions (see Santamaría and Mendez, 2012).

The CBD is a global and legally-binding instrument, put into effect in 1993, on biodiversity conservation, sustainable development, and equity. The CBD's 196 signatory Parties (195 countries plus the European Union) 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, 2010). The CBD framework and targets help member countries to guide policy, allocate resources to needs, motivate and enable action, and measure progress. Because they drive policy focus and funding, it is critical that targets and goals of CBD and other entities be comprehensive and ambitious. However, the wording of prior CBD targets emphasized genetic diversity primarily for species of direct human use, especially agricultural species (Hoban et al., 2020a). The 2010 Target 3 focused on "crops, livestock, and harvested species of trees, fish and

wildlife and other valuable species" and the 2020 Target 13 focused on "cultivated plants and farmed and domesticated animals and wild relatives, including other socio-economically and culturally valuable species" (CBD, 2004; CBD, 2010). Other commitments such as the Global Strategy for Plant Conservation (GSPC, a program under the CBD, <https://www.cbd.int/gspc/targets.shtml>) and the UN Sustainable Development Goals (<https://sdgs.un.org/>) also primarily focus on genetic diversity within agricultural species. It has been suggested that if investment is focused entirely or mostly on protecting genetic diversity in domesticated or economically important species, the genetic diversity of wild species may go unmonitored and unprotected (Laikre, 2010).

Since 2000, signatory Parties have been required to submit National Reports approximately every four years on their progress towards CBD targets and have implemented National Targets. Reports are typically compiled by government agencies, such as Ministries of the Environment, and other relevant stakeholders. In addition to reporting progress on targets, these reports summarize biodiversity status, threats, advances in sustainable development, and inclusion of indigenous and local communities (CBD, 2014). These reports help evaluate the status of biodiversity conservation including progress towards the implementation of the CBD targets, communicate lessons learned during implementation of the Convention, identify gaps in capacity, and formulate appropriate requests and guidance to Parties and stakeholders (CBD, 2014; Birdlife et al., 2016; IPBES, 2019).

Because National Reports are submitted periodically by most Parties, and follow a common template provided by the CBD, they are also a unique source of information that can indicate biodiversity conservation priorities for each signatory Party, and identify data gaps and policy shortcomings. Previously, National Reports have been analyzed to assess national challenges in meeting CBD goals (Chandra and Idrisova, 2011), indicators and knowledge gaps towards their use to achieve CBD targets (Bhatt et al., 2020), implementation of the GSPC (Paton and Lughada, 2011), and protected area management effectiveness (Coad et al., 2013). Most recently, 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 rarely been evaluated- but this is an urgent task. Currently CBD is in the process of setting a post-2020 framework. Within the CBD and beyond, there is substantial room for improving the scope, ambition and clarity on the importance of genetic diversity conservation of wild and domestic species, including in wording of goals, targets and indicators (Hoban et al., 2020a). Laikre et al. (2010) found little mention of genetic diversity in 24 National Biodiversity Strategy and Action Plans (a document used by countries to set their biodiversity agenda). Genetic diversity has since been noted as a principal data gap in assessing biodiversity progress (OECD, 2019). In the Global Biodiversity Outlook 4, loss of genetic diversity was mentioned primarily in agricultural species and global food security (CBD, 2014), which is important but neglects genetic diversity within all species. In the context of Aichi Target 16 (benefits and sharing

of genetic resources), data gaps to monitor genetic diversity were also mentioned (Aguilar-Støen and Dhillon, 2003). Others have recognized challenges in translating genetic data and knowledge in a policy context (Chandra and Idrisova, 2011), and noted that a standardized set of agreed-upon, easy-to-use, universally applicable metrics for monitoring genetic diversity is needed (Bubb et al., 2011; Bruford et al., 2017; OECD, 2019).

To describe and better understand how countries are assessing and protecting genetic diversity, we systematically evaluated the consideration of genetic diversity in a large representative sample ($n=114$) of 5th and 6th CBD National Reports (submitted in 2014 and 2018, respectively, though many reports were submitted late). Our specific aims were to:

- Assess how many countries included targets pertaining to genetic diversity.
- Assess which indicators (measures of effort and outcomes) were used to report on status (present state) and trends (change) in genetic diversity.
- Assess reported genetic diversity actions (e.g. management interventions, policy, funding), threats (e.g. concerns or drivers of change), and values (e.g. utility or benefits).
- Assess the frequency with which different categories of species are mentioned in reference to genetic diversity.
- Determine whether the above results change across time, space and socio-economic categories.

This analysis also contributes to a general understanding of how genetic diversity is considered in policy, following numerous calls to increase such consideration (Laikre, 2010; Shafer et al., 2015; Taylor et al., 2017).

2. Methods

2.1. National report assessment

We reviewed 57 pairs of 5th and 6th National Reports (NRs) (9 written in Spanish, 10 in French, and 38 in English, countries shown in Fig. 1), available prior to 1 July 2019 (details in Appendix A) from the CBD Clearinghouse (chm.cbd.int/). This sample represented >90% of the 6th NRs available at the time and 31% of the 5th NRs. We evaluated reports using a structured questionnaire composed of standardized questions (hereafter “questionnaire”) developed over several trial phases to ensure consistent interpretation among reviewers (Appendix A). We devised nine questions (Table 1) based on CBD instructions to Parties. We limited our questions to thematic sections that were common between the 5th and 6th NRs (Appendix B explains how each question matches CBD instructions). We developed instructions (Appendix C) to ensure consistent interpretation and completion of the questionnaire among reviewers.

The questionnaire was completed by the 20 authors of this manuscript, who have experience in applied conservation genetics (hereafter “reviewers”). This protocol is similar to Pierson et al. (2016), Bhatt et al. (2020), and Chandra and Idrisova (2011) in which experts evaluated text documents to answer a series of categorical questions regarding issues or actions included in the documents. Each reviewer evaluated six to eight reports. Each reviewer received several 5th and 6th NRs so they would be familiar with each report series, but reviewers did not receive 5th and 6th NRs from the same country (e.g. a reviewer might receive the 5th NR from Bhutan and 6th NR from Cameroon, but not the 5th and

6th NR from Bhutan). Reviewers were allocated reports from multiple continents and with differing levels of economic income (we used income levels from the International Monetary Fund, IMF). Each reviewer carefully read the entire report (mean length 140 pages) to identify all mentions of genetic diversity and related concepts and terminology. To ensure nothing was missed, the reviewers also performed a keyword search, querying the document for 15 predetermined genetic diversity-related keywords (see Appendix A, C). After reading, highlighting and taking notes on each report, the reviewer completed a web-based questionnaire (built using *Google Forms*, Google LLC). Each reviewer spent on average 4.25 h per report. The collected information was automatically compiled in a .csv file.

We made a strong effort to standardize the review approach and to provide precise instructions and examples for reviewers. To maximize standardization of questionnaire completion, we had an extensive period of questionnaire development, trial, discussion, and revision. Once the questionnaire was finalized and data collection began, we frequently checked agreement among reviewers and discussed disagreements as a group. Additionally, 15 reports (eight for 6th and seven for 5th) were reviewed independently by two reviewers to ensure consistency (Appendix A).

We note that although the CBD intended consistency across NRs to facilitate tracking progress (cbd.int/reports/guidelines/), the structure, instructions, and formats were moderately different in each reporting period. Therefore, our study focused on equivalent sections between the 5th and 6th reports: status, threats, actions, obstacles, and progress towards the different biodiversity conservation targets (see Appendix B). We also note that NRs are summaries of activities and progress and that some conservation actions or knowledge in a country may not be included due to limited time, space, or access to data by the report writers (see Discussion, Recommendation 6). Also, although we aimed to make our questionnaire responses comprehensive based on initial reading of numerous NRs, some examples of genetic diversity may not clearly fit the categories of responses we created (e.g. there may be other actions or initiatives around genetic diversity that we did not include in our list of options). Therefore an “Other” response was available for questions. Analysis of “Other” responses is explained briefly in Appendix D. See Appendix A for additional caveats to this methodology.

2.2. Data analysis

Data were analyzed in R v3.6.3 (R Core Team, 2018). 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 frequency of each category of indicators differed between the reports (e.g. the relative length of each bar in Fig. 2). We also compared the *number* of responses recorded between the 5th and 6th NRs (for example, the number of reports in which genetic diversity indicators were identified, where each category of answer is paired between the reports, e.g. the Red List Index used as an indicator) using paired *t*-tests when data met the conditions of normality, and Wilcoxon tests when not. Levene’s test was used to test homogeneity of variance. Responses from low-, medium-, and high-income countries (according to the World Bank, see Appendix A) were also compared for 5th and 6th NRs separately and pooled together. Lastly, responses from each continent (listed in Appendix A, Table S1) were compared for 5th and 6th NRs separately and pooled together. The questionnaire results and R scripts used for analysis can be found at https://github.com/smhoban/CBD_National_Reports

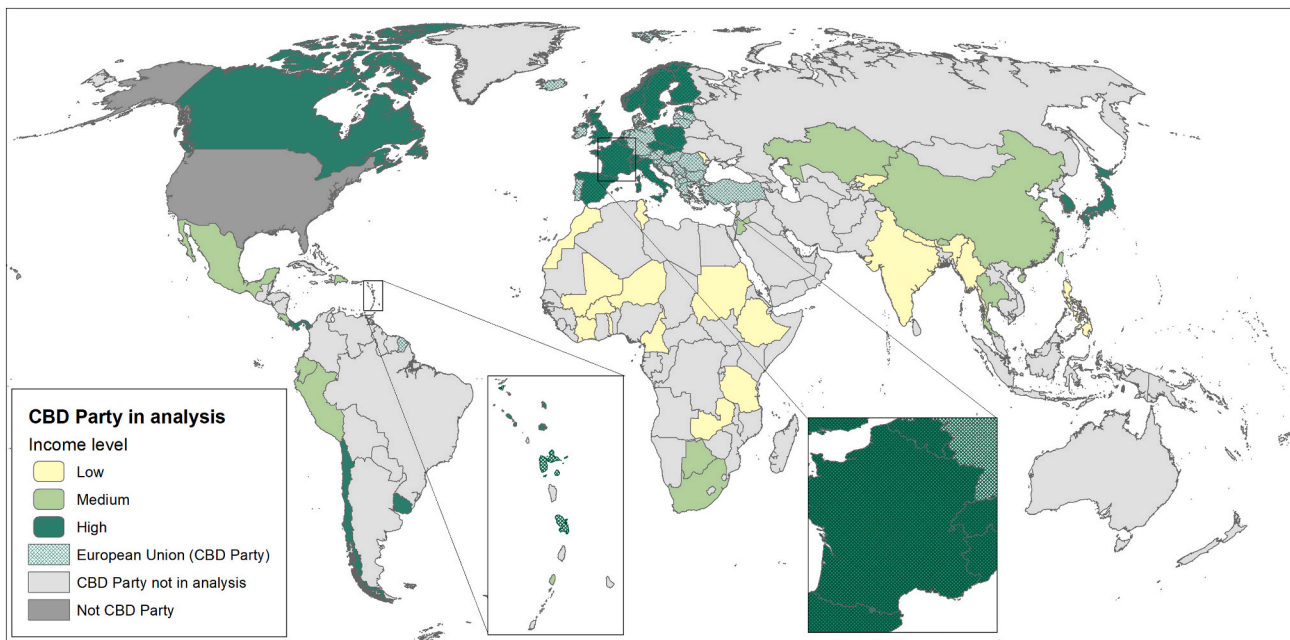


Fig. 1. Geographic distribution and income levels of Parties to the CBD that were included in this study relative to CBD Parties not included and non CBD Parties.

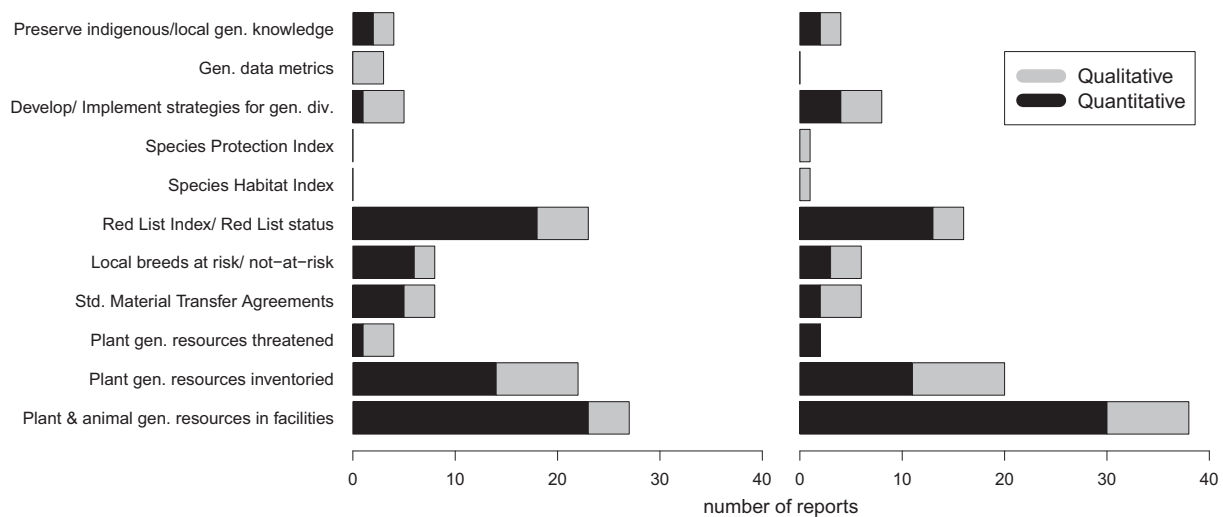


Fig. 2. Number of Parties whose 5th (left) and 6th (right) National Reports include each indicator of genetic diversity status with a Quantitative (numeric, such as a percentage) or Qualitative (descriptive, such as “high” or “low”) value. Both periods are shown to emphasize the high similarity between reporting periods; 57 reports were included in each period.

3. Results

Question 1. Genetic diversity in executive summary. A majority of countries (82%) included an executive summary for the 5th NR (as noted in Table 1, the 6th Report instructions did not request an executive summary). Of these, 60% mentioned genetic concepts relating to agrobiodiversity (e.g. gene banks, breeds, or varieties); 38% mentioned genetic studies, gene conservation actions, or genetic processes; and 36% mentioned biotechnology or access to and benefit sharing of genetic resources (Appendices D and E for details and Figures).

Question 2. Values of genetic diversity. The most frequently noted values of genetic diversity included resilience to environmental or climate change (37% 5th NR, 23% 6th NR), productivity in agriculture/forestry/ fisheries (37% 5th NR, 23% 6th NR), developing new varieties in these sectors (26% 5th NR, 23% 6th NR), and adaptation to environmental change (26% 5th NR, 19% 6th NR, see Appendices D and E).

There were 34% more mentions of values of genetic diversity in the 5th NR compared to the 6th ($p = 0.04$).

Questions 3 and 4. Genetic diversity targets wording and progress. Of the 57 country reports reviewed, 70% and 79% referred to a national-level genetic diversity target in the 5th and 6th NRs, respectively (Appendices D and E). Of those with such a Target, many NRs (53% 5th NR, 69% 6th NR) mentioned conserving genetic diversity of 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 at present (25% 5th NR, 40% 6th NR). For target progress, the most commonly reported progress was “Some progress, but insufficient” (57% 5th NR, 44% 6th NR), followed by “on track to achieve” (30% 5th NR, 38% 6th NR; Appendices D and E). Most countries also mentioned genetic diversity under Aichi Target 16, which regards access to and benefit-sharing of genetic resources (56% 5th NR, 60% 6th NR).

Table 1

Questions included in the questionnaire to assess the consideration of genetic diversity in 5th and 6th National Reports to CBD.

Question from questionnaire	Notes
1. Is genetic diversity (e.g. genetic threats, genetics-related policy or gene conservation actions, etc) mentioned in the executive summary? [*]	Reviewers chose from multiple categories representing genetic diversity (e.g. agrobiodiversity, population genetics, biotechnology, etc.)
2. Is the importance, value 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
3. Is there a national-level target focused on "conserving/ maintaining genetic diversity," "genetic erosion," "genetic resources," 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
4. What is the degree of progress regarding outcomes of the National Target corresponding to Target 13, or if National Target progress was not reported, then progress on Aichi target 13?	Reviewers selected one of six categories of progress; 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 progress
5. Is there a different national-level target that refers to "genetic diversity," "genetic erosion," "genetic resources," or other genetics concepts terms or genetic data?	Reviewers were asked if genetic diversity is mentioned under Aichi Target 16 ^{**} (access and benefits) or any other Targets (and to specify which one)
6. What indicators are used to report on the status ^{***} of genetic diversity? What indicators are used to report on trends in genetic diversity?	Eleven indicators (Fig. 2) and an "other" category 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"
7. Are there actions planned regarding genetic diversity or actions taken regarding genetic diversity, in or by this country?	Nine categories of action (Fig. 3) and an "Other" response were provided; reviewers could select as many as applicable and categorized each as "general" or "specific"
8. What genetic threats/ pressures 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
9. Identify any mention of species/ taxa 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 (of eleven categories, see Fig. 4) and categorized the mention as relating to actions, status, threat, trend, or other

^{*} Executive Summaries were only requested by CBD for the 5th Report.

^{**} 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. See Glossary for further definitions.

There were few significant differences in the reporting on genetic diversity by countries between 5th and 6th National Reports (NRs) ($p < 0.05$). In other words, the frequency of the different choices and the overall response rate was similar between the two reporting periods. This is evident in visual examination of Figs. 2, 3, and 4, and also in the statistical tests; all p values irrespective of their significance are reported in Appendices D and E. The results are organized here by the questions in each questionnaire.

Question 1. Genetic diversity in executive summary. A majority of countries (82%) included an executive summary for the 5th NR (as noted in Table 1, the 6th Report instructions did not request an executive summary). Of these, 60% mentioned genetic concepts relating to agrobiodiversity (e.g. gene banks, breeds, or varieties); 38% mentioned genetic studies, gene conservation actions, or genetic processes; and 36% mentioned biotechnology or access to and benefit sharing of genetic resources (Appendices D and E for details and Figures).

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Question 5. 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 Aichi Targets 13 and 16. The number of countries doing so increased from the 5th NR (19%) to 6th NR (49%), a significant increase of 250% ($p = 0.001$). In addition, the number of targets for which at least one country included a genetics-related reference increased over time. Genetics was mentioned under 13 different Aichi Targets in the 5th NR, and under 19 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 Aichi Targets 12 and 18 (relating to conservation of threatened species and respect for traditional knowledge, respectively), and 19% mentioned genetics for Target 19 (relating to biodiversity knowledge sharing).

Question 6. Indicators used for genetic diversity status and trends. The most commonly mentioned indicators of genetic diversity status were the number of genetic resources in conservation facilities (Fig. 2, Appendix S1), the number of plant genetic resources known/surveyed, and the Red List status. Rarely reported indicators were the state of preservation of indigenous/local knowledge, use of genetic diversity or metrics from analysis of DNA.

Question 8. Threats. National Reports documented a variety of threats to genetic diversity. The most common threats mentioned were replacement of native varieties or breeds, habitat fragmentation, and climate or environmental change (Appendices D and E). Other genetic concerns were also mentioned, including decrease in species' range size, overharvest, pests or invasive species, small population problems, genetic modification, and hybridization. More threats were identified in the 5th than the 6th NR ($p = 0.02$).

Question 9. Species mentioned. The top species types (Fig. 4; Appendices D and E) mentioned in regards to genetic diversity conservation were domesticated crops and animals (each >20% in both reports), followed by species of conservation concern (11%), forestry species (10%), and crop wild relatives (11%). There were few references to "other socio-economically important species" such as wild-harvested species, species providing ecosystem services, and/or culturally valuable species or wild relatives of domesticated animals (all <5% both reports).

Differences related to income levels and continents. Significant differences in countries' responses according to income level were observed in only two areas: threats, and species types. (See Appendix D for additional but non-significant trends). Regarding threats to genetic diversity, NRs from middle- and low-income countries had fewer mentions of small population size and habitat fragmentation, but more mentions of replacement of traditional varieties (significant only when 5th and 6th NRs are pooled, $p = 0.04$). Middle- and low-income countries less frequently mentioned species of conservation concern and species providing ecosystem services, but more frequently mentioned horticultural species (cultivated but not food or forestry species), compared to high-income countries (only marginally significant when 5th and 6th NRs are pooled, $p = 0.08$).

Trends of genetic diversity were mentioned half as often as status, and showed a mix of increasing, decreasing, and no change. A strong directional trend in indicators was only seen for "genetic resources secured ex situ," which were typically reported as increasing (Appendices D and E).

Question 7. Actions. The most common genetic diversity actions or initiatives related to establishing seed banks, research agencies or breeding programs, and laws or policies (Fig. 3). Single time point genetic studies and genetic monitoring were rare.

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Question 9. Species mentioned. The top species types (Fig. 4; Appendices D and E) mentioned in regards to genetic diversity conservation were domesticated crops and animals (each >20% in both reports), followed by species of conservation concern (11%), forestry species (10%), and crop wild relatives (11%). There were few references to "other socio-economically important species" such as wild-harvested species, species providing ecosystem services, and/or culturally valuable species or wild relatives of domesticated animals (all <5% both reports).

Differences related to income levels and continents. Significant differences in countries' responses according to income level were observed in only two areas: threats, and species types. (See Appendix D for additional but non-significant trends). Regarding threats to genetic diversity, NRs from middle- and low-income countries had fewer mentions of small population size and habitat fragmentation, but more mentions of replacement of traditional varieties (significant only when 5th and 6th NRs are pooled, $p = 0.04$). Middle- and low-income countries less frequently mentioned species of conservation concern and species providing ecosystem services, but more frequently mentioned horticultural species (cultivated but not food or forestry species), compared to high-income countries (only marginally significant when 5th and 6th NRs are pooled, $p = 0.08$).

Responses grouped by continent differed for only two questions—species types and reported progress—and even these results are inconclusive. For the 5th Report (but not 6th), continents differed significantly in species types mentioned in the reports ($p < 0.001$). South American countries mentioned genetic diversity in wild relatives of domesticated animals more often, Africa and Europe mentioned crop wild relatives more often, Asia mentioned horticultural species more often, and Europe and Asia mentioned species providing ecosystem services more often. For the 6th Report (but not 5th), continents differed on reported progress, though not significantly ($p = 0.07$), with Asian Parties tending to report higher levels of progress.

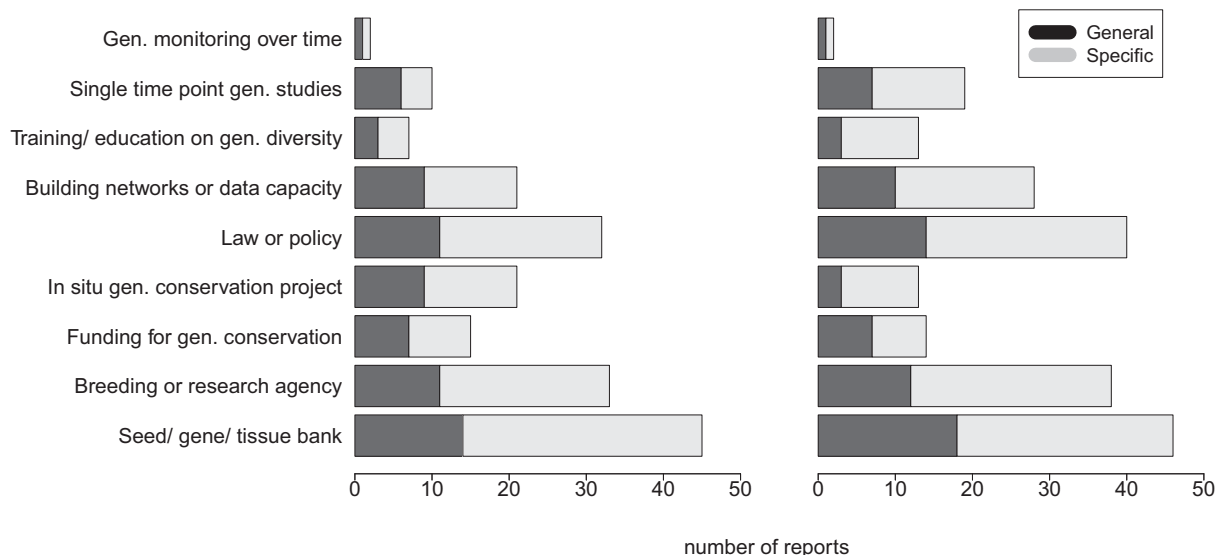


Fig. 3. Number of Parties whose 5th (left) and 6th (right) National Reports report each type of genetic diversity action with General (e.g. non-specific action, black) or Specific (grey) information.

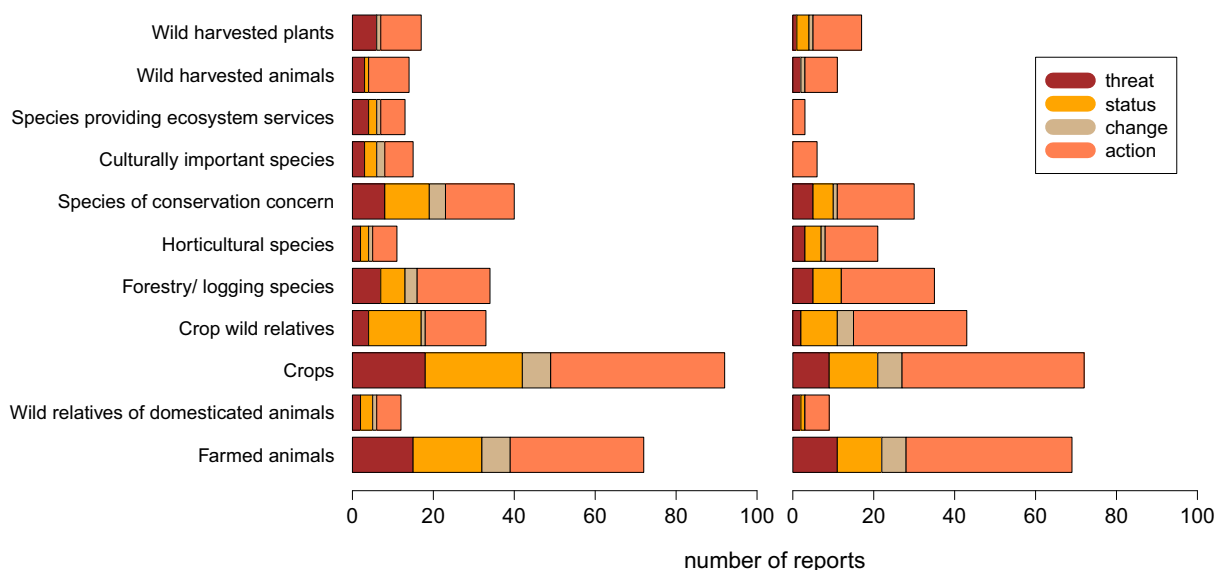


Fig. 4. Number of 5th (left) and 6th (right) National Reports mentioning each species type (y-axis) in four different contexts (whether the mention of the species' genetic diversity related to a threat, status, change, or action) for each report. Both periods are shown to emphasize the very high similarity between reporting periods.

4. Discussion

Parties signatory to the CBD are legally bound to design effective interventions and adequately report on how they value, monitor, and manage biodiversity, in accordance with the CBD's guidance documents. Yet, to date, genetic diversity has received little attention, likely attributable to policies which have focused primarily on genetic resources in domesticated species, and a lack of well-defined genetic indicators. This was evident in our assessment of 5th and 6th CBD National Reports. Our main finding is that although most countries mentioned the importance of genetic diversity, actual reporting was rather limited. Specifically, when status and actions relating to genetic diversity were reported, they primarily referred to agricultural species and were limited in scope. Additionally, the indicators used most often are not well connected to genetic diversity status or change, such as the Red List index. There were only minor differences in findings for the 5th vs. 6th Report, suggesting that consideration of genetic diversity has not increased over the time period. Below, we discuss the findings and how they can help to improve future National Reports and post-2020 genetic diversity targets, indicators and capacity efforts, and other global policy efforts to maintain genetic diversity necessary to counter current global crises, including climate change, biodiversity loss, and hunger (Di Falco and Perrings, 2003; Reusch et al., 2005; Sjöqvist and Kremp, 2016; Raffard et al., 2019).

4.1. Genetic diversity awareness and targets (questions 1 through 5)

Numerous benefits of genetic diversity were recognized, including maintaining ecosystem stability or services, food production, pest/disease resistance, adaptation to changing environments, and helping individuals avoid inbreeding (see Appendix E). Encouragingly, most countries have sufficient awareness of genetic diversity to include it in the Executive Summary (>80%) and to have a genetic diversity-related National Target (>70%). Laikre et al. (2010) found that 67% of 24 National Biodiversity Strategies and Action Plans mentioned the importance of genetic diversity, but less than half mentioned genetic diversity in non-agricultural species. A decade after that report, we found that genetic diversity is still predominantly considered for agricultural species, with only 37% (21 out of 57) of 5th and 55% (31 out of 57) of 6th genetic diversity National Targets mentioning non-

agricultural species (Appendix E, Supplemental Table S5, two rows for 'non agricultural species'). This may be driven by the emphases of Aichi Targets 13 and 16 on genetic diversity within a socio-economic context, especially for agricultural species. Also encouraging, genetic diversity was mentioned in relation to all but one Aichi Target by at least one country. The high number of reports that mentioned genetic diversity in relation to Aichi Target 12 (prevention of species' extinctions) may reflect increasing recognition of genetic diversity's role in supporting species survival (Booy et al., 2000; Sgrò et al., 2011; Ralls et al., 2020). Meanwhile, references to genetic diversity in Aichi Targets 18 (recognition, respect and integration of traditional knowledge for biodiversity conservation) and 19 (improving scientific knowledge of the values, functioning, and status of biodiversity, and the consequences of its loss) may reflect increasing recognition of the importance of indigenous and scientific knowledge on genetic diversity (e.g. Collier-Robinson et al., 2019; Des Roches et al., 2021). We emphasize that reporting guidelines should explicitly state that genetic diversity is important for multiple targets (see below, Recommendation 6) in order to increase knowledge of, capacity development for, and access to genetic data for use in policy and practice (Recommendations 1 and 2 in Section 5).

4.2. Genetic diversity indicators (question 6)

The number of genetic resources in conservation facilities, the number of plant genetic resources known/surveyed, and the Red List status were commonly mentioned indicators of the status of genetic diversity. These indicators are recommended by the CBD (Appendix S2), and have high 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 do not directly or indirectly assess genetic diversity (see Glossary) and are inadequate for reporting on genetic diversity change (Willoughby et al., 2015; Garner et al., 2020; Hoban et al., 2020a). Imperfect surrogates for genetic diversity are not uncommon in global policy. The Montréal Process (an international forest sustainability framework; montrealprocess.org) includes three genetic diversity indicators: 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.

Overall, the paucity of reliable indicators of genetic diversity emphasizes that the scientific community needs to develop affordable, standardized indicators that clearly track genetic change (Hoban et al., 2020a; Hoban et al., 2021a; Laikre et al., 2020; Lefèvre et al., 2020) (see below, Recommendation 4).

Only 5% of countries referenced genetic studies (e.g. measured through DNA sequencing) or recorded indigenous and local knowledge or maintenance of genetic diversity, possibly because there are no official CBD indicators on these aspects (see below, Recommendation 3). Reporting depends on availability of data on baselines and trends, as well as capacity (resources, technical expertise), which is lacking in many countries (Vanhove et al., 2017). Similarly, only 13% of countries reported measures to develop or implement strategies for minimizing genetic erosion, even though Aichi Target 13 called for such strategies. There is no available database for, or guidance on how to develop and apply, such strategies.

4.3. Genetic diversity actions and threats (questions 7 and 8)

The most commonly reported actions related to the conservation of genetic diversity were ex situ strategies (seed banks, research agencies, laws, etc.). Less commonly mentioned were in situ actions (developing in situ genetic conservation projects, single time point genetic studies, etc.). While ex situ actions, laws and policies are important to forestall absolute loss of genetic diversity, they cannot be relied upon exclusively, because a limited representation of species genetic diversity can be maintained ex situ (Hoban et al., 2020b). Also, sustaining genetic diversity in situ is important to allow for natural processes such as adaptation to environmental change (Sgrò et al., 2011).

Genetic data (as indicators) and genetic monitoring (as an action) were mostly absent from reports; only Kazakhstan and Czech Republic for the 5th Report and Panama and Morocco for the 6th Report mentioned genetic monitoring. Genetic monitoring programs exist in numerous countries (e.g. European trees: Aravanopoulos et al., 2015; California Chinook salmon: Meek et al., 2016; European grey wolves: Dufresnes et al., 2019), but may not always be published or made accessible to policy makers, or were not considered vital to include in National Reports. Laikre et al. (2010) previously noted a near absence of genetic monitoring in National Biodiversity Strategies and Action Plans (NBSAPs); our results suggest there has been little advancement in reporting on genetic monitoring in most countries ten years later. These findings complement the observation by Pierson et al. (2016) that European countries rarely include genetic diversity monitoring in species recovery plans due to a lack of legislative requirements, and relatively limited involvement of geneticists on conservation projects (see also Taft et al., 2020). One-time genetic studies (a snapshot of the genetic variation levels observed in one or more populations or species) were more commonly reported, and nearly doubled between 5th and 6th Reports, but remain scarce. However, assessing and reporting on change in genetic diversity requires standardized genetic monitoring across decadal time frames (Hoban et al., 2014; Mathieu-Bégné et al., 2019). Although requiring significant resources, capacity, and strategic planning timeframes, long-term monitoring programs will improve understanding of genetic diversity status and trends and help to meet the goals of the CBD and other international commitments (e.g. Sustainable Development Goals).

4.4. Types of species (question 9)

References to genetic diversity in National Reports were mostly focused on cultivated crops and farm animals. Genetic diversity of crop wild relatives, forestry species, and species of conservation concern was discussed to a lesser degree, and there were even fewer mentions of “other socio-economically important species” such as wild harvested species, species providing ecosystem services, and culturally valuable species. Because trends in one of these groups does not necessarily

correlate to change in other species groups, monitoring and reporting should be conducted on multiple representatives of each “group” (Hollingsworth et al., 2020). Our observations may reflect the relative emphasis of the Aichi 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), because agriculturally valuable species make up a small fraction of life on Earth and the genetic diversity of many non-agricultural species underlies nature’s contributions to people (Stange et al., 2021) (Recommendation 3).

4.5. Changes in reporting over time

The relative frequencies in each category or response for all questions were not significantly different between the 5th and 6th National 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. As noted in Section 4.3, our general conclusions are in line with Laikre et al. (2010)’s analysis of NBSAPs, that reporting of genetic diversity within most species is still scarce. However, the 6th National Report contained significantly more mentions of genetic diversity-related topics under Aichi Targets not specifically focused on genetic diversity (i.e. Targets other than 13 and 16). It is possible, but by no means conclusive, that this increase may be attributable to increasing awareness and affordability of genetic approaches 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). On the other hand, significantly more trends, values, and threats to genetic diversity were identified in 5th Reports, possibly related to the more detailed instructions provided at that time (Appendix B). It appears that the wording of CBD instructions (not just targets) is extremely important for accurate reporting (see Recommendations 3, 5 and 6 in Section 5). We also note that trends (change over time) were reported less than half as often as status. This emphasizes that more clearly reported temporal comparison of genetic diversity indicators is needed (see below, Recommendations 4 and 6).

5. Conclusion and recommendations

We conclude that in reporting to the CBD- the largest and most comprehensive instrument for directing biodiversity conservation globally- Parties focused on a small set of genetic diversity conservation actions, a biased subset of species, and insufficient indicators or genetic monitoring programs. Here, we make recommendations for addressing issues we uncovered in our survey of 114 National Reports, starting with general work needed to improve assessing genetic diversity in the CBD post-2020 framework and beyond.

1. Increase awareness and knowledge sharing of the essential role of genetic diversity in the benefits it brings to nature and people. Assessments of genetic diversity in agricultural and natural systems were limited in the National Reports and therefore its critical importance must be better communicated to policy makers and conservation managers via networking and capacity building. The effectiveness of such communication should be assessed (e.g., Lundmark et al., 2019).
2. Increase quality and quantity of reporting on genetic diversity in wild species, especially long-term monitoring to evaluate trends. This must be made feasible for all countries, not simply those with highly developed scientific infrastructure. Collaborations between geneticists and conservation managers can provide guidance on cost-effective monitoring (Peréz-Espona and ConGRESS Consortium, 2017; Taft et al., 2020; Hoban et al., 2021b).

We also provide recommendations for reporting on genetic diversity 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 and enable comparisons of progress over time.

1. Reporting on the genetic diversity in all species, not just species associated with agriculture, is essential to maintain stable, resilient ecosystems. We recommend that the CBD request reporting of targets, status, threats, and actions relating to genetic diversity in each category of species (Fig. 4) and in major taxonomic groups.
2. Consider recent suggestions on genetic goals, action targets, and genetic diversity indicators by Hoban et al. (2020a, 2020b, 2021a, 2021b), which are quantifiable, better reflect changes in genetic diversity and enable evaluation of actions taken to protect and restore genetic diversity (also see Frankham, 2021 and Laikre et al., 2021). Indicators and data relating to indigenous and local use and knowledge of genetic diversity should be developed. Databases on national strategies for conserving genetic diversity would also be very useful for tracking and reporting.
3. Adopt improved and consistent terminology relating to genetic diversity and genetic approaches. Clear definitions of terms in reporting instructions via glossaries, with examples, in at least the six major CBD languages would help to improve consistency in reporting on genetic diversity.
4. Enable clearer comparisons of reporting on genetic diversity among countries and over time. We suggest clearer structure for National Reports and greater guidance to countries on what to report and how. For example, National Report formatting could include lists of genetic diversity support actions performed, or categories of species managed, which can be “checked off”. Also, countries should maintain a database of genetic studies, genetic management programs, and genetic diversity strategies on taxa within their territory and report an updated list of studies, management, strategies, and publications in their NR, using a standard form. Standardization and higher frequency of reporting on genetic diversity would allow better analysis of upcoming reports, and comparison among countries. Meanwhile, to allow unstructured information, the CBD could encourage inclusion of additional reports and/or case studies (for example Scotland included a supplemental report entirely on genetic diversity conservation, see Hollingsworth et al., 2020).

Implementing these recommendations should increase reporting of indicators, actions, and progress towards the protection of genetic diversity in all species, and consideration of genetic diversity in other targets. These recommendations also present an opportunity for CBD to facilitate capacity building and international collaboration, to equip countries to monitor genetic diversity post-2020. Of course, conservation geneticists need to actively participate at the science-policy interface, and we anticipate their increased inclusion to advance discussions of CBD and global work on genetic conservation.

Supplemental Methods (Appendix A), CBD Instructions (Appendix B), and Questionnaire Details (Appendix C), Supplemental Results (Appendix D), and Tabulated Results (Appendix E) are available online. The authors are solely responsible for the content of these materials. Queries should be directed to the corresponding author. The questionnaire results and R scripts for analysis can be found at https://github.com/smhoban/CBD_National_Reports. Supplementary data to this article can be found online at doi:<https://doi.org/10.1016/j.biocon.2021.109233>

CRedit authorship contribution statement

Conceptualization- SH; Data Curation- all authors; Formal analysis- all authors, led by SH; Methodology- all authors, led by SH and MH; Project administration- SH and MH; Visualization- SH and KP; Writing-

all authors, led by SH and MH.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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 (e.g. 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 (e.g. at the DNA level) and trait differences that vary among individuals and populations within a species

Genetic erosion: a loss of genetic diversity

Genetic resource: 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, see also <https://biodiversity.europa.eu/topics/genetic-resources>). Often used to refer to species diversity, e.g. number of plant wild relative species

Indicator: a measure used to present a high-level summary of biodiversity; we include in our questionnaire official CBD indicators 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 starting in 2014 and 6th Reports were submitted starting 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”

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.

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 from genetic diversity