



BGCI Technical Review

Scaling ecosystem restoration through botanical garden networks









NYBG

BOTANIC GARDENS CONSERVATION INTERNATIONAL

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BOTANIC GARDENS CONSERVATION INTERNATIONAL (BGCI) is the largest global plant conservation network with over 950 member institutions in more than 120 countries. BGCI plays a key coordinating role, facilitating collaboration between botanic gardens and other conservation organisations, and supports the development and long-term functioning of botanic garden networks. BGCI ensures that local expertise contributes to global impact, and mobilises funding and technical assistance for practical conservation efforts worldwide.

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Foreword

Authors: David C. Bartholomew[1,2] and Emma C. Grover[3]
Institutions: [1]Botanic Gardens Conservation International, [2]The Global Biodiversity Standard, [3]New York Botanical Garden

Botanical gardens have long stood as custodians of plant diversity. Today, they are increasingly emerging as catalysts of a far more ambitious agenda: the restoration of ecosystems at scale. Across continents and biomes, these institutions are uniquely positioned to bridge science, practice, and society—mobilising knowledge, plant material, and partnerships to transform ecosystem restoration from aspiration into measurable impact.

This publication synthesises evidence and perspectives from contributors to the Nurturing Nature Initiative and the Ecological Restoration Alliance of Botanic Gardens (ERA) to examine this catalytic role. It is grounded in the work of the Nurturing Nature Initiative, led by the New York Botanical Garden (NYBG) in partnership with Botanic Gardens Conservation International (BGCI), and draws upon a series of reports commissioned from Climate Resilience Advisory Group members, ERA members, invited subject-matter experts, and NYBG scientists and practitioners. The perspectives presented here reflect the experience and expertise of these contributors, while the initiative aims to broaden participation and exchange across regions and contexts as it expands. Together, these efforts reflect a growing movement to position botanical gardens at the forefront of global ecosystem restoration and climate resilience efforts.

The Nurturing Nature Initiative is a global programme designed to accelerate ecosystem restoration by mobilising the unique capabilities of botanical gardens and their local partners. At its core, it strengthens a network of institutions rooted in their local contexts while connected through shared knowledge, standards, and learning. Through this approach, Nurturing Nature equips botanical gardens and communities with the tools and training needed to propagate, plant, and steward climate-appropriate and locally adapted species—supporting biodiversity recovery, ecosystem resilience, and community well-being.



Biodiverse tropical plant assemblages at Xishuangbanna Tropical Botanical Garden (XTBG) in Yunnan, China. Photo: Mauricio Diazgranados.

More than 3,600 botanical gardens operate worldwide (BGCI GardenSearch, 2026), collectively maintaining important expertise in fields including plant taxonomy, horticulture, biodiversity conservation, and environmental education. These institutions also serve as trusted public platforms that connect scientific knowledge with community engagement and local environmental stewardship. Anchored in a global survey conducted jointly between BGCI and NYBG, this publication assesses the diverse ways in which botanical gardens can contribute to restoration, drawing on both quantitative insights and grounded case studies to highlight where impact is already being realised and where further potential lies.

The breadth of topics covered in this publication reflects the inherently interdisciplinary nature of ecosystem restoration and the unique capacity of botanical gardens to operate across these domains. The reports span foundational botanical areas such as plant collection, ex *situ* conservation, and propagation, while also addressing emerging frontiers including genomic applications, climate-adaptive variation, and integrative biotic assistance. They extend beyond ecological science to explore community engagement, livelihoods, capacity building, policy integration, and sustainable finance. Together, these contributions illustrate how botanical gardens function not only as scientific institutions, but also as conveners, educators, and implementers. In this multifaceted capacity, they actively bridge gaps between research and practice, local knowledge and global frameworks, and ecological outcomes and human well-being.

Within this analysis, the experience of the ERA provides a critical foundation. The ERA has shown how a coordinated network can translate restoration principles into practice across diverse contexts, strengthening technical capacity and embedding ecological restoration within the core work of botanical gardens. Examples drawn from ERA sites throughout the publication ground the review in implementation, illustrating how shared principles are applied in practice.

Several core messages emerge across the publication. One is the role of botanical gardens as connector institutions—linking *ex situ* and *in situ* conservation, bridging research and on-the-ground practice, and illustrating the importance of plants and fungi to local communities. Distinct from this, the report highlights the critical role of native species in shaping effective restoration, ensuring that efforts are grounded in ecological appropriateness, support genetic diversity, conserve and enhance biodiversity, and contribute to long-term ecosystem resilience.

Botanical gardens also emerge as critical actors along the full restoration pathway, from plant collection and conservation through propagation and deployment to long-term stewardship. This is paired with a strong emphasis on community-centred restoration, including the importance of local knowledge, livelihoods, and community engagement in shaping durable and relevant outcomes. At the same time, the publication underscores the broader enabling conditions required to sustain restoration at scale, including capacity building, supportive policy environments, and sustainable financing.

Another central theme emerging from the survey and advisory inputs is the need to prioritise ecological integrity. As restoration efforts increase, there is a growing risk of measuring success through area-based targets rather than outcomes. Botanical gardens are well placed to address this gap, ensuring restoration delivers biodiversity recovery, ecosystem function, and resilience. The development of The Global Biodiversity Standard (TGBS) is one example that reflects this shift. Emerging from the ERA's strategic direction, TGBS provides an outcome-based framework to assess restoration performance and verify biodiversity impacts at the site level. Early implementation demonstrates its value in strengthening project design, supporting adaptive management, and improving accountability.



A living collection of tropical plant biodiversity in NYBG's Enid A. Haupt Conservatory. © New York Botanical Garden. Photo: Marlon Co.

The findings presented here point to a broader conclusion: botanical gardens are critical enablers of effective restoration. However, scaling this role will require greater coordination and investment.

Botanical gardens have traditionally operated within defined physical boundaries, often delivering high-quality but localised restoration. The evidence presented here suggests that their greatest potential lies in extending this influence beyond their walls—mobilising expertise, partnerships, and standards to operate at landscape scales. This shift from site-based action to system-level engagement is where their catalytic role becomes most significant. By supporting larger restoration programmes, informing policy, and guiding investment through knowledge-based frameworks, botanical gardens can help ensure that scale does not come at the expense of ecological integrity, but instead amplifies impact.

In this context, the Nurturing Nature Initiative offers a pathway to expand impact by positioning botanical gardens as hubs for restoration and climate resilience.

As restoration moves from commitment to delivery, the need for credible, evidence-based approaches is increasingly clear. This publication highlights the progress made, while identifying opportunities to strengthen and expand the role of botanical gardens as catalysts of effective, outcome-driven restoration.

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Introduction: Restoration and Resilience

Author: George D. Gann
Institution: Society for Ecological Restoration

The degradation of native ecosystems and the loss of biodiversity negatively affect the resilience and sustainability of social-ecological systems, including in the context of climate change (Díaz et al., 2019). The restoration of ecosystems is widely recognized as a core mechanism for addressing these challenges as expressed in the Strategy of the UN Decade on Ecosystem Restoration 2021–2030 (UNEP, 2020) and by multiple other global initiatives (Box 1). Key guidance for ecosystem restoration is provided by the Standards of practice to guide ecosystem restoration (Nelson et al., 2024) and the Society for Ecological Restoration (SER) Principles and standards for the practice of ecological restoration (SER Standards; Gann et al., 2026). As articulated in the UN Decade on Ecosystem Restoration Strategy, the objectives of the United Nations Sustainable Development Goals (and in turn other global agreements) cannot be met "unless ecosystem degradation is stopped and ecosystem restoration is undertaken at the immense scale of hundreds of millions of hectares globally."

One of the key contributions of ecosystem restoration is to combat climate change, including through climate change mitigation, adaptation, and increased social-ecological resilience (Shin et al., 2022). While not a substitute for decarbonization, restoration helps mitigate climate change through the restoration of ecosystems that store carbon above and below ground, including forests, wetlands, grasslands, and production ecosystems. Restoring healthy, high-integrity native ecosystems also contributes in essential ways to climate change adaptation for nature and people, such as through the restoration of ecosystems that buffer communities from floods or rising sea levels (Duarte et al., 2013), and through improving ecosystem connectivity so that plants and animals can migrate more freely in response to climate change, preventing extinctions, and allowing ecosystems to shift and reassemble.



Volunteer-led restoration efforts at the New York Botanical Garden support the recovery and stewardship of local ecosystems.
© New York Botanical Garden. Photo: Marlon Co.

Box 1. Key global restoration guidance and initiatives with connections to climate change (adapted from Gann et al., 2026)

- The United Nations (UN) Sustainable Development Goals (SDGs) for 2030 call for the restoration of marine and coastal ecosystems (Goal 14), forests and other terrestrial ecosystems (Goal 15), and urgent action on climate change (Goal 13).
- The (2021–2030) UN Decade on Ecosystem Restoration aims to prevent, halt and reverse the degradation of ecosystems on every continent and in every ocean to combat climate change, halt mass extinction, and improve human wellbeing.
- The UN Convention on Biological Diversity (CBD) Kunming-Montreal Global Biodiversity Framework (KM-GBF) calls for all parties to the convention to begin restoration of at least 30% of their degraded terrestrial, inland water, and coastal and marine ecosystems by 2030 (Target 2), and to use nature-based solutions and/or ecosystem-based approaches to minimize the impacts of climate change on biodiversity and to build resilience (Target 8).
- The UN Convention to Combat Desertification (UNCCD) Strategic Framework (2018–2030) promotes land restoration and rehabilitation including to achieve Land Degradation Neutrality (LDN), in order to conserve and sustainably use biodiversity and address climate change.
- The G20 Global Land Initiative, aligned with the UNCCD Strategic Framework, aims to prevent, halt and reverse land degradation and reduce degraded land by 50% by 2040.
- The Bonn Challenge and the New York Declaration on Forests seek to bring 350 million hectares under restoration, reducing emissions from deforestation and forest degradation, by 2030, largely through Forest and Landscape Restoration (FLR). Regional programs include Initiative 20x20 in Latin America and AFR100 in Africa.
- The GEF-8 supports 11 Integrated Programs, including the Ecosystem Restoration Integrated Program, including 20 countries in Asia, Africa, and Latin America working to restore degraded landscapes and mitigate climate change through carbon sequestration, in support of the Bonn Challenge.
- The Freshwater Challenge, with 50 participating countries plus the EU aims to restore 300,000 kilometers of degraded rivers and 350 million hectares of degraded wetlands by 2030, while securing the protection of freshwater ecosystems important for biodiversity and ecosystem services, and tackling the climate crisis.
- Kelp Forest Challenge, a global initiative, aims to strengthen relationships with the ocean and safeguard and restore 4 million hectares of carbon-sequestering kelp forests by 2040.
- The Coral Reef Breakthrough, a global initiative to protect and restore coral reefs, aims to secure at least $12 billion in investments by 2030 to safeguard 125,000 km^2 of reefs, supporting resilience in the face of climate change for half a billion people.

Growing awareness of the need for ecosystem restoration has resulted in an expansion of the scale and scope of restoration ambition globally (Bartholomew et al., 2026, Box 1). In addition to global efforts, regional initiatives such as the European Union (EU) Nature Restoration Regulation (European Union, 2024), and growing investments in restoration by national and subnational governments, nonprofit and community groups, and the private sector are occurring in nearly all ecosystems, at all scales, and across the world. A key restoration agreement is articulated in Target 2 of the CBD Global Biodiversity Framework, which is to "ensure that by 2030 at least 30% of areas of degraded terrestrial, inland water, and coastal and marine ecosystems are under effective restoration, in order to enhance biodiversity and ecosystem functions and services, ecological integrity and connectivity" (CBD, 2022).

The concept of ecosystem restoration includes a broad spectrum of restoration activities and major restoration types as illustrated by the SER Restorative Continuum (Fig. 1). Major restoration types include: 1) sustainability practices (e.g., reduction of unsustainable consumption, pollution, invasive species, and increase in sustainable resource use and management); 2) remediation (e.g., removal of contaminants, pollutants and other threats); 3) rehabilitation (e.g., renewing ecosystem functions and services in highly modified areas such as urban areas, former mine sites, and degraded production ecosystems); and, 4) ecological restoration. Ecological restoration, which is imperative for the recovery of native biodiversity, ecosystem integrity, and increased social-ecological resilience, is defined as "the process of assisting the recovery of a native ecosystem that has been degraded, damaged, or destroyed" (Gann et al., 2026). Critically, ecological restoration does not attempt to immobilize an ecosystem at some specific point in time, but accounts for past and predicted environmental shifts, including climate change. Expanding the spatial extent of native ecosystems as well as increasing the integrity of existing degraded native ecosystems are both critical for climate change response, while supporting the long-term conservation of biodiversity and the health and well-being of people.

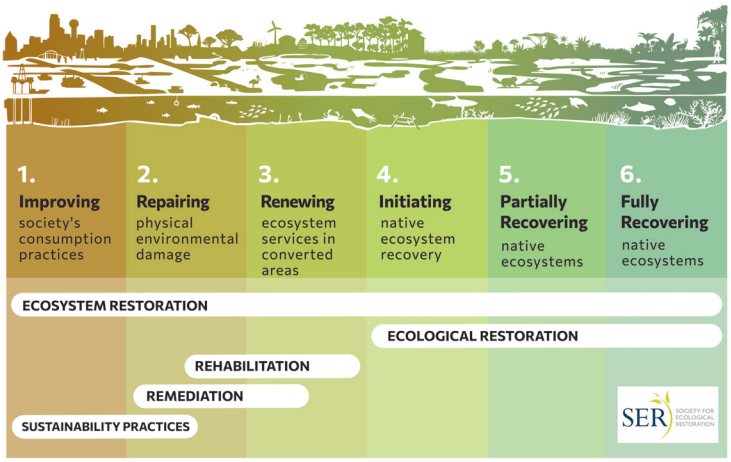


Figure 1. The Restorative Continuum includes a range of restorative activities and major restoration types (lower bars) that, collectively, can reverse ecosystem degradation, leading to enhanced biodiversity, ecosystem functions and services, ecosystem integrity, and connectivity. The combination of ecological restoration and all other restorative activities along the continuum is accommodated under the UN's overarching term ecosystem restoration (FAO et al., 2021, Nelson et al., 2024). To address the biodiversity and climate crises and recover the natural capital needed to provide for human health and wellbeing, ecosystem restoration projects and programs should strive for the highest ambition possible within each column of the Restorative Continuum, as illustrated by the upward arrows. The ambition to plan activities that enable further movement to the right on the continuum when possible and appropriate is illustrated by the rightward arrows. Ecosystem restoration is needed in all types of land-use contexts, including in highly urbanized landscapes and intensive production ecosystems, whether native or converted (Gann et al., 2026).

Principles and standards are critical for optimizing outcomes from restoration, and effective restoration is defined as standards-based restoration underpinned by agreed principles that results in appropriately balanced sustainable net gain that benefits and enhances biodiversity, ecosystem integrity, and human well-being (FAO et al., 2024). Standards for both ecological restoration and ecosystem restoration have been developed. The SER Standards have been widely downloaded and cited in the literature (e.g., Gann et al., 2019) and are available for download from Restoration Ecology. Key tools included in the SER Standards include the Social Benefits Wheel and the Ecological Recovery Wheel, each of which is underpinned by six key attributes and 18 or more sub-attributes and a 5-star assessment system. The SER Standards also provide detailed guidance on project assessment, planning, implementation, monitoring, and ongoing management. Eight principles provide guidance on broad engagement, sources of knowledge, documenting pre-project baseline conditions, the development of native ecosystem reference models, and other key topics. Standards of Practice for all types of ecosystem restoration along the Restorative Continuum have also been published, covering five components, 45 subcomponents, and more than 300 best practices (Nelson et al., 2024).

Botanical gardens can play a vital role in supporting restoration to enhance climate resilience, as they are uniquely qualified to contribute to key areas of restoration practice, including the selection, curation, and production of plant materials; expertise in rare and threatened plants; and long-term monitoring of ecosystems undergoing restoration. Although concentrated at northern latitudes, the geographic spread of these institutions across the world positions the botanical garden community to make a significant contribution to the scaling up of restoration. Botanical gardens also specialize in understanding intraspecific plant variability, the actual and potential responses of plants to climate change, and their role in increasing climate resilience.

Importantly, botanical garden expertise can support the uptake of standards-based restoration, such as through The Global Biodiversity Standard (Bartholomew and Mosyaftiani et al., 2024). Cross-training botanical garden staff in ecological restoration practice and promoting SER's Certified Ecological Restoration Practitioner (CERP) program is critical to increasing global capacity for restoration. The botanical garden-based CERP community can then support emerging ecological restoration project certification programs, such as those underpinning insurance products for restoration that are essential to reducing risk and uncertainty for restoration projects.



Ecological restoration using tree guards at Kadoorie Farm and Botanic Garden, Hong Kong. Photo: Kadoorie Farm and Botanic Garden.

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Introduction: Overview of Botanical Gardens' Roles in Conservation and Restoration

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NYBG



Invasive species management along the Bronx River at the New York Botanical Garden. © New York Botanical Garden. Photo: Marlon Co.

Executive Summary

Botanical gardens are dynamic living museums of plant diversity and knowledge whose functions have expanded over more than four centuries. From their origins as medicinal plant collections in 16th-century Europe to their current roles as hubs for conservation, science, education, and climate resilience, botanical gardens have continuously adapted to meet societal needs. Today, a global network of thousands of botanical gardens—over 3,600 institutions currently identified and still growing—collectively cultivates more than 30% of all known plant species, including over 40% of threatened plant species, in living collections and seed banks. With a broad public reach (roughly 500–750 million visitors annually), these institutions serve as trusted centers for plant science education, community engagement, and sustainable development outreach. This report defines botanical gardens, outlines their global distribution and evolving capacities, and examines their contributions to biodiversity conservation, ecological restoration, botanical education, and climate-change adaptation.

Botanical gardens possess distinct strengths—taxonomic expertise, horticultural skills, extensive living collections and seed banks, long-term research infrastructure, and deep community ties—that distinguish them from other restoration actors. These strengths enable botanical gardens to serve as active restoration practitioners (planning and implementing their own projects) and as critical enablers (providing plant material, expert knowledge, training, and partnerships for broader restoration and climate resilience initiatives). In line with global frameworks such as the UN Decade on Ecosystem Restoration and the Kunming-Montreal Global Biodiversity Framework, recent research and policy emphasize that fully mobilizing botanical gardens is essential to achieving international restoration, biodiversity, and climate goals.

Current State of Knowledge

Defining Botanical Gardens & Global Presence:

Botanical gardens are institutions devoted to the collection and cultivation of living plants, documented and curated for scientific research, conservation, education, and public display (Wyse Jackson & Sutherland, 2000; BGCI, 2018). The concept of botanical gardens traces back over 450 years to the first European physic gardens of the Renaissance, which were established for studying medicinal plants and training physicians (Neves, 2024; Heywood, 2017). Over subsequent centuries, botanical gardens developed as centers of plant taxonomy, plant acclimatization, and economic botany, often linked to colonial expansion and the exchange of economically important crops (Neves, 2024; Krishnan & Novy, 2016). Prominent colonial-era institutions, such as the Royal Botanic Gardens, Kew (founded 1759) and the Real Jardín Botánico de Madrid (1755), served imperial interests by cataloging global flora and introducing new species for agriculture and horticulture (Krishnan & Novy, 2016). In the latter half of the 20th century, however, botanical gardens increasingly adopted biodiversity conservation as a core mission, responding to rising environmental awareness and the biodiversity crisis (Wyse Jackson & Sutherland, 2000; Neves, 2024). This shift was formalized through the establishment of Botanic Gardens Conservation International (BGCI) in 1987 and the launch of the Global Strategy for Plant Conservation (GSPC) in 2002 under the Convention on Biological Diversity.

Today, botanical gardens form a vast global network, with institutions present in well over 100 countries (O'Donnell & Sharrock, 2018). BGCI's GardenSearch database identified more than 3,600 botanical institutions worldwide. New botanical gardens continue to be established, particularly in Asia, Latin America, and Africa as countries recognize their value for conservation and sustainable development, counteracting resource degradation and biodiversity loss (Neves, 2024; Li et al., 2023). Recent analyses indicate that the establishment of national botanical gardens accelerated significantly after 1945, with substantial growth in China, Southeast Asia, and other developing regions during a rapid expansion phase (Li et al., 2023). Across all types of institutions, from small private university botanical gardens to large national public centers, botanical gardens collectively manage an extraordinary array of plant diversity *ex situ*. A 2017 global assessment estimated that botanical gardens maintain at least 105,000 plant species in their living collections (roughly 30% of known plant diversity), including more than 13,000 threatened species (Mounce et al., 2017). This scale positions botanical gardens as important safeguards against plant extinction and as strategic assets for global biodiversity conservation.

Evolving Functions and Unique Capacities

A defining feature of botanical gardens is the integration of scientific research and practical horticultural management within a single institution. Historically, botanical gardens played central roles in the advancement of plant sciences (including classification, taxonomy, breeding, morphology, and physiology) while also serving as trial sites for cultivating species under new environmental conditions (Powledge, 2011; Krishnan & Novy, 2016). As their missions expanded in the late twentieth century, botanical gardens retained their scientific foundations while increasingly engaging in applied conservation and environmental education (Hardwick et al., 2011; Neves, 2024). Many modern botanical gardens have multidisciplinary teams that include taxonomists, ecologists, conservation biologists, educators, landscape architects, and horticulturists, and operate substantial infrastructure such as herbaria, seed banks, nurseries, greenhouses, DNA and propagation labs, botanical libraries, and often adjacent natural lands. Together, these assets support the development of propagation and seed storage protocols for rare or challenging species, the maintenance of genetically diverse collections of wild-origin plants, and long-term research on plant responses to environmental change.

In particular, the capacity of botanical gardens to cultivate large numbers of species—often including threatened or poorly studied taxa—distinguishes them from most commercial nurseries and many conservation organizations (Hardwick et al., 2011).

Equally important is the public-facing role of botanical gardens. Most are cultural institutions open to visitors, and collectively they attract large and diverse audiences, positioning them as trusted venues for plant science education and public outreach (O'Donnell & Sharrock, 2018). Since the late twentieth century, many botanical gardens have embraced a social and sustainable development agenda, expanding programming to include urban agriculture, citizen science, Indigenous and local knowledge, horticultural therapy, and issues addressing environmental justice and equitable access to nature (Neves, 2024; Krishnan & Novy, 2016). Botanical gardens increasingly participate in municipal sustainability initiatives, climate adaptation planning, and biodiversity policy processes, aligning their activities with global frameworks such as the UN Sustainable Development Goals and partnering with governments and civil society to implement nature-based solutions in urban and regional contexts (Neves, 2024; Frediani, 2024). This reflects a growing recognition that plant conservation is intertwined with human well-being and requires broad societal engagement.

Recent scholarship further highlights the potential of botanical gardens to function as platforms for institutional and social transformation toward sustainability. Concepts such as nature-based solutions and the "Just Transition" emphasize the role of botanical gardens in advancing equitable and inclusive climate responses and in integrating multiple knowledge systems, including Indigenous and Western scientific traditions (Frediani, 2024).

The emerging concept of the botanical garden as an open knowledge center (Hortus apertus) captures a shift from historically insular institutions toward more networked, outward-facing models that support environmental innovation and collaboration (Neves, 2024; Frediani, 2024). Leading institutions now formalize these expanded roles into their strategic planning; for example, the New York Botanical Garden's Science Strategy (2025–2030) highlights cross-cutting initiatives like "Plants for Climate Resilience" and the use of emerging technologies, including artificial intelligence and AI-enabled remote sensing applications, to accelerate plant science and conservation (Diazgranados et al., 2025). At the same time, realizing the full scientific and conservation potential of botanical gardens will require improved coordination of data and collections across institutions, prompting calls for globally integrated digital systems that link living collections and associated knowledge (Brockington et al., 2026).

Integration into Restoration and Climate Resilience Efforts

Recent international policy frameworks emphasize that achieving large-scale restoration and climate adaptation targets will require mobilizing institutions with specialized expertise in plant science and conservation.

The United Nations Decade on Ecosystem Restoration (2021–2030) calls on governments, civil society, and scientific institutions, including botanical gardens, to help restore 350 million hectares of degraded land by 2030 through knowledge-based and evidence-driven actions (UNEP & FAO, 2020). Similarly, the Kunming-Montreal Global Biodiversity Framework (CBD, 2022) highlights ecosystem restoration as a core objective, with Target 2 calling for the restoration of at least 30% of degraded ecosystems by 2030. Achieving this target implicitly depends on applying botanical expertise to ensure the use of appropriate native species, maintain genetic diversity, and conduct long-term monitoring in restoration programs (CBD, 2022).



Sunset over the Enid A. Haupt Conservatory at the New York Botanical Garden. © New York Botanical Garden. Photo: Marlon Co.

In response to these mandates, botanical gardens have increasingly assumed active roles as both leaders and partners in ecological restoration initiatives worldwide (Aronson, 2014; Hardwick et al., 2011). Formal networks such as BGCI's Ecological Restoration Alliance of Botanic Gardens (ERA), founded in 2012, now connect several institutions across more than 20 countries that implement demonstration projects and exchange technical knowledge and best practices (Aronson, 2014; Shaw et al., 2016). Beyond such networks, many botanical gardens engage directly with governments, NGOs, and local communities to support restoration efforts across a wide variety of ecosystems, including tropical forests, island systems, urban landscapes, and green infrastructure (Hardwick et al., 2011; Neves, 2024). These activities illustrate how botanical gardens operate across scales, from local implementation to international knowledge exchange.

Botanical gardens contribute to restoration by applying scientific and horticultural expertise to improve the ecological quality and durability of restoration outcomes. They support biodiversity-rich plantings by providing and propagating diverse native species, often sourced from their living collections or seed banks, and they design species assemblages informed by taxonomy, biogeography, and climate projections (Hardwick et al., 2011; Mounce et al., 2017). This approach helps reduce risks associated with genetic bottlenecks, maladaptation, and low functional diversity. Botanical gardens also function as sites of applied experimentation, testing restoration-relevant techniques such as seed pre-treatment, assisted gene flow, and soil or microbiome interventions, and disseminating results through training programs, data sharing, and scientific publications (Hardwick et al., 2011). Through these combined roles, botanical gardens have become recognized not simply as repositories of plant diversity but as active implementers and knowledge brokers within restoration and nature-based climate solutions.

Knowledge Gaps and Capacity Needs

Despite their strengths, significant gaps and challenges must be addressed for botanical gardens to fulfill their potential in global restoration and resilience efforts:

- **Integration into Policy & Planning:** Botanical gardens remain underutilized in formal restoration, biodiversity, and climate adaptation strategies. Their scientific, horticultural, and infrastructural capacities are not yet consistently embedded in national and international planning frameworks, limiting their influence on large-scale implementation and standard setting (Hardwick et al., 2011; Aronson, 2014).

- **Plant Material Supply and Genetic Diversity:** A central challenge in restoration is the limited availability of diverse, ecologically appropriate, and climate-resilient plant materials, particularly native plants and rare and threatened species (Hardwick et al., 2011; Mounce et al., 2017). Although botanical gardens collectively maintain extensive living collections and propagation expertise, these resources remain insufficiently mobilized to meet restoration demand at scale.



Preparation of herbarium specimens for preservation and inclusion in botanical collections. © New York Botanical Garden. Photo: Marlon Co.

- **Coordination of Living Collections ("Metacollection" Approaches):** Improved coordination among botanical gardens and strategic investment are needed to manage living collections as an integrated global resource. Expanding seed banking, nursery capacity, and shared stewardship frameworks would allow botanical gardens to function more effectively as a distributed conservation and restoration infrastructure (Mounce et al., 2017; Cano et al., 2025; Brockington et al., 2026).

- **Horticulture Workforce & Training Capacity:** A shrinking pool of qualified horticulturists and technical staff is a growing concern for many botanical institutions. This capacity constraint can hinder large-scale propagation and restoration efforts, highlighting the need for sustained investment in horticultural training, education, and recruitment to ensure adequate expertise for future restoration demands.

- **Resource and Institutional Capacity:** Many botanical gardens—particularly in low-income and biodiversity-rich regions—face persistent constraints related to funding, staffing, and infrastructure. These limitations restrict their ability to initiate, scale, or sustain restoration activities, despite locations in regions of highest conservation priority (Neves, 2024; Shaw et al., 2016).

- **Equity and Inclusive Practice:** As botanical gardens expand their roles in restoration and sustainability, ensuring socially just and inclusive approaches remains a critical challenge. Many institutions are working to address colonial legacies by partnering with Indigenous peoples and local communities, diversifying staff and governance, and respecting multiple knowledge systems. However, embedding these principles consistently requires sustained institutional change rather than isolated initiatives (Neves, 2024; Frediani, 2024).

- **Plant Health and Biosecurity:** Restoration and plant exchange activities carry inherent biosecurity risks. Historical evidence shows that botanical gardens have contributed, unintentionally, to the spread of invasive species and pests, particularly in biodiversity-rich regions (Hulme, 2011). This legacy underscores the need for rigorous risk assessment, quarantine, and biosecurity protocols in contemporary restoration practice.

- **Integrative Biotic Interactions:** Successful restoration often requires reestablishing fundamental plant–animal–microbe interactions. The recovery of below-ground mutualists (e.g., mycorrhizal fungi) and above-ground partners (e.g., pollinators, seed dispersers) is essential for long-term ecosystem function, yet these are often overlooked in restoration planning. Botanical gardens can help integrate such biotic partnerships by researching these dependencies and supporting their incorporation into restoration projects.

- **Long-Term Monitoring, Evaluation, and Learning:** Effective long-term monitoring remains a weak point in many restoration efforts, with projects often concluding before ecological recovery can be adequately assessed (Hardwick et al., 2011). Stronger monitoring, evaluation, and learning frameworks—alongside open data practices and shared standards across institutions—are essential for generating robust evidence on restoration outcomes and biodiversity recovery (Brockington et al., 2026).

- **Intellectual Property & Benefit-Sharing:** The need to address access and benefit-sharing issues (e.g., equitable use of plant genetic resources under frameworks like the Nagoya Protocol) presents a challenge. Botanical gardens can serve as intermediaries to ensure fair benefit-sharing and respect for intellectual property rights when sourcing and distributing plant materials for restoration.

Potential Contributions of Botanical Gardens

Despite persistent constraints, botanical gardens are well-positioned to make several high-impact contributions to ecological restoration and climate resilience by leveraging their distinctive institutional assets:

- **Plant Conservation Hubs: Living Collections, Seed Banks, and Propagation:** Botanical gardens function as key repositories and sources of plant diversity for restoration. Their living collections and seed banks encompass a wide range of native and threatened species, often supported by detailed provenance and ecological data (Mounce et al., 2017; BGCI, 2018). Many gardens participate in coordinated seed conservation initiatives, such as the Millennium Seed Bank Partnership, which safeguard wild germplasm and provide a foundation for supplying climate-resilient and ecologically appropriate plant material for large-scale restoration efforts (Ren & Blackmore, 2023). With targeted investment and coordination, these systems can be more effectively mobilized to support habitat recovery at scale.

- **Scientific Expertise and Research:** Botanical gardens contribute essential science-based guidance to restoration and climate adaptation planning. Their research infrastructure—including herbaria, long-term field data, and experimental collections—can be used to reconstruct historical baselines for degraded ecosystems, assess ecological requirements of species, and inform the selection of plant provenance suited to future climatic conditions. Botanical gardens also contribute to global knowledge initiatives, such as the Global Tree Assessment and phenology monitoring networks, which generate baseline data critical for restoration prioritization and climate resilience strategies (Beech et al., 2017).

- **Education, Training, and Community Engagement:** As widely trusted public institutions, botanical gardens play an important role in education, capacity building, and stakeholder engagement related to restoration and climate action (O'Donnell & Sharrock, 2018). Many gardens work directly with Indigenous peoples, local communities, farmers, urban planners, and policymakers, using their convening power to support dialogue, training, and co-production of knowledge around sustainable land use (Neves, 2024; Frediani, 2024). In urban contexts, botanical gardens often serve as anchors for city greening and climate adaptation initiatives, advising on native species selection, coordinating volunteers, and, in some cases, managing or supporting municipal tree-planting and green-infrastructure programs (Cavender et al., 2019; Diazgranados, 2015).

- **Partnerships, Innovation, and Policy Influence:** Botanical gardens are well placed to catalyze partnerships, mobilize resources, and contribute to policy development for restoration and climate resilience. Their long institutional histories and public credibility often afford them influence in conservation, planning, and funding arenas. Many maintain close relationships with government agencies, international NGOs, and philanthropic organizations, enabling them to act as bridge institutions between science, policy, and on-the-ground implementation (Aronson, 2014; Neves, 2024). Through global and regional networks—such as BGCI, the American Public Gardens Association, and Botanic Gardens Australia and New Zealand—even smaller gardens can participate in collaborative research, funding proposals, and technical working groups, extending their impact beyond local contexts (Neves, 2024).

While opportunities are abundant, restoration initiatives involving botanical gardens also face risks and potential trade-offs. Some projects may not achieve intended ecological outcomes due to unpredictable factors (e.g., climate extremes, socioeconomic challenges), and introductions of new plant material can carry unintended consequences. Recognizing and openly evaluating failures and trade-offs is important for adaptive learning and responsible practice.

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Practice Insights

Urban restoration and climate resilience in Bogotá Jardín Botánico de Bogotá "José Celestino Mutis": the challenge of greening a megacity



Volunteer participating in a tree-planting restoration event at the Thomas van der Hammen Forest Reserve in Bogotá, Colombia. Photo: Mauricio Diazgranados, 2015.

Context:
The Jardín Botánico de Bogotá (JBB) exemplifies how a botanical garden within municipal government can play a central role in urban restoration and climate resilience. Founded in 1955, JBB is a public garden under Bogotá's city administration, with a dual mandate: managing its 20-hectare botanical garden and leading citywide programs in urban forestry, ecological restoration, climate adaptation, and environmental education (Diazgranados, 2015).

Over the past two decades, JBB has served as the lead technical agency for Bogotá's urban greening strategy in this high-altitude megacity (~2,600 meters of elevation), coordinating arborization, restoration of wetlands and riparian corridors, urban agriculture initiatives, and public engagement programs.

Its formal integration into city governance provides stable funding, regulatory authority, and a clear mandate to act as both a direct implementer and a technical advisor supporting broader municipal sustainability goals.

Approach:
JBB's urban restoration strategy is science-based, participatory, and operational at scale. By 2025, JBB had planted more than 650,000 trees across streets, parks, and waterways, contributing to an urban forest of approximately 1.45 million trees under its management (Diazgranados, 2015; García, 2025). Its nurseries and seed bank supply diverse, climate-resilient native material, ensuring species selection is ecologically appropriate and minimizing biosecurity risks associated with non-native or potentially invasive species.

To support planning and long-term management, JBB maintains a GIS-based inventory of approximately 1.7 million trees (the SIGAU system; https://jbb.gov.co/sigau/), which enables strategic planting, health monitoring, and identification of priority greening sites (Diazgranados, 2015). Beyond tree planting, JBB leads restoration of urban wetlands and riparian corridors, replacing invasive species with native vegetation to restore ecological function, improve flood regulation, and enhance carbon sequestration. Projects such as the renaturing of the Tibabuyes (Juan Amarillo) have improved hydrological regulation and provided habitat for birds and other wildlife.

Community participation is a core component of JBB's model. Through its *Rutas Agroecológicas* program, the garden supports urban agriculture, environmental education, and greening initiatives in low-income neighborhoods (Diazgranados, 2015). JBB also organizes volunteer tree-planting events, engages citizen scientists in monitoring urban tree health, and collaborates with schools to integrate plant science into educational programs. These efforts foster public ownership of urban green spaces and contribute to their long-term maintenance.

Outcomes:
Bogotá's urban canopy cover has expanded significantly as a result of JBB's work, delivering measurable benefits, including improved air quality, moderated urban temperatures, and enhanced stormwater management (García, 2025). Biodiversity indicators have also improved, with restored parks, riverbanks, and wetlands supporting increased bird and pollinator populations, even in dense urban neighborhoods (Diazgranados, 2015). JBB's educational reach is substantial, engaging more than 1.2 million students and residents annually through its programs and reinforcing a citywide culture of environmental stewardship (Diazgranados, 2015).

These achievements have been recognized internationally: Bogotá has been designated a "Tree City of the World" multiple times by the Arbor Day Foundation and the UN Food and Agriculture Organization, highlighting the effectiveness of JBB's urban forestry leadership (García, 2025). JBB's technical expertise and monitoring are increasingly embedded in municipal climate adaptation and sustainability plans, ensuring that nature-based solutions are embedded in robust botanical science. The garden also contributes to international knowledge exchange, sharing its urban greening model with other Latin American cities through networks such as the Ibero-American Association of Botanical Gardens.

Lessons Learned:
The JBB experience demonstrates how a botanical garden can function as a linchpin of urban climate resilience. **First**, it shows that when botanical gardens are institutionally integrated into city governance, their horticultural and scientific capacities can be scaled to metropolitan impact. **Second**, it underscores the importance of sustained community engagement in ensuring the durability of urban restoration outcomes. **Finally**, the case highlights the strategic value of botanical gardens as dual actors—both hands-on practitioners implementing nature-based projects and trusted advisors shaping long-term policy. Bogotá's experience offers a transferable model for cities seeking to mobilize botanical gardens as leaders in climate adaptation and ecological restoration.

Insights from a Global Survey on Roles, Capacities, and Constraints of Botanical Gardens in Restoration

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Executive Summary

Botanical gardens represent a critical, and often underrecognized, component of the global restoration and climate resilience community. To better understand and amplify their role in these areas, the New York Botanical Garden (NYBG) and Botanic Gardens Conservation International (BGCI) jointly developed and distributed a global survey to document the current scope, diversity, and characteristics of restoration activities across the global botanical garden community, encompassing institutions of varying sizes and mandates.

The goal was to generate foundational insights to guide the Nurturing Nature Initiative's efforts to mobilize this important community to deliver scalable, plant-centered restoration for biodiversity recovery and climate resilience, supporting engagement across the full restoration lifecycle. In addition, the survey collected information from members of the Ecological Restoration Alliance of Botanic Gardens (ERA) to assess their progress and impacts during the 2021–2025 strategy period and to identify priorities for the next five years.

A total of 73 institutions responded, representing all continents where botanical gardens are present (i.e., all continents except Antarctica), although responses were unevenly distributed, with greater representation from North American and European institutions. Results indicate that botanical gardens are actively engaged in restoration across multiple spatial scales and consistently contribute specialized expertise in plant science, horticultural practices, and ecological monitoring. At the same time, the survey identifies persistent constraints related to funding, staff capacity, quality seed and plant materials, and long-term monitoring support. Notably, technical expertise is rarely identified as a primary limitation, suggesting that the sector's core technical and scientific capacity is strong but undersupported.

Outputs building on these findings, including the forthcoming Nurturing Nature Initiative's Action Plan (expected Fall 2026), aim to strengthen the enabling environment for botanical gardens to engage with local restoration efforts, highlight opportunities for collaboration and knowledge sharing, and articulate the sector's collective capacity to advance global restoration and climate targets. They also identify key gaps, challenges, and barriers across the sector, establishing a critical baseline to guide where targeted training, funding, and institutional support are most needed.

Methods

The survey was developed collaboratively by NYBG and BGCI and distributed to botanical gardens and arboreta globally through newsletters, direct outreach, and regional networks. It remained open from summer 2025 through winter 2025–2026 and was conducted in English.

The survey included questions on how and where gardens engage in restoration efforts, roles and capacities, current and planned restoration project information, spatial and ecosystem contexts, strategic objectives, monitoring practices, and key challenges and capacity needs. Respondents also provided institution-level context to help interpret patterns across variables such as garden size, staff capacity, and geographic location. The number of respondents varied across questions because not every institution responded to every survey item.

The survey combined a range of question formats, including multiple choice (single and multiple response), dropdown selections, and optional open response fields to allow respondents to elaborate on their answers. Categorical survey responses were analyzed using descriptive statistics in R, and qualitative responses were reviewed to identify recurring themes and provide illustrative context for key findings.

Results & Discussion

Spatial scope of restoration work

Respondent gardens reported engaging in restoration across multiple spatial scales: within garden boundaries (52%); in the surrounding locality (44%); elsewhere in the same country (42%); and less commonly internationally (8%) (Fig. 1).

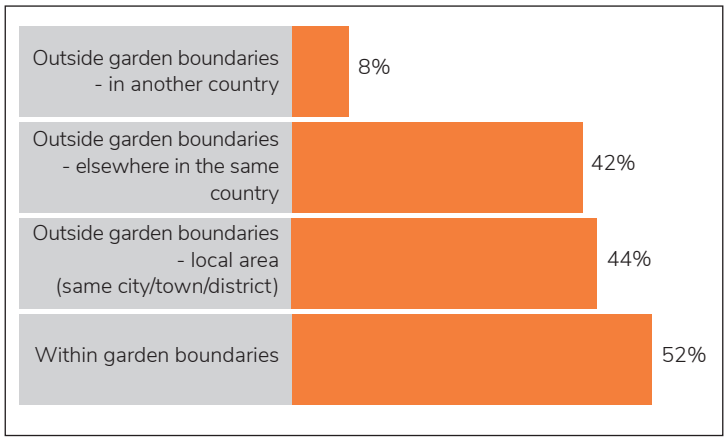


Figure 1. Location where respondent gardens conduct restoration work. Percentage totals exceed 100%, as respondents were able to select multiple answers (n = 62).

The dominance of within-garden and local work reflects a strong operational base near each institution, with many gardens extending into national programs where partnerships and mandates allow, a pattern that is generally consistent across geographic regions. This emphasis on place-based work is also reflected in respondents' open-ended survey responses, which highlight the importance of local partnerships and context-specific knowledge. One respondent emphasized that local communities are "essential strategic partners with local knowledge" and noted that, with appropriate training and compensation, they can play a key role in monitoring and data collection and should be fully involved in long-term project sustainability and benefit planning.

International engagement is comparatively limited, likely reflecting that most restoration work remains rooted in place-based relationships, ecological familiarity, and the practical advantages of operating close to home. This pattern may also point to capacity constraints, particularly around resourcing, project logistics, and/or sustained personnel time, which can make engagement beyond local or national contexts less feasible despite strong underlying technical capacity. Overcoming these barriers could be valuable since that strong capacity has the potential to be used to support restoration in international contexts where the technical capacities are not so prevalent.

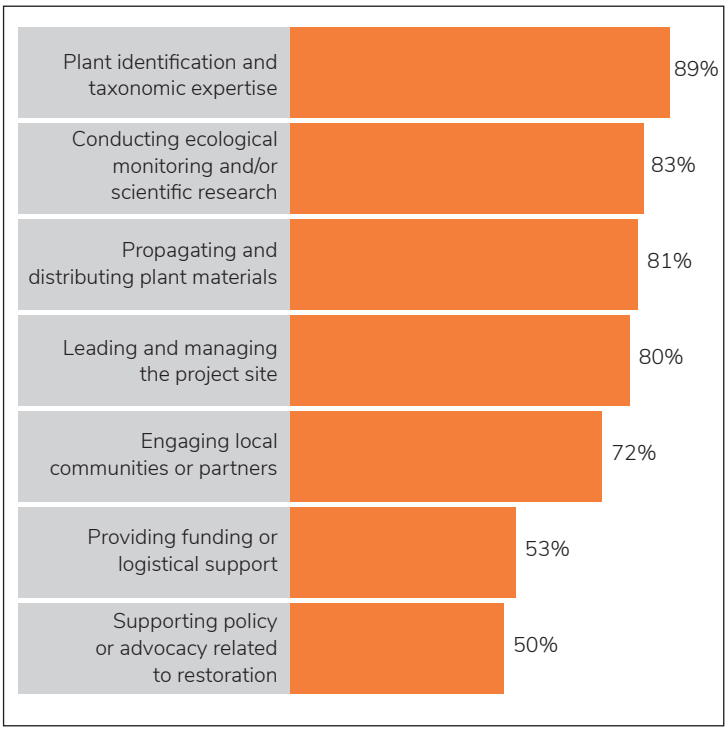


Figure 2. Roles that respondent gardens report playing in restoration. Percentage totals exceed 100%, as respondents were able to select multiple answers (n = 64).

Roles gardens play in restoration

Gardens report fulfilling roles aligned with their core institutional strengths and distinctive assets: plant identification and taxonomic expertise (89%), ecological monitoring and scientific research (83%), propagation and distribution of plant materials (81%), and site leadership/management (80%) (Fig. 2). Many also report community engagement (72%) and funding/logistics support (53%), with a smaller but meaningful cohort reporting a policy/advocacy focus (50%), though increasing this could be valuable to achieving wider/scaled restoration impacts. The larger pattern suggests a shared core set of capabilities and strengths that botanical gardens contribute to restoration efforts, reflecting a common functional identity within restoration systems even as gardens tailor their involvement to local needs and contexts.

A complementary view of this functional consistency emerges when examining which internal departments gardens draw upon to carry out restoration work (Fig. 3). Most respondent gardens indicate that restoration work draws on multiple units—led primarily by conservation and restoration teams (76%), botanical science and research staff (70%), and horticulture or living collections teams (52%). Operational support (30%), education (29%), and community engagement (25%) units also play meaningful roles, while policy involvement (10%), though less common, remains present across the network. The broad participation of internal departments highlights the unique strength of botanical gardens in bringing together science, horticulture, and community engagement to support adaptive, learning-driven restoration processes.



Collecting and documenting plant specimens during fieldwork in Yanachaga–Chemillén National Park, Peru. © New York Botanical Garden.

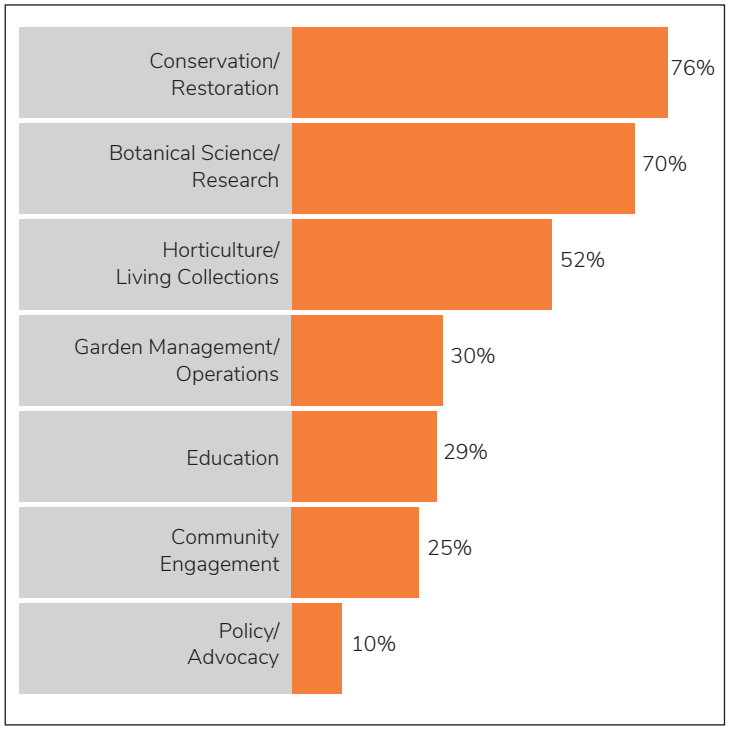


Figure 3. Institutional departments reported by gardens as being involved in restoration activities. Percentage totals exceed 100% as respondents were able to select multiple answers (n = 63).

Key challenges and capacity gaps

Across the sample, the most frequently cited barriers to delivering restoration are funding constraints (74%), limited staff capacity (51%), and insufficient support for long-term monitoring (48%), while technical expertise is generally not a primary bottleneck (12%).

Regionally, funding appears as a cross-cutting constraint, with staff capacity and monitoring support frequently co-selected, and this pattern is consistent across regions despite different operating contexts (Fig. 4). Taken together, the results suggest that the primary constraint is not knowledge, but the ability to sustain effort over time. Restoration by botanical gardens is therefore limited less by capability and more by resourcing structures that do not align with long-term ecological processes. High-leverage solutions could include developing public-private frameworks for multi-year funding and expanded staff capacity to support long-horizon monitoring, while targeted training is likely most effective in specialized niches rather than as a system-wide solution.

In addition to funding and staff capacity constraints, multiple respondents identified broader systemic and environmental challenges that shape restoration outcomes. For example, environmental uncertainty linked to climate change emerged as a recurring theme. Respondents described difficulties in planning restoration under increasingly variable conditions, noting that "climate change makes predicting the timing and intensity of the rainy season difficult," while cumulative impacts have led to "severe local forest degradation," making it challenging to identify appropriate reference sites. Others framed these pressures more broadly, citing "the accelerating effects of climate change and the urgent need to raise public awareness."

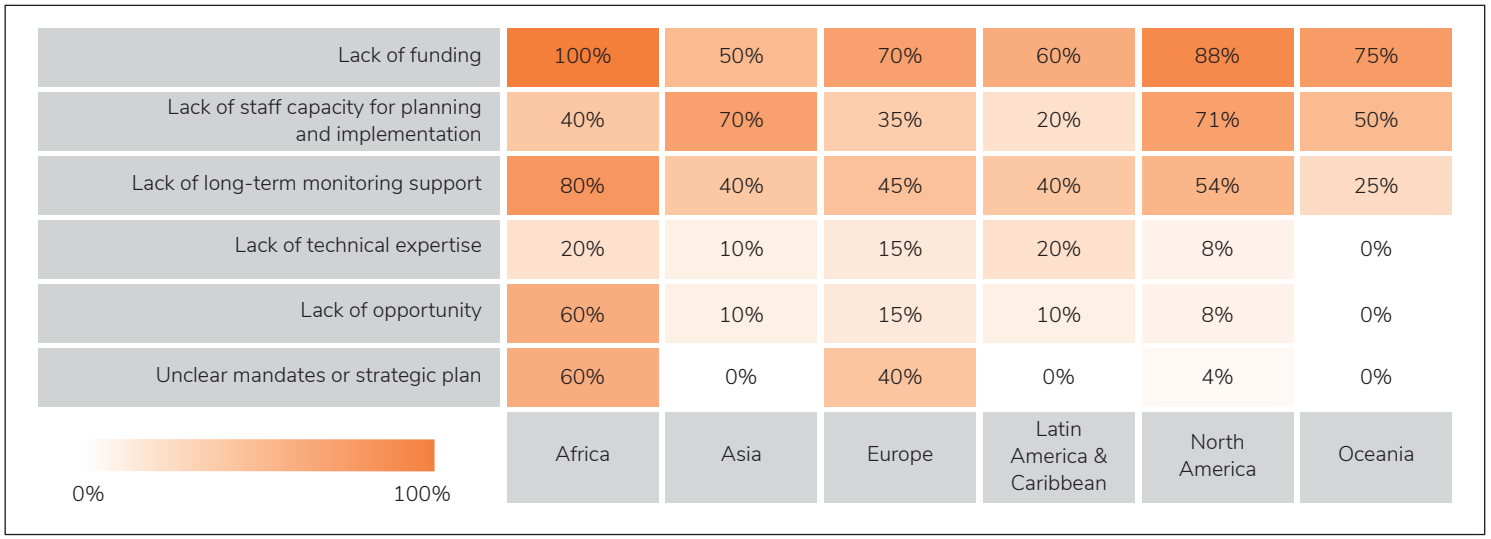


Figure 4. Challenges by region. Heatmap of the most commonly selected barriers within each global region. Survey counts by region: Africa = 5, Asia = 10, Europe = 20, Latin America & Caribbean = 10, North America = 24, Oceania = 4. Multiple selections were allowed, so percentage totals can exceed 100%.

A second, frequently cited set of constraints was related to the availability and quality of native plant material. Several gardens emphasized that "seed supply issues are inherently problematic for the whole restoration industry," describing persistent bottlenecks in "local ecotype plant material availability," propagation infrastructure, and "the availability and quality of plant material." Others highlighted gaps in applied knowledge and capacity beyond gardens themselves, citing "limited availability of native seeds and seedlings due to a lack of knowledge about how to propagate native species among community nurseries, farmers, and the government," and the need for "well defined (genetically and ecologically) seed production areas to support effective restoration." While widely recognized as systemic barriers, respondents also described successful models in which botanical gardens helped overcome these challenges by linking seed collection, propagation, and local livelihoods.

Priority objectives for the next five years

When asked to select their top three near-term priorities, respondent gardens most frequently chose outcomes associated with biodiversity conservation and ecosystem functionality (Fig. 5). There is also a noticeable but still secondary rise in focus on climate resilience. The pattern suggests strong alignment around species' recovery and functional landscapes, with growing attention to climate readiness.

Regional patterns show more similarity than divergence, as nearly every region places biodiversity conservation and ecosystem function among its top priorities, with climate-related objectives also widely selected (Fig. 6). Where differences do emerge, they may reflect local context. For example, the "Community: Practices" objective is selected far more often in Africa, where about 40% of respondents rank it within their top three priorities, compared with much lower selection rates elsewhere. In addition, climate resilience is most prominently prioritized in Oceania, consistent with the region's acute climate pressures that disproportionately impact the small island states (Veron et al., 2019).

Conclusions

This survey provides a systematic characterization of how botanical gardens engage in ecological restoration, documenting patterns of roles, priorities, and constraints across institutions of varying sizes, mandates, and geographic contexts. The results reveal a sector whose shared institutional strengths, centered on plant science, propagation capacity, and taxonomic expertise, converge with markedly similar challenges across regions. These findings serve as a critical empirical foundation for the forthcoming Nurturing Nature Initiative's Action Plan (expected Fall 2026) and illuminate both where the sector is well positioned to expand its contributions and where targeted investment is most urgently needed.

The predominantly place-based character of botanical garden restoration work, with most activity concentrated within garden boundaries and the surrounding locality, highlights both a strength and an area for potential growth. Deep local embeddedness supports the kind of context-specific, partnership-driven restoration that is most likely to persist and succeed. At the same time, the comparatively limited engagement at the international scale may partly reflect resourcing constraints rather than a ceiling on ambition or capability. As the Nurturing Nature Initiative scales, creating pathways for gardens to extend their reach beyond immediate geographies, for example through knowledge exchange platforms, while preserving the relational and ecological integrity that local embeddedness provides, will be an important design challenge.

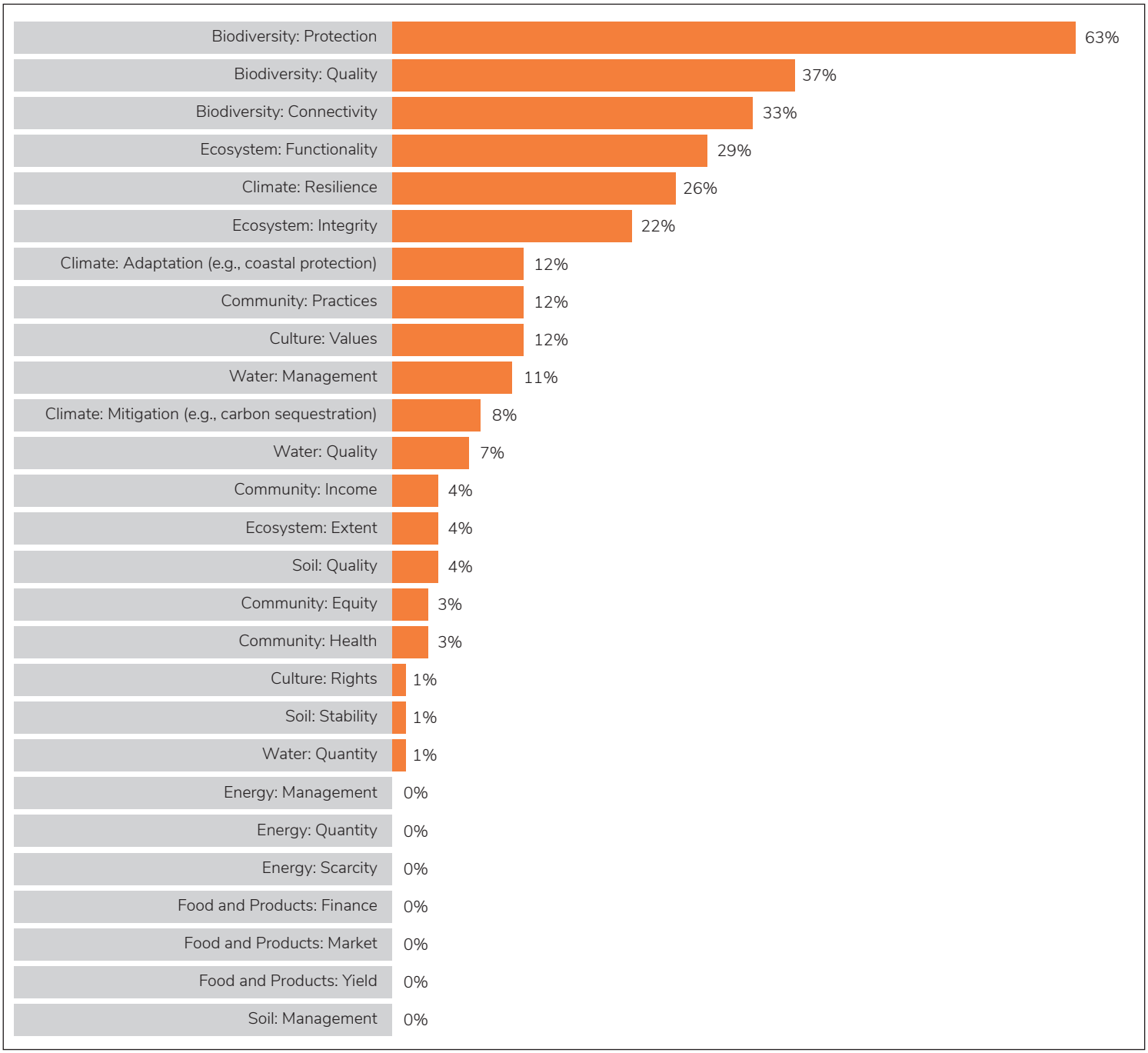


Figure 5. Distribution of objectives that respondents ranked in their top three priorities for the next five years. Percentages reflect responses from all 73 gardens that answered this question, and gardens were able to select up to three key priorities, so percentage totals exceed 100%. All 27 categories, pulled from the Aurora monitoring tool, were available for selection.

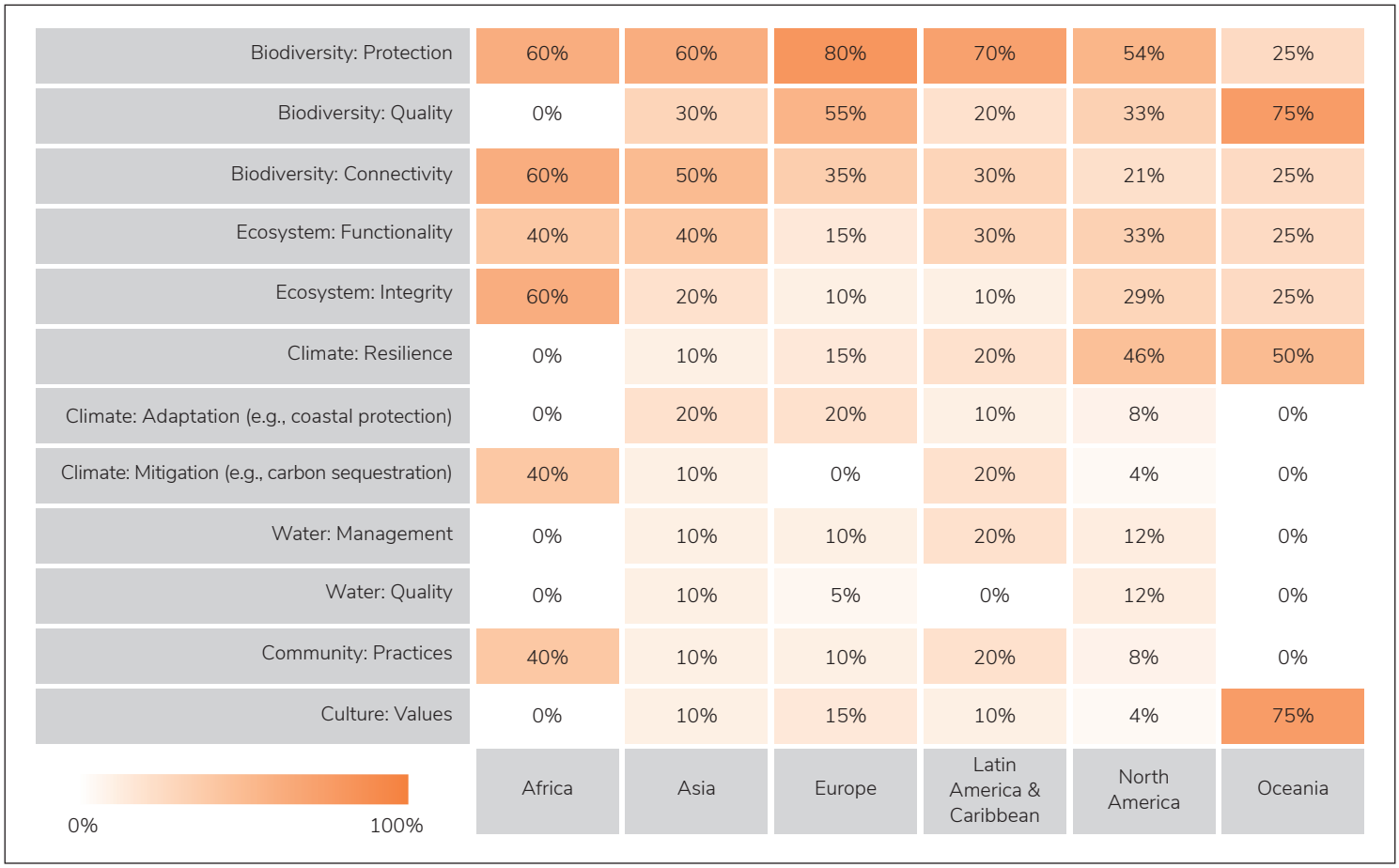


Figure 6. Priorities by region. Heatmap showing the share of respondents in each region who ranked each objective in their top three for the next five years; up to three selections per respondent. Survey counts by region: Africa = 5, Asia = 10, Europe = 20, Latin America & Caribbean = 10, North America = 24, Oceania = 4. Figure only includes the top 12 selected priorities; all 27 categories, pulled from the Aurora monitoring tool, were available for selection.

The survey is instructive in what it reveals about the architecture of botanical garden capacity. Technical expertise is rarely reported as a primary constraint. Across staff sizes and regions, the barriers that dominate are funding, limited personnel time, and insufficient support for long-term monitoring.

This finding carries direct implications for the Action Plan. It suggests that the sector requires structural support that allows existing knowledge to be sustained and applied over ecologically meaningful timeframes. Multi-year funding mechanisms, expanded staffing for project sustainability, and systems that reduce the administrative burden of project management are therefore higher-leverage investments than broad-based technical training, which is likely most effective when targeted at specialized niches. Beyond resourcing, respondents also identified constraints that extend beyond individual institutions and into the broader restoration sector. The inadequacy of seed and plant supply chains emerges as a systemic barrier, with practitioners noting that supply issues are inherently problematic across the restoration industry as a whole. This points to an area where botanical gardens, given their propagation expertise and seed banking capacity, are distinctively positioned to contribute to solutions (Faraji & Karimi, 2022).

When compared with priorities commonly reported across the broader restoration sector, the strong convergence in this survey around biodiversity conservation (protection, quality, and connectivity) and ecosystem functionality as dominant objectives suggests something distinctive about restoration where botanical gardens are involved. Large-scale restoration programs frequently prioritize landscape connectivity, carbon sequestration, and livelihood outcomes as primary drivers (Caparrós et al., 2010). The emphasis botanical gardens place on species recovery, plant diversity, and functional ecosystems reflects the sector's distinctive scientific identity and its deep institutional commitment to threatened plant conservation. This divergence is not a limitation; it is a comparative advantage. Botanical gardens bring a level of taxonomic rigor and species-centered restoration practice that is rare in the broader restoration landscape, and the consistency of this pattern across regions and institution sizes suggests it reflects a defining and reproducible characteristic of the sector (Volis, 2019; Bartholomew et al., 2023).

However, the data also suggest room to more explicitly integrate climate resilience objectives into garden-led restoration strategies, particularly the direct links between species recovery, ecosystem function, and long-term climate risk reduction. The relatively higher priority given to climate resilience in Oceania (Fig. 6), a region facing acute climate pressures, points toward the direction the sector may need to move collectively and the role that botanical gardens can play. Botanical gardens can help ensure that native species, including rare and threatened species, are centered in climate-related restoration and carbon sequestration efforts, rather than displaced by mass plantings of non-native species or monocultures (Seddon et al., 2021). Integration between networks focused on ecological restoration (e.g., the ERA) and climate change (e.g., the Climate Change Alliance of Botanic Gardens) will thus become increasingly important.

Taken together, these results define a sector that reports having strong scientific and technical skills, is operationally place-rooted, and is constrained not by knowledge but by the resourcing structures necessary to act on it at scale. The Nurturing Nature Action Plan will respond by strengthening the enabling environment for botanical garden-led restoration: securing sustained funding, building staffing and infrastructure capacity, supporting improved seed and plant supply chains, facilitating cross-institutional learning, and articulating the sector's collective potential to contribute to global biodiversity and climate targets, such as the Kunming-Montreal Global Biodiversity Framework and the United Nations Decade on Ecosystem Restoration.

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Botanical Gardens and Arboreta as Essential Partners in Restoration: Collection, Propagation, Deployment

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Executive Summary

Restoration projects often struggle to access taxonomically verified, locally adapted, and genetically diverse plant materials, which are important for ensuring that plants used are resilient to future climates. With their deep expertise in taxonomy and species identification, active field collecting and research programs, as well as ex situ curation of diverse living collections and horticultural expertise, botanical gardens and arboreta can serve as a key source for plant material and knowledge to guide restoration. To maximize their impact, botanical gardens and arboreta should develop and strengthen collaborative relationships with land and/or project managers to enable acquisition and scalable propagation of appropriate and diverse plant materials for restoration, as well as facilitate research to inform adaptive management strategies. In these ways, botanical gardens and arboreta have great potential to play a leading role in building resilient landscapes in the face of climate change.



Invasive species management and habitat restoration along the Bronx River through New York Botanical Garden programs.
© New York Botanical Garden. Photo: Marlon Co.

Current State of Knowledge

Restoration plantings may require high species diversity and access to high-quality, genetically diverse plant material (Engelhardt et al., 2014; Shaw, 2019). Genetic diversity and adaptation to the conditions at the restoration site are critical for outplanting success, supporting survival, reproduction, and long-term adaptability in the face of environmental change (Havens et al., 2015).

Botanical gardens and arboreta (BGA) have long recognized the need to build ex *situ* collections that are both species-rich and genetically diverse. The Global Strategy for Plant Conservation (2011–2020), for instance, had set goals to conserve 75% of threatened species ex *situ* and capture 70% of genetic diversity of crops, wild relatives, and other culturally or economically important species by 2020 (CBD, 2011). Work towards reaching these targets with limited resources requires strategic, efficient, science-based approaches, and many gardens have been undertaking research to improve them.

Recent studies led by BGA have shown that targets for capturing genetic diversity in ex *situ* conservation vary widely among taxa, even within the same genus, and most existing collections fall short of meeting those targets, particularly for exceptional species conserved in living plant collections (Hoban et al., 2020). In response, gardens are increasingly collaborating to manage metacollections across institutions (Griffith et al., 2019), with some building pedigrees or conducting strategic crosses to boost genetic diversity (Fig. 1; Wood et al., 2020; Foster et al., 2022).

BGA also run strong taxonomic and systematic research programs, helping ensure proper species identification, which is especially important as botany and taxonomy degree programs continue to decline (Stroud et al., 2022). Propagule collection protocols often include vouchers housed in on-site herbaria, verifying species identification and documenting past and current distributions.

Even when not leading restoration projects directly (although many do; e.g., Limahuli Preserve of the National Tropical Botanical Garden and Shaw Nature Reserve of the Missouri Botanical Garden), BGA are uniquely positioned to support land and/or project managers by supplying diverse, well-documented, and correctly identified plant materials, making them critical partners in restoration projects.

Knowledge Gaps, Capacity Needs and BGA Potential Contributions

Challenge 1: Uncertainty in species identification and poor taxonomic resolution

Botanical expertise is in decline globally, while formal botany degree programs continue to shrink or disappear (Stroud et al., 2022). As a result, there are growing challenges in accurately identifying species. Poor taxonomic clarity can undermine restoration efforts by leading to the use of misidentified or inappropriate plant material, which can reduce ecological function and adaptive capacity over time (Miller et al., 2016).



Figure 1. Chicago Botanic Garden's living plant collection of ʻālula (Brighamia insignis), an extinct-in-the-wild Hawaiian endemic species that has become a model for exceptional species collections management using a pedigree-based population management approach. Photo: Seana K. Walsh.

BGA Contribution

BGA serve as hubs of taxonomic and systematic expertise. Many institutions house herbaria, reference libraries, and expert staff who contribute to accurate species identification and the resolution of complex taxonomies. These resources are essential to verifying plant identities for restoration. BGA also provide training opportunities to students, early-career professionals, and partners through internships, workshops, and collaborations with academic institutions, helping to sustain and grow botanical expertise in the long-term.

Challenge 2: Low species diversity and limited genetic representation in restoration projects

Plant material used in restoration is often restricted to a narrow range of species and genetic sources. Even when a broader list of target species is desired for restoration projects, there may be limited access to genetically appropriate or diverse material. This can undermine the long-term viability of restored populations, especially under shifting environmental conditions (Kramer et al., 2018).

BGA Contribution

BGA have a longstanding role in field collecting, building, and then curating genetically diverse, provenance-documented collections. Many are actively working toward global targets, such as those outlined in the Global Strategy for Plant Conservation, and manage multi-institutional metacollections to increase genetic representation and resilience. These collections are often tracked using pedigrees and molecular tools and can serve as trusted sources of diverse plant material with accurate species identifications and known source populations for restoration efforts.

Challenge 3: Limited propagation and outplanting knowledge, and therefore, adaptive management

Many rare and underused species lack standardized propagation and outplanting protocols, including dormancy-breaking treatments for optimal germination. Restoration success often depends on trial-and-error efforts that are often not rigorously documented. Without adequate monitoring of planting success, restoration outcomes remain uncertain and difficult to scale.

BGA Contribution

Many BGA possess the research infrastructure and expertise needed to fill these knowledge gaps. With access to seed labs, propagation facilities, experimental plots, and scientific staff, they can conduct trials on seed dormancy breaking treatments, propagation techniques, and outplanting strategies. BGA working with rare species often generate species-specific protocols, track performance in outplanting trials, and contribute data that helps refine best practices. Close relationships with land and/or project managers can position them to help implement and monitor adaptive restoration efforts at scale, including through facilitation of citizen science or volunteer monitoring programs. Although these types of community research engagement efforts have typically focused on tracking the status of rare plant species in wild or reintroduced populations, they could be broadened to evaluate the success of multi-species restoration projects (Havens, 2017).

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Practice Insights

Taxonomic insights with conservation implications from the National Tropical Botanical Garden (NTBG) palm collection

Context, Approach, and Outcomes:
The Hawaiian archipelago is home to a radiation of approximately 23 endemic palm species in the genus *Pritchardia* (loulu) (Wagner et al., 2023). Previous treatments have proposed conflicting species taxonomies, and many species were first described based on limited material, and often did not include detailed descriptions. One example is *Pritchardia aylmer-robinsonii*, endemic to the privately-owned island of Niʻihau and now extinct in the wild. Based on its similarity to *Pritchardia remota*, a Critically Endangered Hawaiian endemic known from two small populations on the island of Nīhoa over 200 km to the northwest of Niʻihau, these two species have been considered synonymous in recent treatments. Through ongoing taxonomic study leveraging the living collection of more than 1,000 plantouts of *Pritchardia* at NTBG (Fig. 2), using morphometric data in conjunction with DNA, a more detailed comparison of these taxa has been made. Observations of the living collection throughout the growing season revealed that the two taxa differ in flower color: orange flowers for *P. remota*, and yellow for *P. aylmer-robinsonii*. Further study including living representatives from both extant populations of *P. remota* and direct descendants of the last surviving wild *P. aylmer-robinsonii* revealed consistent, quantifiable differences in leaf shape and size, and inflorescence structure, while molecular data provided additional evidence for recognition of two distinct species.

Lessons Learned:
Given the challenges associated with accessing extremely rare wild species such as *P. remota*, coupled with the limited flowering times of many species, it is unlikely that ephemeral floral traits such as those observed in this case would have been observed outside cultivation, and herbarium specimens often do not yield the same quality and consistency of morphological data. Living collections curated in BGA, which include detailed provenance data linked with the plantouts, as well as taxonomic expertise at these institutions, make such studies possible. Further conservation attention may be given to taxa previously treated in synonymy, such as the rare and unique *P. aylmer-robinsonii*, which, although extinct in the wild, is represented by hundreds of individuals in cultivation thanks to decades of curation by NTBG staff and partners.



Figure 2. Research Botanist Dr. Susan Fawcett climbing an individual of the Kauaʻi single-island endemic loulu, Pritchardia waialealeana, in the National Tropical Botanical Garden's living plant collection to collect morphological data and tissue samples for ongoing taxonomic research. Photo: Kenneth R. Wood.

Preserved Botanical Science Collections Support and Facilitate Restoration

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A pressed Penstemon specimen, a fragment packet, and collection label are mounted to archival paper by NYBG herbarium staff.
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Executive Summary

Preserved botanical science collections (PBSCs: herbaria, seed banks, and tissue/DNA banks) provide foundational data and germplasm that underpin plant restoration efforts worldwide. These collections document taxonomic diversity, capture genetic variation across species ranges, and offer historical baselines for understanding ecological interactions. However, significant challenges limit their potential: capacity gaps in biodiverse low-income countries, vast "plant diversity darkspots" where collecting remains insufficient, poorly understood plant-fungal symbioses critical to restoration success, complex permitting frameworks, and a persistent lack of peer-reviewed restoration case studies. Botanical gardens are uniquely positioned to address these gaps by building integrated specimen networks linking living and preserved collections, leading targeted expeditions to underexplored regions, advancing tropical seed banking research, and rigorously documenting restoration outcomes for publication. As demonstrated by the successful seed bank driven restoration of endangered *Petrocosmea grandiflora* in China, strategically managed PBSCs can directly enable species recovery at meaningful scales.

Current State of Knowledge

In addition to living collections, botanical gardens often maintain preserved botanical science collections (PBSCs: including herbaria, seed banks, and tissue / DNA banks), which in turn contain preserved specimens of plant species. PBSCs are critical components of the Convention on Biological Diversity's Global Strategy for Plant Conservation (CBD, 2012). These collections differ from living collections, which are curated assemblages of cultivated plants, in that the accessions are generally dead or held in a state of prolonged stasis, specifically for the purposes of facilitating research. Herbaria typically hold dried and pressed plants glued to paper; seed banks maintain lots of viable germplasm (seeds), typically at extremely low temperatures to promote extended dormancy; tissue and DNA banks hold samples of dried plant tissue in silica and extracted DNA aliquots, specifically for inclusion in molecular-based research. Herbarium specimens are intended to last into perpetuity, whereas seed and DNA/tissue bank lots are collected as resources intended for (destructive) research consumption. These collection types are interrelated, such that a living collection accession or plant collected in the wild will ideally be represented by an herbarium specimen, a seed collection, and a tissue sample, all digitally linked with specimen derived (meta)data and citing publications in virtual data portals (i.e., the extended specimen network, Lendemer et al., 2019).



Petrocosmea grandiflora. Photo: Jie Cai of the Kunming Institute of Botany.

PBSCs collectively document the plants and fungi of the world, providing the critical baseline data and taxonomic frameworks that support research into biodiversity and evolution, distributional and genetic diversity patterns, ecological interactions, community and species changes over time (particularly in response to climate change), and (potential) sources for germplasm to facilitate conservation and ex *situ* restoration. They range from globally comprehensive in scope (with millions of accessions or lots) to highly specialized and localized. Critically, PBSCs provide the physical data needed to contextualize global plant biodiversity (e.g., Bebber et al., 2010).

PBSCs offer an unparalleled window into historical plant biotic interactions and geographic occurrences, providing restoration practitioners with baseline data on how plant communities once functioned and co-existed. As genomic and analytical methodologies continue to advance, PBSCs are unlocking new possibilities for understanding how plants interact with fungi, herbivores, pollinators, and the abiotic environment (e.g., Daru & Zhigila, 2025), and how that has shifted across time and landscapes. Seed banks in particular are major sources for germplasm in restoration efforts (e.g., National Academies, 2023); at the same time, there is growing interest over the past 10 years in also strategically using herbaria for the potential restoration of recently extinct taxa (Albani Rocchetti et al., 2022). Together, these examples underscore a central point: PBSCs are already relevant to restoration, but their full value remains underused and unevenly developed.

Knowledge Gaps and Capacity Needs

Challenge 1: Capacity and technical challenges.

Although few botanical gardens maintain all three categories of PBSCs (under ca. 25 globally), many hold at least one collection type (typically an herbarium, ca. 300+ globally). The most common combination of PBSCs is an herbarium and a seed or germplasm bank (ca. 150 globally). Very few botanical gardens contain designated DNA or tissue banks (ca. 50 globally). Although botanical gardens stewarding herbaria are globally well-represented, they remain underrepresented in botanically rich low-income countries, and seed and DNA banks remain highly concentrated in high-income countries. For seed banks, tropical plants (representing the majority of plant biodiversity) pose several unique and fundamental challenges, including recalcitrant and freeze sensitive seeds (seeds that cannot tolerate the drying and freezing that conventional seed banking requires), high levels of fungal contamination or seed predation, and very low densities of available seed to collect given the frequency of tropical fruit ripening asynchronicity (e.g., Wyse et al., 2018; Ley-López et al., 2023). Furthermore, while the global sum of all herbaria likely captures the full genetic diversity of most species, it is difficult for seed banks to fully capture genetic diversity across a given species' distribution, particularly for widespread species that are under threat of extinction debt.

Challenge 2: Plant diversity darkspots

The full scope of botanical diversity remains undescribed; this is particularly true for tropical regions. Thus, restoration efforts in these areas are often operating under an incomplete conceptual framework —for example, when determining appropriate species selection, genetic sourcing, or community assembly strategies. In particular, the northern Andes, western, central, south, and southeast Asia (stretching from Türkiye to southern China, the Philippines, and Sumatra), and New Guinea are "plant diversity darkspots" (Ondo et al., 2024) in need of focused collecting efforts for all PBSC types. It is highly likely that the majority of plant diversity from these areas is absent from global seed bank collections.

Challenge 3: Understudied and under-collected taxa and symbioses

Many plant families and genera lack active research efforts, and thus present restoration practitioners with incomplete conceptual frameworks. Tropical taxa remain particularly understudied and generally underrepresented in seed banks. Collection efforts are also decreasing (Forbes et al., 2025). Conversely, ca. 2,100 to 2,600 new plant species are described every year (Cheek et al., 2020), presenting a constantly refined yet evolving baseline of overall botanical diversity that is essential but can be difficult to incorporate into restoration efforts. Lastly, the vast majority of plants are at least partially reliant on symbiotic fungi for competitive nutrient acquisition. In some plant groups such as orchids (particularly terrestrial orchids), they are greatly reliant on symbiotic fungi for their early development. Although these partners are critical for plant growth and successful restoration activities, scientific understanding of plant-fungal symbioses remains elemental at best, with the majority of known plant species lacking any confirmed fungal symbiont partner. Although fungal collections are maintained by PBSCs, they are even more understudied and under-collected relative to plants (Lofgren & Stajich, 2021). Increased understanding of these symbiotic relationships is critical for successful reintroduction efforts.

Challenge 4: Permitting and regulatory issues

The permitting and regulatory landscape for collecting plants for PBSCs, and using some of those collections in restoration efforts, is complex and ever changing. For example, herbaria are increasingly being used to supplement designated seed banks for rare or recently extinct species (e.g., Godefroid et al., 2011). However, in the US, herbaria must obtain import permits from the US Department of Agriculture's Animal and Plant Health Inspection Service. In the application for this critical permit, applicants are asked to certify "yes" or "no" to questions including "will all the imported plant material be rendered incapable of propagation or destroyed during the life of the permit?" If the 'incorrect' answer is chosen, the permit will not be issued, or if the applicant certified the 'correct' answers and the collections are later used contrary to this certification, future permits may not be granted or other negative noncompliance actions may be taken against the institution. Similarly complex regulatory conflicts occur in many other countries, and the variation in legal frameworks across jurisdictions further complicates the planning and execution of botanical sampling.

Challenge 5: Few peer-reviewed case studies

There is a persistent and noted publication gap, such that the results and efficacy of seed bank facilitated restoration efforts are not reported in the peer-reviewed literature (White et al., 2023), giving restoration practitioners few case studies. If they are reported, it is typically in 'grey literature,' which is harder to track and include in meta-analyses, or the results are never reported. The majority of papers on the topic of seed banks and restoration focus on seed collection efforts, or are policy focused.

Botanical Gardens' Potential Contributions

These five challenges are substantial, but botanical gardens are well positioned to address them because they combine taxonomic expertise, living collections, preserved collections, and the institutional continuity needed for long-term restoration work. Four priorities are especially important:

Investing in Infrastructure and Building Integrated Specimen Networks

Botanical gardens are among the only institutions that maintain both living plants and preserved botanical science collections. This dual capacity means they are uniquely positioned to build out "the extended specimen network," where a single accession is represented by digitally linked herbarium vouchers, seed lots, and tissue samples. Most other actors in the restoration space (universities, government agencies, NGOs) hold at most one collection type. Botanical gardens have the staff expertise to fill in these collection gaps, creating richer, more interconnected datasets that restoration practitioners can actually use to support on-the-ground implementation appropriately tailored to local contexts.



A tropical Melastomataceae is newly collected and pressed in the field for preservation as an herbarium specimen. © New York Botanical Garden. Photo: Marlon Co.

To build in-country capacity in the global south, botanical gardens in high-income countries should form MOU partnerships with botanical gardens in low-income countries, sharing funding efforts, expertise, and networks, to better augment PBSCs in biodiverse areas. Investment in infrastructure yields compounding returns when collections are genuinely integrated, supporting the identification of restoration-relevant germplasm that captures adequate genetic diversity across a species' range, a persistent challenge particularly for widespread species facing extinction debt. Critically, integration requires not just physical collections but investment in the digital infrastructure, shared data standards, linked portals, and open-access publishing norms, that allows these records to be discovered and used across institutions and borders. The practical value of this infrastructure for restoration is substantial but currently unrealized at scale. Investment in integrated specimen networks should be paired with investment in the research capacity to document, analyze, and publish restoration outcomes, turning infrastructure into a continuously improving evidence base for the practitioners who depend on it.

Targeted Collecting Expeditions to Plant Diversity Darkspots

Botanical gardens have long-standing traditions of fieldwork and international partnerships and, as universities continue to divest themselves of biodiversity-focused staff, are among the only institutions to employ taxonomic specialists who can identify species and collect in botanically underexplored regions. This expertise sets them apart from general conservation organizations. Gardens should prioritize focused collecting expeditions to the identified darkspots (the northern Andes, western, central, south, and southeast Asia, and New Guinea) specifically to fill gaps where tropical biodiversity is most poorly known. These efforts will have a multiplying effect, as darkspots often overlap with Important Plant Areas (IPAs) and regional biodiversity hotspots, which are used to guide global conservation efforts. Critically, botanical gardens in high-income countries could formalize partnerships with gardens and universities within those biodiverse low-income regions, helping to build local PBSC capacity rather than simply extracting specimens. These efforts should be holistic in approach, with special emphasis on linking mycologists, botanists, zoologists, and ecologists, to better collect symbiosis data.



Petrocosmea grandiflora seedlings, grown from seed bank collections of the Kunming Institute of Botany.
Photo: Jie Cai of the Kunming Institute of Botany.

Practice Insights

Restoring populations of endangered *Petrocosmea grandiflora*

Context:
Petrocosmea grandiflora Hemsl. (Gesneriaceae) is a perennial herb endemic to Yunnan Province, China (an area included within a "plant diversity darkspot"), with large bluish-violet flowers of potential horticultural value. For more than 120 years this species remained unseen after its description, until it was rediscovered in the wild in 2016 with only three small populations, numbering under 1,000 individuals in total. It was categorized as a "Plant Species with Extremely Small Populations" in Yunnan Province and as a threatened species of China. An initiative led by the Kunming Institute of Botany developed a program of combining seed collection and in vitro regeneration to multiply the individuals of this endangered species for successful restoration.

Approach:
Mature seeds of *P. grandiflora* were collected in 2022 and 2023 and preserved at -20°C after drying for long-term conservation (Meng et al., 2024). Seed germination was low and asynchronous due to seed dormancy. Limited seeds were germinated under *in vitro* conditions, and the individuals were multiplied using tissue culture techniques (shoot organogenesis). Plantlets were transferred to a nursery for continued growth before reintroduction.

Outcomes:
Hundreds of plantlets are available for reintroduction in 12 months, and the juveniles established well in the reintroduced site with a more than 65% survival rate, and several individuals are flowering and setting fruits in the first year.

Lessons Learned:
The viable seeds in the seed bank preserved the genetic diversity of targeted species, compared with living collections of botanic gardens, which usually keep limited numbers of individuals. Seed-derived individual multiplication will boost the population enhancement or population restoration of the threatened species.

Addressing Tropical Seed Banking Challenges Through Targeted Research

Botanical gardens with seed banks are among the only institutions that combine the taxonomic breadth, horticultural expertise, and long institutional time horizons needed to systematically develop and test alternative preservation protocols for these difficult taxa. Investing in this research would address a gap that directly limits the restoration community's ability to work with the majority of global plant biodiversity.

Generating and Publishing Peer-Reviewed Restoration Case Studies

Botanical gardens, particularly those that employ research staff or are affiliated with universities, are uniquely positioned to close the publication gap. They have the scientific credibility, institutional infrastructure, and the long time horizons needed to design rigorous restoration trials, track outcomes over years or decades, and publish results. By intentionally treating their restoration projects as documented experiments from the outset, rather than treating publication as an afterthought, botanical gardens could generate the evidence base that the entire field currently lacks.

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Ex situ Conservation as a Foundation for Restoration

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Inside the vault of Kew's Millennium Seed Bank at Wakehurst, United Kingdom. © RBG Kew.

Executive Summary

Ex situ conservation—the conservation of components of biological diversity outside their natural habitats—is increasingly recognised as a cornerstone of ecological restoration. By safeguarding plant diversity beyond natural ecosystems, this strategy secures the genetic resources, scientific knowledge, and technical capacity needed to restore ecosystems under changing environmental conditions. However, significant challenges remain. Native species and their genetic diversity are often underrepresented in *ex situ* collections, particularly in their countries of origin; propagation knowledge for many species remains limited; exotic species still dominate public and commercial plant nurseries; and community engagement is often inadequate. Botanical gardens are uniquely positioned to help address these gaps by combining infrastructure, horticultural expertise, scientific knowledge, and public engagement. To maximise their impact, botanical gardens should align their activities and research with national and regional restoration priorities, with a particular focus on the collection, propagation, and use of native species, and co-develop inclusive, place-based approaches that are integrated with *in situ* conservation and restoration programmes. In doing so, they can meaningfully contribute to the goals of the Kunming-Montreal Global Biodiversity Framework and the UN Decade on Ecosystem Restoration.

Current State of Knowledge

Ex situ conservation—the conservation of components of biological diversity outside their natural habitats (CBD, 1992)—encompasses a suite of techniques including seed banking, tissue culture, cryopreservation, and the maintenance of living plant collections. These approaches are vital for conserving plant diversity and enabling the recovery of rare, threatened, and extinct-in-the-wild species (Abeli et al., 2020; Wyse et al., 2018).

Over the past two decades, ex situ conservation has gained widespread recognition as a cornerstone of integrated plant conservation and ecological restoration strategies (Moloney et al., 2023; León-Lobos et al., 2012; Havens et al., 2006). Ex situ collections and associated expertise provide essential genetic material, propagation resources, and biological knowledge to support ecological restoration, ranging from species reintroduction to large-scale restoration programmes.

Botanical gardens have advanced their *ex situ* roles by developing species prioritisation frameworks, propagation protocols, and tools to better integrate *ex situ* resources into ecological restoration. Best practices now include restoration-focused seed banking aligned with national strategies and global targets, alongside participatory and community-based restoration initiatives (Sacande & Berrahmouni, 2016).

Practice Insights

The Millennium Seed Bank Partnership: Supporting Ecological Restoration through *Ex Situ* Conservation

Context:
Since 2000, the Royal Botanic Gardens, Kew (RBG Kew), through the Millennium Seed Bank Partnership (MSBP), has collaborated with partners in more than 100 countries and overseas territories to conserve wild plant species *ex situ*. Over the past decade, this work has increasingly supported restoration in climate-vulnerable regions, including the Sahel under the Great Green Wall initiative and tropical forest landscapes in the Dominican Republic and Mexico through the Global Tree Seed Bank Programme (Breman et al., 2021).

Approach:
Kew's MSBP has combined seed collection, long-term *ex situ* conservation, seed biology research, and the development of germination and propagation protocols for native useful species. This work has been coupled with local capacity building, support for national seed banks and nurseries, and participatory species selection, helping ensure that restoration priorities reflect both ecological suitability and community needs (Sacande & Berrahmouni, 2016; Breman et al., 2021).

Outcomes:
In Burkina Faso, Mali, and Niger, seeds of 84 useful native species were collected and banked, 55 species were propagated and used in restoration activities, and more than 100 village technicians were trained. More than one million seedlings were planted across approximately 200 experimental plots, supporting land restoration and livelihood opportunities (Sacande & Berrahmouni, 2016; Breman et al., 2021).

In the Dominican Republic, seeds from 315 native tree species were banked and studied, helping the Jardín Botánico Nacional (JBN) "Dr. Rafael M. Moscoso" in Santo Domingo strengthen its role as a key institution for seed conservation and as a source of plant material and information to support the restoration of protected, urban, and peri-urban areas (Breman et al., 2021).

In Mexico, the programme supported integrated conservation actions for endemic, protected, and useful native tree species. These included studies on seed ecology and species' climate responses to guide reforestation planning (Sampayo-Maldonado et al., 2019; Ordoñez-Salanueva et al., 2021), as well as the prioritisation and enrichment of native tree species to support biodiversity conservation, carbon capture, and livelihood improvement in shade-grown coffee regions in Veracruz and Chiapas (Toledo-Garibaldi et al., 2026; Chávez Hernández et al., 2026; Flores-Ortiz et al., 2025).

Lessons Learned:
This case study demonstrates that *ex situ* conservation is most effective when embedded within local institutions, restoration planning, and community priorities. It also underscores the importance of combining seed conservation with horticultural expertise, nursery development, research, and training. Through the integration of these capacities, botanical gardens can play a distinctive role in advancing scalable, climate-resilient restoration while supporting local livelihoods.

A flagship example is the Millennium Seed Bank Partnership (MSBP), coordinated by the Royal Botanic Gardens, Kew, which links *ex situ* collections to field-based restoration activities globally (Breman et al., 2021). Another important example is Seeds of Success (SOS), the national native seed collection programme led by the U.S. Bureau of Land Management, which uses standardised protocols and coordinated species targeting to support research, germplasm conservation, and restoration activities (Barga et al., 2020; Bureau of Land Management, 2026).

Despite progress, important limitations remain. *Ex situ* collections often do not capture the full genetic diversity of wild populations, are resource-intensive, and cannot fully replicate the complex ecological interactions that species experience within their natural habitats (Abeli et al., 2020; Moloney et al., 2023). In addition, many restoration programmes still lack the propagation knowledge and plant nursery capacity required to scale up the use of diverse native species. To address these challenges, best practice increasingly emphasises integrated *ex situ* and *in situ* strategies that support more ecologically meaningful and locally adapted restoration.



This building houses Kew's Millennium Seed Bank at Wakehurst, United Kingdom. © RBG Kew.

There is broad consensus that multi-stakeholder collaboration, including botanical gardens, seed banks, government agencies, local communities, and restoration practitioners, is essential to scale up, sustain, and monitor successful interventions over time (Di Sacco et al., 2021).

Knowledge Gaps and Capacity Needs

While the role of *ex situ* conservation in restoration is gaining traction, several key gaps and capacity challenges hinder its broader and more effective application:

1. Species selection and prioritisation: Many native species lack sufficient botanical, ecological, horticultural, or genetic data, complicating their inclusion in restoration plans and limiting the development of propagation protocols and evidence-based prioritisation frameworks.
2. Availability of planting material: Native species and their genetic diversity are often underrepresented in restoration supply chains and nurseries, while more familiar, easily propagated, or commercially available species are frequently favoured (Flores-Ortiz et al., 2025; Di Sacco et al., 2021). This creates a major bottleneck for restoration, especially as projects increasingly require climate-resilient plant material suited to stressful and rapidly changing environments. For example, in urban contexts, challenges such as heat stress, drought, soil compaction, and limited rooting space further highlight the importance of ex situ collections as sources of knowledge, propagules, and climate-resilient native plant material.

3. Recognition of the value of native species: The climate and ecological benefits of native, locally adapted species—and the ecosystem services they provide, including cultural value with associated traditional knowledge—are often undervalued, reducing support for their conservation and use in restoration programmes (Moloney et al., 2023).

4. Insufficient community engagement: Restoration projects often overlook Indigenous and local knowledge systems, limiting social legitimacy, uptake, and long-term sustainability (Sacande & Berrahmouni, 2016).

Addressing these challenges requires increased interdisciplinary collaboration and targeted capacity building. Priority actions include generating and sharing propagation and cultivation protocols; developing decision-support tools that integrate ecological, genetic, and traditional knowledge; and strengthening awareness of the ecological and social value of native biodiversity. Building the capacity of plant nurseries, reforestation actors, schools, and community organisations is essential to scaling up restoration with appropriate, diverse, and climate-resilient plant material.



Collecting hemlock seeds. © New York Botanical Garden. Photo: Marlon Co.

Botanical Gardens' Potential Contributions

Botanical gardens (BGs) are uniquely positioned to bridge *ex situ* conservation and ecological restoration through their infrastructure, expertise, and credibility. Their specific contributions include:

1. Infrastructure and technical capacity: BGs provide a range of infrastructure and technical capabilities that support plant conservation and restoration, although the facilities and expertise available vary considerably among institutions. Depending on their size, mandate, and resources, BGs may host seed banks, nurseries, tissue culture laboratories, living collections, and herbaria that support the collection, documentation, propagation, cultivation, and testing of diverse plant species. These resources are vital for supplying high-quality native plant material and associated knowledge for restoration (Havens et al., 2006; Breman et al., 2021).

2. Data and knowledge systems: Botanical gardens curate extensive taxonomic, ecological, horticultural, and phenological data. Their herbaria, seed records, germination data, and long-term collections support species selection and evidence-based restoration planning (Mattana et al., 2022).

3. Demonstration and learning hubs: Through arboreta, field trials, nursery systems, and restoration plots, BGs may serve as living laboratories for experimentation, training, and public engagement. They are especially well placed to test the cultivation and performance of native species under changing environmental conditions and to translate this knowledge into practice.

4. Bridging science, policy, and communities: Trusted by both scientific communities and the wider public, BGs can play a catalytic role in co-designing inclusive and locally relevant restoration strategies aligned with national and regional priorities (Di Sacco et al., 2021). In doing so, they can help connect scientific evidence with policy objectives and community perspectives, thereby contributing to the implementation of the goals of the Kunming-Montreal Global Biodiversity Framework and the UN Decade on Ecosystem Restoration (CBD, 2022; United Nations, 2019).

5. Acting as hubs for collaboration: BGs can also serve as coordinating institutions, linking seed banks, herbaria, plant nurseries, research institutions and universities, restoration practitioners, municipalities, and local stakeholders through network-based restoration initiatives.

These strengths position BGs as essential actors in advancing scalable, place-based, and ecologically grounded restoration strategies.

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CASE STUDY

Botanic Gardens Leading Plant Translocation and Habitat Restoration – the LIFE SEEDFORCE Project

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Institution: MUSE, Science Museum of Trento

1. Project Background & Context

In the European Union, the Habitats Directive (Council Directive 92/43/EEC) provides a framework for biodiversity conservation policies, listing priority habitats (in Annex I) and species (in Annex II) to be conserved in a network of protected areas named 'Natura 2000' (European Commission, 1992). Every six years, the EU provides an update on their conservation status, classified as Favourable (FV), Unfavourable Inadequate (U1), or Unfavourable Bad (U2). Each class also has an associated trend, indicated in brackets as positive (+), negative (-), or stable (=). For example, U2(-) would denote an Unfavourable Bad status with a negative conservation trend (DG Environment, 2023).

In addition to these regulations, the EU Biodiversity Strategy for 2030 (European Commission, 2020a) has set the goal of maintaining all listed habitats and species in favourable conservation status and restoring those classified as U1 or U2 to favourable status. The EU also supports implementation of the strategy through the LIFE Programme, which issues annual competitive, bottom-up calls for project proposals (Delbaere, 2020). According to the latest report (European Commission, 2020b), 81% of protected habitats and 63% of protected species are classified as having an unfavourable conservation status. For example, in the central Mediterranean, particularly in Italy, 58 of 84 Annex II vascular plant species (69%) have an unfavourable conservation status and require urgent conservation action.

To address this need, 14 botanic gardens and seed banks collaborated to restore 29 vascular plant species to favourable conservation status through an integrated *in situ–ex situ* approach. Key actions included mitigating major threats such as forest encroachment and discontinued haymaking, and translocating large numbers of propagated individuals into their natural habitats to reinforce or restore depleted populations and to re-establish gene flow between isolated and fragmented populations. The project, *Using SEED banks to restore and reinFORCE the endangered native plants of Italy (SEEDFORCE)*, applied this approach to 139 populations across the main Mediterranean islands, the Alps, and the Apennines (Fig. 1). The partnership included 11 Italian, 1 French, 1 Slovenian, and 1 Maltese botanic gardens and seed banks. The targeted habitats ranged from coastal environments to high-altitude cliffs, and from dry grasslands to wetlands.

2. Implementation Approach: Activities, Partnerships, and Enabling Conditions

SEEDFORCE began with a set of preliminary analyses to inform the selection of appropriate conservation actions on a robust scientific basis. First, the ecological niche of each species was characterised and projected under three climate change scenarios. For narrow endemic species, climate envelope modelling helped identify nearby areas that could become suitable in the future, allowing for a potential expansion of their distribution and improving their resilience to climate change. Second, the genetic diversity of both existing and donor populations was assessed using ddRAD sequencing. This analysis provided insight into key demographic processes affecting population viability, including inbreeding and reduced gene flow. Third, trophic dependencies were investigated for a subset of species exhibiting reduced reproductive performance, such as low seed set or high levels of predation or herbivory.

All preliminary evidence was integrated to define the most appropriate translocation strategy for each site. These strategies aimed to establish populations with high genetic diversity and pre-adaptation to future conditions, prioritising locally adapted genotypes while incorporating a small proportion of non-local genotypes to restore gene flow between isolated populations, in line with IUCN guidelines (IUCN/SSC, 2013).



1. *Adenophora liliifolia*
2. **Astragalus verrucosus*
3. **Bassia saxicola*
4. *Botrychium simplex*
5. **Campanula sabatia*
6. *Centranthus amazonum*
7. *Crepis pusilla*
8. **Cytisus aeolicus*
9. *Dracocephalum austriacum*
10. *Elatine gussonei*
11. *Eleocharis carniolica*
12. *Eryngium alpinum*
13. **Galium litorale*
14. *Gentiana ligustica*
15. *Gladiolus palustris*
16. *Himantoglossum adriaticum*
17. *Kosteletzkya pentacarpos*
18. *Leucojum nicaeense*
19. **Limonium strictissimum*
20. *Linaria flava*
21. *Linaria pseudolaxiflora*
22. *Linum muelleri*
23. *Liparis loeselii*
24. *Marsilea quadrifolia*
25. *Primula palinuri*
26. **Ribes sardoum*
27. *Saxifraga tombeanensis*
28. **Silene hicesiae*
29. *Woodwardia radicans*

*Figure 1. Location of the 76 SEEDFORCE translocation sites in Italy, France, Slovenia and Malta and the related target species list (taxonomy complies with the one adopted by the Habitats Directive and might be out of date, * denotes priority species according to the Habitats Directive).*



Figure 2. Site preparation at the Le Grave project site (Trento, Italy) prior to the translocation of Gladiolus palustris. A) Original state, with dense tree and shrub vegetation, summer 2023; B) Result of the clearing work, spring 2024.

Before translocation, site-specific threats were identified and removed or mitigated to ensure long-term effectiveness. Most threats were linked to changes in traditional land management, as well as pressures from agriculture, tourism, and invasive species. Many target species occur in secondary habitats, such as lowland grasslands and open woodlands, and have been negatively affected by forest encroachment and the abandonment or mistiming of haymaking. Management actions therefore included shrub removal, periodic grassland cutting, invasive species control, and fencing of sensitive areas (Fig. 2).

The known populations were systematically surveyed to assess their size and improve understanding of their life cycle and reproductive biology where this information was lacking. In some cases, this led to refined species characterisations. For example, *Dracocephalum austriacum* was reclassified as a rhizomatous geophyte (GRhiz) due to the presence of an underground woody storage organ, whereas previous floras had incorrectly described it as hemicryptophyte (H) or chamaephyte (Ch) (Fig. 3).

Advanced technologies were also applied, including UAV surveys and AI-based image analysis, to count individuals, particularly in populations located in inaccessible areas such as vertical cliffs. These approaches led to significant updates in species knowledge. For example, a previously unknown population of *Cytisus aeolicus* was discovered in a hidden ravine on Alicudi Island, where the species had been considered extinct, while populations of the cliff-dwelling *Saxifraga tombeanensis* were found to be at least twice as large as previously recorded.

Core conservation actions included germplasm collection from selected sites (Fig. 4) and large-scale plant propagation (Fig. 5). Biosecurity protocols and nursery protection guidelines were implemented to minimise the spread of pathogens and prevent contamination by invasive species, including pot sterilisation and the use of fine mesh protective screens. SEEDFORCE is supported by €8 million in funding over a six-year period (2022 to 2027) and brings together a multidisciplinary team of experts in botany, ecology, genetics, and climate modelling, alongside a network of stakeholders and managing authorities.



Figure 3. Underground woody storage organ in Dracocephalum austriacum (Trentino, Italy) not described in current floras.

3. Plant and Seed Supply Strategy

Plant propagation material was sourced from both target populations and nearby donor populations and subsequently propagated in large quantities at each partner site. Spores, seeds, and cuttings were collected in the wild using a stratified sampling design to capture maximum genetic diversity while minimising impacts on natural populations, following the ENSCONET seed collecting manual (ENSCONET, 2009a & b).

Collected material was stored and propagated in partner facilities, including seed banks, laboratories, and nurseries, as appropriate. Germination requirements were assessed under controlled conditions, and dormancy-breaking treatments were identified and applied where needed. Propagation methods were selected based on species-specific performance and cost-effectiveness, ranging from standard nursery techniques to in vitro propagation for orchids and ferns.



Figure 4. Mature capsules of A) Himantoglossum adriaticum (Abruzzo, Italy) and B) Liparis loeselii (Trentino, Italy) collected for propagation.

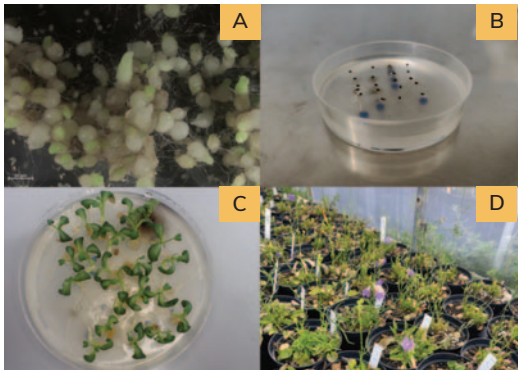


Figure 5. Different propagation and cultivation techniques of target species: A) in vitro propagation of the orchid Liparis loeselii in sterile conditions, with protocorm development (Latium, Italy); B) germination of Linaria flava (Sardinia, Italy); C) germination of Astragalus verrucosus (Sardinia, Italy); and D) cultivation of Campanula sabatia on greenhouse bench (Liguria, Italy).

For some species, alternative propagation methods proved more effective. For example, *Saxifraga tombeanensis* was more successfully propagated from cuttings than from seed, both in terms of speed and success rate, while species with low seed production, such as *Dracocephalum austriacum*, required a combined approach using both seeds and cuttings. Other species had specific growth requirements; for instance, *Adenophora liliifolia* required large pots for successful development, as individuals declined when grown in small cell trays. Temporary pond species such as *Elatine gussonei* required anoxic conditions for seed germination. Full details of the propagation protocols for each species will be made available on the project website by the end of the project (lifeseedforce.eu).



Figure 6. Translocation of A) Marsilea quadrifolia at Risorgive dello Stella (Friuli, Italy) and B) Saxifraga tombeanensis at Valvestino (Lombardy, Italy). These pictures show the variety of habitats covered by the SEEDFORCE project.

Seeds collected in the past from populations that are now extinct and stored in participating seed banks proved highly valuable for reintroduction, highlighting the critical role of seed banks in conservation. In general, historical seed collections were combined with fresh collections to maximise genetic diversity. Propagation material was also exchanged among partners working on the same species in different locations to further increase the diversity of translocated material (Fig. 6).

Genetic analyses are being conducted on propagated material to compare it with wild donor populations and ensure that no unintended selection for nursery-adapted genotypes has occurred. Results are pending. Following translocation, a monitoring programme will be implemented to assess the establishment and performance of introduced individuals.

4. Results, Impacts, and Metrics

By the end of the project, SEEDFORCE will have carried out 153 translocations across 76 Natura 2000 sites. This includes the reinforcement of 107 declining populations of 27 species in 58 sites, the reintroduction of 24 populations of 8 locally extinct species in 17 sites, and the establishment of 8 new populations of 4 species in 8 sites. Habitat restoration actions will have addressed key threats, including trampling, overgrazing, invasive species, and vegetation encroachment, across more than 90 hectares.

As of April 2026, the SEEDFORCE partnership had collected 2,801,934 seeds and spores for both long-term conservation and propagation, and produced 49,947 plants. Propagation targets were achieved for 16 of the 29 target species. To date, 19,248 plants have been translocated, with activities completed at 35 of the 76 sites. All remaining translocations are scheduled for completion by the end of 2027.

By 2028, SEEDFORCE will have engaged the wider public and raised awareness of plant conservation, highlighting the value of endemic and threatened species. Outreach activities include the development of a children's sticker album on plant conservation, an artist competition to design jewellery inspired by target species, a redesigned mini-seed bank to promote public engagement, demonstration flower beds in participating cities showcasing native plants, and a partnership programme with local growers and retailers to promote the use of native species in horticulture.

5. Lessons Learned and Recommendations

Developing effective plant conservation projects is complex and requires a multidisciplinary and inclusive approach, drawing on diverse expertise to address ecological, genetic, and management challenges. In this context, the integrated in situ–ex situ approach adopted by SEEDFORCE proved particularly effective, offering multiple benefits. It not only strengthened conservation outcomes but also provided opportunities to showcase threatened species in botanic gardens and to engage local communities, building awareness and support.

Research conducted within SEEDFORCE generated new insights into the life cycles, reproductive biology, and population dynamics of priority species that had previously been poorly understood. In addition, substantial new species- and site-specific knowledge was produced and is being progressively shared with the scientific community through the project website (lifeseedforce.eu). Plant propagation was highlighted as a core strength of botanic gardens. The active involvement of stakeholders, particularly protected area managers, was essential to ensure appropriate site management and the long-term survival of translocated populations. Volunteer participation also played a valuable role, supporting field activities and fostering local stewardship of plant diversity.

One of the main challenges encountered was the difficulty of propagating certain species, particularly orchids and ferns. However, the project is still ongoing, and specialised teams in in vitro propagation are working to ensure that all target species can ultimately be successfully propagated.

Native species remain an underutilised resource in horticulture. They are often better adapted to local conditions and require fewer inputs to grow. Wider adoption of native plants could reduce the spread of invasive alien species and create mutual benefits for both the horticultural sector and plant conservation.

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Harnessing Within-species Climate-adaptive Variation for Ecological Restoration

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Dead Eucalyptus gunnii in Central Plateau, Tasmania. Photo: Suzanne Prober.

Executive Summary

Traditionally, ecological restoration has followed a "local is best" approach to sourcing plant material ("provenancing"), based on the assumption that local populations are best adapted to their local environments (Broadhurst et al., 2008). However, because climate change is rapidly altering local environments, this assumption is unlikely to hold into the future.

At the same time, plant species have adapted to climate over many millennia. Research has shown that widespread species possess significant climate-associated genetic variation across their ranges (Hoffmann et al., 2021a), which could be harnessed to improve restoration resilience. This has led to proposals for alternative, "climate-adapted" provenancing strategies, which source germplasm from a broader mix of populations across a species' range (e.g., Breed et al., 2013; Prober et al., 2015).

To meet the challenge of provenancing in a changing climate, botanical gardens have demonstrated leadership by developing tools to inform uptake of alternative provenancing strategies (e.g., Rossetto et al., 2019). These tools aim to help balance potential genetic risks such as outbreeding depression with potential benefits of introducing preadapted genotypes.

Although there is a strong theoretical basis for climate-adapted provenancing strategies, their effectiveness has not been widely tested. To guide effective sourcing of plant material, botanical gardens can play a leading role in supporting coordinated trials comparing provenancing strategies. They can also contribute to developing a heuristic framework to help guide provenancing strategies in the absence of adequate species-level genetic data. This could involve establishing relationships between climate-adaptive variation and plant distributions, functional traits, taxonomy, and potential interactions with other ecological factors, to help practitioners gauge where alternative provenancing strategies may be most effective or more risky.

Current State of Knowledge

Plant populations have long been known to vary morphologically and genetically along climate gradients. Over the past 15 years, this adaptive capacity has been increasingly explored as a potential tool to enhance climate resilience in ecological restoration (Hoffmann et al., 2021b).

Two key approaches—provenance trials and genomic surveys—have demonstrated that both genetic variation and phenotypic plasticity contribute to climate adaptation in plants (Anderson & Song, 2020; Hoffmann et al., 2021a). Genetic variation refers to inherited differences between individuals that shape how they grow and survive, while phenotypic plasticity is a plant's ability to adjust its growth or behaviour during its lifetime in response to changing conditions. Reciprocal transplant provenance trials (comparing plantings of at least two provenances in their 'home' and contrasting 'away' environments) provide a particularly powerful way to detect adaptation in plants, as they enable distinction of genetic variation from phenotypic plasticity. However, provenance trials require long timeframes to capture the full life cycle of long-lived species often used in ecological restoration. Genomic techniques, including whole-genome sequencing and transcriptomics, offer faster insights into the genetic basis of adaptation, although they are less readily related to plant performance (Chung et al., 2023). When combined with modelling tools, these approaches can support projections of climate vulnerability and guide restoration strategies (Jordan et al., 2017, Hoffmann et al., 2021b).

Research across a range of eucalypt species illustrates this well: traits like photosynthetic rate and water-use efficiency tend to be plastic, whereas variation in leaf and hydraulic traits tends to be genetic. Along with a range of genomic markers, this genetic trait variation has been linked to climate variables (Prober et al., 2016, 2022). Putatively adaptive genetic variants often persist across species ranges, indicating potential for natural selection to enhance climate resilience if natural selection can keep up with the rate of climate change (Jordan et al., 2017, Hoffmann et al., 2021b). Further, genetic variation has been demonstrated in the capacity for phenotypic plasticity. For example, dry- but not wet-origin provenances of *Eucalyptus tricarpa* can adjust leaf traits to help tolerate arid conditions (McLean et al., 2014).

This growing understanding of climate-adaptive variation in plant species has led to hypotheses that new, climate-adapted provenancing strategies could help leverage existing climate-associated variation to enhance adaptive capacity in ecological restoration. These strategies include a number of related approaches, for example composite, admixture, and climate-adjusted provenancing, that differ in emphasis but share a common underlying concept (Breed et al., 2013, Prober et al., 2015, Silva et al., 2025). All aim to introduce diverse germplasm from a range of populations, whilst still incorporating local provenances to harness genes associated with adaptation to local, non-climate environmental parameters.



Preparing to plant climate-adjusted provenances in Western Australia. Photo: Georg Wiehl.

Knowledge Gaps and Capacity Needs

While tools for incorporating climate projections in ecological restoration are increasingly available (e.g., Rossetto et al., 2019; Kindt, 2023), and there is growing evidence for climate-adaptive variation in plant species (Hoffmann et al., 2021b), direct evidence for the effectiveness of climate-adapted provenancing strategies remains limited. Research in three key areas is needed to address this gap and ensure appropriate application of provenancing strategies.

First, there is ongoing need for characterising the distribution and nature of climate-adapted variation across a wide range of plant species. Such data would contribute towards a predictive framework to support choice of provenancing strategy, based on characteristics of the planted species. Such characteristics could include distributional pattern (e.g., widespread, disjunct or narrow endemics), plant functional types (e.g., bird versus insect pollinated), and taxonomy (Prober et al., 2016).

Second, direct field testing via *provenancing* strategy trials (as opposed to the more common reciprocal *provenance* trials) is imperative. Ideally, trials would form a coordinated global network of simple, comparable field experiments, testing restoration outcomes using climate-adapted versus local provenancing. Conducting trials across diverse species, environments and restoration contexts (e.g., degree of soil degradation) would enable testing and refinement of the proposed predictive framework, and characterisation and mitigation of risks (Broadhurst et al., 2017). Such a network has already been initiated at four sites in Australia (Jordan et al., 2026).

Third, climate-adaptive variation in plants has been shown to interact with ecological factors such as herbivory, disease, local adaptations, changes in ecological processes at the restoration site (e.g., microclimates, soil degradation), and elevated CO_2 (e.g., Prober et al., 2016). Further, mixing source populations to incorporate climate-adaptive variation comes with potential genetic risks such as outbreeding depression (whereby mixed offspring can perform poorly compared with local offspring). Developing a systematic understanding of these interactions and risks would help guide the application of climate-adapted provenancing strategies.

Botanical Gardens' Potential Contributions

Botanical gardens are well-positioned to lead efforts in advancing these future directions. **First**, they have played and can continue to play a key role in advancing recommendations for expanding the characterisation of variation within species and adaptive capacity in plants, leveraging the genomic and taxonomic expertise of botanical gardens' researchers (e.g., Rossetto et al., 2019).



Grassy Hut diverse plantings in Tasmania. Photo: Suzanne Prober.

Second, the scientific expertise and outreach capacity of botanical gardens can facilitate implementation of climate-adapted provenancing strategies by practitioners. This includes integrating population-level data into restoration planning and decision-guiding tools such as Restore and Renew (e.g., Rossetto et al., 2019) and providing scientific advice on embedding trials to test provenancing strategies within these restoration activities (Broadhurst et al., 2017).

Third, resources housed in herbarium collections, commonly associated with botanical gardens, can provide tangible evidence for both the occurrence and rates of adaptation in plant species. For example, using herbarium specimens, Guerin et al. (2012) demonstrated a 2 mm decrease in leaf width of the widespread shrub *Dodonaea viscosa* over 127 years, consistent with the expected morphological response to climate change. Similarly, DeLeo et al. (2019) used herbarium and germplasm collections to demonstrate shifts over >200 years in leaf carbon:nitrogen ratios and phenology of *Arabidopsis thaliana*, associated with changes in land use and climate.

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CASE STUDY

Restore and Renew: Guiding Resilient Restoration through Genomic Knowledge Infrastructure, Collaboration and Sharing

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BOTANIC GARDENS OF SYDNEY

For the past eight years, the Botanic Gardens of Sydney's Restore and Renew project has shared genetically informed seed sourcing guidance for ecological restoration. Supported by a robust genomic knowledge infrastructure that facilitates collaboration, the project is set to continue improving the adaptability and resilience of ecological restoration across Australia and beyond for many more years to come.

Moving beyond generalisations

Generalised guidance such as "local is best" has prevailed regarding seed sourcing strategies for ecological restoration in the past. This well-intended guidance aimed to promote the use of locally adapted material and to avoid unintended consequences of mixing distantly related individuals. However, local conditions are rapidly changing due to climate change and habitat destruction, and research has consistently found that we can't generalise about how far is too far when it comes to safely mixing material from different geographic areas (Rossetto et al., 2020).

To be self-sustaining, restored populations need genetic diversity. Unfortunately, the material used in many restoration projects has low genetic diversity because it is sourced from a small number of plants, a narrow geographic area, or natural populations that have already lost genetic diversity due to habitat loss and fragmentation.

Fortunately, advances in genomics mean that we no longer need to rely on generalisations and assumptions about the best seed sourcing locations. We can now map patterns of natural gene flow across the landscape, even in places where habitat has been fragmented and gene flow disrupted, and use that insight to inform seed collections for multiple co-occurring species (Fahey et al., 2025).

Sharing genetically informed species-specific seed sourcing guidance

The Restore and Renew webtool (Rossetto et al., 2019, https://www.climatechange.environment.nsw.gov.au/restoreandrenew), developed by the Research Centre for Ecosystem Resilience at the Botanic Gardens of Sydney, Australia, enables restoration practitioners, planners, and policymakers to make informed decisions regarding the sourcing of plant material to maximise the genetic diversity and climate-readiness of restoration plantings. It proposes that genetic diversity, and hence adaptive capacity, is maximised by sourcing material from multiple locations across the full span of a genetic collection area that aligns with natural gene flow across the landscape. Climate readiness is further enhanced by incorporating material from future climate matched sites.



Tens of thousands of Eucalypts are being grown for a Taronga Conservation Society Australia restoration project. Genomic information is guiding seed sourcing to maximise genetic diversity and minimise collecting hybrid or misidentified material. Photo: Research Centre for Ecosystem Resilience, Botanic Gardens of Sydney.

The webtool guides restoration of resilient, climate-ready native vegetation across the east coast of Australia, with a focus on New South Wales, but will soon expand to national coverage. The webtool enables users to identify the location of their restoration site, select from a list of local species for which comprehensive genetic data has been collected and analysed for this purpose, and view a genetic collection area inferred from actual genetic relatedness and connectivity rather than generalisations based on geographic distance. For additional guidance, users can also view future climate matched locations—areas currently experiencing climatic conditions similar to what the restoration site is predicted to experience in the future.

The scale of Restore and Renew is unprecedented in restoration and conservation genomic research. So far, leaf samples have been collected from more than 101,000 plants across eastern Australia, with DNA sequencing of 61,250 plants finished and over 110 species available on the webtool.



Propagules being grown for the Big Scrub Rainforest Conservancy's genetically diverse seed bank plantation. Seed harvested from the carefully designed living seed bank will be distributed to rainforest restoration planting contractors and nurseries for use in plantings on private land to restore critically endangered lowland subtropical rainforest.
Photo: Renee Borrow, Big Scrub Rainforest Conservancy.

Genomic knowledge infrastructure

The Restore and Renew project is underpinned by a 'genomics knowledge infrastructure' comprising standardised workflows and data management tools that ensure the collection, management, sequencing, and analysis of a vast number of samples is easily managed. Being able to receive, store, sequence, and analyse thousands of samples from many species for numerous projects at any one time facilitates collaboration with multiple stakeholders.

Collaboration provides the building blocks

Numerous multi-species collaborative projects have funded the research that populates the Restore and Renew webtool. For example, Taronga Conservation Society Australia is using genomic information to guide seed sourcing for their restoration of 5,000 hectares of critically endangered box-gum grassy woodland in the Northern Tablelands of New South Wales. In stage 1 of the project, genetic analysis was undertaken for 11 dominant and widespread woodland eucalypt species (Fahey et al., 2024). The resulting genetic guidance helps optimise seed sourcing to maximise adaptive potential and resilience, while also avoiding misidentification and collection from hybrid zones, two issues prevalent in eucalypts. The resulting genetic data have been incorporated into the Restore and Renew webtool, where they are freely available to guide seed sourcing for the 11 target species.

The Big Scrub Rainforest Conservancy's Science Saving Rainforests project (https://bigscrubrainforest.org/science-saving-rainforests/) in Northern New South Wales is using genomic information to design a genetically diverse seed production area (Dimon et al., 2026) for 60 rainforest tree species, including 30 threatened species and 30 key structural species. The project aims to reverse the lack of genetic diversity in small, isolated populations that are threatened with extinction or crucial to the structure of the Big Scrub but are no longer self-sustaining. Seed harvested from the carefully designed living seed bank plantation will be used in restoration planting on private land to restore critically endangered lowland subtropical rainforest. But the benefits do not end there, as the data obtained for the 30 key structural species is being added to the Restore and Renew webtool, enabling other conservation organisations across the region to freely access genetic guidance relevant to their restoration efforts.

Data generated through collaborative projects provide a foundation that can be built upon in future work. For example, the genetic health and representativeness of a network of seed production areas established by Murray Local Land Services in southern New South Wales is currently being assessed using this shared dataset. Samples from these seed production areas can be analysed within the broader context of samples already collected for the same species across the state, a task that would likely not be feasible or affordable without the existing genomics knowledge infrastructure.

Solid infrastructure facilitates continuous growth

At this point, Restore and Renew serves as a robust genomic knowledge infrastructure that includes extensive genomic datasets, digital tools for sample collection, a sample management database, and standardised sequencing and analysis workflows. This system can be used by the ReCER team and other researchers across Australia and beyond, and is designed to accommodate a very large number of projects and samples.

For example, the webtool will soon expand to national coverage through a partnership with Bioplatforms Australia. Its Forest Resilience Initiative (https://bioplatforms.com/project/forest-resilience/) will support whole-genome resequencing and analysis for forest species across Australia. This effort will enable the genomic infrastructure to be upgraded to accommodate whole-genome data, which it does not currently support, demonstrating its capacity to evolve alongside advances in technology.



Researcher Marlien van der Merwe (centre) and collaborators collecting leaf material for genetic analysis from a Seed Production Area to assess genetic diversity and representativeness. Photo: Research Centre for Ecosystem Resilience, Botanic Gardens of Sydney.

The Restore and Renew genomic knowledge infrastructure, including both its concept and implementation, is scalable and can be replicated at different scales and in other geographic contexts. The ReCER team welcomes collaboration with interested partners. This approach has strong potential to support practitioners globally in maximising adaptive capacity and climate resilience when sourcing material for restoration.

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Improving Restoration Outcomes through Strategic Site Prioritization and Species Selection

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MISSOURI BOTANICAL GARDEN



Team in Tanah Merah building the nursery in Sulawesi, Indonesia. Left to right. Deby Arifiari, Laura Toro, Pandi, Riyal Kunjae, and Ronal Candra. Photo: Kate Farley.

Effective restoration requires prioritizing areas and species with the greatest need, threat status, and/or potential impact. Botanical gardens can support this by guiding species selection and restoration approaches that are ecologically appropriate, tailored to local environmental conditions, and cost-effective. Equally important, restoration must align with the cultural, economic, and social context of each site. With their strong regional presence and long-standing community relationships, botanical gardens are well positioned to ensure that restoration efforts are both scientifically grounded and appropriate to place.

Executive Summary

Nearly 40% of the world's terrestrial ecosystems are degraded. Restoring these ecosystems is crucial to support climate change mitigation, biodiversity conservation, and livelihoods. However, most restoration interventions focus on seeding or planting a narrow set of plant species that are common or easy to propagate. These practices can lead to biotic homogenization, reducing ecosystem services and the long-term resilience of restored ecosystems. Because terrestrial ecosystem restoration activities are costly and resources are limited, it is critical to strategically prioritize restoration in areas where ecosystem services are maximized and social conflicts are minimized. Leveraging the expertise of botanical gardens in identifying, seed banking, and growing native and rare species is key to expanding the knowledge and capacity needed to restore native plant communities. Botanical gardens' long-lasting partnerships with local communities, the private sector, and policy makers, together with active lines of research on key plant species, can promote biotic diversity and ensure the long-term resilience of restoration projects.

Current State of Knowledge

There is high uncertainty around where restoration interventions can and should be deployed (Strassburg et al., 2020). To ensure that restoration activities are implemented in the right places to maximize social, environmental, and climate benefits, there is a need for clear habitat definitions, an understanding of potential impacts, safeguards for local communities (i.e. prioritizing areas with strong environmental laws, secure land tenure, and low nature-dependent livelihood conflicts), and the inclusion of protected areas and national forest restoration efforts (Fesenmyer et al., 2025).

Restoration hotspots and areas with high levels of threatened endemic species often overlap (Brancalion et al., 2019). However, most assisted recovery results in biotic homogenization (Chazdon et al., 2024). For example, these efforts often involve planting monocultures of non-native species (Lewis et al., 2019) or a small number of widespread, easy-to-propagate native generalist species (Bilyaminu et al., 2020; De Almeida et al., 2024). Both non-native and generalist species tend to outcompete endemic and rare native species, ultimately compromising recovery trajectories in disturbed ecosystems.

To increase the likelihood of restoration success, there is a need to diversify the taxonomic, functional, and genetic composition of planted species and to include rare and at-risk species (Heywood, 2019; Prober et al., 2019). These combined approaches can support ecosystem recovery, reduce biotic homogenization, and expand the distribution ranges of endangered species beyond protected areas (Chazdon, 2019). Botanical gardens' economic and scientific resources, expertise in propagating less common plant species, and ability to collect species that are legally protected position them to play a key role in enhancing restoration outcomes globally.

Knowledge Gaps and Capacity Needs

Challenge 1: Restoration projects favor planting widely available early successional or non-native species sourced from a limited number of locations because propagating less common or endangered species is both costly and challenging (De Almeida et al., 2024), and most land managers are risk-averse.

Challenge 2: Botanical gardens have traditionally focused on propagating and reintroducing endangered species, often at the level of individual populations. However, effective restoration requires a broader approach that prioritizes locally relevant rare and threatened species and integrates in situ conservation. Shifting from a population-level to an ecosystem-based restoration approach, at both local and regional scales, is needed to support the long-term success of restoration and conservation efforts.



Collecting Crataegus ouachitensis. Pictured in the photo Kayla Flamm and Danielle Ellsworth collecting. Photo: Rebecca Sucher.

Challenge 3: There is a need to optimize synergies and minimize tradeoffs between productive systems, community needs, and conservation and restoration activities. Considering the existing land-use practices alongside the legal rights, livelihoods, and food security of local communities will help to ensure long-term conservation and restoration benefits (Fleischman et al., 2022).

Botanical Gardens' Potential Contributions

Contribution 1: Botanical garden staff have expert knowledge of the plant diversity (genetic, functional, and taxonomic), ecology, and the ethnobotanical uses of the flora where they are located, so they can help to identify the appropriate pool of plant species that can be used to restore an area. Botanical gardens typically have the personnel and resources to experiment with propagation methods for understudied species that are of high conservation concern. These institutions can also more easily obtain collection permits for species with legal protections. Botanical gardens' knowledge and resources will ensure that invasive species are not being planted, and that rare species and those with ethnobotanical uses are included in restoration programs.

Botanical gardens cultivate at least one third of all known plant species (Mounce et al., 2017). Therefore, scientific teams working at botanical gardens can facilitate large-scale restoration by: 1) collecting high-quality plant material (maximizing genetic diversity), 2) managing seeds stored in seed banks, 3) building cost-effective nurseries, 4) propagating plants by seed or vegetatively, and 5) growing, outplanting, managing, and monitoring a diverse pool of resilient plant species. Finally, the education and communication teams in large botanical gardens can train members of other gardens and local restoration groups (Hardwick et al., 2011; Miller et al., 2016).

Contribution 2: Botanical gardens engage with governments, universities, research centers, and the private sector. Their influence can help develop, expand, and link existing plant knowledge and environmental databases within the scientific community to develop workshops and communication resources that integrate local knowledge (Hardwick et al., 2011; Shaw, 2019). Revitalizing the Ecological Restoration Alliance of Botanic Gardens could help to consolidate this approach, influence policy and decision making, and engender financial and political support for restoration activities.



Kate Armstrong, Yudil Ndilao, Irvan Fadli Wanda, and Muhammad Rifqi Hariri collecting plants near Pagkalaseang, Sulawesi, Indonesia. Photo: Natalie Konig.

Practice Insights — The Participatory Propagation of the Tropical Dry Forest in Montes de María

Context:
This project was developed in Vereda Camarón, Bolívar, Colombia in 2019 to restore tropical dry forest habitat. The project was a partnership between the local community of the Vereda Camarón, the Cartagena Botanic Garden "Guillermo Piñeres", the local association of agroforestry growers of Santo Domingo Mesa, and USAID.

Approach:
The project adopted a community-led ecosystem restoration approach focused on the tropical dry forest of Vereda Camarón. Local initiatives to protect watersheds, conserve native plant species, and strengthen the climate resilience of food systems provided a strong foundation for restoration activities and partnerships with regional stakeholders.

The Cartagena Botanic Garden played a key role in supporting these efforts. Through a series of interactive workshops, the botanic garden and the local community jointly selected native tree species for restoration based on their ecological suitability, local uses, and resilience to climate change. They also developed species-specific propagation protocols, established a community nursery, and identified priority areas for restoration interventions (Londoño-Lemos et al., 2020).

Outcomes:
This partnership: 1) established a communal nursery "Bosque de Agua de Camarón" to grow 16 native dry forest tree species to restore the river basin, recover biological connectivity, and provide trees for biodiversity offsets and livelihoods; 2) exchanged botanical, horticultural, conservation, and restoration knowledge; and 3) created an illustrated guide to facilitate the propagation of 16 native dry forest tree species.

Lessons Learned:
Partnerships between botanical gardens and local communities can facilitate funding acquisition that supports community-led restoration and the dissemination of restoration and conservation knowledge through propagation guides, teaching materials, and hands-on workshops.

Contribution 3: Many botanical gardens have ethnobotanical teams that help facilitate the restoration or conservation of areas owned by local communities (Aronson & the ERA of Botanic Gardens, 2014). Their strong scientific expertise and trustworthy partnerships with local communities have allowed the establishment of community-based restoration that maximizes both biodiversity and social benefits without putting peoples' rights and livelihoods at risk. Areas where community-based restoration has occurred have been acting as long-term living laboratories to test restoration methodologies. There is potential to keep expanding and replicating this model in other areas and to develop training programs for ecological restoration (Miller et al., 2016).

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CASE STUDY

Botanical Gardens as Anchors for Intermunicipal Collaboration in Urban Watershed Restoration: The Bronx River

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NYBG



Native plant materials prepared for restoration efforts in the Bronx River watershed.
© New York Botanical Garden. Photo: Marlon Co.

Urban watersheds face pressure from climate change, aging infrastructure, and environmental inequities. Addressing these challenges requires governance models that integrate ecological science, community engagement, and cross-jurisdictional collaboration. Botanical gardens, long seen as cultural and scientific institutions, are now emerging as key players. The New York Botanical Garden's (NYBG) Bronx River Watershed Health and Resilience Program shows how botanical gardens can bridge boundaries, advance restoration, and strengthen regional environmental governance.

To understand the growing importance of institutions like NYBG, it is necessary to examine the ecological, social, and political factors shaping the Bronx River watershed—factors that highlight both the urgency for coordinated action and the limitations of traditional governance.

Urban Watershed Challenges in a Fragmented Landscape

The Bronx River flows 23 miles (~37 kilometers) through a 56-square-mile (~145 square kilometers) watershed spanning 15 municipalities across Westchester County and the Bronx (Bronx River Alliance et al., 2024) in New York State. Like many urban rivers, it has been extensively modified by channelization, industrial activity, and urbanization. High levels of impervious cover, stormwater runoff, and combined sewer overflows contribute to persistent water quality impairment, erosion, and sedimentation. These impacts disproportionately affect downstream communities in the Bronx, which experience cumulative environmental burdens (Finewood et al., 2023).

These ecological and social challenges are intensified by the watershed's political fragmentation. Watershed governance scholarship demonstrates that ecological processes operate independently of municipal boundaries, making issues such as stormwater management, habitat connectivity, and water quality inherently cross-jurisdictional. As a result, effective restoration requires coordinated action among municipalities, agencies, and community-based organizations (Arnold, 2018; Imperial, 2005).

These realities prompted the development of a shared governance tool that could align diverse actors around common priorities for the Bronx River. The Bronx River Intermunicipal Watershed Management Plan (IWMP) emerged as a direct response to this fragmentation.

The IWMP as a Shared Governance Framework

Through a cross-sector partnership, including local municipal agencies, nonprofits, academia, and NYBG, the IWMP emerged as a shared framework for watershed restoration and resilience. It defines collective priorities, strategies, and pathways for continued management of the Bronx River that cross jurisdictions (Bronx River Alliance et al., 2024). In this way, the IWMP functions not only as a technical document but also as a mechanism for long-term collaboration. However, shared frameworks require institutions capable of putting plans into action. They depend on organizations that are trusted across boundaries, grounded in science, and able to convene partners who rarely collaborate. NYBG has emerged as one such institution.

Botanical Gardens as Interjurisdictional Conveners

Boundary organizations are institutions that operate at the interface of science, policy, and society to facilitate collaboration, knowledge exchange, and decision-making across sectors with differing mandates and forms of expertise (Gustafsson & Lidskog, 2018). Boundary organization scholarship highlights the importance of such institutions in enabling interaction, co-production, and mutual understanding across science, policy, and stakeholder domains (Gustafsson & Lidskog, 2018).

Botanical gardens are particularly well-positioned for this role. Their missions intersect conservation, climate resilience, public health, and education, and their interjurisdictional identities allow them to convene diverse partners without the political constraints that often limit governmental agencies. In a fragmented landscape, NYBG serves as a boundary-spanning institution, supporting the development and implementation of shared governance frameworks like the IWMP. This role is evident in NYBG's co-leadership in convening the annual Bronx River Assembly, which brings together municipal agencies, scientists, community groups, and elected officials to coordinate watershed-scale planning.

The Bronx River Assembly is a space where partners can share data, align priorities, and advance the updated Bronx River IWMP. NYBG uses its expertise in horticulture and environmental education as well as its public presence to translate ecological knowledge into practice. By bringing together multi-sector partners and facilitating knowledge exchange, NYBG fosters coordination and supports co-produced restoration and resilience strategies across the watershed.

This boundary-spanning function becomes fully operational through NYBG's cross-scale restoration model, which links site-based experimentation with watershed-scale planning and implementation.



Community members gathered at the 2026 Bronx River Assembly to discuss the health of the watershed and plan collaborative action.
© New York Botanical Garden. Photo: Marlon Co.

NYBG's Cross-Scale Restoration Framework

NYBG's Bronx River Watershed Health and Resilience Program combines plant-based restoration, research, community engagement, and partnership-building into a unified framework. The Garden's 250-acre (~101 hectares) campus is a living laboratory for testing, monitoring, and refining forest and riparian zone restoration strategies before broader application.

At the core of this model is the Thain Family Forest, a 50-acre (~20 hectares) remnant old-growth forest in the heart of NYBG's 250-acre historic landscape in the central Bronx. NYBG scientists and external collaborators actively use the Forest for long-term ecological research. This research informs adaptive management that addresses a range of anthropogenic threats to forest health, including canopy shifts driven by invasive pests, urban stressors, and climate pressures (New York Botanical Garden, 2016). Ongoing work includes invasive species management, native plant establishment, and long-term ecological monitoring. In 2025, restoration efforts in the Thain Family Forest included the planting of more than 500 trees and 800 herbaceous plants, as well as the removal of 6,127 non-native plants representing more than 60 species.

This site-based expertise forms the foundation for NYBG's broader contributions to watershed-scale planning and implementation. As a result, NYBG is able to play a central role in advancing the goals of the Bronx River Intermunicipal Watershed Management Plan (IWMP), which outlines 169 priority projects spanning restoration, green infrastructure, dam removal, and other interventions across the watershed (Bronx River Alliance et al., 2024).

One key restoration initiative is the Bronx River Riparian Forest Restoration Project, supported by the New York State Department of Environmental Conservation's Community Reforestation (CoRE) Grant Program. This cross-sector project includes NYBG, Westchester Parks Foundation, Westchester County Parks, NYC DEP, and the Bronx River Parkway Reservation Conservancy. Beginning in 2026, this multi-year effort will restore 5.9 acres (2.4 hectares) across six sites in four Westchester County municipalities (Bronxville, Mount Vernon, North Castle, Yonkers) and the Bronx (within NYBG). Planned activities include planting 755 containerized native trees and implementing site-specific invasive species management using manual, thermal, and targeted chemical treatments. Implementation will be focused on degraded sites, including floodplain forests and areas facing renewed invasives, emphasizing the need for adaptive, ongoing management.

The project will also advance workforce development and community engagement by involving staff, partners, youth, and local community members in restoration activities, building technical skills while supporting long-term stewardship. Lessons from the Thain Family Forest's long-term restoration will guide these interventions and offer replicable models for municipalities throughout the watershed.

Key Perspectives for Botanical Gardens

Several insights arise from the Bronx River Watershed Health and Resilience Program. Botanical gardens can strengthen restoration outcomes by investing in long-term monitoring, building convening capacity, and linking on-site experimentation with regional planning. Integrating community engagement into restoration fosters local stewardship and ensures interventions reflect community needs. Demonstration projects, such as those in the Thain Family Forest, provide models that partners can adapt across the watershed.

Although botanical gardens are often perceived as static institutions, the Bronx River case demonstrates their dynamic potential. By uniting research, horticulture, engagement, and convening, NYBG bridges gaps that frequently hinder urban watershed restoration. Its work anchors collaboration, translates ecological knowledge into action, and sustains stewardship across boundaries.

As cities confront intensifying climate impacts and environmental inequities, botanical gardens can serve as authorities, partners, and conveners. The Bronx River case shows that when gardens embrace this role, they help shape more resilient, connected, and equitable urban ecosystems.

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Integrative Biotic Assistance to Enhance Restoration Success

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UC SANTA CRUZ



Small bee (Lasioglossum sp.) visiting coast buckwheat (Eriogonum latifolium) in coastal scrub habitat in northern California. Photo: Andy Kulikowski.



Ectomycorrhizae on loblolly pine (Pinus taeda) seedlings planted in the southeastern U.S. Photo: Lily Gannon.



Sandhill cranes in Curtis Prairie at UW–Madison Arboretum.
Photo: Heidi Neidhart / © Board of Regents of the University of Wisconsin System.

Executive Summary

Restoring ecosystems resilient to climate change necessitates re-establishing complex biotic interactions. To date, however, most terrestrial restoration research has been short-term, small-scale, and focused on plants. Botanical gardens and arboreta can move restoration efforts to scale up in space, time, and complexity by undertaking ecosystem-level restoration projects on their land that target biodiversity recovery of a suite of guilds. They should serve as hubs for long-term, observational and experimental research, as well as education. Botanical gardens should also be leaders in developing methods to propagate and reintroduce microbial communities.

Current State of Knowledge

Botanical gardens and arboreta (BGA) typically focus on *ex situ* conservation and restoration of plants. However, it is well known that plants are affected both positively and negatively by interactions with a range of other biota, including animals, fungi, and various other microbes. These interactions are crucial to the survival and reproduction of many, if not all, plant species, and in turn, key to ecosystem resilience to various disturbances, including climate change (Holl, 2020). Commonly studied plant-animal interactions include seed dispersal, pollination, herbivory, and seed predation, with a predominance of research on seed dispersal and interactions involving mammals and birds (Genes & Dirzo, 2022). Only a small portion of these studies have been conducted in botanical gardens and primarily comprise pollination studies.

There has been less prior research on the varied fungal and microbial interactions with plants in restoration, as well as their influence on biogeochemical cycles, in part due to the challenge of identifying these species. The amount of research in this area has grown substantially in the past decade, facilitated by the proliferation of modern genetic methods enabling the identification of different taxonomic units and their functional roles (Peddle et al., 2025). Extensive research has addressed the positive role of mycorrhizae on facilitating plant survival, growth, and diversity (Koziol et al., 2018), though, as with any mutualism, mycorrhizae can have variable effects depending on the species involved and site conditions (Neuenkamp et al., 2019). Inoculation of degraded sites with reference ecosystem soil communities has often been shown to increase the survival of desirable native plants and shift the successional trajectory (Averill et al., 2022; Peddle et al., 2025).

Nurseries and BGA can be key drivers of the spread of plant pathogens, in particular various species of the water mold *Phytophthora*, through propagation and revegetation activities (Mitchell, 2023). At the same time, botanical gardens have played a key role in developing best practices for limiting their spread and educating the public about the risks (Hayden, 2020).

Knowledge Gaps and Capacity Needs

Challenge 1: Transformative change is needed to align common small-scale ecological restoration approaches with expectations to restore millions of hectares of degraded lands globally (Brancalion & Holl, 2025). Currently, many restoration projects and studies are conducted in small areas using methods that are infeasible to scale up (Brancalion & Holl, 2025). This increase in scale is particularly important for better integrating plant and faunal restoration including rewilding, given that many fauna require large areas for their habitat and to restore associated ecosystem processes (McAlpine et al., 2016). It is also critical to coordinate conservation and restoration efforts across environmental gradients to make them more resilient to climate change (Carroll & Noss, 2021). A challenge for increasing the size of restoration experiments is the land available to conduct controlled, replicated experiments comparing different methodologies side by side, as restoration practitioners tend towards tried-and-true methods to ensure they meet restoration targets (Luong et al., 2023). Likewise, the temporal scale of most restoration projects is extremely short, typically 1–5 years, relative to the multidecadal time-scale characteristic of the recovery of many ecosystems (Brancalion & Holl, 2025).

Challenge 2: Whereas ecological restoration best practices aim for the highest attainable recovery (Gann et al., 2019), in practice, much of what is referred to as "restoration" has more utilitarian aims, like providing income and direct benefits to local landholders (e.g., timber, agroforestry) or maximizing carbon sequestration (Brancalion et al., 2025). Many projects state restoring biodiversity as a goal, but in reality, biodiversity is often an afterthought of large-scale restoration (Brancalion et al., 2025). For example, in the case of large-scale reforestation efforts, the focus has largely been on the number of trees planted rather than biotic interactions needed to sustain those trees and the recovery of forest ecosystems.

Challenge 3: As noted previously, most research on biotic interactions has been focused on above-ground communities that are visible. There is a paucity of information on what components of soil microbial communities are most important to reintroduce and the most effective methods for inoculating sites with whole communities or individual target species (Peddle et al., 2025).

Botanical Gardens' Potential Contributions

BGA Contributions 1: Whereas botanical gardens and arboreta have primarily focused on the propagation and display of individual plant species, a number have implemented restoration of ecosystem types at the scale of tens of hectares or more (e.g., University of Wisconsin Arboretum, see Practice Insights; Chicago Botanic Garden's McDonald Woods; Brackenhurst Botanic Garden; Kadoorie Farm and Botanic Garden). These ecosystem restoration efforts on BGA land serve several roles. First, they allow experimentation with different restoration methodologies, typically without the strict compliance measures required by legislatively mandated projects. Second, if the land has strict protection, this allows for long-term studies and monitoring to evaluate ecosystem recovery over time, ideally with minimal risk of major human intervention, which is often the case in working landscapes. Finally, conducting ecological projects at or near well-visited botanical gardens provides ample opportunities for education about biotic interactions in these systems.

In addition, botanical gardens have increasingly served as regional convening organizations for studies that bring together various nonprofit, government, and academic institutions to coordinate conservation and restoration across the landscape (Chen et al., 2009). Such coordination is key to the conservation of biotic interactions, particularly of larger fauna. Botanical gardens are well situated to engage with a range of stakeholders and agencies in their region and typically are not viewed as strongly politically aligned with a single participating institution.

BGA Contributions 2: Conserving plant biodiversity is a top priority for most botanical gardens, which means they can promote and test propagation and restoration methods that put biodiversity at the center of restoration. Doing so means expanding the focus from just plant conservation to restoring the many biotic interactions described earlier, in addition to enhancing collaborations with non-BGA institutions and experts. Moreover, BGA are in an excellent position to educate the public not only about the importance of such interactions for plants and ecosystems, but also the key role that research plays in improving the outcomes of restoration and conservation.

BGA Contributions 3: Botanical gardens, as part of their standard practice, test and refine propagation methodologies, which provides an excellent opportunity to set up well-designed experiments to test the impacts of reintroducing individual species or whole communities of microbes when propagating individual plant species or conducting ecosystem restoration projects. Some botanical gardens either have their own laboratory facilities or relationships with academic institutions that enable them to use modern methods for identifying and isolating species.

Practice Insights

University of Wisconsin-Madison Arboretum long-term whole ecosystem restoration

Context, Approach, and Outcomes:
The University of Wisconsin-Madison (UW) Arboretum has long been viewed as one of the earliest restoration projects in the United States. In the 1930s, Aldo Leopold envisioned the ecosystems of the Arboretum as a teaching and education resource for students, faculty, and the public about the past, present, and future of Wisconsin ecosystems (Jordan III, 1984). Over the next few decades, restoration of prairies and various types of forests and freshwater wetlands was undertaken in both a trial and error and experimental manner by various people, including Henry Greene and John Curtis. While much of the research has focused on vegetation restoration and fire management of these ecosystems, there has also been extensive research on birds, small mammals (e.g., rabbits, voles, mink), various insects, and even worms (Jordan III, 1984). Research on these organisms and their interactions with plants has resulted in hundreds of publications (arboretum.wisc.edu/science/publications/). For example, Woods (1984) found that failure of two reintroduced understory herbs to disperse in a forest at the UW Arboretum was due to the low abundance of seed-dispersing ants, which led to further research on the role of ants in seed dispersal. Research continues to the current day with an annual research symposium (arboretum.wisc.edu/science/research-symposium/) and student research fellowships (arboretum.wisc.edu/science/arboretum-research-fellowships/). Staff, UW students and faculty, volunteers and community members continue to manage these ecosystems through removing invasive species, implementing prescribed fire, and managing nutrient inputs from the surrounding urban areas (arboretum.wisc.edu/land-stewardship/).

Lessons Learned:
The UW Arboretum and other botanical gardens that have similar whole ecosystem-focused restoration programs illustrate the important role that botanical gardens can play in providing long-term protected sites for research that informs ecological restoration well beyond the boundaries of land owned by the gardens. The long-term effort at the UW Arboretum shows that most restoration requires or benefits from ongoing interventions rather than being the 1–3-year process assumed by many funding organizations.

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A morning view of Curtis Prairie at UW–Madison Arboretum.
Photo: Susan Day / © Board of Regents of the University of Wisconsin System.

Mycorrhizal Fungi in Restoration Practice

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SPUN
SOCIETY FOR THE PROTECTION OF UNDERGROUND NETWORKS



Natural regeneration in the tropical forest understory. Photo: Adriana Corrales.

Executive Summary

Mycorrhizal fungi play a foundational role in long-term ecosystem recovery, providing critical benefits that enhance plant nutrient acquisition, growth, stress tolerance, and pathogen defense. Increasing evidence demonstrates that soil microbiome inoculation—particularly with high-quality, native, and locally adapted inoculum—can substantially improve restoration outcomes. Attention to belowground components can increase plant survival, suppress invasive species, and accelerate native community recovery beyond what plant-based restoration alone typically achieves. In parallel, pre-restoration assessment and monitoring of underground communities have been proposed as key steps for improving the design and long-term success of restoration interventions.

Despite growing recognition of mycorrhizal fungi as a critical yet underutilized component of restoration, significant knowledge gaps remain regarding their effective and practical implementation in the field. Botanical gardens are uniquely positioned to address these challenges by serving as hubs for native inoculum production, sharing expertise on plant-mycorrhizal associations, and raising public awareness about underground biodiversity.

Current State of Knowledge

Integrating mycorrhizal fungi into restoration programs is increasingly recognized as essential for long-term ecosystem recovery. Mycorrhizal fungi provide critical benefits to most plant species on Earth, including enhanced nutrient acquisition, higher growth rates, pathogen defense, and improved pollination success (van der Heijden et al., 2015). Because certain types of mycorrhizal fungi can colonize early successional sites more rapidly than plant communities, these organisms likely play an active role in shaping vegetation dynamics during secondary succession and ecological restoration efforts (García de León et al., 2016). Accordingly, pre-restoration assessments that evaluate the baseline composition of soil fungal species already present at a restoration site have been proposed as key steps for diagnosing site conditions prior to intervention (Fu et al., 2025), informing assessments of plant-mycorrhizal symbiosis compatibility and the potential need for active management.

A major challenge in restoration is ensuring compatibility between the dominant mycorrhizal fungi present in a site and the plant species used for restoration. Most plants only associate with one type of mycorrhizal fungal partner (van der Heijden et al., 2015). In some cases, mycorrhizal systems could be so altered by land use change that the mycorrhizal partners of the original ecosystem could be completely changed, strongly reduced, or replaced (Raczka et al., 2023; Stewart et al., 2026). These changes not only hamper the establishment of native plants but might also bias successional trajectories. The dominant mycorrhizal type in an ecosystem influences plant species composition and ecosystem function: arbuscular mycorrhizal (AM) fungi are most widespread in grasslands and tropical forests and typically prevail in soils with low phosphorus availability, whereas ectomycorrhizal (EcM) fungi are more common in temperate and boreal forests and are essential in environments with lower nitrogen availability. Therefore, it is critical to identify the specific mycorrhizal associations of both the plant species used in the restoration program and the original community being targeted for recovery in order to select compatible partners.

Soil microbiome inoculation has emerged as a key innovation in restoration practice (Werden et al., 2024). Evidence indicates that inoculation using high-quality native and locally adapted mycorrhizal taxa can significantly improve restoration outcomes, including increased plant survival and establishment, suppression of invasive plant species, and enhanced recovery of native plant communities compared with plant-based restoration alone (Averill et al., 2022; Cheeke et al., 2019; Koziol & Bever, 2016; Koziol et al., 2025b; Fu et al., 2025; Neuenkamp et al., 2019). Nonetheless, significant knowledge gaps persist regarding the practical implementation of inoculation and the avoidance of its numerous potential pitfalls. For example, commercial mycorrhizal inoculants often exhibit low propagule viability and contamination with non-targeted species including pathogens (Koziol et al., 2025a). These products, which are often composed of one or a few non-native mycorrhizal species, raise concerns around the introduction of non-native fungal strains that may fail to adapt to local conditions or become invasive and displace indigenous soil communities (Hart et al., 2018).

The successful establishment and persistence of an inoculated fungal community is not guaranteed and instead highly context-dependent, governed by a complex interplay of environmental and biological factors (Bennett & Groten, 2022; Fu et al., 2025). For example, soil abiotic factors—often shaped by land-use history—such as soil pH and organic carbon availability, serve as the primary drivers of fungal species composition. In addition, plant–mycorrhizal compatibility and host specificity require the careful selection of native plant species that are aligned with the ecological traits of the introduced mycorrhizal fungi, which is critical for successful establishment and long-term persistence. Furthermore, interactions with the soil microbiome could highly influence the survival and functional performance of the mycorrhizal communities (Fu et al., 2025).



SPUN sampling the mycorrhizal fungal communities of Joshua Tree seedlings in a Mojave Desert restoration project. Photo: Gabriel De La Rosa.

Knowledge Gaps and Capacity Needs

Despite growing scientific interest and demonstrated potential, several persistent knowledge and capacity gaps continue to constrain the effective integration of mycorrhizal fungi into restoration practice.

Challenge 1: Establishing locally relevant baselines for restoration programs remains challenging due to the scarcity of available datasets that characterize historical or reference conditions for mycorrhizal community composition and function across ecosystems. In addition, baselines and pre-restoration assessments for mycorrhizal fungi are currently hindered by the lack of standardized, practitioner-friendly protocols. Because these organisms primarily exist underground as microscopic structures, more commonly utilized methods, such as environmental DNA sequencing or microbial biomass measurements, are often difficult to incorporate due to high costs, technical demand, absence of local expertise, and inaccessible infrastructure for analysis. Furthermore, information on the compatibility among host plants, the environment, and fungi remains limited, especially within underexplored or highly diverse ecosystems, thereby hindering informed decision making regarding whether and how to intervene to promote native plant–fungal species interactions.

Challenge 2: Significant uncertainty persists regarding appropriate inoculum sources for restoration practices, including how to identify, source, or produce high-quality, native, and locally adapted mycorrhizal inoculum at meaningful scales. In addition, limited data exists regarding the factors necessary for successful inoculation, including plant–fungi compatibility, the optimal timing and application rates for inoculation, and the relevant biotic and abiotic interactions for long-term establishment (Verbruggen et al., 2013; Salomon et al., 2022; Koziol et al., 2025a; Lutz et al., 2023; Fu et al., 2025). Furthermore, experimental evidence on the impact of mycorrhizal inoculation on plant performance is primarily derived from controlled environments rather than field conditions (Fu et al., 2025). Field-based experiments conducted over longer time periods remain a key research need to better understand the effects of inoculation on plant performance and successional trajectories.



Ectomycorrhizal fungi growing in Nothofagus forests of Chile. Photo: Mateo Barrenengoa.

Practice Insights

Native arbuscular mycorrhizal fungi inoculation improves tallgrass prairie restoration in Kansas, USA

Context:
In 2017, a tallgrass prairie restoration experiment was established in the Perennial Agriculture Project Field Station near Lawrence, KS, USA by researchers from the University of Kansas. The purpose of this study was to assess the long-term impact of field inoculation, using varying densities of native mycorrhizal inoculum, on both the diversity and species composition of plant communities (Koziol et al., 2025b).

Approach:
A native fungal community mixture of AM fungi inoculum was created and applied at different densities ranging from 0 to 8192 kg/ha. The researchers monitored plant communities, particularly the richness and abundance of late-successional plant species, over 72 months in 4 x 4 m plots in the field.

Outcomes:
Applications of native AM fungi inoculum at the highest densities greatly increased the abundance and richness of desirable, late-successional native plant species and suppressed the abundance of non-native exotic species. Inoculation strongly influenced the successional trajectory of the landscape, with inoculated plots more closely resembling local prairie remnants identified as reference sites. Positive effects of native AM fungal inoculation are consistent over time (7+ years of monitoring to date).

Lessons Learned:
This long-term study shows that active restoration of belowground components, particularly native mycorrhizal fungal communities through inoculation, can improve plant community restoration trajectories. Inoculation promoted desirable late-successional species and helped move communities toward reference conditions, highlighting the importance of incorporating native mycorrhizal management into restoration strategies.

Challenge 3: Empirical studies assessing the long-term effects of active mycorrhizal interventions on plant performance and the successional trajectory of plant communities are scarce (Koziol et al., 2025b), and the highly context-specific nature of plant–fungi–soil interactions, including the relationships between mycorrhizal fungi and other soil biota within the broader soil microbiome, is frequently underrepresented in monitoring frameworks (Zhang et al., 2022; Lutz et al., 2023). Moreover, interactions among invasive plant species, native mycorrhizal communities, and introduced fungal taxa—including risks of fungal invasion or plant–fungal co-invasion—are rarely incorporated into restoration monitoring and adaptive management due to insufficient data.

Botanical Gardens' Potential Contributions

Contribution 1: Botanical gardens are well positioned to act as regional hubs for the production of locally adapted mycorrhizal inoculum. Given their role as centers for plant and fungal taxonomy and ecology, they possess specialized expertise. This knowledge, coupled with a strong understanding of the regional drivers of ecosystem disturbance, makes them invaluable partners for local practitioners engaged in ecological restoration. Botanical gardens can help to identify and cultivate appropriate host plants—specifically native, rare, and endangered species—acting as reservoirs of locally adapted mycorrhizal diversity. By maintaining these plants under controlled or semi-natural conditions, gardens can serve as living sources of native mycorrhizal inoculum that reflect local ecological contexts while reducing reliance on commercial, non-native products.

Contribution 2: Mycorrhizal fungi can be categorized into broad functional groups (e.g., arbuscular vs. ectomycorrhizal fungi), and these functional groups have unique geographic patterns and associate with different plant types. Botanical gardens can support local restoration efforts by sharing relevant knowledge on plant–mycorrhizal symbiosis types, helping practitioners to identify which functional groups and host associations are appropriate for specific ecosystems. Such guidance could inform proper soil management, species selection, and fungal inoculation decisions aligned with project goals.

Contribution 3: Through their public education, outreach, and policy engagement activities, botanical gardens are uniquely positioned to raise public awareness of the critical importance of mycorrhizal fungi and other belowground organisms for conservation and restoration. By integrating belowground processes into restoration narratives and programming, gardens can help shift perceptions of restoration from a plant-centric practice toward a more holistic, ecosystem-level approach.



Invasive African oil palm in a tropical forest. Photo: Adriana Corrales.

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The Role of Invasion Science and Ornamental Horticulture in Climate-Resilient Restoration

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NYBG

Executive Summary

Biological invasions are a leading driver of biodiversity loss and a serious obstacle to effective restoration. With climate change, the impacts of invasions are increasing harm to many ecological and socioeconomic systems around the world, and thus invasive species present a major barrier to effective climate resilience planning. Yet, it is relatively rare for botanical gardens to develop research programs and provide specialized expertise on plant invasions, likely due to historical tensions between invasion science and ornamental horticulture. This lack of specialized knowledge represents both a challenge and an opportunity: Rather than acting as unintended vectors of spread, botanical gardens are uniquely positioned to serve as early detectors of invasive species, monitoring introduction pathways, mapping distributions, identifying emerging threats, and providing the public with solutions. As hubs of both scientific and horticultural expertise, botanical gardens can provide critical knowledge on invasive species and means of achieving climate resilience in restoration.



NYBG volunteer managing invasive knotweed in the Thain Family Forest. © New York Botanical Garden. Photo: Marlon Co.

Current State of Knowledge

Biological invasions are defined by the spread and negative impacts of introduced species (Brondízio et al., 2019), and they are causing increasing harm with climate change (Colberg et al., 2024; Vilà et al., 2021). Because botanical gardens showcase introduced plants from around the world, they have long been recognized as an unintentional pathway for invasive species introduction and spread (Reichard & White, 2001; Van Kleunen et al., 2018), including plants, plant diseases, and pests. For example, in the United States, ornamental horticulture is considered responsible for 53% of intentional invasive plant introductions (Lehan et al., 2013) and up to 70% of forest pest and pathogen introductions (Liebhold et al., 2012). These invasions have massive cascading impacts on ecosystems and economies (Brondízio et al., 2019; Roy et al., 2024), yet ornamental horticulture continues to serve as a pathway of spread (Beaury, Patrick, et al., 2021).

To reduce the spread of invasive species through horticulture, risk assessments (Conser et al., 2015), policy interventions (Lakoba et al., 2020), and voluntary initiatives (Burt et al., 2007) have been put forth, but all have limitations. For example, international, national, and state policies identify high-impact species that should no longer be used as garden plants (Beaury, Fusco, et al., 2021; Early et al., 2016; Hulme et al., 2018), but these policies often focus on species that are already widespread. Moreover, such policies are inconsistently applied across borders, leaving many gaps in efforts to proactively reduce invasions at scale (Beaury, Fusco, et al., 2021; Reaser, 2019). Without a policy incentive, the nursery industry is slow to remove harmful species from trade, likely due to economic drivers and the ease of propagating species that are hardy and fast-growing—traits that both appeal to horticulturalists and increase invasion risk (Guo et al., 2019; Van Kleunen et al., 2018). Recognition of these tensions has increased in the past decade, yet solutions are still slow to be implemented.

Practice Insights — Emerging plant invasions in the northeastern United States

Context:
Research, horticulture, and conservation staff at the New York Botanical Garden combine field surveys and biogeographic models to identify and forecast emerging invasive plants

Approach:
At the New York Botanical Garden (NYBG), science, horticulture, and conservation staff collaborate to address invasive species issues across multiple scales, with an emphasis on identifying and forecasting emerging invasive species for the northeastern United States. Using botanical and taxonomic expertise, NYBG documents changes in the flora across the region and within the Thain Family Forest located on NYBG's grounds, which is the largest remnant of old-growth forest left in New York City. NYBG's long history of data collection and invasive species management has enabled early detection of emerging species and the development of new best management practices. Through this work, NYBG has identified and evaluated the invasion risk of newly arriving plant species, shared emerging species alerts online (https://sweetgum.nybg.org/science/projects/northeastflora/emerging-invasive-alerts/), and contributed high-risk observations to the Public Gardens as Sentinels Against Invasive Plants program (https://pgsip.mortonarb.org/BoI/pgsip). Using biogeographic and ecological expertise, NYBG also collaborates with partners across the region to map distributions and project climate range shifts of invasive plants (https://doi.org/10.1111/ddi.13787) and to forecast invasion risk associated with ornamental horticulture (https://doi.org/10.7275/avq3-ma30). These are just a few examples of NYBG's cross-disciplinary efforts to identify, manage, and mitigate the harm of invasive species, as a key barrier in our efforts to restore ecosystems and bolster climate resilience.

Outcomes:
Emerging invasive species alerts at multiple scales, including:

- Local risk documented in the Public Gardens as Sentinels Against Invasive Plants database
- Regional risk alerts based on botanical surveys
- Forecasting risk based on biogeographic modeling
- Contributing to New York State's Invasive Species Regulations
- Tools for identification of emerging invasive plant species and platforms for reporting observations

Lessons Learned:

- Collaborations between science, horticulture, and conservation are necessary to reduce the spread and impacts of invasive species.
- This expertise is uniquely housed at botanical gardens, and thus botanical gardens could play a stronger role in invasion science, management, and education.
- More work could be done to support practitioners and the public in early detection and data reporting.

Knowledge Gaps and Capacity Needs

Solutions to invasive species issues, and their impacts on climate resilience, hinge on more effective collaborations between invasion science and ornamental horticulture. Although surveys show that horticulturalists recognize invasive species as a problem and are interested in supporting solutions (Culley et al., 2022; Knuth et al., 2021), measures to reduce invasive species introductions have not been widely adopted (Beaury et al., 2023; Beaury, Patrick, et al., 2021). This may be due to knowledge gaps regarding where along the supply chain risk of introduction and escape is highest (Hulme et al., 2018), inaccessible information on which species are considered invasive, and the economic burden of implementing more risk-averse practices. For example, conducting a formal risk assessment (e.g., Conser et al., 2015) for a single new introduced species takes a minimum of a few hours, whereas it only takes a few minutes to purchase a new plant. As a result, there is a gap between the pace at which plant trade introduces new species and the pace at which invasion science can properly assess and share information about invasion risk.

Botanical Gardens' Potential Contributions

Given the tension between the economic value of introduced plants in industry and the ecological damage they cause in natural areas, it is only in the past few years that botanical gardens have embraced their potential in mitigating impacts of invasive species. Reducing this tension in favor of more collaborations is needed, including finding and implementing solutions that are both ecologically sound and cost-effective.



Lesser Celandine removal at the New York Botanical Garden.
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While research programs at botanical gardens are diverse, common scientific expertise includes plant taxonomy, evolutionary processes, biogeography, and ecological forecasting. All of these areas of expertise can provide critical knowledge on the botany, ecology, and management of biological invasions, and how invasions affect climate resilience. For example, taxonomists can help practitioners identify newly established plants, understand their origins and interactions, and thus the invasion risk they may pose. Many botanical gardens themselves manage natural areas or conduct field work locally, thus gathering firsthand information on species invasions, best management practices, and ecosystem responses to climate change. This information can be shared with the diverse audiences that engage with botanical gardens.

Botanical gardens also have expansive horticulture and public education programs, such that they could play a significant role in increasing invasive species awareness, developing best management practices, and providing stakeholders with solutions to reduce unintentional spread. For example, botanical gardens could compile and share lists of recognized invasive species for their region, compile and share lists of climate-resilient species for landscaping and restoration, recommend non-invasive alternatives for horticulture, and inform the public on how to design climate-resilient gardens that provide ecosystem services. In these ways, botanical gardens can function both as museums of global plant diversity and partners in climate-resilient restoration and conservation.

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Linking Research and Practice: Botanic Gardens as Catalysts for Native Plant Restoration

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DENVER BOTANIC GARDENS



Native forb establishment after minimal site preparation at CommonGround Golf Course. Photo: Rebecca Hufft.

Executive Summary

Global climate change is driving landscape-scale impacts that underscore the urgent need for regionally suitable ecosystem restoration practices across scales and habitats. However, several critical barriers limit effective implementation, including insufficient native seed and plant stock availability, a lack of evidence-based protocols for practitioners, and limited guidance for emerging use cases such as urban turf conversions and green infrastructure projects. The lack of native plant material and know-how is a global issue, but the solutions are decidedly regional (species and techniques must be tailored to ecoregions). This is precisely why botanic gardens, with their regional focus and expertise, are excellent facilitators.

Botanic gardens, with their unique capacity for applied research, plant production, and public engagement, are well positioned to address these gaps and lead by integrating horticultural expertise, applied research, community outreach, and regional knowledge within a single institution. They are particularly suited to demonstrate restoration techniques across spatial scales, from backyards to larger open spaces, considering factors from genetic diversity to community dynamics. Within this report we present a case study in which Denver Botanic Gardens exemplifies this potential through the development of a restoration toolkit that encompasses diverse site preparation methods, custom seed mix design, and scalable planting techniques tested across a range of urban to rural contexts. Early results demonstrate that both intensive and minimal-disturbance approaches can successfully establish native plant communities, increase pollinator habitat, and inform region-specific best practices. Dissemination of these findings to stakeholders, from policymakers to individual land managers and gardeners, positions botanic gardens as essential connectors between restoration science and on-the-ground implementation.

Current State of Knowledge

The demand for native plants in restoration has grown significantly in recent years. This trend is evident across scales, from large federal land restoration projects (PCA, 2015; PCA, 2025) to urban yards and green spaces (Teixeira et al., 2022; Sexton and Lawhorn, 2025). Climate change is simultaneously intensifying the need to create resilient landscapes in rural and urban areas to support biodiversity, enhance ecosystem services, and adapt to changing conditions. Native plants offer important ecological benefits, including supporting wildlife and pollinators (Russo et al., 2025). Although there is widespread desire – from individuals and land managers to municipalities – to include native species in restoration and landscaping (Beck et al., 2025; Martinson, 2020), several well-documented challenges remain.

There is often insufficient seed or plant stock available to meet restoration needs, especially in the face of climate change (Havens et al., 2015; NASEM, 2023). Even when native seeds are accessible, successfully establishing plants can be difficult due to various issues (James et al., 2013; Nolan et al., 2021). For example, selecting the appropriate seed mixes (Shryock et al., 2022) or planting methods (e.g., seeding versus planting, Leverkus et al., 2021) presents additional challenges as it depends on site conditions, available resources, and desired management outcomes. Identifying or implementing the best maintenance strategy for these different contexts can also pose difficulties (Boch et al., 2025; da Silveira et al., 2025; Schmithals & Kühn, 2014; Wan et al., 2026).

Knowledge Gaps and Capacity Needs

While the ecological benefits of using native species in restoration have been well documented, they remain underutilized in implementation efforts, especially in urban environments (Higgins and Russo, 2025). Furthermore, only a small subset of extant native flora is used for restoration and landscaping, and many species remain untested and unavailable to practitioners, particularly in quantities sufficient for larger-scale projects (NASEM, 2023). Meanwhile, expanding use cases beyond traditional wildland restoration—from small-scale turf conversions to urban parks—is driving demand for new, evidence-based approaches (James et al., 2009; Lartey et al., 2025; Zhu & Ling, 2026). The following challenges represent some of the most critical barriers limiting the effective use of native plant materials in restoration across scales.

Challenge 1: Native Plant Material Availability

Limited availability of native plant material remains a challenge in both the seed and nursery markets. Many plant nurseries still mainly produce non-native, ornamental cultivars, and native plant production continues to represent a small share of production despite growing demand for native plants from home gardeners, municipalities, and restorationists (Fertakos et al., 2026). Within the seed industry, native plant seeds face similar availability issues, often caused by a lack of germination, propagation, and seed bulking data, which results in only a small portion of the potential restoration species pool being accessible (Ladouceur et al., 2018). In urban, residential, and municipal settings, native plant adoption is hindered by a lack of clear, evidence-based plant lists, cultural information, and management techniques, emphasizing the need for increased outreach and extension efforts (Davis and Stoyko, 2022). Together, informational gaps and the absence of industry incentives continue to restrict the availability of native plant material.

Challenge 2: Paucity of Evidence-Based Implementation Techniques and Protocols for Practitioners

Restoration success with native plants is heavily contingent on the implementation methods and management practices employed (Suding, 2011). Risk of failure contributes to low adoption rates and hesitation among stakeholders, especially in urban areas. Restoration approaches must account for available resources, desired outcomes, time constraints, and spatial scale, and these considerations should be paired with trusted, synthesized sources of information that offer clear best practices to inform establishment protocols, maintenance regimes, or cost-effective approaches across contexts, as these elements are often missing. The need for these context-specific solutions becomes even greater as restoration techniques and native plant interventions gain broader acceptance.

Challenge 3: Approaches to Fit Emerging Use Cases, Especially in Urban Contexts

Restoration approaches are increasingly being applied beyond traditional wildland contexts (Watson et al., 2020). For example, semi-arid and arid ecoregions have seen increased interest in using restoration methods to support climate adaptation in cities, such as transforming lawns and non-functional turf into low-water landscapes and ecologically functional urban greenspaces (Kiers et al., 2022). This trend reflects a global recognition that urban conservation gardening provides a new way to combat biodiversity loss and ecosystem decline, but practical, region-specific information remains limited and mostly anecdotal (Segar et al., 2022). Restoring urban areas also involves significant challenges, including the lack of relevant reference states, challenging site conditions including soil compaction and irrigation limitations, and the need to balance ecological advantages with human recreation and aesthetic appeal—factors that often fall outside traditional success measures for restoration projects.

Botanical Gardens' Potential Contributions

Botanic gardens are uniquely positioned to support restoration across scales by integrating expertise in horticulture, research, conservation, and public engagement within a single institution. This capacity range allows gardens to directly address the key challenges that limit native plant use in restoration today. Gardens have an important opportunity to leverage these strengths to expand the pool of native plant material available to practitioners, for example, by initiating a seed increase program, developing germination and propagation information for underdocumented species, and providing clear, evidence-based plant lists and cultural information that the home gardener, municipalities, and restorationists lack.

Gardens can also conduct applied research that is often beyond the scope of practitioners but below the radar of universities and large funding agencies – for instance, investigating implementation techniques and emerging use cases for regional practitioners. This applied research generates evidence-based best practices for native plant establishment and long-term maintenance across a range of contexts and resource levels. Most importantly, research staff can conduct monitoring to assess the long-term outcome of different strategies in various settings. Monitoring is critical to understand project outcomes but is often not done due to limited resources and expertise. Botanic gardens can provide both the expertise and additional capacity to land managers to conduct this crucial monitoring step. Through demonstration gardens, community outreach, extensive education programs, and digital platforms, gardens are well positioned to disseminate these findings broadly allowing them to connect municipalities, home gardeners, large land managers, and policymakers with actionable, regionally grounded solutions.

This regional expertise is especially valuable as restoration approaches expand into urban and residential landscapes, where evidence-based guidance remains limited and public acceptance is critical to success. By operating at the intersection of research, practice, and public engagement, botanic gardens can help move native plant restoration beyond traditional wildland contexts and into the places where it is increasingly needed most.



Research plots at Denver Botanic Gardens used to develop custom seed mixes with high floral abundance and aesthetic appeal for urban areas. Photo: Michael Guidi.

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Practice Insights

Development of a toolkit of restoration best practices to address a diversity of scales and desired outcomes

Context:
At Denver Botanic Gardens, we get asked a lot of specific questions about how to best improve native habitats. The answers we provide depend largely on the context: What is the desired outcome of the restoration? What is the capacity of the restoration team to prepare and maintain the site? What resources are available to carry out the restoration? Here, we share an example of how we are working to meet the needs of the Denver community by offering evidence-based restoration approaches that address these diverse requirements. We are refining our restoration approaches to determine suitable species mixes, site preparation methods, and planting techniques to boost native biodiversity in both irrigated and non-irrigated systems.

Approach:
An interdepartmental team, including the research and conservation, horticulture, and farm programs at Denver Botanic Gardens is developing a toolkit of restoration approaches with the hope that they can be selected and put into practice as needed to serve our community. The aim of this toolkit is to develop actionable, evidence-based, and regionally suitable best practices for native plant use in restoration schemes – from site preparation, seed mixes, and planting palettes, to planting techniques, and maintenance methods. For each of these areas, we understand the importance of offering a variety of options that fit different scales and needs. Multiple experiments are necessary to develop methods suited for various conditions. While we are working to expand our toolkit across a broad range of scenarios, here we share a few examples of the types of research needed to develop specific considerations.

1. **Site Preparation - Intensive:** On our 700-acre (~283 hectares) farm, Denver Botanic Gardens Chatfield Farms, we can demonstrate different restoration techniques to the public. We conduct a range of experiments to demonstrate the best ways to prepare an area for planting, including harrowing, spraying herbicides, tarping, and core aeration. We have established a native prairie restoration that involves intensive site preparation, including a full year of pre-seeding treatment with herbicides, solarization tarping, and light harrowing to effectively reduce the pressure from non-native vegetation and weed seed banks.
2. **Site Preparation - Minimal:** While we have demonstrated success in establishing native plants when we can dedicate time and resources to preparing a site by removing existing weeds, there are situations where removing existing vegetation before restoration is not preferred. We are developing a core aeration technique for cases where there is a desire to introduce native forbs into an established native grass area or existing non-native grass that the manager lacks the time or capacity to remove beforehand. One such project is in partnership with the Colorado Golf Association and CommonGround Golf Course, where in 2022 we used their equipment to core aerate an area of non-native grass. We then hand-seeded a native forb mixture over the aeration holes with the goal of increasing pollinator habitat on the active golf course.
3. **Seed Mix Design for Specific Outcomes and Site Constraints:** At the site level, we are conducting experiments to develop novel, low-cost seed mixes and sowing mulches to establish native vegetation in urban areas. These experiments aim to develop seed mixes that foster plant communities with high vegetation coverage, a long and vibrant blooming season for visual appeal, and minimal maintenance needs such as weeding and watering, all while addressing the unique challenges of urban environments—like height restrictions to maintain visibility or compatibility with municipal maintenance schedules. We are also exploring seed mix design and implementation for green infrastructure projects such as green roofs.

Outcomes:
1. **Site Preparation - Intensive:** Over six seasons, we have demonstrated that this intensive site preparation successfully allows for the establishment of native prairie. The ability to quickly attain full coverage with native species in the first season prevents non-native, weedy species from taking over and significantly reduces weed management that is required in subsequent seasons.
2. **Site Preparation - Minimal:** This minimal disturbance approach is working to promote forb germination and establishment. Even with minimal native forb increases in these plots, we saw increases in pollinator visitations.
3. **Seed Mix Design for Specific Outcomes and Site Constraints:** We have found that custom seed mixes—developed through experimenting with species composition, sowing rates, and growth form ratios—improve multi-year success when targeting specific outcomes, such as high floral abundance and low grass density, or in specialized environmental settings like roadway rights-of-way. Our experiments also demonstrate that urban soils and recycled aggregate substrates are suitable for direct sowing, expanding the range of possible use cases. As we gather new information, we are collaborating with regional partners, and as a result, novel seed mixes and sowing mulches are already being used in turfgrass conversion projects, public parks, roadway medians, and even green roof projects on Colorado's Front Range.

Lessons Learned:
- Timely development and dissemination of practical, evidence-based resources is critical for supporting restoration uptake. Botanic gardens are uniquely positioned to both generate these best practices through interdisciplinary expertise and rapidly disseminate the information to a broad range of stakeholders.
- Gardens operate at the intersection of research, practice, land management, and public education and engagement. Thus, they are in a unique position to connect key stakeholders to move beyond research towards active implementation and decision-making. This positioning allows gardens to both identify real-world restoration challenges and develop context-appropriate, scalable solutions

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Advancing Urban Restoration through Tiny Forests and Botanical Garden Leadership

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Early-stage planting site with spatial planning and logistics. Photo: © Francesco Sellari.

Executive Summary

Micro-afforestation practices are increasingly promoted as a nature-based solution to address biodiversity loss, urban heat, soil degradation, and the lack of accessible green space in cities. However, evidence on their ecological performance in Mediterranean conditions remains limited. The Botanic Garden of Rome is implementing a national multi-site network of Miyawaki-based Tiny Forests as experimental platforms to test high-density native afforestation in and around urban areas.

Each Tiny Forest is designed as a standardised monitoring plot, using native species selected according to potential natural vegetation, local site conditions, and a constant size (200 m^2) to evaluate survival, growth, carbon sequestration, soil regeneration, and social co-benefits, and ultimately to determine whether interspecific competition among Mediterranean woody species selects the most suitable plant assemblages.

The project shows how botanic gardens can move beyond advocacy and play an operational role in restoration design, plant production, monitoring, and adaptive learning. Early results indicate high tree survival, measurable carbon sequestration, and strong educational and social benefits, while also confirming the need for long-term monitoring.

Current State of Knowledge

Reforestation refers to the re-establishment of forest cover in areas where trees have been previously removed, while afforestation involves planting trees in areas with no recent forest history (FAO, 2020). At smaller spatial scales, these efforts are often described using terms such as micro-forests, pocket forests, or tiny forests, referring to dense, multi-layered plantings of native species implemented in limited areas, including urban parks, roadsides, and degraded plots.



Planting and irrigation setup for a high-density restoration plot.
Photo: © Francesco Sellari.



Aerial view of a planting plot within a mixed landscape.
Photo: © Francesco Sellari.

The Miyawaki method is increasingly adopted worldwide as a rapid afforestation technique based on high-density planting of native species in relation with potential natural vegetation (Miyawaki, 1998; Miyawaki & Box, 2006). In urban settings, Tiny Forests are promoted as Nature-based Solutions (NbS) for biodiversity enhancement, carbon sequestration, microclimate regulation, and community engagement. However, most applications remain promotional rather than experimental. At the conceptual level, the method draws on vegetation ecology, especially the use of reference vegetation and successional thinking, while more recent applications also intersect with urban ecology, ecosystem services, and restoration monitoring frameworks.

Over the past 5–10 years, Miyawaki-inspired practice has expanded rapidly across Europe and beyond, with growing attention to small urban plots, educational settings, and community-led greening initiatives. At the same time, the evidence base has not kept pace with implementation. A recent systematic review found that quantitative studies remain limited, and that only a small share of published assessments include controls or replication, making many widely repeated claims difficult to verify rigorously (Morales et al., 2026). Overall, scientific evidence is still limited regarding:

- long-term structural stability under high-density competition;
- species-specific responses in Mediterranean climates;
- soil–plant–microclimate interactions in early establishment phases.

From an applied perspective, a broad consensus is emerging among practitioners around a few core best practices: the use of locally native species, plant assemblages matched to site conditions, relatively high planting density, and the need for post-planting monitoring rather than assuming automatic self-sustainability. In Mediterranean contexts, climatic constraints such as summer drought and heatwaves require particularly careful selection of plant assemblages, as strong site heterogeneity can substantially shape outcomes.

Knowledge Gaps and Capacity Needs

A first major gap concerns **the lack of long-term evidence**. Although early monitoring results are encouraging, they remain preliminary, and many core ecological responses, such as interspecific competition, structural stabilisation, self-thinning, soil regeneration, and microclimatic effects, can only be interpreted reliably over a multi-year period. This is particularly important in Mediterranean environments, where early establishment success does not necessarily predict medium-term resilience under drought and heat stress.

A second gap **is the high ecological variability among sites and species**. Early results show that performance is strongly species- and site-dependent. In central Italy, for instance, arboreal species generally performed better than shrubs, while treatment effects such as fertilisation were not consistent and, in several cases, did not improve outcomes. This indicates that Mediterranean Tiny Forests cannot rely on generic planting recipes and need careful ecological tailoring.

A third challenge is the **need for more robust and diversified monitoring indicators**. So far, monitoring has focused mainly on survival, growth, and leaf condition, but the project identifies the importance of expanding this to pollinators, soil properties, microclimate, and additional ecosystem service indicators. Without this broader evidence base, claims about biodiversity and climate benefits remain only partially quantified.

Finally, there is a **capacity gap in scaling while maintaining comparability**. As the network expands geographically, technical consistency, local site stewardship, and standardised protocols become increasingly important. Without this, data quality and transferability may weaken.



Native tree planting. Photo: © Francesco Sellari.

Practice Insights

An Italian Tiny Forest Programme for Testing the Miyawaki Method in Mediterranean Urban Settings

Context:
Since 2023, the Botanic Garden of Rome, together with the Società Botanica Italiana and local partners, has implemented a national network of 16 Miyawaki-inspired Tiny Forests across seven Italian regions. The first experimental sites were established in Rome (Lazio) and Lusciano (Campania). The programme was designed to test whether high-density native Tiny Forests can function as effective restoration tools under Mediterranean urban conditions.

Approach:
Each Tiny Forest was standardised at 200 m² with 400 plants, combining native trees and shrubs selected according to local potential natural vegetation (Cambria et al., 2024). The design included treated and untreated subplots to compare management options such as soil amendments, while monitoring focused on survival, height, diameter, vitality, and vegetation dynamics. The project deliberately framed these sites as experimental restoration plots rather than simple greening interventions.

Outcomes:
Results across sites reveal a consistent pattern of species- and site-dependent performance. Tree species generally established successfully and showed measurable survival and growth, while shrub species performed less well across multiple sites. Soil amendments, applied as a treatment in dedicated subplots, did not produce consistently positive effects and in several cases failed to improve outcomes, suggesting that Mediterranean Tiny Forests cannot rely on generic management recipes regardless of site context.

At the ecosystem level, early estimates indicate that a 400-individual Tiny Forest may sequester 100–150 kg of CO_2 annually in its early phase, with substantially greater cumulative storage over time.

Lessons Learned:
The main lesson is that Tiny Forests should not be implemented through fixed recipes: in Mediterranean cities, success depends on site-specific floristic design, native provenance, and long-term monitoring. A second lesson is that botanic gardens can play a central role not only in designing and planting these Tiny Forests, but in transforming them into living laboratories for restoration science, biodiversity education, and climate adaptation.

Botanical Gardens' Potential Contributions

Botanic gardens are especially well placed to support this field because they combine ecological expertise, nursery capacity, scientific monitoring, and public engagement. In the Tiny Forest project, the Botanic Garden of Rome contributed to species selection, propagation of native plant material, planting design, and post-planting monitoring, demonstrating a full-cycle contribution from restoration planning to evaluation.

First, botanic gardens can provide **scientifically grounded species selection**. In this case, species were chosen on the basis of potential natural vegetation, phytosociology, and site conditions rather than ornamental or generic urban greening criteria. This is a distinctive contribution that helps align urban forestation with restoration principles.



Field monitoring and vegetation sampling in a growing Tiny Forest.
Photo: © Francesco Sellari.

Second, botanic gardens can act as **native plant supply and provenance hubs**. The project used seedlings raised in certified nurseries, including the Experimental Nursery of the Botanic Garden of Rome, with local genotypes sourced from well-documented areas and handled in accordance with Italian provenance rules. This ensures ecological suitability and increases restoration integrity.

Third, botanic gardens can lead **standardised ecological monitoring and adaptive learning**. The project's repeated monitoring of survival, growth, vitality, and treatment effects illustrates how botanic gardens can generate evidence rather than simply implement planting actions. This is essential for understanding what works, for whom, and under which Mediterranean urban conditions.

Finally, botanic gardens can connect restoration with **education and social inclusion**. The broader Tiny Forest programme has been embedded in schools, social farms, and inclusion pathways, showing that ecological restoration in cities can also strengthen environmental education and local community engagement.

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Centering Community Knowledge in Restoration: Ensuring Relevance, Resilience, and Local Support

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Executive Summary

Successful restoration depends on aligning interventions with community needs and integrating traditional ecological knowledge (TEK). Botanical gardens and arboreta (BGA) can support this by employing participatory approaches and fostering strong local partnerships that ensure restoration projects are culturally relevant, socially inclusive, and broadly supported by communities. Long-term, interdisciplinary, and politically neutral institutions by nature, BGA are well positioned to mediate tensions between broader restoration goals and the realities faced by Indigenous peoples and local communities (IPLCs), who possess deep TEK yet remain vulnerable to climate change and market forces. As scientific research centers, stewards of living collections, and cultural and educational institutions, BGA can integrate interdisciplinary and participatory frameworks into projects that honor TEK and are compatible with the local land uses, food systems, and cultural values—local livelihoods inclusive of income-generating activities and other means of living—while restoring degraded and deforested landscapes.

Current State of Knowledge

Conventional definitions of ecological restoration often neglect the intrinsic relationships between people, culture, and their natural environment, further marginalizing the cultural value systems of IPLCs (Robinson et al., 2021). However, scientists and practitioners are increasingly recognizing the importance of TEK and collaboration with IPLCs to advancing climate resilience, landscape restoration, and biodiversity conservation interventions. Participatory approaches like co-management and participatory management—in which resource users share in decision making over resources—have positively impacted conservation and restoration outcomes and helped governments, scientists, and practitioners to better understand the environments they are trying to conserve or restore (Charles and Berkes, 2021). At the same time, the success of community-based approaches often relies upon specific conditions like secure land and resource rights, respect for TEK holders and systems, effective conflict resolution, and the extent to which the benefits of stewardship are felt by IPLCs (Charles and Berkes, 2021).

Several BGA have demonstrated the value of collaboration with IPLCs in improving conservation and restoration outcomes. Missouri Botanical Garden, through the Madagascar Ethnobotany Program, employs a four-pronged community engagement approach including capacity building, conservation planning, ethnobotanical research, and livelihood improvement projects (MBG, Madagascar Ethnobotany). Their approach both gathers community perspectives on local flora and incorporates cultural preferences and practices into conservation strategies. The National Tropical Botanical Garden (NTBG), Hawai'i, uses Indigenous language to describe plants to holistically reflect and distinguish their ecological and cultural identity (NTBG, Perpetuating Cultural Knowledge). NTBG also uses frameworks from ancient Hawaiian cultural practices like *ahupua'a* for restoring endemic plants (NTBG, Perpetuating Cultural Knowledge).

Knowledge Gaps and Capacity Needs

Despite mounting evidence and increasing recognition of the importance of integrating community knowledge and livelihoods, several key barriers remain to unlock integration into sustainable restoration practice, including the following three challenges:

Challenge 1: Traditional ecological knowledge (TEK) and Western science often differ in their scope and approach, with Western science historically lacking an understanding of, and often failing to engage with, the holistic, interdisciplinary, and integrative nature of TEK. In many cases, TEK finds its roots in spiritual beliefs and creation accounts—foundations foreign to most professionally trained practitioners—and is often seen as deficient in the rigor that characterizes Western science. While restoration and conservation science has increasingly embraced the marriage of culture and nature, an implementation gap remains (Senos et al., 2006). Because it is often the land use practices of human communities—guided by cultural and social values as well as economic pressures—that necessitate restoration, knowledge of the historical and contemporary intersections between culture and nature in the form of TEK is key for designing sustainable restoration initiatives.

Challenge 2: Many restoration and conservation projects include the participation of local communities to fulfill donor requirements but fail to effectively co-create strategies with IPLCs and respond to their input, needs, and knowledge. Insufficient collaboration with IPLCs can at best reduce the effectiveness of the project and at worst have adverse impacts on both IPLCs and the environment. Co-creation, co-design, inclusion of local and traditional governance systems, and shared decision-making have proven to drive long-term conservation and improvement of livelihoods (Dawson et al., 2021).

Challenge 3: Given the heterogeneous nature of IPLCs at the local scale, the extent to which TEK remains relevant to IPLCs' livelihoods and economies varies greatly. While some IPLCs practice their ancestral traditions and livelihoods, others have adopted modern economies. In the case of the latter, TEK may still be practiced, even where cash crop cultivation, monocultures, or other intensive land uses dominate. Conservation and restoration projects must acknowledge this reality and the tension between traditional livelihoods and identity and the modern economic forces driving land use change (Adefila et al., 2024).

Botanical Gardens' Potential Contributions

Botanical gardens possess distinct assets that position them to tackle barriers to landscape restoration and enhance these efforts with integrated TEK toward resilience, biodiversity conservation, and community wellbeing. As institutions with both long-term commitments to advancing biodiversity conservation in places where they operate and strong scientific foundations and staff expertise, BGA have an opportunity to work collaboratively with scientists and keepers of TEK toward informed and effective restoration work. Similarly, BGA may also be able to leverage their legacy and trust with local partners to drive co-creation and co-management. Finally, BGA can leverage the depth of their botanical knowledge to address community needs and potential drivers of degradation by identifying native species that could complement or diversify cultivated species in the landscape. Below, we elaborate on specific ways BGA can tackle barriers and contribute to restoration.

Contribution 1: As place-based organizations that often serve as reservoirs of regional botanical knowledge, BGA are well positioned to collaborate with local communities on appropriate methods for gathering, documenting, and applying TEK to inform restoration activities. BGA could also serve as advocates for intellectual property rights and model how other institutions can better understand the potentially sacred or private nature of TEK and how to follow free, prior, and informed consent protocols that ensure respectful and mutually beneficial knowledge exchange (Chakraborty, 2024). BGA are often enduring institutions that provide a stable, long-term foundation for collaboration, serving not only as repositories of knowledge but as active partners in restoration and conservation efforts. Their research, education, and outreach functions also enable opportunities to record and disseminate culturally informed ecological information and practices (Hardwick et al., 2011). The New York Botanical Garden in concert with the Vanuatu Department of Forests, the Vanuatu National Herbarium, the Vanuatu Cultural Centre, and communities in Vanuatu have already embarked on this—working with a diverse team to document knowledge on islands' plant species, uses, and conservation—leading to community-driven conservation actions (Plunkett et al., 2025).

Contribution 2: Botanists and other scientists embedded in or collaborating with BGA commonly infuse knowledge from across multiple sources and a diversity of disciplines to create a scientific backstop for inter- and transdisciplinary knowledge related to plants. Because of this, they are poised to respond to the heterogeneous needs and concerns of IPLCs, whether in the case of habitat loss, rare and threatened species, culturally important species, or climate risk and the adaptive capacity of important species (Narkhede, 2024; Drew and Henne, 2006). These attributes and aptitudes of BGA and their staff highlight the potential for BGA to emphasize, encourage, or even mandate co-creation and co-design of projects from research to implementation and long-term sustainability.

Contribution 3: In landscapes where native vegetation cover has been displaced by ornamental, exotic, or cultivated plant varieties, BGA can play an important role in helping conservation and restoration initiatives as well as IPLC incorporate native biodiversity in ways that accommodate the modern land use regime and the economic and social context driving it. The scientific foundations upon which BGA operate can serve as a natural link between ecological restoration and conservation objectives and the needs of IPLCs. Climate change and market forces often impact cultural integrity, food security, and spiritual and religious traditions, and increasing biodiversity can help guard against vulnerabilities. As a result, the botanical knowledge harnessed by BGA could help IPLC incorporate crops, shrubs, and trees of economic and traditional relevance into landscapes where intensive agriculture and mono-cultivation occur, enhancing resilience attractive to both IPLC and international conventions, like the Convention on Biological Diversity (Miller et al., 2016).

Practice Insights

Riparian buffer restoration with indigenous species, Mpenge River, Musanze District, Rwanda

Context:
Rwandan law states that land within ten (10) meters from the banks of all rivers is public property (Order No. 007/16.01) and that agricultural and livestock activities are prohibited within ten (10) meters from streams and riverbanks and fifty (50) meters from lake shores (Law No. 48/2018 on Environment). In 2021, Rwandan non-governmental organization Nature Rwanda (NR) began engaging with both local government and local farming community members to restore indigenous species cover to the riparian buffer zone (RBZ) of Mpenge River, Musanze District. At the project's inception, local landholders practiced intensive cultivation of the RBZ, including crops (climbing beans, corn, cassava, sweet potatoes), timber and firewood production (Eucalyptus species), and animal husbandry (pigs, cows), thus encroaching on the mandated buffer.

Approach:
With endorsement from local government, Nature Rwanda (NR) began a community engagement process. They used two approaches for communicating the importance of RBZ conservation and related ecosystem services and achieving buy-in: community-level meetings and household-by-household consultations. During household consultations with those cultivating in the RBZ, NR negotiated with farmers on two fronts: (1) ways to increase production on their farms outside the buffer zone (e.g., providing fruit trees or pigs); (2) extent of abandonment of encroached buffer zone acceptable to the farmer (e.g., abandoning annual crops in first five meters after one year; allowing timber or firewood species to continue to mature in the RBZ but abandoning fodder cutting to allow for assisted natural regeneration).

Household consultation ensured inclusion of women and children in the restoration process. In most cases, women were designated the head of household for purposes of this project.

Outcomes:
Together, NR and local farmers have set in motion >6 km of RBZ restoration on the Mpenge River. After four years, NR reported an increase in water flow from 1.5 to 3.4 cubic meters/sec, an increase in bird species from 15 to 102 recorded, and a dramatic shift from bare soil and crop fields to regenerating native shrubs and trees within the RBZ. The Mpenge River's ecosystem services extend to cultural and socioeconomic benefits: a swimming hole frequented by children and an ideal bird watching habitat for ecotourism.



Mpenge River was heavily encroached upon prior to restoration work beginning in 2021. Photo: Nature Rwanda.



Native trees planted in the Mpenge River's buffer zone have begun to recruit native herbs and shrubs since the restoration process began. Photo: Grace Bachmann.

Lessons Learned:
1) Botanical gardens will need strong and sustained relationships with organizations that understand the livelihood demands on land if they are to unlock restoration and climate resilience solutions. NR's Mpenge River restoration project highlights that RBZ restoration depended on understanding the importance of livelihood due to high population density and land scarcity in Rwanda. Despite knowledge of and value for Indigenous tree and plant species, farmers were driven to cultivate in the RBZ by their economic needs and lack of alternatives. NR's livelihood support, as well as stewardship of the RBZ over time, were crucial to setting restoration in motion.

2) Botanical gardens may be well positioned to support the sustainability of restoration projects by endorsing them as important eco-cultural areas. The long-term sustainability of a restoration site like the Mpenge River depends upon constant community engagement, monitoring, and protection. NR's work there has generated recognition of the site as a biodiversity haven for bird watching and other recreation (swimming, forest bathing). Further endorsement or official designation of the site would generate a deeper sense of pride and respect for the area and potentially enhance its protection and sustainable use. BGA could leverage their reputation and national and international partnerships toward such an endorsement or designation in support of long-term conservation and management.

BGA serve as public-facing educational and cultural institutions, which is a significant differentiator from other stakeholders in the restoration realm. Gardens possess inherent convening power and are often seen as trusted, neutral spaces. This facilitates genuine engagement with diverse community groups, including Indigenous peoples, fostering dialogue and co-creation of restoration goals. They can translate complex ecological concepts into accessible educational programs, building public understanding and support for TEK-informed restoration. Their unique combination of living collections, scientific rigor, and public engagement capabilities make botanical gardens indispensable partners in fostering holistic, community-led, and culturally resonant landscape restoration for a resilient future.

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CASE STUDY

Kastom Forest Konsevesen in Vanuatu: An Indigenous Approach to Forest Stewardship and Guardianship

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NYBG

Plants and People of Vanuatu is a partnership between the New York Botanical Garden, the Vanuatu Department of Forests, and the Vanuatu Cultural Centre, together with local communities throughout this South Pacific Island nation. Since 2013, this program has documented the diversity of plants and their associated cultural uses and language names and has been establishing forest conservation and cultural preservation initiatives throughout this archipelago of 83 islands. As part of this work, a movement called Kastom Forest Konsevesen (KFK) is emerging in Vanuatu as an Indigenous approach to forest conservation. It is a powerful demonstration of innovation from within, developing out of the desire of Indigenous peoples to protect their forests and natural resources in a way that respects local control, local priorities, and traditional values. It is built around the concept of "*kastom*", a simple word in Vanuatu's creole language that encompasses a very complex network of traditional practices, beliefs, governance structures and lifestyles. KFK started as a grassroots effort based upon the desire of landowners to maintain and protect their forests at a local level, rather than through initiatives promoted by the government or NGOs. Emphasizing local control, KFK sites are maintained only by the actual landowners and communities that control and govern these forests. KFK sites range from large areas of many thousands of hectares to very small parcels of forest. Large sites have special value for preserving biodiversity, but protecting forests of any size (even less than 1 hectare) can be of great importance, providing ecosystem services and contributing to livelihoods of local communities, especially in the context of island ecosystems and cultures.

Presently, conservation activities in much of the Pacific Island region are initiated through large, outside agencies (especially multilateral organizations such as the United Nations, the World Bank, and various international non-governmental organizations). These efforts are often well-funded, top-down approaches. In some places they can be very effective, but sometimes, they can lead to conflicts between Western values and the values of Indigenous landowners in the target country, as has been the case in Vanuatu. Long-term management plans developed by outsiders often cannot be sustained much beyond the initial period of intensive funding. While well-meaning and scientifically sound, sometimes these programs can weaken traditional culture by assigning responsibility for success and funding to a group outside the community, which in turn can result in an alienation from the very land targeted for protection. We have seen in Vanuatu that enticements of local communities to commodify their forested lands, frequent elements in top-down models, can raise expectations for benefits that often do not materialize. These can include ecotourism, use of carbon credits, or biodiversity credits.



Kastom ceremony celebrating the official opening of a KFK site in northern Pentecost Island. Photo: Gregory Plunkett.

At face value, these approaches can be viewed as practical solutions to provide financial benefits as replacements for other values that the land might provide to local communities (e.g., agriculture, timber, housing, etc.). However, they often serve to monetize the land—a practice that is particularly destructive to Pacific Island cultures, where wealth has traditionally been measured in land, not money. Increasingly, in most of the world, people recognize that precious forest resources, once lost, are difficult and costly to restore, and that re-establishment of forests can take many decades. *Ni-Vanuatu* communities are learning that pressures from globalization (tourism, road construction, seasonal worker programs, international trade in timber and crops, etc.) are heavily impacting the availability of important ecosystem services derived from forests, including sources of fresh water, firewood, timber for building traditional houses, and materials used in *kastom* ceremonies. By contrast, the system of KFK that is emerging in Vanuatu relies on traditional governance at the community level, as local systems of land ownership and chiefly authority vary widely across the archipelago. KFK acknowledges and respects these differences and relies on them to establish and maintain protected sites. This is not a "one-size-fits-all" approach to conservation that can be successful in every place but rather is tailored to on-the-ground realities in each locale.

An important element of the stewardship of these conservation areas is that KFK uses *kastom* practices already embedded in the culture to help manage and enforce the protection of these sites, including: (1) the concept of *tabu* areas and *tabu* signs/symbols used to help regulate activities; (2) organizing activities in the forests by season and life events, and following traditional calendars; (3) valuing traditional lifestyles and livelihoods over a globalized, cash-based economy; (4) recognizing forests as an essential part of traditional life in Vanuatu, with special benefits and uses that cannot be replaced by other ecosystems. The principles that underpin KFK do not envision a formal administrative role for provincial or national governments in managing these sites, but these levels of government are consulted and informed.

KFK sites are learning places. They help landowners and communities learn about nature and pass on knowledge about the cultural uses of plants, animals, and other aspects of nature, helping to maintain traditional, healthy, and sustainable livelihoods. These can be supported through the development of educational programs (*kastom skuls*) that help teach traditional practices and support traditional values, such as forest stewardship. To facilitate these teaching programs, many communities have chosen to develop physical infrastructure to support KFK, such as propagation nurseries for reforestation, and *kastom* schoolhouses or community botanical gardens to help maintain and pass down forest-based *kastom* knowledge.

KFK sites have been piloted on four islands in Vanuatu: Tanna, Aneityum, Pentecost, and Vanua Lava. As of March 2026, over two dozen KFK sites have been established, supported by 21 facilities (*kastom* nurseries, schoolhouses, and botanical gardens). Interest in this culturally centered, community-based approach to forest conservation is growing as more and more people in Vanuatu learn about its benefits and advantages over other approaches to forest guardianship.

One example of an effective conservation action has been the establishment of protected sites to ensure the survival of one of Vanuatu's most threatened species, *Carpoxylon macrospermum*, a critically endangered palm tree that grows wild only on three islands in southern Vanuatu. Prior to our work, only 37 mature trees were left in the wild, making this a global priority for plant conservation. At the same time, this species and its habitats are associated with a wide variety of traditional practices in each community. Working with six of these local communities on the islands of Tanna and Aneityum, the project team conducted inventories to determine the structure and viabilities of these palm populations, harvested seeds, germinated them in community nurseries, and planted over 3,500 saplings to enrich natural populations and to reforest degraded buffer areas in order to maintain this highly threatened species in its native habitat, all while engaging local leadership from the communities to serve as stewards of these forests. Currently, these six protected areas safeguard 60% of the world's remaining wild populations of this endemic palm species.

Kastom Forest Konsevesen has shown that partnerships between organizations with practical experience and scientific and technical expertise, including the New York Botanical Garden, the Vanuatu Department of Forests, and the Vanuatu Cultural Centre, and local communities that seek to protect their forests and maintain their traditional livelihoods can yield highly effective conservation models in Vanuatu, with the potential to enhance forest protection in other Pacific Island nations and beyond.



Nirinejom, an emerging community botanical garden to support KFK efforts in Aneityum Island. Photo: Gregory Plunkett.

Enhancing the Role of Botanical Gardens in Capacity Building for Nature-based Solutions (NbS): A Case for Forest Landscape Restoration

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Successful nature-based solutions (NbS) projects require that all stakeholders, from local community members to technical experts, be equipped with the skills, knowledge, tools, and support needed to collaborate effectively and sustain efforts over time. Botanical gardens can play a pivotal role by delivering hands-on training, capacity building, and peer-to-peer exchanges while sharing their deep expertise in horticulture and plant taxonomy and serving as long-term institutional partners.

Executive Summary

Botanical gardens are uniquely positioned and well equipped to provide expertise and strengthen the capacity of stakeholders to support large-scale, high-quality forest landscape restoration (FLR). Their contributions are critical to advancing global, regional, and national restoration commitments, while addressing two of the most pressing planetary crises: climate change and biodiversity loss. Although there are many gaps in capacity building that limit restoration as an effective strategy—ranging from governance and policy to financing, technical, and scientific challenges—botanical gardens and their global networks can play a leading role in addressing these gaps. Moreover, there is an urgent and strategic opportunity to develop and implement a robust capacity-building program for FLR, aligned with the goals of the UN Decade on Ecosystem Restoration and other international and national commitments. This can be achieved through active participation in the 2026–2030 strategic planning of the Ecological Restoration Alliance of Botanic Gardens (ERA) and by engaging key global actors and networks, such as the Global Partnership on Forest and Landscape Restoration (GPFLR), Initiative 20x20, AFR100, and others.

Current State of Knowledge

Nature-based solutions (NbS) can provide more than 30% of the cost-effective CO_2 mitigation needed through 2030 to hold global warming to below 2 °C (Griscom et al., 2017). Among the solutions, forest landscape restoration (FLR) is one of the largest mitigation opportunities. Restoration of forests can also achieve multiple goals in addition to climate mitigation, such as biodiversity conservation, socioeconomic benefits, food security, and ecosystem services (Chazdon and Brancalion, 2019).



Botanical fieldwork in Brazil supports the documentation and study of tropical forest biodiversity. © New York Botanical Garden.

Over the last two decades, several land restoration initiatives have been proposed, targeting between 765 million and nearly 1 billion hectares globally (Sewell et al., 2020). These ambitious efforts stem from a range of international, regional, and national restoration commitments and targets (Mariappan and Rodríguez Zumbado, 2024). Implementing these initiatives could cost between 0.04% and 0.27% of annual global GDP (Verhoeven et al., 2024), highlighting the need to improve the effectiveness and efficiency of forest landscape restoration to achieve desired outcomes for climate change mitigation and biodiversity conservation. In this context, many calls to action and policy frameworks aimed at scaling up forest landscape restoration have identified capacity development as a critical foundation for meeting global restoration targets (Bloomfield et al., 2019).

Although botanical gardens have long been involved in the study and conservation of plants and in making global plant diversity better known to the public (Chen and Sun, 2018), their role in ecological restoration has received comparatively less attention. It is increasingly clear, however, that botanical gardens can play a crucial role in restoration by providing expertise, resources, and research to support the recovery of degraded ecosystems. This includes identifying the species composition of reference ecosystems, planning and designing succession strategies, selecting, propagating, and cultivating plant species for reintroduction, monitoring restoration outcomes, contributing to education and capacity building, and advocating for ecological restoration as part of a broader sustainability paradigm (Miller et al., 2016). Many botanical gardens also have extensive experience in plant conservation and contribute to restoration capacity by supporting learning exchanges and providing on-the-ground training for diverse stakeholders (Oldfield, 2013; Shaw et al., 2015). In addition, an estimated 3,600+ botanical gardens and related institutions form a global network coordinated by Botanic Gardens Conservation International (BGCI), which launched the Ecological Restoration Alliance of Botanic Gardens (ERA) in 2012 and has developed a suite of e-learning modules for forest restoration that are widely used for capacity building and training.

Knowledge Gaps and Capacity Needs

Several key gaps limit the effectiveness and scalability of forest landscape restoration and highlight the need for strengthened capacity:

1. Due to increased demand for high-quality seeds and seedlings for large-scale restoration projects targeting carbon credits, and limited supply in target regions, seeds and seedlings are not always sourced from the same ecological regions or biomes where projects are implemented.

2. Climate change is projected to substantially alter environmental conditions affecting tree growth over the coming decades, such that species that are locally adapted today may not remain suitable in the future. Addressing this challenge requires improved models to predict species responses and the identification of genetically diverse and ecologically appropriate tree populations.

3. Critical information on species selection, seed collection, propagation protocols, and restoration ecology is often not fully integrated into national FLR strategies.

4. There is a need for more long-term reference restoration sites across diverse biophysical, political, and cultural contexts to support evidence generation, learning, and replication.

5. Restoration capacity at the landscape level remains uneven and requires stronger collaboration among local communities, professionals, academia, industry, government, NGOs, and international bodies.

6. Awareness of the role of urban greening and ecological corridors in enhancing resilience and well-being remains limited among urban populations, companies, and sectors.

7. There is a need for greater understanding of how to ensure that restoration efforts achieve adequate taxonomic and genetic diversity, including appropriate provenance.

8. Capacity gaps persist in plant collection and identification, species inventory, conservation assessment, and nursery and restoration practices in priority countries for FLR.

Botanical Gardens' Potential Contributions

Botanical gardens are uniquely positioned to address key knowledge gaps and capacity needs in forest landscape restoration through their expertise, infrastructure, and global networks. Over centuries, botanical gardens have accumulated extensive scientific and applied knowledge on the genetic, physiological, horticultural, ecological, and broader biological characteristics of plants. Together, they hold an estimated 40% of global plant diversity in their living collections, act as long-term custodians of rare and threatened species, and manage some of the most thoroughly documented repositories of living plants, preserved specimens, and seeds worldwide.

Building on this foundation, botanical gardens can contribute to forest landscape restoration in several key ways:

1. Botanical gardens can promote the development of networks of seed orchards and genetic seed banks to produce high-quality, locally adapted seed materials for restoration and conservation of endangered and threatened species.

2. Botanical gardens can generate and share data on species responses to climate change across environments and support the identification of genetically diverse and resilient plant populations. They can also train restoration practitioners in maintaining and enhancing genetic diversity.

3. Botanical gardens can provide training programs in species selection, seed collection, propagation, and restoration ecology, and support their integration into national FLR strategies (Heywood, 2017).



Dr. Brad Oberle conducting ecological research in the Thain Family Forest at the New York Botanical Garden to inform long-term ecosystem understanding and management strategies. © New York Botanical Garden. Photo: Marlon Co.

4. Botanical gardens can establish and maintain long-term reference restoration sites to generate evidence, support adaptive learning, and train local practitioners in science-based restoration approaches.

5. Botanical gardens can strengthen restoration capacity through interdisciplinary collaborations with local communities, academia, industry, governments, NGOs, and international organizations.

6. Botanical gardens can raise awareness among urban populations, businesses, and sectors about the role of urban greening and ecological corridors in enhancing resilience and well-being.

7. By combining landscape knowledge with scientific expertise, botanical gardens can help ensure that restoration efforts achieve appropriate taxonomic and genetic diversity, including the use of suitable provenance.

8. Botanical gardens can support capacity building through training in plant collection and identification, species inventories, conservation assessments, and nursery and restoration practices in priority FLR regions.

Practice Insights

Brackenhurst Botanic Garden Restoration Program, Kenya

Context:
Brackenhurst Botanic Garden, located near Nairobi, Kenya, is a member of the Ecological Restoration Alliance of Botanic Gardens (ERA). The garden is implementing a long-term ecological restoration program aimed at demonstrating the role of African botanical gardens in restoring degraded landscapes and contributing to regional restoration efforts. The project is also designed to strengthen connections between botanical gardens and broader forest landscape restoration initiatives. The Royal Botanic Gardens, Kew provided technical support, including guidance on planting design and monitoring approaches.

Approach:
The project focused on restoring 40 hectares of former eucalyptus plantation to indigenous forest. Restoration activities included the removal of non-native eucalyptus stands and the reintroduction of native tree species using ecologically informed planting strategies. The site was structured to include restoration plots of different ages, enabling long-term monitoring and comparison of restoration outcomes.

Outcomes:
The project successfully converted a eucalyptus plantation into a recovering native forest and established Brackenhurst Botanic Garden as a regional hub for restoration, training, and knowledge exchange. The site hosts 170 species of birds, which is two times the number that were present at the start of restoration. In addition, colobus monkeys have returned to the site after an absence of more than 60 years. The project has also created local livelihood opportunities through training and employment.

Lessons Learned:
The use of restoration plots of different ages provided valuable insight into the timelines and ecological benefits of forest restoration. This approach also enabled the identification of high-performing native tree species, which are now being promoted to restoration practitioners in the region. The project demonstrates the importance of long-term monitoring and of botanical gardens serving as demonstration sites for restoration practice and capacity building.

Additional Information:
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https://www.bgci.org/files/ERABG/ERAProspectusMed.pdf

In addition, BGCI has developed a suite of e-learning modules on forest restoration that support practitioners in planning restoration and selecting appropriate native species. More broadly, effective implementation of nature-based solutions and forest landscape restoration requires cross-disciplinary skills. Botanical gardens can contribute by offering structured curricula, internships, and interdisciplinary training programs that integrate horticulture, ecology, social sciences, and policy, preparing professionals to address complex restoration challenges.

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Annex:

Additional information to support and strengthen capacity building programs in partnership with botanical gardens.

1. The Global Partnership on Forest and Landscape Restoration https://forestlandscaperestoration.org/about-us/

2. Initiative 20x20 https://initiative20x20.org/

3. AFR100 (the African Forest Landscape Restoration Initiative) https://afr100.org/

4. FTA HIGHLIGHTS OF A DECADE 2011-2021 Forest and Landscape Restoration & ICRAF - Co-learning and sharing lessons learned. https://www.cifor-icraf.org/publications/pdf_files/FTA/FTA-Highlights-4.pdf

5. The Restoration Launchpad: A Step-by-Step Guide for Restoration Planners and Practitioners - https://www.wri.org/research/restoration-launchpad-step-step-guide-restoration-planners-and-practitioners

Advancing Conservation Action Planning for Threatened Tree Diversity in Africa

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Executive Summary

A key piece of scaling up conservation in Africa is conservation action planning for tree diversity, yet most countries lack conservation action plans. Even among those who have successfully developed plans, implementation remains challenging. Limited taxonomic expertise, undocumented mother trees (healthy, well-grown trees that produce seeds and can provide good-quality seeds for forest regeneration and restoration), and limited financial resources are key underlying factors in the failure of successful conservation action.

Botanical gardens bridge the research-practice gap by documenting species-specific phenology, propagation protocols, and establishing field gene banks for threatened, rare, and socioeconomically important species. This report recommends mobilizing global and national expertise for national conservation action planning, mapping native tree diversity (mainly threatened species), and mobilizing financial resources to implement the plans. Furthermore, botanic gardens should empower local communities as primary custodians of forest restoration while integrating Indigenous knowledge. The National Conservation Action Plan for Uganda 2025 provides the strategic framework necessary to translate these science-based findings into field-level implementation.

Current State of Knowledge

Conserving Africa's tree diversity is important for climate resilience, while providing essential ecosystem services such as carbon sequestration and temperature regulation. Africa reflects a significant extinction crisis, with approximately 27.4% of its tree species potentially threatened under the combined IUCN criteria for population reduction and geographic range (Stévart et al., 2019). In Uganda, forest cover declined from 23.8% to 9.9% between 1990 and 2019, driven by agricultural expansion and unsustainable logging (Harvey-Brown et al., 2025).

Current tree conservation in Africa centers on Integrated Conservation, bridging *in situ* habitat protection with *ex situ* backup collections at restoration sites and botanic gardens. Practitioners increasingly utilize the Assess to Plan (A2P) methodology, which groups multiple species sharing characteristics (e.g., overlapping habitats or threats) to enable efficient multi-species planning. Another approach is the identification of Tropical Important Plant Areas (TIPAs), which prioritize site-based conservation where threatened flora is most concentrated. Uganda has successfully identified 42 TIPAs.

A major advance in the last decade is the Global Tree Assessment (GTA), an initiative launched in 2015 that has now evaluated the extinction risk of nearly 60,000 tree species. The Global Tree Portal and BGCI's Conservation Action Tracker, launched in 2021, enable practitioners to monitor species-level progress and identify global conservation gaps (Harvey-Brown et al., 2022).



Threatened tree seedlings at Tooro Botanical Gardens.
Photo: Tooro Botanical Gardens.

In Africa, efforts using GTA data have led to the development of national conservation action plans for threatened trees in Kenya, Ghana, and the recently published National Conservation Action Plan for Uganda 2025. Botanic gardens have been key stakeholders in the development of these action plans.

Knowledge Gaps and Capacity Needs

The lack of current botanical data and specialized identification skills is a key challenge for the conservation action plans being developed. In Uganda, several threatened tree species have not been collected for many years, and the locations of mother trees, essential for seed collection, are often undocumented (Harvey-Brown et al., 2025). This is a collective continent-wide shortage of taxonomic expertise. In countries such as Ghana and Kenya, the inability of field staff to identify non-commercial species leads to threatened trees being inadvertently included in legal logging quotas (BGCI, 2023). There is a gap in biological knowledge about propagation and phenology. Successful restoration is limited by a lack of effective germination protocols and dependence on outdated phenological calendars. Climate change further disrupts these natural cycles, making it harder for practitioners to time seed collection accurately or ensure natural regeneration.

Conservation Action Plan implementation is also challenged by limited enforcement capacity and resource exploitation. Management bodies often lack the personnel, equipment, and real-time monitoring technology required to patrol remote areas against illegal logging and charcoal production. Furthermore, unclear land tenure and boundary disputes remain persistent obstacles. In Uganda, land conflicts affect between 33% and 50% of holders, often politicizing conservation efforts and facilitating encroachment into protected central forest reserves (Harvey-Brown et al., 2025).

Another persistent implementation challenge is the severe scarcity of financial resources across most African countries, a primary constraint to the conservation and sustainable management of tree diversity. In most African countries, current efforts are often under-financed, making it difficult to translate strategic priorities into field-level actions. In Ghana, inadequate financial and material resources prevent the effective enforcement of regulations against illegal logging and charcoal production (BGCI, 2023).

Finally, the loss of Indigenous knowledge impedes community-led conservation, as traditional storytelling and ecological wisdom are not being systematically passed to younger generations. Bridging these gaps requires a move away from landscape-only approaches toward species-specific planning that integrates scientific research with local custodian empowerment (Quintana et al., 2024). A key example could be sought from the African sacred forest models, such as Kenya's Kaya forests, where traditional Elders' Councils have incorporated youth and women to facilitate knowledge transfer while employing participatory plant breeding to merge scientific genetic research with local wisdom regarding climate-resilient wild crop varieties (Ndalilo & Wekesa, 2022).

Botanical Gardens' Potential Contributions

Botanic gardens are central hubs that can link international scientific knowledge with national conservation priorities. In many cases, they possess the institutional credibility to mobilize financial resources required to translate strategic priorities into field-level implementation. They can also leverage their institutional credibility to access diverse funding streams, including international grants and philanthropic funding.

Botanic gardens provide an important insurance policy against extinction by maintaining genetically representative *ex situ* living collections and field gene banks. This is critical for unique species such as those with recalcitrant seeds that cannot be preserved through conventional seed banking methods. For example, Tooro Botanical Gardens (TBG) in Uganda actively manages a 60-hectare field gene bank in the Kagombe Central Forest Reserve (CFR) and a 6.8-hectare seed orchard in Fort Portal of threatened tree species. These collections serve as fundamental resources for research, propagation, and the long-term preservation of the genetic diversity required to return species to the wild if natural populations disappear.

Botanic gardens are positioned to address the research-practice gap by documenting species-specific germination and propagation protocols. They translate scientific research into applied restoration by conducting experiments to determine optimum growing conditions for threatened species that are often technically difficult to cultivate. Botanic gardens develop and update phenological calendars that have been disrupted by climate change, tracking natural cycles to ensure restoration practitioners can accurately time seed collection and support natural regeneration efforts that might otherwise be overtaken by changing environmental conditions.



A dissemination workshop at the Tooro Botanical Gardens. Photo: Tooro Botanical Gardens.

Practice Insights

Tree Conservation and Forest Restoration in Uganda

Context:
The Tree Conservation and Forest Restoration in Uganda is a collaborative initiative implemented by Tooro Botanical Gardens in partnership with BGCI and the National Forestry Authority (NFA). It is a progressive initiative building upon 25 years of TBG conservation practice, and other tree conservation and forest restoration initiatives led by the government and NGOs in Uganda. Between July 2022 and June 2025, the project's activities focused on threatened tree diversity in biologically diverse regions dedicated to safeguarding Uganda's botanical heritage. The project targeted 48 threatened tree species through integrated *in situ* and *ex situ* conservation strategies, technical capacity building, and the development of the National Conservation Action Plan (NCAP25).

Approach:
The project utilized a multi-stakeholder model to develop the National Conservation Action Plan (Harvey-Brown et al., 2025), synthesizing data from national prioritization workshops and regional forest range management meetings. TBG established technical infrastructure, including a 60-hectare field gene bank at Kagombe CFR, and expanded its seed orchards by 6.8 ha. They transferred propagation expertise for 34 threatened species to local communities through integrated training and community nursery programs.

Outcomes:
These efforts resulted in mapping 94 tree species (34 threatened and 60 non-threatened native tree species), providing important baseline data for national conservation efforts. 453,000 seedlings of 94 species were propagated to support the restoration of the degraded forests in Fort Portal and Kagombe. The initiative also provided planting materials for conservation organizations and communities in the region. The initiative trained 1,361 individuals in technical skills and developed NCAP25 for threatened tree species of Uganda.

Lessons Learned:
Botanic gardens can transition from traditional living collections to national policy leaders by bridging the gap between scientific data and government implementation agencies. Restoration success is significantly enhanced when local communities are empowered to act as primary custodians of implementation.



A conservation planning workshop in Makerere, Kampala, Uganda. Photo: Tooro Botanical Gardens.

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Barriers to Botanical Gardens' Engagement with National and Global Restoration and Climate Policies

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Executive Summary

Botanical Gardens (BGs) are uniquely positioned to contribute to global restoration and climate resilience efforts. However, many currently lack formal strategies to engage with key international frameworks such as the Kunming-Montreal Global Biodiversity Framework (KM-GBF), the Paris Agreement, the UN Decade on Ecosystem Restoration, the Convention on Biological Diversity (CBD), as well as national strategies, such as Access and Benefit Sharing Agreements (ABSA) in the UK. This short report outlines key barriers and how botanical gardens can align their operations with these frameworks, adopt governance structures that embed restoration and climate resilience, and strengthen policy engagement to expand their impact and secure support for long-term initiatives. BGs need to shift from being passive conservation entities to more proactive actors.



At the UNFCCC COP30 in Belém, Brazil, NYBG's Dr. Eric Sanderson joined Dr. Marcela Quintero (Alliance of Bioversity International and CIAT), Dalia Atallah (Community Jameel), and Gry Bossen (Forest Friendly Foods) in a discussion on the role of botanical gardens and seed banks as catalysts for scalable, plant-based solutions for climate resilience. The discussion was moderated by Sid Mehta (Greenworks INC). Photo: World Green Economic Organization.

Current State of Knowledge, Knowledge Gaps, and Capacity Needs

Botanical gardens hold immense promise for supporting forest landscape restoration, ecological rehabilitation, and addressing climate change through their work in *in situ* and *ex situ* conservation, research, and community education. However, many botanical gardens around the world lack formal plans that connect with national and international restoration efforts (e.g., NDCs, CBD restoration goals) and climate action. They also have limited engagement with the private sector, restricted access to corporate funding, and insufficient awareness of their own capacities. This gap arises from a range of institutional, structural, and strategic limitations.

A significant hurdle is that botanical gardens have traditionally focused on *ex situ* conservation and public education rather than large-scale conservation (Mounce et al., 2017) and restoration projects (e.g., landscape connectivity and functionality). Historically, their missions and practices have revolved around collecting plants, studying taxonomy, and showcasing horticultural beauty, which does not necessarily encourage active involvement in policy-driven ecological restoration and climate action. This historical focus can slow their response to evolving environmental needs.

Another obstacle stems from institutional fragmentation. Botanical gardens operate under a mix of governance models in different countries—be it governmental, nonprofit, or academic—which, sometimes, affects their ability to engage in coordinated policy initiatives (Miller et al., 2021). Without a unified strategic direction or mandates tied to restoration and climate change objectives, like those outlined in the UN Decade on Ecosystem Restoration, their alignment with global policies tends to be inconsistent.



Visitors enjoy autumn foliage in the Thain Family Forest at the New York Botanical Garden. © New York Botanical Garden. Photo: Marlon Co.

The botanical garden community and its governance are varied and often disjointed, comprising institutions with different missions, funding sources, and capacities. This diversity can hinder the development of cohesive strategies aligned with global restoration targets. Lacking networks or shared policy frameworks, many gardens end up working in isolation, thus limiting their collective impact on restoration efforts (Heywood, 2017).

Resource limitations further complicate the situation. Numerous gardens struggle with financial constraints, staffing shortages, and a lack of expertise with new opportunities, particularly in areas like ecological restoration science and climate policy advocacy. These challenges impede their ability to enhance climate change and restoration projects or effectively engage in policy-making processes (Havens et al., 2015). Furthermore, many gardens lack spatial planning tools and technical frameworks for landscape-scale restoration, necessary to support the implementation of meaningful restoration strategies at the landscape level.

Additionally, a communication gap exists between scientists, policymakers, botanical institutions, and the private sector. Although botanical gardens possess vital plant diversity and expertise, they often find themselves excluded from policy discussions. This exclusion can happen due to false assumptions about their relevance or their historical lack of engagement with policymakers (Miller et al., 2021). As a result, their potential contributions to national biodiversity strategies or climate adaptation plans go largely unrecognized.

Despite their scientific input, botanical gardens frequently do not receive explicit acknowledgment as key players in international restoration or climate frameworks, especially in urban and peri-urban scenarios. This lack of formal recognition can dissuade these institutions from aligning with global policy objectives and lead to missed chances for integration and funding (Maunder et al., 2001).

Practice Insights

Royal Botanic Gardens, Kew and Its Engagement with Global Restoration and Climate Policies

The Royal Botanic Gardens, Kew (RBG Kew) stands out as a strong example of a botanical institution that aligns its work with global efforts in restoration and climate action. By integrating restoration ecology and climate resilience into its operations, RBG Kew has made significant progress through focused research, conservation initiatives, and policy engagement.

In partnership with local and international organizations, RBG Kew has supported large-scale ecological restoration projects. One notable example is in Madagascar, where they worked to restore degraded landscapes. This effort involved reintroducing native and endangered species using carefully sourced seeds and established propagation methods (Winchester et al., 2018). The project supports goals set by the Convention on Biological Diversity (CBD) and the UN Decade on Ecosystem Restoration.

In addition, Kew's Millennium Seed Bank Partnership (MSBP) demonstrates how botanical gardens can engage with global policy frameworks. It plays a key role in the Global Strategy for Plant Conservation (GSPC), now reflected in the Kunming-Montreal Global Biodiversity Framework (KM-GBF), by helping to conserve plant genetic diversity and promote restoration through seed science. Through these efforts, RBG Kew demonstrates how botanical gardens can act as key actors in linking conservation science with broader sustainability goals.

Botanical Gardens' Potential Contributions

To address these challenges, it is crucial to embed restoration and climate goals into botanical garden institutional strategies, foster strategic collaborations with governments and environmental policy networks, and implement outreach and capacity-building initiatives. Botanical gardens have an opportunity to strengthen their role as proactive participants in ecological restoration, climate solutions, and policy engagement. However, they need structured strategies and alliances to amplify their impact.

First, botanical gardens should explicitly include climate adaptation and ecosystem restoration objectives in their institutional missions and master plans (the Ecological Restoration Alliance of Botanic Gardens (ERA) is working to overcome this gap) (Havens et al., 2015). Aligning objectives and activities with global frameworks—such as the Kunming-Montreal Global Biodiversity Framework (KM-GBF), UN Decade on Ecosystem Restoration, and the Global Strategy for Plant Conservation (GSPC)—ensures relevance and accountability (Sharrock et al., 2014). Second, building partnerships with governments, NGOs, the private sector by engaging with environmental and corporate social responsibility initiatives, and academic institutions is vital. Such collaborations can empower botanical gardens to contribute to national biodiversity strategies and restoration goals (Aronson et al., 2020).

Third, creating seed banks to support restoration activities, maintaining living collections, developing plant propagation protocols, conducting germination studies, and implementing ecological restoration trials (e.g., forest landscape restoration, urban greening to cool cities) can enhance technical capacity while providing evidence-based practices to inform practitioners and policymakers in urban and peri-urban communities (Mounce et al., 2017).

Finally, engaging in policy dialogues through networks like Botanic Gardens Conservation International (BGCI) can amplify their voice in climate and restoration policymaking and increase awareness of their potential contributions.

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NYBG staff workshop ideas for the institutional Science Strategy, including engagement with international plant and biodiversity policy frameworks.
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Practice Insights

South American Network of Botanical Gardens, Red Sudamericana de Jardines Botánicos (RSAJB)

The first workshop for the establishment of the Red Sudamericana de Jardines Botánicos (South American Network of Botanical Gardens) took place at the Universidad del Tolima and the Jardín Botánico Alexander von Humboldt in Ibagué, Colombia, in December 2019. The event was attended by more than 40 participants from countries including Argentina, Brazil, Chile, Colombia, Guyana, Mexico, Paraguay, Peru, Suriname, Uruguay, and Venezuela. During the meeting, botanical gardens and related institutions emphasized the need to create a regional network and expressed their commitment to its consolidation (BGCI, 2019).

The Red Sudamericana de Jardines Botánicos (RSAJB) was created to establish and strengthen collaboration among botanic gardens in the region, promote research, support the development and management of botanic gardens, contribute to plant and habitat conservation, and foster environmental education and awareness. The specific objectives of the network are:

- Establish standards among botanic gardens in the region,
- Generate scenarios for the exchange of experience and technical assistance,
- Facilitate and strengthen communication between botanic gardens and botanic institutions in the region,
- Guide the members towards the implementation of the Convention on Biological Diversity, specifically the Global Strategy for Plant Conservation,
- Carry out joint conservation actions among the members of the network (BGCI, 2019).

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CASE STUDY

From Policy to Practice: Scaling Restoration in the Colombian Amazon

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After collection, seeds enter the Native Seed Laboratory, where they are processed, evaluated for viability, and subjected to germination trials. Photo: Jhony Briñez.

Scaling ecological restoration in Colombia faces a fundamental constraint: limited investment and technical capacity to develop restoration supply chains that are sufficiently robust to support economies of scale. While investments per hectare in commercial reforestation systems—typically based on monocultures of fast-growing (often introduced) species—may range between US$2,500 and US$3,000 (1,111 trees/ha; 4-year monitoring), ecologically based restoration using diverse native species and more intensive management (e.g., site preparation, enrichment planting, and maintenance) can cost between US$6,500 and US$9,500 or more (Rozo, 2022). This cost differential reflects not only the great ecological complexity of restoration, but also the limited development of seed supply systems, propagation knowledge, and production infrastructure. As these restoration supply chains mature and scale up, costs are likely to decline.

Consequently, despite growing global attention to restoration, many initiatives in Colombia struggle to move beyond small-scale interventions, particularly in the Amazon, where deforestation pressures remain high. According to the Colombian Ministry of Environment, 79,256 hectares of forest were lost in 2023 and 113,608 hectares in 2024, with the Amazon region accounting for more than 65% of the national deforestation.

In recent years, however, Colombia has strengthened its policy framework for ecosystem restoration. The 2022–2026 National Development Plan set a national restoration target of 753,000 hectares while promoting bioeconomy strategies for sustainable development. Complementing this effort, the 2025 Tree Law requires medium- and large-sized companies to plant two native trees per employee annually, creating demand for nearly 15 million native trees each year. The regulation frames restoration as a comprehensive process, including maintenance and monitoring, and establishes technical and institutional mechanisms, such as designated *Áreas de Vida* and a national registry system, to ensure implementation and traceability. Together, these initiatives signal a shift toward a stronger national restoration agenda and increased opportunities for private-sector participation.

Despite this progress, translating policy commitments into effective implementation remains difficult. National restoration targets continue to exceed the operational capacity available at the territorial level, and instruments such as the Tree Law depend on monitoring and compliance systems that are still limited in many regions.

In response to these challenges, Amazonía Emprende has developed an integrated approach to consolidating restoration supply chains in the Colombian Amazon, to achieve economies of scale and promote restoration cost efficiencies. Over the past six years, the organization has focused on improving the availability of native plant material while developing economic models that link ecological restoration with local livelihoods. This work is concentrated in Caquetá, the department with the highest deforestation rates in Colombia and an economy historically dominated by cattle ranching, where approximately 3.1 million hectares of forest have been lost over the last 80 years.



An Escuela Bosque training session. Caro, a restoration biologist, is teaching local cattle ranchers how to identify and collect native seeds for ecological restoration. Photo: Jhony Briñez.

A central component of this strategy is the Native Seed Center, a business unit supported by the Inter-American Development Bank's Innovation Laboratory (IDB Lab) and the Amazonía Forever Multi-Donor Fund. The Center strengthens technical, scientific, and community capacities to produce native plant material for restoration while expanding knowledge needed to support restoration initiatives led by public and private actors.

The Native Seed Center contributes to Amazonía Emprende's long-term strategy to restore 150,000 hectares and conserve 600,000 hectares by 2050 under the Andean–Amazon Connectivity Plan for Caquetá. This watershed-based strategy seeks to reconnect the Eastern Andes with Serranía de Chiribiquete National Park, a landscape increasingly fragmented by the expansion of cattle pastures.

At the Native Seed Center, restoration begins long before planting. Each tree established in the field follows a process that starts with the identification of a mother tree in the forest and continues through seed collection, propagation, nursery production, and finally the establishment of seedlings in restoration sites. This "life cycle of a restoration seed" connects research, community participation, and restoration practice into a coordinated supply chain for native plant material.

The process begins in the forest through the Native Forest Seed Tree Network (Red de Árboles Semilleros – RAS). The Network conducts forest inventories and community-based monitoring of potential mother trees across the Amazonian piedmont. Trees are selected based on visual health indicators, prioritizing individuals that appear vigorous and free from heavy infestation by termites, excessive vines (bejucos), or dense epiphytic loads such as bromeliads that may interfere with flowering and fruiting. Accessibility is also considered to ensure safe and efficient seed collection.

Through conservation agreements with local landowners, particularly cattle-ranching families, the RAS promotes the sustainable use of non-timber forest products such as native seeds while encouraging the protection of standing forest. To date, the Network has identified more than 2,000 mother trees, of which 540 are currently under phenological monitoring, covering 123 species from the Amazonian piedmont. This represents one of the most extensive community-based seed sourcing efforts in the Colombian Amazon. The Network continues to expand through ongoing training and engagement of cattle-ranching families, thereby increasing the number of monitored mother trees every year. Additionally, drone technology has improved the detection of flowering and fruiting events in tall-canopy species such as *Cedrelinga cateniformis* and *Hevea* spp., reducing field tree identification time by about half. Nevertheless, seed collection remains technically challenging due to tall canopies and forest stratification, which often prevent fruits and seeds from reaching ground-based traps.



Over 1,200 community leaders from multiple Colombian regions have participated in programs on green business models and restoration-based bioeconomies. Photo: Jhony Briñez.

To achieve species selection that integrates ecological, social, and economic criteria the RAS conducted interviews with local communities to identify species of cultural and economic importance. The resulting list was then combined with a list of 74 restoration species identified by CORPOAMAZONIA, ensuring that restoration supports both ecological recovery and local livelihoods.

After collection, seeds enter the Native Seed Laboratory, where they are processed, evaluated for viability, and subjected to germination trials. The Laboratory develops protocols for seed treatment, germination, and nursery management while conducting research on plant health and phytopathology. It is currently developing ten propagation protocols, including sexual and asexual methods for species such as *Terminalia congesta* and *Cedrelinga cateniformis*, for which little technical information previously existed.

Propagation knowledge is then transferred to the Community Native Plant Nursery Network, where protocols are applied at scale. These community-run nurseries produce seedlings using locally collected seed material, translating scientific research into practical restoration capacity while generating economic opportunities linked to emerging bioeconomy initiatives. Together, the nurseries currently have the capacity to produce more than two million native seedlings.

Seedlings produced by the nursery network are planted in restoration areas established through partnerships with public and private actors. These projects aim to recover degraded landscapes while reconnecting forest fragments across priority watersheds in Caquetá. In addition, monitoring systems evaluate ecological outcomes, including biodiversity recovery, nitrogen fixation, carbon sequestration, and social co-benefits for local communities.

Importantly, the process does not end with planting. Monitoring results feed back into the restoration system: restoration sites help identify species with higher survival rates, nurseries adjust production priorities, and the RAS refines seed collection strategies and mother tree selection. This adaptive cycle allows the Native Seed Center to continuously improve restoration supply chains.

Complementing this work, the *Escuela Bosque* (Forest School) serves as a platform for training, collaboration, and knowledge exchange. Located on a 30-hectare restored site on the outskirts of Florencia, it has become a national hub for restoration learning. More than 800 public- and private-sector leaders have received training in decarbonization strategies based on Amazonian forest restoration, while over 1,200 community leaders from multiple Colombian regions have participated in programs on green business models and restoration-based bioeconomies. The school has also helped attract investment through partnerships with organizations including Bancolombia, the United Nations Development Programme, the Food and Agriculture Organization, and the Inter-American Development Bank.

The experience of Amazonía Emprende in Caquetá highlights the importance of building restoration supply chains in humid tropical forest regions. Through the Native Seed Center, the organization addresses key bottlenecks such as limited seed availability, gaps in propagation knowledge, and the need for community-based production systems. By integrating research, nursery networks, and local capacity building, this approach supports the transition from isolated planting efforts to coordinated landscape-scale restoration, while incorporating climate change considerations into species selection and restoration design to enhance ecosystem resilience under changing environmental conditions.

As policy incentives such as the Tree Law and emerging carbon markets increase demand for native tree planting, the success of restoration will depend on continued investment in decentralized seed systems, applied research, and local restoration economies. Strengthening these enabling conditions will be essential for translating restoration commitments into long-term ecological recovery across the Amazon.

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Sustainable Funding of Ecological Restoration

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BOTANIC GARDENS CONSERVATION INTERNATIONAL



A vegetation survey at the Royal Botanic Garden, Jordan. Photo: Royal Botanic Garden, Jordan.

Introduction

To meet ambitious global targets for reversing biodiversity loss and mitigating climate change, ecological restoration needs a substantial increase in financing. Finance flows to Nature-based Solutions (NbS) in 2022 were US$154 billion per year, less than half of the US$384 billion per year investment in NbS needed by 2025 and only a third of investment needed by 2030 (US$484 billion per year) (UNEP, 2022). This funding shortfall necessitates a fundamental shift away from ad-hoc, siloed funding models toward a robust system of sustainable financing. Sustainable financing for ecological restoration necessitates a strategic and diversified approach that leverages public, private, and blended capital to fund projects that are ecologically effective, socially equitable, and financially viable over the long term. This essay outlines key challenges in financing ecological restoration, details a range of innovative financing instruments, and highlights the critical role of robust governance and collaboration in building resilient and sustainable funding models.

Current outlook on sustainable financing of restoration

The traditional model for financing restoration relies primarily on public funds and philanthropy, which are demonstrably insufficient to meet the scale of need—the Bonn Challenge alone aims to bring 350 million hectares under restoration by 2030. Numerous barriers have historically hampered efforts to attract more diverse and substantial funding.

First, the benefits of restoration—such as improved water quality, biodiversity, and climate regulation—are often treated as public goods that are difficult to monetise, limiting clear revenue streams for private investors. Moreover, the financial benefits that do arise, such as increased productivity from restored landscapes, often take a long time to materialise, further disincentivising investors who seek short-term returns. This creates a clear mismatch between ecological recovery timelines and investors' expected return horizons. Second is the inherent risk and uncertainty associated with ecological projects. The complex, dynamic nature of ecosystems, combined with unpredictable climate impacts, can affect recovery trajectories and investment outcomes. Furthermore, the lack of standardised governance, transparent metrics for measuring ecological outcomes, and verifiable data on investment returns makes it difficult for investors to assess risks accurately. Without clear, robust standards, investments remain opaque, expensive to monitor, and less attractive to institutional capital. Many projects also face high transaction costs due to their small, fragmented nature, making them unsuitable for large-scale investment portfolios unless aggregated.



Tree diameter measurements during The Global Biodiversity Standard assessment of the Nyantonzi restoration site. Photo: Tooro Botanical Gardens.

Valuing nature and ecological restoration

Over the past two decades and longer, it has been argued by economists that 'natural capital' (i.e., the goods and services provided by nature) is insufficiently captured and accounted for in Gross Domestic Product and other economic measures. As a result, governments, businesses, communities, and individuals consistently underestimate society's reliance on nature and consequently underinvest in conserving and managing it. The Dasgupta Review of 2021 (Dasgupta, 2021) is one of a long line of studies (e.g., Costanza et al., 1997) that have attempted to quantify the economic value of nature and integrate it into decision-making frameworks.

Natural capital accounting is an imprecise science because of the number of variables and complexity of ecological processes and supply chains. However, economists accept the principle that natural capital comprises a portfolio of goods and services provided by nature. As an example, the economic value of the English Public Forest Estate (EFTEC, 2010) was calculated by measuring the combined value of provisioning services (timber, fuelwood, etc.); regulating services (carbon sequestration, air quality regulation, flood regulation, water purification, pollination and pest control); cultural services (recreation, aesthetics, heritage, education, employment); and supporting services (primary production, soil formation, nutrient cycling, water cycling, biodiversity etc.).

These same approaches can be applied to the economic valuation of ecological restoration (Iftekhar et al., 2017). The value generated can be calculated for specific attributes of individual sites, including added recreational value (Alvarez, 2010), economic growth and employment (BenDor et al., 2015), enhanced ecosystem services (Gao et al., 2024) and other benefits resulting from restoration interventions.

Although natural capital accounting methodologies exist, and in some cases have been extensively tested and refined, such approaches are not yet mainstreamed into policy or applied consistently where ecological restoration is planned or underway. If it became standard practice to value nature economically, and thus to value interventions that sustain or enhance it, then we might build economic systems that would restore rather than destroy nature and incentivise restoration rather than degradation (Sanderson, 2013).



Tree planting underway in the Tropical Rainforest Living Collection Merisuli forest restoration site. Photo: Tropical Rainforest Conservation and Research Centre.

Innovative financial instruments for a sustainable future

To overcome the challenges of mobilising funding for ecological restoration, a diverse array of financial instruments is needed to mobilise capital across sectors. These can be grouped into public, private, and blended finance mechanisms.

Public finance and policy as market enablers

While insufficient on its own, public finance (i.e. government funding) is foundational to catalysing a sustainable funding ecosystem. Governments can act as market shapers and co-investors, using public funds to de-risk projects for private capital and establish the necessary enabling conditions. Examples include direct grants, subsidies for land managers, and strategic public investment that creates the infrastructure for larger nature markets.

Examples of direct government payment schemes to landowners and managers for protection and restoration of nature include Costa Rica's National Forest Fund (FONAFIFO), which provides support to landowners for protecting forests, and the UK Government's Environmental Land Management (ELM) scheme, which includes payments for sustainable farming practices, countryside stewardship, and landscape recovery (Defra, 2023).

In the United States, the restoration of degraded habitats in response to a range of human impacts is a legislative requirement for various federal land management agencies, and the use of native plant material is encouraged or mandated by national environmental policies. The Bureau of Land Management (BLM), which manages about 10% of the land in the United States, is responsible for restoring degraded forests, rangelands and wetlands. BLM has built up native seed stocks for ecological restoration through key partnerships within the federal, nonprofit, and private sectors, and funds restoration programmes on public land affected by fire, hurricanes, and other natural disasters (Oldfield, 2019).

A key governmental tool is the establishment of environmental markets, such as carbon and biodiversity markets. Regulatory frameworks, like England's mandatory Biodiversity Net Gain (BNG) policy, ensure that development leaves biodiversity in a measurably better state, creating compliance-driven demand for off-site habitat creation. Ecological restoration funded by the private sector to comply with licenses granted by governments to extract natural resources is now common in many countries, and international principles and standards for restoration of mine sites are well established (Young et al., 2022). However, as critics note, compliance markets primarily prevent further loss rather than actively restore nature, highlighting the need for complementary, high-integrity voluntary markets to drive additional investment. For example, the Forest Stewardship Council (FSC) and Roundtable on Sustainable Palm Oil (RSPO) certify commodity production systems rather than assessing ecological recovery in forestry projects. Similarly, carbon standards such as Verra's Verified Carbon Standard and Gold Standard include biodiversity safeguards, but these are primarily designed to ensure projects do no harm, rather than to measure and certify biodiversity recovery as a primary outcome.

Harnessing private sector investment

The private sector, driven by reputational risk management, corporate social responsibility, and the growing demand for sustainable investments, is a crucial source of finance. Innovative financial instruments designed to appeal to private investors include:

- **Green bonds:** These are fixed-income instruments in which the proceeds are earmarked for climate or environmental projects. While historically focused on renewable energy, there is growing interest in directing green bond finance toward nature-based solutions and biodiversity projects (PwC, 2025).

- **Environmental impact bonds:** In this model, investors provide upfront capital, and returns are linked to the achievement of specific ecological outcomes. The Forest Resilience Bond, used in California, is a prime example in which investors finance forest restoration and are repaid by beneficiaries of improved forest health (Green Finance Institute, 2025).

- **Nature-based enterprises (NBEs):** These are businesses that use nature sustainably as a core part of their product or service. They attract investment by offering financial returns alongside environmental benefits, whether through ecotourism, sustainable agriculture, or certified nature-positive products. For example, members of the UK Food and Drink Pact fund watershed restoration where it directly affects their supply chains. Similarly, companies may sponsor restoration activities linked to product branding. For example, *The Botanist* gin (https://www.thebotanist.com/pages/bcgipartnership) partners with BGCI to fund plant conservation projects as part of its environmental positioning.

The power of blended finance

Given the financial characteristics of many restoration projects, blended finance—the strategic use of public or philanthropic capital to leverage private investment—is a crucial mechanism. Public funds can be used to absorb risk, thereby improving the risk-adjusted returns for private investors. This can take many forms:

- **Concessional loans:** Public entities or development banks offer loans at below-market rates to reduce the overall cost of capital for restoration projects.
- **Guarantees:** A public backer provides protection against project failure, making investments more secure and attractive to risk-averse private investors.
- **Debt-for-nature swaps:** Often used in developing countries, this mechanism involves forgiving a portion of a country's debt in exchange for a commitment to fund environmental conservation and restoration.

For example, the Global Fund for Coral Reefs uses a blended finance model involving grants and private investment to support projects that enhance reef resilience (https://globalfundcoralreefs.org/). Such approaches allow for the pooling of capital and risk-sharing, enabling larger-scale and more impactful restoration projects that might otherwise struggle to secure funding.

Governance, standards, and community engagement

Effective, sustainable financing must be underpinned by strong governance, clear standards, and meaningful community engagement.

Establishing robust, high-integrity standards is vital for building investor confidence. The nascent state of nature-based finance means that defining what constitutes a "green" or "nature-positive" investment is still evolving. Initiatives like the International Capital Market Association's Green Bond Principles and the work of the British Standards Institution on Nature Investment Standards are critical for ensuring transparency, accountability, and the delivery of verifiable environmental outcomes.

Involving Indigenous Peoples and Local Communities (IPLCs) is essential for both equity and long-term project success. Community-based finance ensures that restoration efforts are culturally sensitive and meet local needs, increasing community buy-in and long-term sustainability. This bottom-up approach can also support the development of local business cases around restoration, creating pathways toward financial self-sufficiency. Without proper safeguards and equitable decision-making processes, private finance can lead to land grabbing or projects that misalign with community priorities, undermining long-term outcomes. Recent interest in biodiversity credits has led to a growing body of work on principles and 'guardrails' related to high-integrity biodiversity uplift projects (World Economic Forum, 2023).

Measuring ecological and biodiversity impacts remains challenging given the complexity of ecosystems. For carbon accounting, the common metric is tonnes of carbon dioxide equivalents (CO_2e) emitted or sequestered. The Biodiversity Credit Alliance defines a biodiversity credit as "a certificate that represents a measured and evidence-based unit of positive biodiversity outcome that is durable and additional to what would have otherwise occurred" (BCA, 2024). However, the definition of that unit, and how it is measured, is not prescribed. Existing standards from forestry (e.g., FSC), sustainable agriculture (e.g., Rainforest Alliance) and carbon (Gold Standard, Verra) are being adapted to better account for biodiversity, but each methodology is designed to measure different outcomes. In most cases, practitioners are required to measure attributes themselves and report them to the certification bodies, which is difficult in highly diverse habitats where specialised taxonomic and ecological survey skills are required. For these reasons, BGCI, the Society for Ecological Restoration, CIFOR-ICRAF, and other partners have developed The Global Biodiversity Standard (TGBS), a site-based certification, which measures change in biodiversity and ecosystem integrity. The TGBS methodology measures 21 attributes from SER's ecological restoration recovery wheel, and benefits from the local biodiversity knowledge of institutions in BGCI's network.

The role of botanical gardens

It can be argued that botanical gardens have been practising ecological restoration for centuries, particularly in the naturalistic landscapes or even natural habitats present in many botanical gardens. The botanical sector also cultivates a wider range of plant species than any other professional community, including forestry and agriculture (Mounce et al., 2017). However, over the past two decades, botanical gardens have sought to better define their contributions to the science and practise of ecological restoration (Hardwick et al., 2011), and to become more actively involved in restoration projects.

The Ecological Restoration Alliance of Botanic Gardens (ERA), launched in 2012 by the then Prince of Wales, now King Charles III, is co-ordinated by Botanic Gardens Conservation International (BGCI), and comprises a loose federation of botanic gardens that practise restoration, showcase exemplar biodiverse projects, and share training resources and learning. ERA exemplar sites, for example Arariba Botanical Garden's 17-hectare restoration site in Brazil's Atlantic Forest, tend to be small because botanic gardens have limited financial resources and land area. While some projects have been highly successful, the challenge of scaling up remains.

Impediments to deploying botanical expertise at large scale include competing institutional priorities, limited recognition of botanical gardens in the restoration sector, the comparatively high cost of biodiverse restoration, lack of regulations or financial incentives to plant native species, and resulting supply-chain constraints related to wild and native plant seeds and seedlings.

In 2021, prompted by the rush to plant trees for carbon sequestration and livelihoods, BGCI, Kew, and other ERA members published the paper *Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits* (Di Sacco et al., 2021). This was followed by a virtual conference hosted by Kew, CIFOR-ICRAF, and BGCI entitled *Reforestation for Biodiversity, Carbon Capture and Livelihoods*. This conference led to the Kew Declaration on Reforestation for Biodiversity, Carbon Capture, and Livelihoods (The Declaration Drafting Committee, 2022), which calls on policymakers, financiers, and practitioners in countries that have made reforestation pledges to adhere to the "ten golden rules" and to create policy frameworks, incentives, and audit mechanisms to ensure that biodiversity is enhanced rather than degraded.

The Global Biodiversity Standard (TGBS) (see above) was born out of the Kew Declaration, and was established by the same partners—BGCI, CIFOR-ICRAF, Kew, and SER—with the aim of creating a site-based, biodiversity-specific, third-party auditing mechanism for ecological restoration that combines assessment and mentoring to improve biodiversity outcomes. By 2025, TGBS had established assessment and mentoring hubs—most of them botanic garden ERA members—in 15 countries that together host more than 50% of the world's biodiversity, along with over 200 trained assessors and mentors. TGBS is envisaged as a vehicle for deploying botanic garden expertise in biodiversity survey and inventory (assessment) and in growing a wide range of native species for restoration (mentoring), enabling the botanical community to create impact at scale.

The TGBS theory of change is that, if biodiversity performance, ecosystem integrity, and climate-resilience data are integrated into financial planning, regulatory frameworks, investment appraisal, disclosure, and the design of financing and risk-transfer instruments—and if priority projects are designed, mentored and independently verified against a scientifically robust, outcome-based biodiversity standard (The Global Biodiversity Standard), then:

- Governments can prioritise, budget and programme restoration more effectively in National Biodiversity Strategies and Action Plans, Nationally Determined Contributions, and National Adaptation Plan implementation, using outcome-based standards and certification to reduce performance uncertainty and strengthen accountability in public expenditure.

- Companies can respond to this prioritisation in their planning and investment decision-making, better quantifying dependencies and supply-chain risks, and using certified restoration outcomes to reduce reputational and operational risks, while enhancing long-term resilience and value creation.

- Development banks, public investors and private investors can reduce ecological, performance and reputational risk through independently verified, standardised biodiversity and ecosystem service outcome data, enabling more confident capital allocation and improved pricing of nature-related risk.

- Blended finance facilities, guarantees, green and resilience bonds, insurance products and results-based mechanisms can be structured around certified biodiversity and ecosystem-service performance, reducing information asymmetry, lowering transaction costs and increasing investor confidence.

- Large-scale, high-integrity restoration aligned with KM-GBF Target 2 and its linkages to other KM-GBF targets can become investable, insurable and scalable because risk has been substantively reduced through credible standards, certification and monitoring.

Conclusions

The challenge of financing ecological restoration at the required scale demands a fundamental rethinking of how we value and invest in natural capital. Reliance on traditional public and philanthropic sources alone is no longer sufficient. The future of sustainable financing for restoration lies in a collaborative approach that strategically blends public, private, and community-based capital.

By leveraging innovative financial instruments—such as green bonds, environmental impact bonds, and blended finance structures—while building robust governance frameworks and ensuring meaningful community engagement, it is possible to unlock the investment required. This transition is not merely about finding more capital; it is about creating a resilient and equitable system that recognises both the intrinsic and economic value of a healthy planet and engages all sectors, including the botanical garden community, in its recovery. Ultimately, achieving global restoration targets will depend on our ability to translate ecological necessity into a compelling and sustainable investment opportunity.

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Mobilising Botanic Garden Expertise to Monitor Restoration Impact

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Soil sampling in the Thain Family Forest helps inform research and management of urban forest ecosystems. © New York Botanical Garden. Photo: Marlon Co.

Executive Summary

Monitoring is critical to the long-term success of ecosystem restoration, ensuring that projects deliver tangible, lasting outcomes for biodiversity and climate resilience. However, many restoration initiatives lack robust monitoring systems, particularly in regions where ecological baselines and reference models are challenging to construct, standardised monitoring protocols are lacking, and capacity is limited. Botanical gardens are uniquely positioned to fill this gap. With strengths in taxonomy, ecological surveying, and public engagement, they can contribute to the development of reference models, assist with collecting and interpreting monitoring data, and promote adaptive management. This report identifies four major challenges in restoration monitoring: the absence of site-specific reference models and baseline data, a lack of standardised monitoring protocols, the underuse of data in decision-making, and insufficient capacity and funding. It highlights how botanical gardens—through their scientific collections, education programmes, and long-term presence—can play a pivotal role in addressing these gaps. By mobilising botanical expertise globally, and particularly in biodiversity-rich regions of the Global South, botanical gardens can help ensure that the monitoring of restoration projects is conducted more consistently and is scientifically credible, socially inclusive, and ecologically relevant.

Current State of Knowledge

Monitoring is a critical component of ecosystem restoration, enabling practitioners to track progress, evaluate effectiveness, and adapt interventions to improve targeted outcomes. Diverse approaches are used to monitor restoration including field-based, remote sensing (De Almeida et al., 2025; Wang et al., 2024), and social survey methods (Martin & Lyons, 2018), with numerous monitoring tools developed but rarely standardised (e.g., Reytar et al., 2023). Best practice ecological monitoring involves assessing progress relative to a clearly defined reference model, which describes the target ecosystem structure, function, and diversity (Gann et al., 2026). Reference models are typically derived from well-studied reference sites (e.g., intact or minimally disturbed ecosystems of the same type), supplemented by ecological literature, traditional knowledge, and expert input. These models provide essential context for interpreting whether a restoration site is recovering toward a desired ecological state, or whether interventions need adjustment. However, restoration targets exist along a continuum: while ecological restoration seeks to restore the native ecosystem, rehabilitation and other approaches may aim only to restore selected functions or biodiversity. Objectives therefore need to be clearly articulated, as not all projects will have—or aspire to—a fully defined reference native ecosystem.

The *Standards of practice to guide ecosystem restoration* outline 11 key components that together constitute a rigorous monitoring framework (Nelson et al., 2024):

1. Broad engagement
Monitoring should be co-developed with stakeholders, including local communities, Indigenous peoples, scientists, and practitioners. This ensures that the process is inclusive, locally relevant, and transparent.

2. Monitoring and evaluation plan
A plan should define the monitoring approach, scope, schedule, responsibilities, and anticipated uses of the data. It should align with project goals and available resources. The monitoring and evaluation plan should be developed while the restoration project or programme is being designed, rather than after implementation, to ensure alignment with objectives and feasibility from the outset.

3. Monitoring aims and objectives
Clear, measurable objectives linked to restoration targets are essential to guide what data are collected and why.

4. Selection of indicators
Indicators should reflect the core components of ecosystem integrity and project goals. These may include biodiversity metrics (e.g., plant species richness), structural attributes (e.g., canopy height), functional indicators (e.g., pollinator interactions), and socioeconomic (e.g., change in income) or cultural (e.g., access to materials for traditional crafts or medicines) outcomes.

5. Monitoring and sampling designs
Designs should be scientifically robust and statistically appropriate. Methods must be replicable and allow for meaningful comparisons across time and space.

6. Data collection
Standardised protocols should be used to ensure quality, consistency, and comparability of data across projects in a given ecosystem type. Where feasible, data collection should involve trained community members or citizen scientists to foster ownership and local capacity.

7. Data management, analysis and evaluation
Data should be stored securely and analysed in a timely manner using transparent methods. Interpretation should consider both trends and variability and be tied back to project objectives and reference models.

8. Evaluation of the effectiveness of the monitoring effort
Monitoring should itself be periodically reviewed to ensure it is fit-for-purpose, cost-effective, and generating useful information.

9. Information management and record-keeping
Good documentation practices are essential for accountability and knowledge transfer. This includes metadata, field notes, protocols, and analytical decisions.

10. Reporting and communication
Findings should be shared regularly and in formats accessible to diverse audiences, including project funders, policymakers, and local communities. Communicating findings in the local language helps to make them accessible for local stakeholders.

11. Adaptive management
Monitoring results should directly inform project decision-making. This includes refining techniques, shifting priorities, or scaling successful approaches based on evidence.

Knowledge Gaps and Capacity Needs

Challenge 1: A lack of appropriate reference models and baseline data

Many restoration projects do not assess progress of restoration against well-defined reference models. In many regions, developing reference models is challenging because of limited ecological research, coarse ecosystem classifications, and poorly documented land-use histories. These challenges are compounded by the vast and often poorly documented biodiversity of some ecosystems as well as spatial bias in research (Metcalfe et al., 2025). Without reliable reference models, restoration efforts risk monitoring progress against arbitrary or ecologically inappropriate targets. Meanwhile, many restoration projects lack pre-intervention data on ecological conditions, especially for less-visible and less-monitored taxa, such as insects, understory plants, or soil biota (Key et al., 2022). Social indicators are also rarely collected or integrated into baseline surveys (Mansourian & Stephenson, 2023). This lack of baseline data makes it difficult to evaluate the progress of restoration projects relative to the reference condition.

Challenge 2: Lack of standardised monitoring protocols

Although significant efforts have been made to advance global frameworks for restoration monitoring (e.g., Fox et al., 2021; Bartholomew et al., 2024), there is still a lack of standardised protocols that can be consistently applied across ecosystems and projects. This results in fragmented approaches, with many initiatives developing their own methods, making results difficult to compare or aggregate at broader scales. Funders and policymakers often request only narrow metrics, such as tree survival counts or the growth rates of planted seedlings. While these indicators are important, they are insufficient to capture the broader ecological and social outcomes that restoration aims to achieve. Such limited indicators risk obscuring key dimensions of success, such as biodiversity recovery, ecosystem function, or community benefits.

Practice Insights

Botanical Gardens as Independent Assessors for The Global Biodiversity Standard

Context:
The Global Biodiversity Standard (TGBS) is a science-based certification framework designed to evaluate biodiversity outcomes of ecosystem restoration projects (Bartholomew et al., 2024). It mobilises biodiversity institutions, predominantly botanical gardens, to act as independent assessors of restoration efforts. TGBS was officially launched in 2024.

Approach:
TGBS applies a site- and outcome-based methodology to assess projects against eight criteria using a combination of remote sensing and field survey techniques. The assessment covers changes in ecosystem integrity, level of protection, stakeholder engagement, and the implementation of monitoring, evaluation and adaptive management. As part of the process, assessors develop a site-specific reference model and evaluate both baseline and current ecological conditions. Biodiversity institutions are trained in the TGBS methodology and serve as independent auditors for the certification process.

Outcomes:
Applicants to TGBS have reported that the involvement of biodiversity institutions has strengthened their restoration projects by providing rigorous monitoring and access to specialised technical expertise. The TGBS framework has enabled projects to implement adaptive management by identifying and addressing areas that scored poorly under the assessment. Additionally, the development of reference models during the assessment process has helped some applicants adjust their species selection to better reflect the native ecosystem.



The Global Biodiversity Standard assessors evaluating tree species diversity at the Pandalgudi EcoPark, India. Photo: Auroville Botanical Gardens.

Lessons Learned:
This initiative demonstrated that botanical gardens have the capacity to serve as trusted, independent auditors of restoration quality, linking local ecological expertise with global standards. It has shown that, with appropriate training and modest investment, gardens can expand their role to promote and support high-integrity, biodiversity-positive restoration.

Challenge 3: Limited use of data in adaptive management

Even when data are collected, they are often underutilised in adaptive management because of insufficient indicators, technical capacity, or institutional support (Stephenson et al., 2025), meaning monitoring remains a box-ticking exercise rather than a strategic tool for learning and improvement. As a result, valuable information that could guide corrective actions, refine restoration techniques, and build long-term capacity is frequently overlooked, limiting the effectiveness and resilience of restoration projects.

Challenge 4: Insufficient funding and limited institutional capacity

Monitoring is frequently underfunded or deprioritised in restoration projects, leading to gaps in data collection, inconsistent follow-up, and poor impact assessment (Höhl et al., 2020). Restoration projects regularly overestimate local technical and institutional capacity during the design phase, resulting in overly ambitious monitoring plans that cannot be operationalised and data that do not correspond to objectives (Djenontin et al., 2018). As a result, monitoring efforts do not typically include the full monitoring cycle, including data collection, data analysis, and repeated monitoring over time. Limited staff with ecological surveying, statistical, and data management skills, along with insufficient monitoring equipment and a lack of locally tailored methods, can also restrict monitoring effectiveness. Short-term funding cycles are also misaligned with the timeline for ecological and social changes that may only become evident after decades (Abelson et al., 2020).

Botanical Gardens' Potential Contributions

Botanical gardens possess a unique combination of scientific expertise, living collections, long-term institutional continuity, and public engagement capacity that equips them to address many of the systemic challenges facing restoration monitoring.

Contribution 1: Development of reference models and collection of baseline data

Botanical gardens can support development and refinement of ecologically valid reference models by leveraging their scientific, historical, and community-based knowledge systems, building on initiatives such as The Global Biodiversity Standard (Bartholomew et al., 2024). Their taxonomic expertise enables accurate identification of native plant species and community composition at locally appropriate resolution. Many gardens house extensive herbarium records, historical photographs, floristic survey data, and biological collections (seeds, pollen, wood, etc.) that provide insights into historical species assemblages and ecosystem structures. Botanical gardens also frequently collaborate with Indigenous and local knowledge holders, whose place-based ecological understanding can enrich reference models. Meanwhile, botanical gardens can utilise their taxonomic expertise to collect baseline data, particularly detailed botanical surveys, including often-overlooked taxa such as understory plants, epiphytes, and herbs that are critical to ecosystem recovery. Gardens also engage increasingly in research on plant-soil and plant-microbe interactions, providing insights into ecosystem functioning, which is traditionally overlooked.

Contribution 2: Standardising monitoring protocols

Botanical gardens have deep knowledge of ecological surveying methods, having long monitored plant diversity, phenology, and ecosystem processes in both *ex situ* and *in situ* settings. This expertise positions them to identify the most effective biodiversity survey techniques for different ecosystems and to ensure that monitoring protocols capture more than just the commonly used metrics requested by funders and policymakers, such as tree survival counts or growth rates. By applying their experience, gardens can help develop and validate standardised protocols that are scientifically rigorous yet practical to implement in varied contexts. They can also test and refine these approaches through their living collections, restoration demonstration sites, and partnerships with local communities. Through their networks, gardens are well placed to disseminate these protocols globally, ensuring that monitoring becomes more consistent, comparable, and credible across projects and biomes.

Contribution 3: Enhancing use of data in adaptive management

Botanical gardens are well positioned to strengthen the use of monitoring data in adaptive management. Botanical gardens are trusted public institutions with a strong record in education and engagement, which enables them to integrate participatory methods, such as citizen science and community-based data collection (Chen & Sun, 2018). Their experience in training in diverse topics related to plant conservation can help strengthen local ownership and capacity, which in turn can improve data quality, relevance and use in decision making. Their horticultural expertise can also support the interpretation of plant health, phenology, and growth patterns, which are critical considerations for site-specific adaptive management interventions. Their long-term institutional presence and collaborative ethos can ensure monitoring becomes a strategic tool for learning, adaptation, and restoration success.

Contribution 4: Building long-term capacity for monitoring

Botanical gardens often serve as permanent community institutions, with established infrastructure that can help to maintain consistent monitoring over decades. Their staff are experts in key fields such as plant ecology and phenology, and many gardens are now building capacity to use and locally train others in remote sensing tools for low-cost, landscape-level monitoring. Botanical gardens can act as hubs for knowledge exchange and capacity building, helping to expand the pool of trained practitioners. Moreover, as trusted institutions with strong community links, many gardens are well positioned to attract local philanthropic funding to support long-term monitoring efforts and to develop standardised monitoring protocols and biodiversity monitoring capacity, which are often beyond the scope of short-term projects.

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CASE STUDY

Evolving a Pragmatic Operational Theory for the Ecological Restoration of a Semi-Arid Ecosystem in the Wild Area of the Cadereyta Regional Botanic Garden

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Ecological restoration target site within the Wild Area of the Cadereyta Regional Botanic Garden, showing an overall loss of ecosystem structure and complexity driven by the dominance of Melinis repens (an invasive alien species). Photo: J.A. Aranda-Pineda.

The Cadereyta Regional Botanic Garden "Ing. Manuel González de Cosío" (CRBG), located in the municipality of Cadereyta de Montes, in the state of Querétaro, Mexico, was founded in 1991 under the direction of the Council of Science and Technology of the State of Querétaro (CONCYTEQ). Since its establishment, the garden has become one of the most robust conservation efforts for the arid zones of Central Mexico. Over time, and most notably since 2003, the CRBG's role has evolved from a center primarily dedicated to the safeguarding and exhibition of botanical collections to an institution capable of planning and implementing comprehensive diagnostic, propagation, and ecological restoration projects. This shift marks a transition from the conservation of individual species to the recovery of entire ecosystems.

This institutional evolution is supported by a comprehensive guiding framework—comprising internal operative guidelines and area-specific procedures developed by the CRBG—that integrates scientific knowledge with field-based practice and constitutes the operational theory of the CRBG. A key instrument of this framework is the General Procedure for the Study and Conservation of Plant Biodiversity in the State of Querétaro (JB-02), which defines a critical pathway based on a conceptual mapping of activities that articulated scientific knowledge with management practices and leads to the *ex situ* conservation of the flora of our region (CONCYTEQ, 2024). An operative pragmatic theory is a philosophical approach that defines the meaning, truth, or value of a concept, belief, or statement by its pragmatic consequences and operational success in real-world situations. A pragmatic operational theory for the Cadereyta Regional Botanic Garden is to function as a biocultural restoration engine where every activity—plant collection, propagation, research, education and public engagement—directly contributes to restoring the semi-desert ecosystem.

The restoration plan for the Wild Area—a designated zone within the CRBG's perimeter managed for natural succession—marks a milestone in this institutional evolution. While distinct from the curated botanical collections, the area has remained relatively undisturbed over recent decades; it is enclosed by a perimeter fence, subject to regular surveillance patrols, and receives no active management beyond firebreak and path maintenance, selective pruning of invasive alien species, and basic litter removal. It has also served as a research site for studies documenting ecological, phenological, and behavioral aspects of pollination networks, developed in collaboration with several universities. For this restoration initiative, the garden applies its technical expertise to the recovery of the crassicaule scrub found in the Wild Area, a representative arid-land ecosystem characterized by the dominance of succulent species, such as cacti, agaves, and yuccas, alongside woody shrubs that form a low, partially open canopy.

This site, which shows clear evidence of human disturbance, encompasses eight hectares of wild vegetation that serve as an experimental field laboratory for implementing this plan; active restoration interventions will be focused in the areas identified as priorities following the baseline assessment. The objective is to demonstrate that restoration in arid zones is both feasible and replicable when it is grounded in a pragmatic theoretical framework and translated into rigorous practical application. The restoration challenge is substantial, as the Wild Area exhibits a gradient of degradation ranging from relatively well-conserved scrubland to nearly monospecific grasslands dominated by *Melinis repens*, an invasive alien grass that inhibits the establishment of native species. Connectivity with neighboring vegetation fragments is limited, and natural regeneration alone is insufficient to reverse the trajectory of degradation.

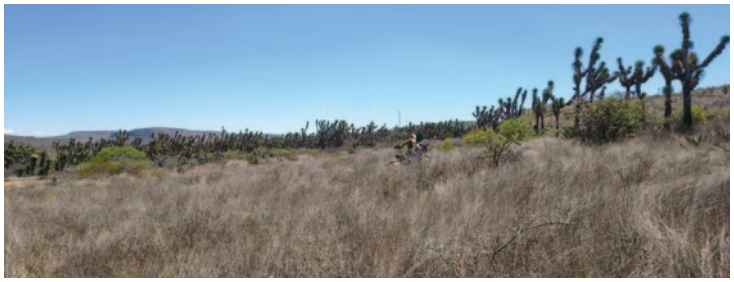
The project is led and executed by the CRBG, with the support of CONCYTEQ and is open to collaborative contributions from academic and research institutions as the initiative advances. The main asset of this project is the technical capacity of the CRBG. The institution operates its own Wild Plant Propagation Unit (UPPS, Spanish acronym), which produces plant batches from local germplasm. Consequently, the individuals used for restoration have the genetic diversity and adaptations necessary for the local environmental conditions.

The project begins with a remote sensing analysis currently underway, in which a historical estimation of the Soil-Adjusted Vegetation Index (SAVI) is being conducted for the 1986–2026 period using multispectral satellite imagery sampled at decadal intervals across four seasonal windows, providing a quantitative record of vegetation condition trends over four decades. This analysis will be complemented by on-site studies to determine vegetation structure and composition, as well as disturbance levels based on indicators such as soil compaction and evidence of livestock and human activities. Together, these steps form a comprehensive diagnosis that will serve as a baseline for prioritizing interventions in different areas, according to the resilience and connectivity of the landscape.

Species selection for the restoration process will be carried out meticulously using a scoring system that prioritizes key plant attributes, such as nitrogen-fixing capacity, soil retention ability, and their role as nurse plants—an essential function for seedling recruitment. The resulting species assemblage will support the formation of a resilient and self-sustaining scrubland in the long-term.



One of the greenhouses of the Cadereyta Regional Botanic Garden's Wild Plant Propagation Unit, where propagation protocols for native species are developed and implemented for conservation and restoration purposes.
Photo: J.A. Aranda-Pineda.



Ground-level view of an ecological restoration target site within the Wild Area of the Cadereyta Regional Botanic Garden. It highlights the overall loss of structural complexity, where invasive alien grasses dominate and only sparse native species typical of crassicaule scrubland persist. Photo: J.A. Aranda-Pineda.

The field establishment of the selected species follows an experimental design intended to generate conclusive evidence on the effectiveness of different restoration strategies. Experimental plots will be installed to compare two treatments: (1) assisted restoration involving the introduction of native species along with permanent threat control, and (2) the initial removal of degradation factors followed by the introduction of native species. Control plots will be used to monitor the site's natural recovery trajectory. This approach ensures that each action occurs within an adaptive learning cycle, in which monitoring results guide any necessary adjustments to the methodology.

For the 2026–2030 period, the CRBG expects to obtain baseline data on six key attributes to measure restoration success over time: species composition, structural diversity, ecosystem functions, external exchanges, absence of threats, and physical conditions. By the end of this period, success will be evaluated based on the successful establishment of the planted species within the experimental plots and on measurable improvements across these six key attributes, reflecting an overall recovery of ecosystem integrity. The plan incorporates a science-based experimental design, and all of its phases will rely on continuous scientific work and documentation to be disseminated through articles and book chapters. The long-term expectation is that established plots will gradually expand to form a continuous vegetation cover, a goal that could be addressed in a subsequent monitoring and implementation project building on the results obtained during this first five-year phase.

The role of the CRBG extends beyond biological recovery to encompass social and educational dimensions. The restoration plots will serve as demonstration sites for visitors and local communities, reinforcing the importance of native biodiversity. Additionally, the development of new specialists will be promoted through collaboration with universities and research institutes. This comprehensive vision aims to position the CRBG as a driver of scientific advancement, demonstrating that ecological restoration in arid zones is possible when scientific leadership is guided by pragmatic principles and executed through a rigorous practical methodology.

The CRBG has dedicated much of its history to developing the technical capacities required to lead this effort. Over time, several of the CRBG's methods have become standard references and sources of inspiration for other members of the botanical garden community (e.g., Sánchez Martínez *et al*., 2006; 2011; 2013; 2017; Ugalde de la Cruz et al., 2014; Guerrero Eloisa *et al*., 2025). It is now time for the next step: the institution has reached a point where it can advance its conservation mission through ecological restoration.

The project's design is aligned with the principles of the Society for Ecological Restoration (SER) and The Global Biodiversity Standard (TGBS), ensuring that the intervention is supported by internationally recognized methodological frameworks. Once the first results become available, the project will be integrated into international platforms such as the REVIVE initiative.

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Garden Grounds for Demonstrating and Communicating Effective Restoration

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Executive Summary

As accessible outdoor spaces where curated plant collections inform diverse communities, botanical gardens are ideally situated to promote ecological restoration through onsite demonstrations and related programming. Although individual gardens may be small, they collectively manage tremendous habitat diversity with horticultural skills necessary for science-based restoration. Beyond the garden gate, onsite restoration informs and inspires millions of visitors to manage their own properties better. By fostering knowledge exchange networks, adopting standardized monitoring protocols, and promoting recognized certification pathways, onsite restoration at botanical gardens can leverage horticultural, scientific, and educational strengths towards climate resilience.

Current State of Knowledge and Botanical Garden Contributions

Botanical garden grounds demonstrate horticultural skills necessary for ecological restoration involving many species and habitats. Public gardens collectively manage more than 30% of known plant species (Mounce et al., 2017), including over 80,000 acres (~32,375 hectares) of diverse habitat in North America alone (APGA, 2023). Whether gardens maintain local endemic plants for ex *situ* conservation or support legacy trees in mixed plantings, horticultural expertise necessary to collect, propagate and maintain native plants can support capacity for local restoration. While gardens manage many collections more intensively than would be practical for typical restoration projects, larger institutions often display collections in different conditions. Of 408 public gardens in the United States, 93 institutions in 38 states include both landscaped and natural habitats (BGCI, 2023). Nature preserves and native habitat demonstrations at botanical gardens require additional skills for managing pests and disturbance that can also transfer to ecological restoration. Even small gardens in highly urban settings can effectively demonstrate local restoration. In rapidly urbanizing coastal Florida, Marie Selby Botanical Gardens highlights native epiphytes in a restored coastal hardwood hammock where resilient plants helped mitigate storm surge damage from a major hurricane. Showing the beauty and resilience of native plants through onsite restoration can advance botanical gardens' missions while climate-proofing their collections.

Translating success from onsite demonstration projects into more effective ecological restoration requires leveraging scientific research to inform generalizable best practices. Collections management and biodiversity research align with the missions of many public gardens (Smith and Harvey-Brown, 2018). A small but growing number host research programs focused on restoration ecology. Nearly 50 participate in the Ecological Restoration Alliance of Botanic Gardens whose goals include promoting a science-driven approach to ecological restoration (Shaw et al., 2015). Such an approach is on display at the Shaw Nature Reserve, a rural campus of the Missouri Botanical Garden (Reid et al., 2020). Acquired after the property had been managed for low-intensity agriculture, many significant habitats had been degraded. Starting in the 1990s, garden staff began implementing experimental restoration across a range of native habitats, including invaded and over-browsed woodlands, old-field prairies, and fire-suppressed glades, each a threatened local habitat with unique plant diversity. Restoration research in glades at the Shaw Nature Reserve catalyzed joint funding with local universities and informed restoration guidelines by state agencies. By combining research capacity with horticultural know-how, onsite restoration can close research gaps for more effective restoration practice.

Beyond the garden gate, science-based restoration supports highly impactful education. Globally, gardens host 500 million annual visitors (Westwood et al., 2021), providing a huge audience for the goals, processes, and outcomes of onsite restoration. Given that restoration often promotes local native plants and habitats, community visitors provide unique educational opportunities. Among people who live within 40 km of a botanical garden, one in six visits annually (APGA, 2023). Local visitors may find inspiration to manage their own property differently and seek direct experience through volunteering. From informative signage to formal coursework, the National Tropical Botanical Garden demonstrates the spectrum of restoration-related education programming (Chang et al., 2019). Centered on Hawai'i, where habitat transformation threatens many endemic species, ecological restoration is core to the Garden's mission and supported by diverse educational programs: visitors can see native plants at both gardens and preserves; volunteers contribute directly to restoration workdays; and college-level interns gain restoration-specific skills during their training. Onsite restoration provides many avenues for impactful education programs.



Marie Selby Botanical Gardens' restored tidal lagoon.
Photo: Marie Selby Botanical Gardens.



Marie Selby Botanical Gardens' hardwood hammock.
Photo: Marie Selby Botanical Gardens.

Knowledge Gaps and Capacity Needs

While many gardens demonstrate restoration with horticultural, scientific, and educational skill, stronger partnerships and emerging technology can improve outcomes on the grounds and beyond. Horticultural techniques for sustaining local plants and habitats can be siloed within and between institutions. Botanical gardens may have capacity for propagating regional endemic species but few outlets for those skills and plant material. Land managers may know low-cost techniques for controlling pest plants that may be less apparent to gardeners. Overcoming such information silos requires convening stakeholders with purpose. Supporting formal knowledge exchange networks, including communities of practice, where people with complementary expertise work together towards improved outcomes, is a concrete action whereby botanical gardens can leverage onsite restoration towards better habitat management.



Marie Selby Botanical Gardens' restored tidal lagoon.
Photo: Marie Selby Botanical Gardens.

At gardens with extensive preserves, naturalistic collections may be more poorly documented than others, limiting adaptive management. Popular collections management systems often lack capacity for abundant unaccessioned plants. However, ecological sampling designs supported by remotely sensed data can lower costs and increase impacts of documenting plants in natural habitats. Designs that are effective for monitoring onsite natural collections are likely suitable for monitoring restoration outcomes. By applying standardized, scalable monitoring protocols to onsite preserves and restoration areas, botanical gardens can improve habitat management while supporting broader efforts to monitor outcomes in restoration areas.

As the need for effective ecological restoration grows, demand for trained restoration professionals will increase. While education programs at botanical gardens raise awareness and provide experience, few grant widely recognized professional certifications. By aligning onsite education programs with professional standards, such as the Society for Ecological Restoration's (SER) Certified Ecological Restoration Practitioner Program, botanical gardens can support in-demand workforce development while adding value for trainees.

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CASE STUDY

Working Woods: How a Public Garden Blends Management, Research, and Outreach to Support Resilient Forests

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Working Woods spans 70 forested acres (~28 hectares). An educational building offers a home base for classes and workshops. Photo: Holden Forests & Gardens.

Project Background & Context

As public-facing institutions deeply rooted in science and conservation, public gardens (including arboreta and botanical gardens) are uniquely positioned to conserve biodiversity, while simultaneously building knowledge and inspiring conservation action well beyond their borders. This role is especially relevant for forested landscapes where stewardship decisions have far-reaching consequences. Forests, covering more than 30% of Earth's terrestrial surface, are key ecosystems that provide habitat for wildlife, regulate climate, filter water, prevent soil erosion, and sustain communities (Pan et al., 2013). Forests are also disproportionately critical to climate regulation, offering the most promising palette of natural climate solutions within the terrestrial sphere (Khaine and Woo, 2015; Griscom et al., 2017; Fargione et al., 2018). As such, climate-smart forest management is important for both protecting biodiversity and combating climate change.

Here, we discuss our experiences developing and running The Working Woods Learning Forest (Working Woods, hereafter), a 70-acre (~28 hectares) demonstration forest and living laboratory located at The Holden Arboretum in northeastern Ohio, focused on researching and showcasing a suite of forest management techniques. Working Woods serves as a place where forest management intersects with research and education to promote healthy forests by supporting landowners and practitioners (Stuble et al., 2025). The mission of Working Woods is particularly salient in this part of the world in which forests are the dominant ecosystem, and much of this land is privately owned (in Ohio, for example, more than 80% of forested land is privately owned). As a result, private landowners play a critical role in shaping the health and resiliency of our forests. Their stewardship decisions directly influence the efficacy of forests as natural climate solutions, making active management, research, and education more important than ever.



Researchers collect data to quantify forest management outcomes. Photo: Holden Forests & Gardens.

The eastern United States, once dominated by forests before conversion as a result of logging, agriculture, urbanization, and other anthropogenic forces, has seen an increase in forest cover over recent decades largely due to abandonment of agricultural lands. This has provided a huge opportunity to support forests and the services they provide. That said, these young forests differ from their old-growth counterparts in both form and function, with young forests often harboring less biodiversity and dominated by a small number of wind-dispersed tree species and high densities of nonnative shrubs in the forest understory (Oliver, 1980; Shifley et al., 1995; Goebel & Hix, 1996; Wagner & Stuble, 2024). A range of forest management techniques can be employed in these young forests to move them to more biodiverse and resilient states.

Implementation Approach: Activities, Partnerships, & Enabling Conditions

The Working Woods is, in many ways, a typical forest facing challenges reflective of those faced by many within the region. As such, management within the Working Woods serves dual purposes of supporting resiliency of the Working Woods forest itself, while also developing lessons directly applicable to regional landowners. The forest represented by Working Woods spans two distinct ecological conditions, illustrating different restoration challenges. The northern portion consists of a relatively young (approximately 70 years old), even-aged forest that regenerated naturally after previous use as pasture. The canopy of this forest is dominated by red maple, with co-occurring sugar maple and tulip poplar, while the understory supports high densities of nonnative shrubs such as multiflora rose and glossy buckthorn. In contrast, the southern portion represents a more mature forest stand containing hickory, oak, and maple, but challenged by historic over-tapping of sugar maples. Past anthropogenic land use can create challenges, with forest form and function in these forests divergent from their old-growth states, often decreasing biodiversity, productivity, and/or the quality of ecosystem services provided (Burke et al., 2016). In such cases, the central restoration challenge is often how to move younger, simplified forests toward the structural complexity and ecological function characteristic of mature forests. Rather than simply allowing forests to age passively, the project explores how active management can facilitate the transition toward more mature forest characteristics such as diverse species composition, structural diversity, and resilient ecological processes. To address this challenge, Working Woods demonstrates several methods of forest management while integrating applied research. Management includes a variety of techniques including sustainable timber harvest, timber stand improvement such as single-tree selection cuts, nonnative species management, edge feathering, and reforestation. The Working Woods largely relies on natural regeneration within the forest. That said, some of the management plots do demonstrate underplanting of native trees, as well as a variety of non-timber forest products such as medicinal and/or edible native plants. These native plantings have prioritized local provenance when possible. By demonstrating how stewardship can build structurally complex, resilient, and diverse forests, the Working Woods Learning Forest encourages thoughtful forest management as an attainable natural climate solution within forests throughout northeastern Ohio and beyond.

As a multi-faceted project blending conservation, research, and outreach, interdisciplinary partnerships have been key to the development and success of the Working Woods. This has included leveraging the full range of expertise within the Holden Arboretum, with staff from research, conservation, and community forestry programs collaborating to design, implement, and interpret projects within Working Woods. Equally important have been partnerships with external organizations, bringing outside perspective to ensure that Working Woods serves the practical needs of woodland owners while simultaneously building knowledge of best practices in forest management through applied research. Key external partners have included the Ohio Department of Natural Resources Division of Forestry, US Forest Service, local Soil and Water Conservation Districts, and university researchers. Based on preliminary conversations with forestry partners, Working Woods intentionally filled a regional need, creating a place where landowners could learn about sustainable woodland management through both research findings and real-world demonstration. As the landowner services associated with Working Woods have expanded over the years, these partnerships have remained critical to maximizing connections with diverse audiences. Today, communities and individuals who have historically had limited engagement with the Arboretum, such as forestry professionals and new landowners, use the space as a learning opportunity. Partner funding, too, has been central to the creation and growth of the Working Woods. The Working Woods Learning Forest was initially established through institutional endowment support from a local foundation. More recently, funding from the United States Forest Service through the Inflation Reduction Act enabled an expansion of the Working Woods initiative, supporting a broader network of resources, partnerships, and demonstration opportunities designed to support woodland owners across northeastern Ohio, and beyond. As part of this growth, we have been able to expand the reach of Working Woods by establishing a restoration seed bank, adding a dedicated education and outreach position, and creating a new consulting forestry business in order to individualize assistance to landowners.



Trails and interpretive signage allow visitors to experience different types of forest management firsthand. Photo: Holden Forests & Gardens.

Results & Impacts

Since initiation of forest management in 2018, we have begun to observe changes within the forest, including increased native species diversity, successful regeneration of target species such as oak and hickory, improved structural complexity with a diversity of age classes and canopy layers, and reductions in nonnative species cover. These results guide an adaptive management approach, allowing practices to be refined over time in response to observed outcomes and changing site conditions.

While conserving biodiversity and ecological function within the Working Woods itself, outreach to facilitate action beyond the Arboretum's borders is at the core of the Working Woods' mission. Through field tours, skill-building workshops, and other educational programs, Working Woods empowers individuals to steward healthy forests throughout northeast Ohio. In 2025 alone, Working Woods hosted 22 educational programs which reached more than 1,100 participants. Further, the consulting forestry pilot program completed 27 site visits and developed seven forest management plans to help landowners tailor forest management to their specific needs. To foster informal learning opportunities, two miles (~3.2 kilometers) of trails and interpretive signage were added to the Working Woods in 2025 to increase forest access and facilitate learning through unguided hikes. Visitors frequently report leaving with a deeper understanding of forest management and a desire to apply what they learn on their own land. There is power in the use of real-world demonstrations of forest management, allowing participants to see multiple types of forest management all in one place, making forestry practices more approachable.

In addition to connections with the woodland owners, the Working Woods also drives novel research findings, which are shared with both the scientific and land management communities. To date, scientific publications have ranged from studies of management-driven shifts in understory biodiversity (Wagner & Stuble, 2024) to the long-term efficacy of nonnative shrub management (Jenkins et al., 2025). When appropriate, publications have targeted journals with expressed aims of facilitating communication of scientific research with direct relevance to land management. Since 2023, research taking place in the Working Woods has resulted in four scientific publications. We also work with a science communicator to translate research for the public, which has resulted in many blog posts and several magazine articles. Working Woods' blending of research and outreach demonstrates how restoration actions within the natural areas of public gardens can catalyze broader stewardship to support healthy ecosystems and strengthen communities.

Lessons Learned & Recommendations

Public gardens are uniquely poised to undertake ecosystem restoration, as well as research best practices and inspire action among landowners. This is particularly critical in regions in which a majority of natural lands are privately owned. The Holden Arboretum has leveraged diverse skillsets within the organization, along with regional partnerships, to build the Working Woods – now a regional hub for the support of climate-smart stewardship of forests – through a unique combination of research and outreach. Collaboration has ensured that within the Working Woods restoration, research, and educational efforts are scientifically grounded, practically relevant, and shared with the broader community.

Public gardens can leverage internal expertise and biological assets with external partnerships to offer durable and timely solutions to environmental challenges within their regions. In addition to the work of individual public gardens, future work should also focus on scaling efforts regionally to amplify impacts. Ultimately, projects like this highlight the importance of targeted, collaborative stewardship in the context of research and outreach to meaningfully advance plant-based solutions to climate change.

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Recommendations Report

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Garden-based learning activities foster connections between people, plants, and local food systems at the Edible Academy at the New York Botanical Garden.
© New York Botanical Garden. Photo: Marlon Co.

Restoring the world's ecosystems matters. The widespread loss of ecosystem services, biodiversity, habitat, and nature-based livelihoods means we must work together to restore nature and heal degraded lands. Recognizing this, the United Nations has declared 2021–2030 as the Decade on Ecosystem Restoration, calling for 350 million hectares of degraded land to be under restoration by 2030 through ecological restoration and rehabilitation, including sustainable land-use approaches. Meeting this goal requires mobilizing every available source of expertise and capacity.

Ecosystem restoration is not only a challenge of scale, but also of quality. Achieving resilient, biodiverse, and ecologically effective outcomes requires restoration efforts to be grounded in sound ecological design, appropriate species selection, and locally relevant knowledge. Botanical gardens can make important contributions in these areas through their expertise in plant science, ecology, horticulture, propagation, and long-term stewardship. By supporting locally-led restoration efforts, botanical gardens can help strengthen both the quality and long-term success of restoration outcomes.

The five recommendations below synthesize insights from across this volume to highlight priority actions for strengthening the role of botanical gardens in restoration. In alignment with the forthcoming **Nurturing Nature Initiative Action Plan** (Fall 2026), these recommendations emphasize enabling implementation, enhancing restoration quality, building long-term capacity, and improving coordination across a global network of gardens.



Community volunteers planting native woody species to support forest ecosystem restoration. © New York Botanical Garden. Photo: Marlon Co.

Recommendation 1: Enable Botanical Gardens to Support Locally-Led Ecosystem Restoration

Findings presented throughout this volume suggest that many restoration efforts are constrained not only by limited resources and capacity, but also by challenges related to species selection, plant material availability, ecological planning, and long-term management. Botanical gardens are well positioned to help address these challenges through their expertise in plant diversity, horticulture, seed conservation, propagation, and restoration practice. Working alongside local communities, practitioners, governments, and other partners, botanical gardens can help improve the quality, resilience, and long-term effectiveness of restoration efforts. The **Nurturing Nature Initiative** offers one mechanism to connect this expertise and support to the local projects that need it most, ensuring botanical knowledge is plugged into on-the-ground restoration efforts where it can have the greatest impact.

Key strategic priorities should include:

- **Guidance and decision-support tools** that strengthen ecological design, species selection, and restoration planning, helping practitioners select appropriate species, increase biodiversity outcomes, and improve long-term ecosystem resilience.
- **Flexible funding mechanisms** to allocate staff time, sustain partnerships, and continue engagement in restoration projects over the long timeframes needed for ecosystem recovery.
- **Practical tools, protocols, and technical resources** to support restoration planning, species selection, seed collection, nursery development, propagation, planting, and monitoring.
- **Context-specific training resources** tailored to local ecological and cultural conditions, so garden staff and partners can apply best practices in their local environments.
- **Partnership frameworks** that integrate botanical gardens' plant expertise directly into restoration initiatives led by communities or other agencies.

These enabling measures will position botanical gardens to support locally-led restoration efforts more effectively and at greater scale, turning their knowledge and resources into tangible ecological gains on the ground.

Recommendation 2: Invest in Long-Term Capacity Strengthening

Successful ecosystem restoration requires skilled practitioners, institutional continuity, and opportunities for adaptive learning. Moving beyond short-term projects toward sustained capacity development within botanical institutions is essential. We recommend significantly investing in capacity and workforce development for botanical gardens and the local restoration practitioners they support through measures such as:

- **Applied, field-based training** in propagation, nursery management, restoration planning, implementation, and monitoring, ensuring garden staff gain hands-on skills in real-world restoration environments.
- **Mentorship and exchanges** that connect garden teams with experienced restoration practitioners and broader professional networks (e.g., the Society for Ecological Restoration's (SER) Certified Ecological Restoration Practitioner (CERP) Program), to support alignment with established restoration practices, principles, and standards.
- **Peer learning networks** linking gardens operating in similar ecological or institutional contexts, fostering mutual support and sharing of best practices across regions.
- **Leveraging new technologies** (e.g., artificial intelligence tools) to accelerate learning about restoration techniques and outcomes, making knowledge transfer more efficient across the network.

Embedding these capacities within botanical gardens helps retain specialized expertise and supports restoration over the decades-long horizons required for lasting impact.

Recommendation 3: Strengthen Coordination, Learning, and Knowledge Exchange

Many restoration efforts remain fragmented, and botanical gardens are often underutilized within formal restoration, biodiversity, and climate adaptation strategies, despite their global knowledge and impact. Improving outcomes will require a more unified approach to knowledge exchange and coordination across the global botanical garden network. Botanical gardens should adopt shared learning systems to connect local experiences with global best practices to address ecosystem restoration. The **Nurturing Nature Initiative Action Plan** provides a primary framework for this coordinated learning and implementation. Key elements include:

- **Long-term monitoring and learning systems** that enable restoration practitioners to evaluate outcomes, share evidence, and adapt approaches over time.
- **Standardized yet adaptable tools and protocols** that harmonize monitoring, reporting, and planning approaches while maintaining scientific rigor and remaining adaptable to local ecological and socioeconomic contexts.
- **Shared case studies and lessons learned** that facilitate regular exchange of restoration success stories, protocols, and failures across sites so gardens can learn from each other's experiences.
- **Spatial and analytical planning tools** that utilize geospatial data and analytic models to help gardens identify restoration opportunities and plan interventions in a coordinated manner.
- **Regular synthesis and reflection** through periodic workshops or publications that distill collective insights from across the network to inform adaptive management and continuously improve practices.

By strengthening these shared learning systems, botanical gardens can transform fragmented efforts into a more cohesive global restoration community.

Recommendation 4: Center Equity, Indigenous Leadership, and Community Stewardship

Long-term restoration success depends on inclusive partnerships with Indigenous Peoples and Local Communities (IPLCs). Indigenous cultures possess Traditional Ecological Knowledge (TEK) from millennia of managing and relating to their environments, and all IPLCs are key to restoration success or failure. Combining this TEK with scientific expertise creates more resilient restoration approaches. Effective community-centered restoration efforts are characterized by:

- **Participatory planning and shared decision-making**, giving local stakeholders a voice in setting goals and methods.
- **Respect for rights, TEK, and fair benefit-sharing**, ensuring that restoration work honors cultural heritage, yields tangible benefits, and is implemented with free, prior and informed consent from IPLCs.
- **Inclusive access to training, jobs, and leadership opportunities** within restoration projects, so that IPLCs drive the work alongside external experts.

As locally embedded institutions, botanical gardens are well positioned to support these long-term relationships, providing continuity, training and institutional backing to community-led efforts. Botanical gardens also have a unique role in bridging scientific and TEK systems through their public outreach and education programs.



Botanical field teams traveling through a tropical forest landscape during plant survey and research activities. © New York Botanical Garden.

Recommendation 5: Strengthen the Global Network of Botanical Gardens

The global network of botanical gardens represents a substantial but under-coordinated resource for restoration. Many gardens currently work in isolation, achieving high-quality local impacts but limited global influence. Greater collaboration can elevate their combined contributions, making the whole more than the sum of its parts. Key steps to better align and amplify this network include:

- **Scaling up collaboration** among botanical gardens, NGOs, governments, and research institutions internationally, moving beyond isolated projects to joint programs and consortia.
- **Expanding and strengthening existing frameworks** such as the Ecological Restoration Alliance of Botanic Gardens, The Global Biodiversity Standard, and regionally focused botanical garden and restoration initiatives to broaden participation, improve coordination, and increase their impact on restoration outcomes.
- **Integrating botanical gardens into policy processes**, and aligning their work with local, national, and global restoration strategies by incorporating their scientific expertise into policy development and implementation.
- **Developing funding models that incentivize collaboration**, encouraging shared learning across gardens and regions.
- **Building global solidarity initiatives**, where resources and expertise from wealthier gardens or countries support restoration efforts in less-resourced regions.
- **Developing a unified voice** for botanical gardens in advocating for ambitious restoration goals, raising public awareness, and influencing policy through collective action.

By strengthening global and regional networks, botanical gardens can achieve far greater impact than by working alone, while still maintaining the diversity of regional approaches and institutional missions.

Concluding Perspective

Some botanical gardens around the world already deliver high-quality ecological restoration at local scales, contributing native plant expertise and engaging communities to heal degraded habitats in their regions. Yet their collective potential remains underutilized on the global stage. Better coordination, targeted investment, and shared learning could enable botanical gardens to strengthen restoration quality, improve biodiversity and climate resilience outcomes, and increase collective impact across regions and restoration contexts.

The next phase of the **Nurturing Nature Initiative** is poised to turn this potential into reality. Its forthcoming Action Plan will focus on establishing botanical gardens as long-term interconnected regional hubs for ecosystem restoration, linking cutting-edge plant science, traditional knowledge, community stewardship, and shared learning across continents. This coordinated network approach will implement the above recommendations, providing a model to amplify botanical gardens' contributions to global restoration and climate resilience while remaining adaptable to diverse ecological and cultural contexts.

Glossary

This glossary is adapted and expanded from existing glossaries in the Society for Ecological Restoration (SER) Principles and standards for the practice of ecological restoration (SER Standards; Gann et al., 2026) and The Global Biodiversity Standard: Manual for assessment and best practices (Bartholomew and Mosyaftiani et al., 2024).

Adaptive management – the incorporation of deliberate learning into professional practice to reduce uncertainty in decision-making in complex or unpredictable systems such as ecosystems. Specifically, it is the integration of design, management, and monitoring to enable practitioners to systematically and efficiently test key assumptions, evaluate results, adjust management decisions, generate learning, and ultimately, improve outcomes.

Arboretum – a managed and documented collection of living woody plants, maintained for research, conservation, education, and/or display. An arboretum is generally considered a specialized type of botanical garden focused primarily on woody plants.

Biodiversity – the variability among living organisms from terrestrial, marine, and other aquatic systems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems. In global environmental agreements and guidance documents, this term is most often used to refer to the Earth's native organisms and the native ecosystems of which they are part.

Botanical (also "botanic") **garden** – a managed collection of living plants, documented according to scientific standards and maintained for research, conservation, education, and display.

Climate change – a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere, and which is in addition to natural climate variability observed over comparable time periods.

Climate resilience – landscapes, communities, and individual livelihoods that are well suited to face rising temperatures, changing weather patterns, droughts and other effects of climate change.

Community well-being – the combination of social, economic, environmental, cultural and political conditions identified by individuals and their communities as essential for them to flourish and fulfill their potential.

Cultural values – the shared beliefs and priorities that influence the behaviors and decisions of members of a community or group.

Degradation (of an ecosystem) – a level of deleterious human impact to an ecosystem that results in the loss of biodiversity and simplification or disruption in its composition, structure and functioning, and generally leads to a reduction in the flow of ecosystem services.

DNA bank (also "tissue bank") – a centralized repository that preserves extracted DNA and dried tissue from plant, fungal, or algal samples for long-term storage and scientific research.



A hummingbird visits flowering plants in the Perennial Garden at the New York Botanical Garden. © New York Botanical Garden. Photo: Marlon Co.

Ecological restoration – the process of assisting the recovery of a native ecosystem that has been degraded, damaged, or destroyed. It aims to recover a native ecosystem to the state it would exhibit in the absence of degradation, while accounting for environmental change. (Ecosystem restoration is sometimes used interchangeably with ecological restoration, but ecological restoration always addresses biodiversity conservation and ecological integrity, whereas some approaches to ecosystem restoration may focus solely on the delivery of ecosystem services.)

Ecosystem – a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit. The term ecosystem can be used to describe a functional ecological assemblage, native or non-native, of any size or scale.

Ecosystem restoration – the process of halting and reversing degradation, resulting in improved biodiversity, ecosystem integrity, and ecosystem functions and services. Ecosystem restoration encompasses a wide continuum of practices, depending on local conditions and societal choice.

Exceptional species – plant species that cannot be preserved long-term using conventional seed banking methods (drying and freezing at -20°C). Instead, they require specialized preservation techniques, such as cryopreservation, tissue culture, or maintenance in living plant collections.



A botanical researcher uses a pole pruner to collect plant specimens from the forest canopy. © New York Botanical Garden.

***Ex situ* conservation** – the conservation of components of biological diversity outside their natural habitats through approaches such as seed banking, tissue culture, cryopreservation, and the maintenance of living plant collections.

Genetic diversity – the variety of alleles and genotypes present in a population, which is reflected in morphological, physiological, and behavioral differences between individuals and populations.

Herbarium – a curated collection of preserved plant, fungal, and algal specimens and associated data used for long-term scientific study, research, and conservation.

Indigenous knowledge (IK) – knowledge and practices learned from experience and observation, and passed from generation to generation informed by strong cultural memories, sensitivity to change, and values that include reciprocity. It is often used interchangeably with Traditional Ecological Knowledge (TEK), which specifically focuses on ecological and environmental knowledge.

***In situ* conservation** – the protection of ecosystems and natural habitats, and the maintenance and recovery of viable populations of species in their natural surroundings.

Interested and affected parties – any individual, group, or institution that has a vested interest in or can influence a project and/or that potentially will be affected by the project and has something to gain or lose if conditions change or stay the same. Interested parties are all those who need to be considered in achieving project goals and whose participation and support are crucial to its success.

Invasive species – species introduced by humans beyond their historical range that spread and cause harm to ecological and/or socioeconomic systems.

Local community – a group of people who live in or near a project area, who share a set of institutions that order all aspects of social life and could be affected by a conservation or restoration project.

Native species – taxa considered to have their origins in a given region or that have arrived there without recent (direct or indirect) transport by humans. Among ecologists, debate exists over how precisely to define this concept.

Natural regeneration – germination, birth, or other recruitment of biota including plants, animals, and microbiota, whether arising from colonization, dispersal, or *in situ* processes. It may occur spontaneously after the removal of the degradation causes or be assisted or facilitated through restoration interventions. The degree of natural regeneration potential in a degraded ecosystem will depend on the extent and duration of the negative impacts and whether they resemble states to which the ecosystem's species have adapted over evolutionary time frames.

Nature-based solutions – actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits.

Plant acclimatization – the gradual adaptation of plants to new climates and conditions.

Preserved botanical science collections (PBSCs) – organized, long-term biological repositories that conserve plant, fungal, and algal diversity. They maintain specimens and associated data in multiple formats for research, taxonomy, evolutionary studies, and conservation. PBSCs include distinct collection types, defined separately under **Herbarium, Seed bank**, and **DNA bank**.

Propagation – the process of creating new plants from existing ones through natural or artificial means, encompassing sexual (seeds) and asexual/vegetative (cuttings, cloning) techniques.

Propagule – any biological material that functions in propagating an organism. Propagules are produced by plants, animals, fungi, and microorganisms.

Provenance – the original geographic source of seed, pollen, or propagules.

Provenancing – the strategy for selecting from where propagules are sourced to support genetic diversity, climate resilience, and long-term project success.

Rare species – species which have a restricted (world) range.

Recovery (of native ecosystems from degradation) – describes the outcome of restoration where an ecosystem regains its integrity, including its composition, structure, and function, through the return of biota and interactions between them and their abiotic environments (as biota grow, breed, recruit, and ultimately build ecosystem complexity). In ecological restoration, recovery, relative to the levels identified for the reference model, is assisted by restoration activities and can be described as partial or full. A key indicator of recovery includes demonstrated or predicted capacity for self-perpetuation of the focal biota.

Reference ecosystem – a representation of a native ecosystem that is the target of ecological restoration (as distinct from a reference site). A reference ecosystem usually represents a non-degraded version of the native ecosystem complete with its flora, fauna, and other biota, abiotic elements, functions, processes and successional states that might have existed on the restoration site had degradation not occurred, adjusted to accommodate changed or predicted environmental conditions.

Reference model – a model that indicates the expected state (in its highest integrity condition) that the restoration site would exhibit in the absence of degradation (with respect to flora, fauna and other biota, abiotic elements, functions, processes, and successional states), reflecting background and predicted changes in environmental conditions. It is not the historical state, nor the baseline condition, but represents a benchmark against which the condition of the site is measured prior to, during, and after restoration.

Reference site – ideally, an undegraded or nearly undegraded extant site that has attributes and a successional phase similar to the restoration project site and that can be used to inform the development of a reference model. Where possible, the reference model includes information from a suitable number of extant reference sites.

Rehabilitation – management actions that reinstate attributes of some physical properties (e.g., soils, water) and a level of ecosystem functioning on degraded or converted sites, along with a renewed or improved and ongoing provision of high-quality and diverse ecosystem goods and services. Native biodiversity and ecosystem integrity are supported but actions do not achieve substantive recovery of a native ecosystem.

Reintroduction – the intentional return of biota, usually individuals of a given population or species, to an area where they previously occurred.

Restoration ecology – the branch of science that provides concepts, models, methodologies, and tools for the practice of ecological restoration, often in collaboration with other scientific and professional disciplines and cultural practices. It benefits from direct observation of and participation in restoration practice.

Restoration practitioner – an individual who applies practical skills, as well as knowledge from a range of sources, to engage in ecological restoration tasks at project sites. Practitioners may be adept at different aspects of restoration practice, whether planning, implementation, or monitoring, depending on training and experience.

Seed bank – a technical facility that collects, processes, and stores seeds at low temperatures and low humidity to preserve genetic diversity and support their potential use in future planting.

Taxonomic group – an organism's location in the biological classification system used to identify and group organisms with similar physical, chemical, and/or structural composition.

Threatened species – number of species at risk of extinction in proportion to the total number of native species. Species in the Vulnerable, Endangered, and Critically Endangered categories in the IUCN Red List are collectively described as 'threatened'.









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