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ADVANCING BIODIVERSITY CONSERVATION IN A RAPIDLY CHANGING WORLD: PLANT-CENTERED STRATEGIES FOR ECOLOGICAL RESILIENCE, RESTORATION AND SUSTAINABLE FUTURE

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ABSTRACT

Biodiversity conservation is shifting from the paradigm of species protection to the maintenance of ecological, genetic, and functional integrity. Earlier biodiversity research and conservation practice focused on understanding and responding to the drivers of biodiversity loss, e.g., habitat loss, climate change, environmental degradation, invasive species, and overexploitation. This review synthesizes the role of plants in sustaining ecosystems, with an emphasis on genetic conservation, ecological restoration, connectivity, conservation biotechnology, monitoring, and adaptive governance. The current crisis of biodiversity loss affects a million species, threatening their extinction, while plant genetic diversity is also disappearing at an alarming rate. According to the Food and Agriculture Organization's (FAO) Third Report on the State of the World's Plant Genetic Resources for Food and Agriculture, 42% of the plant genetic resources evaluated for taxonomic diversity were no longer present in at least one country. By the end of 2024, 6 million plant accessions were stored in medium- and long-term gene bank facilities. Kunming-Montreal Global Biodiversity Framework promotes the restoration of at least 30% of ecosystems and the conservation of 30% of land, inland waters, coasts, and oceans by 2030. These goals will require more than expanding the number of protected areas. To increase resilience to climate change, conserve genetic resources, and restore degraded ecosystems, it will be critical to ensure genetic and functional diversity while promoting native plant species and improving connectivity at multiple scales through restoration and adaptive management. Moreover, achieving the targets set for 2030 will contribute to food security, sustainable livelihoods, and ecosystem service provision.

Keywords: Biodiversity Conservation, Plant Diversity, Genetic Resources, Ecological Restoration, Ecosystem Resilience, Conservation Biotechnology, Climate Resilience, Sustainable Ecosystem Management

INTRODUCTION

Biodiversity is more than just the count of species inhabiting a given ecosystem. It encompasses genetic, species, and ecosystem diversity which determine the response of biological systems to environmental change. Plants are essential to this process since they constitute the foundational layer of most terrestrial ecosystems, providing goods and services that underpin food security, health,

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livelihoods, and wellbeing. They also play a critical role in regulating water, carbon, and nutrient cycles, supporting soil and habitat functions, and supplying fuel, fiber, medicinal, and other materials.

The global state of biodiversity is not favorable, as is evident from the IPBES Global Assessment Report on Biodiversity and Ecosystem Services. This report confirmed that over one million species of animals and plants are at risk of disappearing, with human activities degrading three-fourths of the earth's ecosystems and 66% of marine habitats. Moreover, more than 85% of wetlands that existed before the 1970s have been lost Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2019). Worse still, the drivers of biodiversity loss are not operating in isolation. The combined effects of climate change, habitat modification, pollution, invasive species, and unsustainable resource use have intensified the impacts of individual drivers, thus accelerating the rate of loss.

The previous review, Biodiversity Conservation in an Era of Rapid Global Environmental Change, provided a broad overview of biodiversity status, major drivers, protected areas, restoration, community conservation, international frameworks and emerging technologies. This review goes further to provide an in-depth analysis of plant diversity and plant genetic resources, emphasizing the importance of restoring and conserving natural and semi-natural habitats, improving restoration quality and connectivity, and considering conservation outcomes.

The emphasis is on the need to shift from assessing the amount of biodiversity to understanding what it comprises, how it will respond to environmental changes, and the extent to which it can be conserved, restored, and sustained. Similarly, conserving a species' presence in an ecosystem or increasing tree cover in forests without considering the underlying genetic composition and adaptation potential may undermine the intended benefits of conservation efforts.

FROM BIODIVERSITY LOSS TO BIODIVERSITY RESILIENCE

While traditional conservation has focused on preventing extinction and preserving existing habitats, it is increasingly necessary to adopt a more varied concept of resilience. Ecological resistance is the capacity of an ecosystem to withstand disturbance with little change, whilst resilience is the ability to recover following disturbance. Long-term conservation requires maintenance of evolutionary potential to enable populations to respond to changing conditions.

The Kunming–Montreal Global Biodiversity Framework (KMGBF) adopted in 2022, has four long-term goals and 23 targets for 2030. Its Target 4 has the specific objective of linking species recovery to maintenance and restoration of genetic diversity within and between populations. This is a key recognition of the importance of genetic diversity which had previously been overshadowed by the perceived need for protecting species and habitats.

A resilient ecosystem should contain sufficient biological variation to allow it to absorb disturbance, retaining its functions, structures and processes, and maintaining its capacity to provide goods and services. Functional diversity appears to be of particular importance, since two similar ecosystems may have a similar number of species but include quite different proportions of species with specific traits or roles; the loss of drought-tolerant, nitrogen-fixing, deep-rooted or pollinator-dependent plants will tend to have a much greater impact on ecosystem function than a comparable reduction in overall species number.

Phylogenetic diversity offers another perspective. By conserving species from different evolutionary lineages, we are conserving a greater range of other characteristics, since evolutionary history is strongly linked to biological characteristics. Conservation planning based only on numbers of species therefore fails to take account of this dimension of diversity.

The future conservation approach should therefore move from a simple "protect what remains" model towards a more adaptive sequence: avoid biodiversity loss → protect remaining populations → maintain genetic and functional diversity → restore degraded systems → reconnect fragmented populations → monitor change → adapt management.

PLANT DIVERSITY, GENETIC RESOURCES AND ECOSYSTEM FUNCTION

Plants form the foundation of most ecosystems because they provide structure and energy. Forests, grasslands, wetlands, shrublands, and agricultural systems are dependent on plant communities. Plant species are keystone elements in ecosystems because they provide food and habitat for animals and microorganisms.

An important but often overlooked component of biodiversity is the genetic diversity within a species. Within a species, populations can differ in their responses to biotic and abiotic factors such as drought, temperature, pathogens, and competition. Therefore, the loss of a population of a particular species means the loss of genetic potential that might have been useful for future generations.

The latest Food and Agriculture Organization (FAO) report, The Third Report on the State of the World's Plant Genetic Resources for Food and Agriculture, underlines the gravity of the situation. Based on the information from 128 countries and territories, research institutes, and more than 1,600 experts, it highlights that 42% of taxa surveyed were no longer present in at least one of the areas where they were previously cultivated or occurred naturally. FAO has also reported that approximately 6 million plant

germplasm accessions were held under medium- or long-term conservation conditions in 902 gene banks in 118 countries and 17 regional or international research centres by the end of 2024.

These figures show both progress and vulnerability. Large germplasm collections provide an important safety net, but ex-situ storage cannot completely replace natural populations. Evolutionary processes, pollinator interactions, plant–microbe associations and local adaptation continue in natural habitats. Crop diversity provides another clear example. More than 6,000 plant species have been cultivated for food, but fewer than 200 make major contributions to food production and only nine account for about 66% of total crop production. Such concentration creates genetic and nutritional vulnerability. Crop wild relatives are particularly valuable because they may contain traits associated with drought tolerance, heat tolerance, pest resistance and other adaptive characteristics. Conservation plans should avoid reducing genetically diverse populations to a small number of representatives. Restoration programmes should also consider the provenance and genetic diversity of planting material rather than selecting plants only on the basis of rapid growth.

INTEGRATED IN-SITU, EX-SITU, AND CONSERVATION BIOTECHNOLOGY

IN-SITU CONSERVATION

In-situ conservation is the most complete form from an ecological perspective as plants retain their interactions with soil organisms, pollinators, competitors and other biotic and abiotic factors. Protected forests, biosphere reserves, community managed areas and natural grasslands can maintain ecological processes that cannot be reproduced fully in a laboratory or gene bank.

While protected status confers increased security, it does not guarantee conservation success, as invasion by alien species, fire, pollution, illegal harvesting, fragmentation and climate change can still occur. A comparison of the area protected should therefore be made with ecological integrity and connectivity.

EX-SITU CONSERVATION

Ex-situ conservation can act as an important secondary form of conservation. Seed banks, field genebanks, botanical gardens, tissue culture collections, pollen storage and cryopreservation are all methods that can conserve genetic diversity if natural populations become too small.

The current global scale is considerable, with the Food and Agriculture Organization (FAO) reporting that there were an estimated 6 million plant germplasm accessions in medium and long-term conservation worldwide as of the end of 2024. The International Treaty on Plant Genetic Resources For Food And Agriculture also reported an approximate total of 5.8 million accessions that are stored in medium- or long-term facilities in January 2025, of which approximately 2.6 million holdings were available through its Multilateral System.

However, numbers do not necessarily equal success, as there is the possibility of duplication, lack of characterization, poor regeneration practice, loss of viability and inadequate documentation, all of which can limit use of the collections. Conservation ex-situ therefore needs to be combined with characterization, genetic evaluation, regeneration and end-use.

CONSERVATION BIOTECHNOLOGY

Biotechnology can be applied to both in-situ and ex-situ conservation to supplement traditional approaches. Micropropagation can produce large numbers of plants from small numbers of materials, while tissue culture, cryopreservation and others can conserve species whose seeds have specific requirements or are not suited to storage. DNA barcoding and molecular markers can assist with species identification and determining genetic diversity levels, while genomic approaches can identify naturally occurring populations and assist with choices on what to restore. The main constraint is that technical expertise is unevenly distributed, and sophisticated approaches such as genome sequencing may not be applicable in places where field surveys, taxonomy and post-bank monitoring are lacking. Conservation biotechnology should therefore be seen as an addition to ecological conservation rather than a substitute.

ECOLOGICAL RESTORATION, CONNECTIVITY AND CLIMATE RESILIENCE

The increasing importance of restoration in global biodiversity policy makes it an important area for action. The KMGBF Target 2 calls for at least 30% of areas of degraded terrestrial, inland-water, coastal and marine ecosystems to be under effective restoration by 2030. The UN Decade on Ecosystem Restoration is also promoting global commitments to restoration of at least one billion hectares degraded land.

Restoration, however, should not be thought of narrowly as planting trees. While afforestation refers to establishing trees where there was not previously forest, and reforestation replaces tree cover, ecological restoration focuses on recovering ecosystem structure and function. Plantations may well provide increased habitat extent, but are unlikely to support ecological integrity if they contain few native species, low structural complexity or reduced value for local wildlife.

Sometimes natural regeneration can be a more appropriate restoration intervention than active tree planting, where sources of native tree or shrub seed are available and major barriers to establishment like disturbance have been removed. Active restoration becomes more important when these conditions cannot be met.

The plant material used in any restoration intervention is also critical: using a mix of locally appropriate and genetically diverse native species can support ecological integrity in the restored site. At the same time, future climate projections should be taken into account at the selection stage, since local populations may not be adapted to the future climate.

Connectivity between patches of suitable habitat is another important consideration. Isolated patches are much more vulnerable to loss of genetic diversity and local extinction. Restoration interventions can create stepping stones or corridors for dispersal, allowing gene flow between isolated patches. Connectivity planning is especially important under climate change, since species distributions are likely to shift.

Climate-resilient conservation therefore involves not just protecting and restoring sites, but ensuring there is functional connectivity between them, and a diverse range of genetic diversity within populations to allow adaptation to future conditions.

MULTIPLE PRESSURES AND INVASIVE ALIEN PLANTS

Multiple pressures on natural systems are rarely independent – a forest fragment may be under pressure from warming temperatures, prolonged drought, invasive species, pollution and overharvesting. These different pressures can combine to reduce ecosystem resilience.

Invasive alien species are a good example of this – the IPBES assessment estimates more than 37,000 alien species have been introduced across the world, of which more than 3,500 are invasive. Invasive alien species are continuing to be introduced and can be further facilitated by climate change.

For plants, invasive species can reduce native diversity through competition for light, water and nutrients. Some invasions also alter soil conditions, nutrient cycling or fire regimes. Management should therefore follow a hierarchy: prevention → early detection → rapid response → eradication where feasible → containment → restoration Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. (2023).

Eradication alone is not sufficient when the ecological space created by removing an invasive species is rapidly recolonized. Native regeneration or active restoration may be required after control.

The same approach should be taken for managing multiple pressures – assessing the overall impact rather than individual pressures. For example, climate change can make plants more susceptible to pests – and fragmented habitats may be less able to respond to further disturbance.

MONITORING, GENOMICS AND DATA-DRIVEN CONSERVATION

Conservation decisions are only as good as the information on which they are based. Field inventories remain critically important, particularly for plants given current assessment gaps. The IUCN Red List has assessed over 175,900 species, but designates plants, invertebrates and fungi as groups needing much greater assessment effort.

IUCN information recently revealed significant risks facing well-assessed plant groups. In the IUCN assessment summarized in its 60-year review, 38% of assessed tree species, 71% of assessed cycads and 34% of assessed conifers were classified as threatened. These statistics also illustrate why generalizations about "plant extinction" need to be treated with caution, given large assessment disparities between groups.

Remote sensing and GIS can supply landscape-level information on vegetation dynamics, habitat fragmentation and land-cover transitions. Environmental DNA can augment standard survey approaches, particularly when target detection is challenging. Long-term vegetation plots retain value, as satellite observations cannot replace field-based information on species composition, regeneration and population structure.

Genomics offers a further layer of information. Population-level genetic data can identify isolated populations, genetic bottlenecks and potentially valuable adaptive variation. This information can guide decisions on seed collection, restoration and population reinforcement.

Artificial intelligence and machine learning have potential applications for species recognition, image analysis and spatial modelling, but should be seen as analytical tools rather than stand-alone conservation solutions. Sampling biases, faulty datasets and uncertain models can generate misleading results, and human expertise in taxonomy and ecology remains essential.

A comprehensive monitoring system should integrate: field data + genetic data + spatial data + long-term observations + local knowledge.

COMMUNITY STEWARDSHIP, SUSTAINABLE USE AND GOVERNANCE

Conservation efforts unfold within social landscapes. Forests, grasslands, wetlands and plant resources often provide essential resources for local communities, including food, medicine, fuel and livelihoods. Policies that disregard these interdependencies often generate conflict or poor implementation.

Indigenous and local ecological knowledge can supply valuable information on plant distributions, seasonal cycles, sustainable harvesting and ecosystem behaviour. However, such knowledge should not be assumed universally applicable, as sustainability depends on specific institutional, ecological and socio-economic contexts. The most effective approaches often combine local knowledge with scientific monitoring and participatory governance.

Sustainable use is especially critical for medicinal and aromatic plants. Harvesting of roots, bark or whole plants can be more destructive than leaf or fruit collection, given potential regeneration challenges. Cultivation, propagation, traceability and community-based management can help alleviate pressures on wild populations.

International policy is increasingly recognizing these conservation dimensions. KMGBF Target 4 explicitly addresses both in-situ and ex-situ conservation and maintenance of genetic diversity, while Target 3 focuses on ecologically representative, connected and equitably governed conservation systems.

Implementation remains a key challenge. While global targets can provide guidance, conservation outcomes ultimately depend on national institutions, local management, financing, scientific capacity and monitoring systems.

MEASURING CONSERVATION SUCCESS

An effective biodiversity conservation should be assessed not by the scale of conservation efforts but by the biological outcomes they deliver. The establishment of protected areas, number of trees that have been planted, propagation of threatened species, or increase of gene-bank collections represent conservation effort, but rarely show the true level of biodiversity conservation. More meaningful is an assessment of whether populations are increasing or becoming more stable, diversity is being maintained, habitats are recovered, and ecosystems are more connected.

The relevant indicators are population size and occupancy, recruitment and regeneration, genetic diversity, habitat quality, species composition, and the functional and phylogenetic diversity, ecological connectivity, invasive-species abundance, restoration trajectories and long-term population persistence. Monitoring framework of Kunming–Montreal Global Biodiversity Framework (KMGBF) includes Red List Index, effective population size, and plant genetic resources conserved in medium- or long-term facilities, representing a shift from counting conservation actions towards measuring biological condition, recovery and long-term security.

AN INTEGRATED FRAMEWORK FOR FUTURE BIODIVERSITY CONSERVATION

Based on the evidence discussed above, biodiversity conservation can be viewed as a continuous adaptive cycle:

Threat assessment → biodiversity baseline → plant and genetic assessment → spatial prioritization → in-situ conservation → ex-situ backup → restoration → ecological connectivity → long-term monitoring → adaptive management → community participation → policy implementation → measurable outcomes.

The first step would be to identify direct and interacting pressures. A biodiversity baseline should then record species, populations, habitats and, where possible, genetic variation. Conservation priorities should take account not only of species richness, but also of threatened species, endemic taxa, functional traits, phylogenetic diversity and ecosystem integrity.

Restoration should then focus on restoring ecological integrity rather than simply on cover. Ex-situ collections should provide insurance against irreversible loss, while in-situ populations should be the focus of long-term conservation.

Monitoring should then assess whether populations are recovering, whether genetic diversity is being maintained and whether ecological functions are being restored. Should targets not be met, management should be adjusted. This adaptive approach is especially important under climate change because environmental conditions will not remain static.

The global framework is already moving towards this. KMGBF Target 2 links restoration with biodiversity, ecosystem functions, ecological integrity and connectivity, while Target 4 links species recovery with genetic diversity.

CONCLUSION

Biodiversity conservation is at a stage where both protection of remaining species and habitats must be combined with restoration activities, genetic conservation and ecological resilience building. Plants have particular importance as their biodiversity forms the foundation for ecosystem structure, productivity, food production and various ecosystem services. Recent assessments by the FAO highlight that plant genetic resources are under continued threat despite significant advances in global germplasm

conservation. At the same time, the KMGBF has developed specific international targets for restoration, protected areas and genetic diversity.

The central challenge, therefore, is not the absence of conservation approaches, but rather their integration. Protected areas, seed banks, restoration projects, genomics, remote sensing, community stewardship and policy instruments need to be viewed as elements of a single system for biodiversity conservation. While expanding the area under protection or restoration is critical, the ultimate assessment of conservation success should relate to population viability, genetic diversity, ecosystem integrity, connectivity and long-term persistence.

A plant-centered conservation strategy does not imply a separation of plants from the larger biodiversity context, but rather an acknowledgement that plants represent one of the fundamental pillars upon which ecosystem resilience can be built. The combination of botanical expertise with environmental science, ecological restoration, modern surveying approaches and participatory governance provides a more realistic perspective on how biodiversity loss assessment can be transformed into long-term biodiversity recovery initiatives.

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