Terraformation

The Global Seed Bank Index

Thousands of Seed Banks Are Needed to Address Seed Supply Shortages in Ecosystem Restoration

Executive Summary

The Challenge

Native ecosystem restoration — with the right plants in the right places — is currently the best carbon sequestration solution that is proven both effective and scalable[i]. In addition to addressing climate change, ecosystem restoration can simultaneously stem biodiversity loss. Though many actions are urgently needed to address these interrelated crises, including greenhouse gas emissions reduction and protection of existing ecosystems, the United Nations (UN) Decade on Ecosystem Restoration[ii] recognizes the urgent need to reverse ecosystem degradation to address these global crises, enhance human livelihoods, and meet UN Sustainable Development Goals.

However, we face a critical bottleneck to achieving restoration at scale: native seed supply. Restoration using biodiverse, properly sourced, native species is key for long-term ecosystem resilience and success. Yet wild seed sources are declining due to land degradation and climate change, while restoration challenges cause significant seed waste. Fulfilling the global restoration potential in 10 years without improving seed supply systems will likely lead to unsustainable harvests and harm to native ecosystems.

The Solution

A restoration toolkit can include a variety of components to enable planting success. This paper focuses on the critical contributions of seed banks, which use standardized methods for drying, cooling, storing, and testing seeds to preserve viability for several years. A global network of restoration seed banks can fill long-recognized gaps in infrastructure to prevent delays in planting from poor harvest seasons, enable emergency revegetation with locally adapted species, scale up native seed farming, dramatically reduce seed waste, and empower local communities with seed sovereignty. Seed banks that are equipped to ensure seed quality help generate economic opportunities through native seed production and sales. Restoration seed banks can also support research, which further improves restoration outcomes.

Our Study Approach

We investigated where and how many seed banks are needed to meet the global restoration potential (RP)[III], defined here as the total land area available for ecological restoration. At the country level, we combined the area of RP and the number of existing seed banks that store native species to assess gaps in seed bank capacity to support restoration. Using published literature on highly variable factors of seed germination rates, plant densities, and survival rates, we estimated how much RP a small restoration seed bank can support. Finally, we calculated the number of seed banks needed under different theoretical "need for seeds" scenarios to account for the high variation in the number of seeds required.

Note that country-specific recommendations were developed from a global perspective. Anyone planning or establishing a seed bank must consider local legislation on genetic materials, biodiversity conservation, and natural resources, as well as other local regulations, social/political situations, and considerations.

What We Found

Worldwide, there are 410 seed banks with the potential to support ecosystem restoration, but almost all countries would benefit from having more. A small seed bank can support an estimated 2,200 to 22,000 hectares of planting, and an estimated 46 to 450 seed banks are needed per million hectares of RP, depending on the "need for seeds" scenario. The four countries needing the most seed banks (USA, Australia, Brazil, and China) are among those with the most existing seed banks; however, they also have the greatest RP and total land area.

Despite having less land area, many countries in Sub-Saharan Africa, Latin America, and Asia could still use hundreds or thousands of seed banks to support their RP. The tropics are recognized as the highest priority for restoration based on biodiversity, climate benefits, and cost-effectiveness[IV]. Thus, even a small number of added seed banks in the tropics and other biodiversity hotspots can have major positive impacts on the environment.

Conclusions

A global hub-and-spoke seed bank network would support the UN Decade on Ecosystem Restoration and planting commitments of hundreds of countries and organizations, improving restoration outcomes, preserving threatened plants, sustainably expanding native seed supply systems, and benefiting local communities. Seed banks vary in capacity; in addition to smaller local seed banks, larger regional seed banks could help meet the need for seeds more efficiently. Such a global seed banking network would also empower biodiversity preservation and contribute to Sustainable Development Goals (SDGs).

Calls to Action

Local restoration organizations can greatly benefit from seed banking.

People already restoring ecosystems on the ground who seek to scale their work are ideal candidates to add seed banking to their restoration toolkits. Seed banks can provide new economic opportunities for communities, while improving restoration outcomes and quality of life with healthy ecosystems.

Businesses play a critical role by investing in restoration.

Many businesses prioritize corporate social responsibility within their strategic plans and supply chains. Seed banks are foundational infrastructure with measurable outcomes that directly enable restoration, climate change mitigation, and contributions to SDGs. Businesses can sponsor seed bank establishment and operations to realize sustainability goals.

Government support can help scale seed supply systems.

Government provision of centralized seed banks could enable long-term storage at larger scales, while investment in a hub-and-spoke network of seed banks could empower much-needed localized restoration with adapted, resilient seeds at finer scales.

Everyone can help raise awareness of seed banking as a valuable restoration tool.

Tree planting gets a lot of attention, but whole-ecosystem restoration is far more effective at climate mitigation. However, climate change and other stressors are rapidly depleting native seed sources. A seed bank network can address the seed supply bottleneck, improving species and genetic diversity for more resilient plantings. It can dramatically reduce seed waste, promote sustainable harvests, and empower local livelihoods. Sharing this message is essential if the world is to achieve planting commitments while also restoring biodiversity and mitigating climate change.

I. IPCC (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.
II. www.decadeonrestoration.org
III. Bastin et al. (2019). The Global Tree Restoration Potential. *Science*, 365(6448), 76–79.
IV. Strassburg et al. (2020). Global Priority Areas for Ecosystem Restoration. *Nature*, 586, 1–6.

The Global Seed Bank Index:

Thousands of Seed Banks Are Needed to Address Seed Supply Shortages in Ecosystem Restoration

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Native ecosystem restoration — with the right plants in the right places — is currently the best carbon sequestration solution that is proven effective and scalable[1]. While it is critical for humans and industries to reduce carbon emissions, stop deforestation, and protect existing ecosystems, the world also needs to address the excess carbon in the atmosphere that will still exist even after we achieve net zero greenhouse gas emissions. We need to do this as quickly as possible by scaling up restoration now (Box 1). However, we cannot address climate change without simultaneously addressing biodiversity loss, and vice versa[2]. The United Nations (UN) Decade on Ecosystem Restoration recognizes the urgent need to reverse the degradation of ecosystems worldwide to achieve both of these aims, while also enhancing human livelihoods[3].

> **"We cannot address climate change without simultaneously addressing biodiversity loss, and vice versa.**

To accomplish all these goals, humanity needs to plant enough forests to meet the global restoration potential, but also ensure renewal of ecosystem services and achievement of Sustainable Development Goals (SDGs). Trees alone do not equate to a forest; restoration projects must also include shrubs, herbs, grasses, ferns, and other understory plants that make up healthy ecosystems and support local livelihoods.

Though natural regeneration can restore some degraded ecosystems, in most areas of restoration potential, restoration requires human intervention through assisted natural regeneration, direct seeding, direct planting, or a combination of these methods[4]. To implement all these approaches, we first need to source the seeds that grow the plants used for restoration. Inadequate seed supply is globally recognized, yet often overlooked, as one of the major bottlenecks to restoration[5,6,7,8,9].

Planting monocultures of fast-growing trees to quickly capture carbon has sometimes resulted from a genuine concern about climate change. However, often these trees are non-native species and not well adapted to their new planting environment. Not only are monoculture plantations less resilient and more susceptible to environmental stressors — they can also lead to ecosystem imbalances with socioeconomic impacts, such as water stress[10]. Some tree-planting organizations are only planting a handful of species, simply because those are the only ones available to purchase at local nurseries. These are often exotic species as well, and could even become invasive, harming local ecosystems.

Even when people do collect and use native seeds, they often only collect from a small percentage of species that grow naturally in the area, perhaps only trees, which do not represent the whole community of species that sustain forest ecosystems. In a survey of 120 restoration projects, an average of just 5 to 10 species were used (depending on restoration method), and respondents cited seed or seedling availability as the major constraint to species richness in their projects[11]. In another survey of 139 restoration projects, over 40% of respondents said that challenges associated with obtaining seeds and plants resulted in higher costs, delays, and using fewer species than planned[12].

In addition to low species diversity, restoration projects often face problems with poor genetic diversity within the species they do plant. Often seeds are only collected from a few mother trees and consequently have low genetic diversity, which means the planted trees and resulting forests will be more susceptible to pests, diseases, and other environmental stressors[13]. Therefore, using poorly sourced seeds or plants can cause restoration projects to fail and can even harm local ecosystems and biodiversity. These threats call for sourcing native and diverse seeds from appropriate locations, either from the region or from similar ecosystems near the planting location.

Native plants — plants found naturally in a specific region — are more likely to thrive and contribute to the three pillars of sustainability: society, environment, and economy. They will continue to provide goods and services derived from the ecosystem, essential for Indigenous or local communities that have traditionally used native plants for food, shelter, medicine, and other culturally important needs[14]. The societal and economic needs of millions of people who rely on forested ecosystems can be met by restored native forests[15].

> **"Minimizing seed waste to avoid overharvesting from wild plants is an urgent challenge to address if we are to meet international restoration goals.**

Seed banking based on sound science can contribute to 4 of the 6 Global Forest Goals and 9 of the 17 SDGs directly, and all the other goals indirectly[16,17]. It also directly contributes to Target 8 of the UN Convention on Biological Diversity's Global Strategy for Plant Conservation[18].

Without a holistic ecosystem approach, restoration efforts may not result in resilient, healthy, and sustainable forests that also support the multitude of ecosystem services a forest provides. Species diversity is essential. Because native plants are well-adapted to their home region, they can better survive local climate stressors such as heat, fire, storms, or variations in water availability. Seed collections that are more representative of natural ecosystems can establish plant communities that provide water capture for regeneration of aquifers, shade that helps retain moisture, leaf litter for nutrient cycling, habitat for animals and insects, landscape resilience, and much more. The UN Decade on Ecosystem Restoration calls for urgent action from now until 2030, and it is critical to collect and store seeds even sooner, as seeds are only one of the first steps in restoring healthy ecosystems. However, restoration is an ongoing process if projects are to be successful and sustainable, so we are evaluating the need for seed banks over the next 10 years. Minimizing seed waste to avoid overharvesting from wild plants is an urgent challenge to address if we are to meet international restoration goals. A global network of seed banks, and building the socioeconomic capacity to support them, are solutions to this challenge.

BOX 1

Community seed networks and traditional practices

The Society for Ecological Restoration defines **ecological restoration** as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed"[19]. Seed banks can support ecological restoration in nearly any ecosystem where restoration benefits both the land and the local community. Restoration seed banks[20] store and deliver large quantities of high-quality native seeds to support these landscape-level planting projects, but they can also support numerous other objectives simultaneously.

Many projects focus on **forest restoration** because trees are the largest terrestrial carbon sink, especially when they are part of a healthy ecosystem that includes the rest of the plant community. However, we also recognize the importance of restoring wetlands, grasslands, savannas, mangroves, shrublands, peatlands, and other natural ecosystems.

What about **deserts**? Conservation and restoration of native desert ecosystems are also important. Additionally, we support combating *desertification*[21] with reforestation. This involves restoring land *that used to be forested* before it became degraded by unsustainable land use practices or climate change.

What about **boreal forests, tundra, and taiga**? Most ecologists agree that these biomes should be protected from degradation and conserving them provides the highest contribution to climate change mitigation in these areas. These biomes can also be highly challenging for restoration efforts. For these reasons, we excluded them from the calculation of land included in restoration potential (see Appendix).

Why Seed Banking?

A restoration toolkit can include various components to enable planting success, including seed collection, seed production, seed storage, nurseries, plant propagation techniques, and a variety of strategies for site preparation, planting, maintenance, monitoring, and adaptive management. These on-the-ground aspects often need support from components such as funding mechanisms, business models, research, technology, training, education, and outreach. This paper focuses on the critical contributions of seed banks, which use standardized methods for drying, cooling, storing, and testing seeds to preserve the viability of banked seeds for several years.

What is seed banking?

Seed banking is the practice of cleaning, drying, storing, and testing seeds, using methods that preserve seed viability, so they can be used in the future.

Step 1

Cleaning

Remove seeds from fruits, separating them from chaff or pulp so that the seeds are less likely to mold or rot, and they take up less space.

Step 2

Drying

Dry seeds under controlled temperature and humidity until they reach appropriate relative humidity targets — again to avoid mold and rotting, but also to significantly extend the length of time the seeds stay viable.

Step 3

Storage

After seeds are dried properly for storage, package them in airtight containers. Not all seeds are stored the same way, but if dry seeds can be stored refrigerated or frozen, they stay viable for even longer.

Step 4

Testing

For seeds that are not used quickly, seed banks have different options for monitoring seed viability over time, such as germination testing.

Step 5

Withdrawal

Withdraw seeds for planting while they are still viable, then replenish supplies of stored seeds with fresh collections to continue the cycle.

Drying is the most critical step to keep seeds viable for future use. Seeds begin aging and losing viability, mainly from exposure to heat and moisture, after they are removed from the mother plant. It is essential that the steps above — especially drying — be performed soon after seed collection to avoid wasting seeds. Without drying, most seeds lose viability within weeks or months. Cool storage can extend seed longevity, or how long seeds stay viable in storage, by slowing their metabolism. However, if fresh seeds are placed in a refrigerator, the water inside them can cause rotting — like fresh produce kept in a refrigerator too long. If fresh seeds are placed in a freezer, the water inside them forms ice crystals and expands, damaging cells — similar to how a glass bottle full of water will burst in a freezer. Both can kill the seeds. On the other hand, if seeds are dried to proper levels, just enough water remains inside to keep them alive, without causing the problems described above. Drying seeds and sealing them for storage in a dry environment are essential steps for preserving seed quality, viability, and longevity in storage, which makes climate control necessary in humid regions.

If seeds are both dried and stored at cold temperatures, many can be banked for years, decades, or even centuries[22]. This is true for most species, while an estimated 8% of species may have seeds that quickly die if they begin to dry out ("recalcitrant" seeds)[23]. Seed banks can help identify these seeds, and possibly store them temporarily under carefully controlled conditions (Appendix section 4.g.ii).

> **"If seeds are both dried and stored at cold temperatures, many can be banked for years, decades, or even centuries.**

Seed banking is built on proven practices. Humans have stored seeds for practical purposes — such as sustainable agriculture and food security — for millennia. Seed banks can also be important for scientific research and species conservation. Modern seed banks with climate-controlled laboratories, including those that bank wild native seeds, such as the Kew Millennium Seed Bank, have also existed for decades. Much like ecosystem restoration, seed banking is tried and true. The restoration community owes a debt of gratitude for the wealth of scientific knowledge established by diverse sources, from Indigenous seed-saving practices to large seed banks at established research institutions. Building on this foundation, there is a growing global movement to increase seed banking capacity[24] informed and guided by diverse expert perspectives.

In addition to seed banks, there are ways to temporarily store seeds (up to a year or so). These can include local or Indigenous practices, or innovative low-cost methods using hand-built equipment for processing seeds. They often include traditional drying and short-term storage methods (Box 2). These methods can work well for small-scale restoration projects, if they do not face bottlenecks or need large quantities of seeds. In some regions, centralized seed banking can also be effective if projects are small enough to rely mostly on their own nurseries and/or temporary seed storage, with a centralized seed bank as a backup. However, to meet global goals, there are excellent opportunities to build on existing local knowledge and/or connect short-term seed banks with long-term facilities in a hub-and-spoke network.

Seed banking addresses bottlenecks in native seed availability and diversity. Wild seeds are urgently becoming a more limited resource, and the seed supply bottleneck is an increasing challenge to ecosystem restoration[25,26]. Restoration projects already face problems with sourcing seeds from a variety of local, native species; and limited genetic diversity (with seeds collected from only a few mother plants) leads to decreased planting resilience[27,28]. At the same time, global experts acknowledge that intensely scaling up restoration efforts is critical to fighting climate change and biodiversity loss. For over a decade, ecologists have recognized that there is a huge gap in infrastructure and capacity for restoration seed banking, and that seed storage using international standards is critical to maintain seed viability, help avoid waste of up to 90% of seeds used in projects, and meet restoration goals and commitments[29,30,31,32]. Other solutions besides seed banks may be appropriate at localized levels. However, if we are to scale seed supply systems to meet the global restoration potential within 10 years while enabling sustainable collection practices and protecting ecosystems from overharvesting, seed banks are an essential part of the worldwide restoration toolkit.

BOX 2

Community seed networks and traditional practices

Indigenous peoples have practiced seed-saving methods for generations. Such traditional and local knowledge is the scientific foundation for current seed banking practices and continues today. Below are three insightful case studies.

Community seed banks (CSBs) are a well-established and still active practice, especially in Africa, Asia, Latin America, and the Caribbean[33]. While the large majority of CSBs preserve agricultural crop seeds, they offer diverse economic benefits to smallholder farmers and a model that could expand to native seeds. They often use traditional methods, such as drying seeds in the sun and storing them in mud-sealed containers. Since most seeds still age relatively quickly using these methods, almost all CSBs germinate and replenish their seed stocks annually to maintain viability. For this reason, some CSBs have gradually replaced some traditional methods with more modern equipment. One way to establish new CSBs, if communities desire them, is to start with practices that communities are already experts in, and transition to more technical storage equipment and methods.

In East and Southern Africa, CSBs are crop-focused and decentralized, but they were not always well networked for sharing knowledge, experience, or seeds[34]. Smallholder farmers began facing serious challenges with seed supply exacerbated by the Covid-19 pandemic. In response, local organizations joined forces to connect CSBs to each other, as well as to national seed banks with long-term storage capability.

Results included more robust agricultural systems, technical training, improved seed testing, and development of databases for tracking seeds and linking CSBs. Ecosystem restorationists could establish similar hub-and-spoke networks of long-term and short-term seed banks and adapt this model to help address the native seed supply bottleneck.

Successful economic models of community-led seed supply systems are also found in Brazil and Australia, where Indigenous peoples are the stewards of native ecosystems, expert seed collectors, and in some cases, native seed farmers and producers[35]. While the communities use traditional practices in collection, production, and some processing, modern seed bank facilities provide the infrastructure for proper storage and testing to ensure the viability and quality of seeds for sale. They also coordinate the distribution of inventory. The seed banks may be physically located outside the communities; however, local knowledge is incorporated in technical development, and community members are empowered with opportunities in leadership in all aspects of the seed supply chain.

Why Now?

Human impacts have significantly affected seed availability and quality. Degradation of natural ecosystems — including biodiversity, soil chemical processes, and water and temperature cycling — directly affects plant growth and reproduction processes, including seed production. Extreme climate events, which are predicted to continue increasing in frequency and severity due to climate change[36], can also alter flowering cycles, pollination, and seed production[37]. Changes in land use, import/export practices, and climate have caused increases in pests, invasive species, and diseases that can negatively impact potential seed sources[38]. All these conditions limit what seeds are available in each season. If a backup supply of native seeds is lacking, restoration projects can be forced to compromise on biodiversity or lose a whole season (or more) of propagation.

Rapid disaster response improves landscape resilience. Disasters such as droughts, heat waves, major storms, and wildfires are increasing in severity and frequency as the climate changes. Not only does this kill or slow the growth of existing trees, it also limits the ability of forests to regenerate naturally with seedlings, which often die in subsequent fires or droughts[39]. If seeds are not readily available, revegetation of these landscapes is generally limited to few species or even monocultures, and often relies on non-native species poorly adapted to the area. With each fire cycle or storm season (where ecosystems are not adapted to those conditions), we are rapidly losing biodiversity. Building up seed supplies for emergency response is an urgent priority that can increase resilience.

Seed banking prevents gaps and disruptions in growing and planting. Without seed banking, you can only collect what you can grow immediately. Native seeds can be hard to collect at just the right time for planting, and most can lose viability quickly if not handled correctly. Seed banks allow collectors to be efficient with their time and take advantage of abundant harvest seasons[40]. To ensure an adequate and sustainable harvest of seeds, seed banking may need to start years in advance of large-scale restoration projects to build up seed supplies.

Now is the time to scale up. The great majority of seed banks (such as the Svalbard Global Seed Vault) preserve only agricultural and crop species for food security, which is also essential work, but not the subject of this analysis. There are seed banks of varying sizes that work entirely or partially with wild, native species, but most still focus primarily on the preservation of threatened, endangered, and rare plants — a crucial practice that we fully support. However, demand is rapidly growing to restore ecosystems using holistic plant communities, which requires the storage of common or locally abundant foundational plants that make up the backbone of the ecosystem. Relatively few seed banks store seeds of these species, especially in the large quantities necessary to support large-scale restoration. Increasing global seed banking capacity can address both of these needs. With the ongoing climate disruptions, we do not know what seed production of native ecosystems will be like in the next decades. Our best strategy is to collect and bank seeds now, while we still can.

We cannot afford to waste seeds. Despite well-intentioned plans, people frequently collect more seeds than they can use immediately, and often these seeds die if not stored in seed banks. Seed storage following international standards is critical to maintaining seed viability, reducing waste of natural and economic resources, and increasing success in restoration efforts[41,42]. We can build on the current paradigm of conservation seed banking and scale up with restoration seed banks that can supply native seeds in the quantities needed to meet planting commitments and global restoration goals. These seed banks can also enable the science-based restoration use of seeds, training, and knowledge sharing[43]. To safeguard native species and provide adequate diversity of seeds for restoration, we can also strengthen the storage and research capacity of regional seed banks[44]. We have many opportunities to optimize the seed supply chain, including (but not limited to) improving collection practices, expanding seed banking capacity, expanding seed production, increasing seed quality with testing, and networking seed banks to get the right seeds to the right places at the right time.

A global network of restoration seed banks can improve seed supply systems. Some parts of the world need seed banks that can operate in remote areas, empowering local communities with seed sovereignty, to manage their natural resources and maintain a steady supply of locally adapted, viable native seeds to restore healthy, functioning ecosystems. Some areas may need regional seed banks that can holistically support multiple projects, providing seed storage, training, knowledge sharing, and more. National or centralized seed banks can play important roles in backup storage, long-term research, and more. In some cases, community seed banks may be the best solution, but these usually focus on temporary seed storage (Box 2)[45]. Greater storage capacity, improved long-term storage, and quality testing are essential to support market-based opportunities in native seed production and to meet a growing demand for high-quality native seeds[46,47]. A hub-and-spoke network of diverse types of seed banks has great potential to solve seed supply chain challenges. Restoration seed banks support ecosystem resilience, rapid scaling, continuous planting for large-scale projects, and improvement in seed quality and plant survival (Box 3). In most regions of the world, seed banks are needed to meet the ambitious goals of the United Nations Decade on Ecosystem Restoration[48].

BOX 3

Can't we grow and plant many seeds directly, bypassing seed banks?

Certainly, some seeds can be collected and propagated right away. This is a best practice for an estimated 8% of species with seeds that cannot be stored (Appendix section 4.g.ii). However, most seeds for restoration efforts must be processed, stored, and cultivated[49]. There are several reasons why seed banks are essential, either locally or regionally, to support restoration:

- When people collect seeds intending to propagate them right away, despite best estimations, there are frequently excess seeds that are wasted without access to a seed bank. Not every seed needs to be banked, but some seeds from most collections would need to be banked to avoid this waste and potential unsustainable harvesting of seeds.

- Seed banks are not just for storage. They can also enable processing and drying under climate-controlled conditions. This helps ensure that seeds stay viable, even over shorter periods, such as between collection and planting. Also, this time period often extends past what was anticipated, as plant propagation and restoration plans change and adapt over time.

- If seed banks are to provide economic opportunities for communities and/or organizations through native seed markets, quality control is essential. Wild seeds for sale to restoration projects require testing for purity and viability to provide a marketable product, and seed banks enable such testing and certification, as well as coordinated distribution. Seed banks also help people to properly manage data and organize their inventory.

- We can proactively start amassing seeds now in quantities needed to meet the large-scale goals of the UN Decade on Ecosystem Restoration. Identifying, securing, and preparing appropriate sites for large planting projects takes time. We can bank seeds to be ready to scale up quickly.

- While it is important to simultaneously build capacity in other aspects of restoration, such as seed collecting, nurseries, planting, and monitoring, it is much less efficient to do these things without seed banking. Collecting seeds requires many staff hours, and seed banking maximizes the value of every single collecting trip since seeds are not wasted. Seed banks provide nursery managers access to backup seed collections of prioritized species, enabling continuous propagation, instead of compromising on biodiversity or facing setbacks and disruptions. Nurseries and planting efforts also require significant resources, and seed banking further maximizes the use of limited nursery space and staff time by improving germination rates, plant survival, and ultimately ecosystem health and productivity.

- Seed banks can play a central role in testing seed viability and germination protocols to improve germination rates and plant survival. They also secure seed collections to maintain seed viability while waiting for the results of these tests, and while nursery staff assess the best propagation protocols. These activities can also occur before large-scale propagation begins.

Where Will Seed Banks Have the Highest Impact?

For this network of seed banks to be as effective as possible, it is important to answer the question: How many seed banks do we need in the world, and where do we need them? Many different factors could play a role in addressing this question. These include, but are not limited to: global estimates of restoration potential; planting commitments made by countries[50]; Key Biodiversity Areas[51], threatened species ranges[52], and other indices of biodiversity; climate risk and vulnerability indices; SDG indicators[53]; gross domestic product and other country-level statistics; and many more. In the future, we want to explore these in more detail.

However, since the question is so complex and already includes many highly variable factors, we decided to create, as a first step, a baseline analysis from which to build future models. Below we outline our approach, and we welcome constructive and critical feedback that can refine any of the initial conclusions in this assessment.

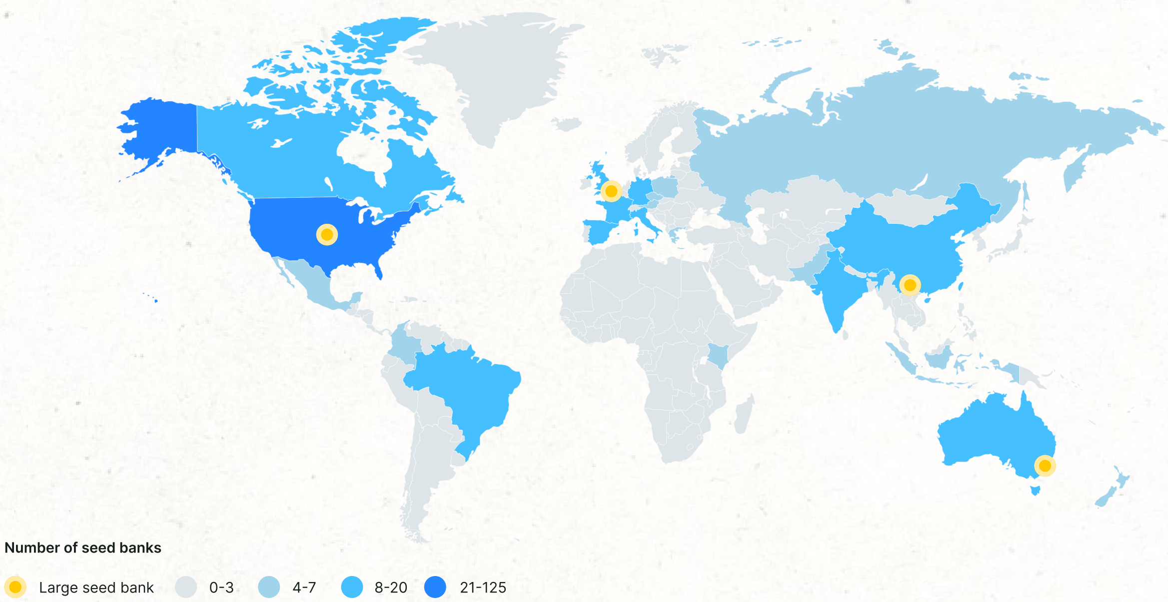
We first answered the following three questions, using methods outlined in summary below and detailed in the Appendix.

01 How many seed banks storing native species currently exist in each country of the world?

We compiled a list of seed banks by country using 11 primary sources, including databases and seed banking networks. We supplemented these sources with personal knowledge, information from seed banking partners and colleagues, and internet searches to fact-check and cross-reference primary sources. We included a seed bank in the list if (1) seeds stored in the seed bank include native species — excluding seed banks that only store agricultural or horticultural seeds, while including seed banks that stored a mix of native and other seeds, and (2) accepted methods were used for storage (see Appendix).

Otherwise, seed banks included in the analysis could be of any size, storing seeds for any length of time, for any purpose, to be as inclusive as possible. Although some seed banks do not currently support restoration projects, we conservatively counted them as having the potential to do so if they met these criteria. We identified 410 existing seed banks storing native species in 96 countries (Map 1).

410 seed banks around the globe currently store native seeds



Map 1. Existing number of seed banks per country storing native seeds, based on assessments of existing databases, networks, and publicly available information. Large research and conservation seed banks of the world include (from left to right): National Laboratory for Genetic Resources Preservation, United States Department of Agriculture (USA); Millennium Seed Bank, Royal Botanic Gardens, Kew (United Kingdom); Germplasm Bank of Wild Species, Yunnan University, Kunming Institute of Botany (People's Republic of China); Australian PlantBank, Australian Botanic Garden Mount Annan (Australia). See Appendix for definition of large seed banks.

02

How much land area can we restore in each country?

We used the open access dataset underlying the Restor Data Platform published by the Crowther Lab at ETH Zurich[54,55], which contained the most comprehensive, publicly available, global-scale dataset, to determine the area available for forest restoration (referred to here as restoration potential [RP]) in each country.

Some criticisms of the Bastin et al. (2019) study and dataset contend that there are several biomes included in the global tree RP that should be conserved or restored as ecosystems other than forests. We agree that it is essential to plant the right trees in the right places.

Areas that currently are or historically existed as wetlands, grasslands, savannas, mangroves, shrublands, peatlands, deserts, and other natural ecosystems should be conserved or restored to those natural ecosystems. However, seed banks can support the restoration of nearly any ecosystem type, so the dataset is appropriate for an assessment of where seed banks are needed.

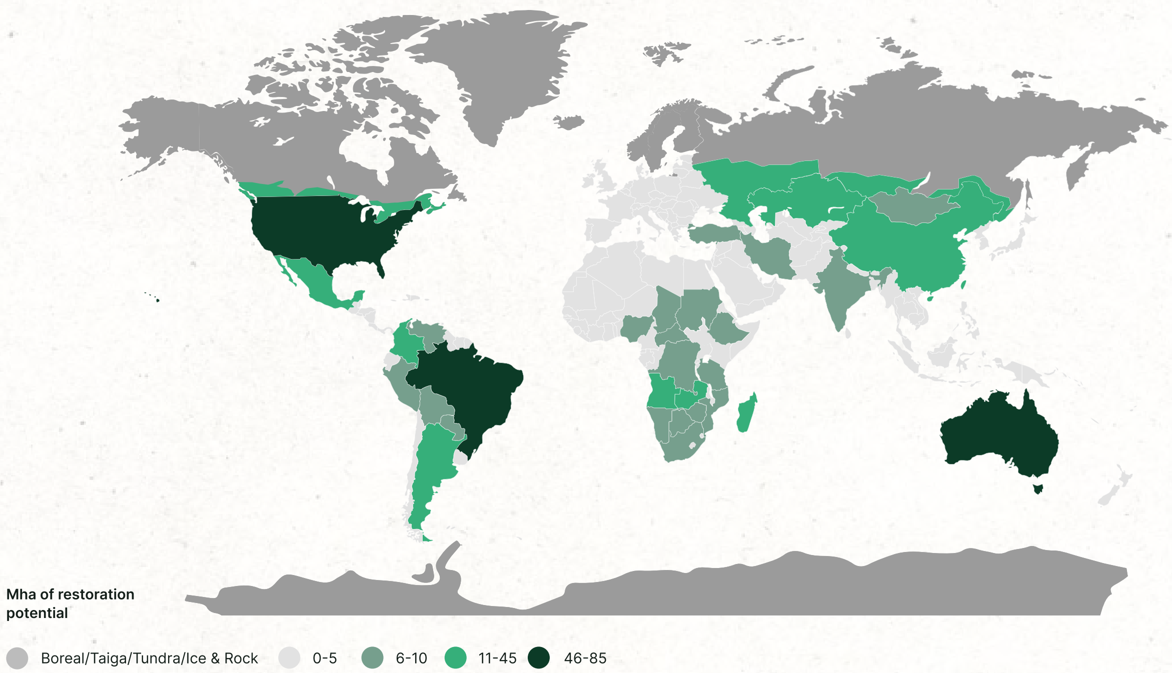
Even though seed banks support many types of habitat restoration, we excluded the large biomes of boreal forest, ice and rock, taiga, and tundra[56] from this analysis. Boreal regions, for instance, have a higher capacity to fight global warming through albedo (sun radiation reflected by the snow) and conservation/ restoration of peatlands (natural moss-dominated ecosystems) than by capturing carbon in planted trees[57,58,59].

Shallow soil, extremely limited biologically active seasons, and often difficult physical access make the restoration of these biomes even more challenging, so it is generally better to limit direct interactions and protect them instead.

We believe in the tenet that off-site conservation of species should not take priority over the vital need for conservation in the wild and, similarly, that restoration for climate mitigation should not replace natural ecosystems or override their protection.

The RP by country is shown in Map 2. Note that country size strongly affects RP, so small countries with low RP are not necessarily less important for restoration than larger countries.

Land restoration potential worldwide



Map 2. Total restoration potential in million hectares (Mha; 2.471 million acres) per country, based on the Restor dataset with boreal, ice and rock, taiga, and tundra biomes excluded.

03

How much land area of RP can each seed bank support?

The answer to this question is complex, because it is based on highly variable factors, including:

Number of plants needed per unit area of restoration, which varies based on restoration methods, ecosystems, and local preferences

Estimated average germination rates across a suite of local species

Estimated plant survival rates across a suite of local species

To bring a more nuanced answer to this question, we studied the ranges of these factors reported in the scientific literature (see Appendix) and estimated the theoretical "need for seeds" (based on varying planting densities, germination rates, and survival rates) under five different scenarios: extra-low, low, medium, high, and extra-high (Appendix Table 1). We eliminated the extra-low and extra-high scenarios as unrealistic on a global scale, and present our results based on low, medium, and high "need for seeds" scenarios to reflect more realistic values (Table 1).

We also estimated the average capacity of a small restoration seed bank, with approximately 1,700 liters (60 cubic feet) of storage space for seeds (Box 4). Seed banks should ideally have a space with controlled temperature and humidity for drying and packaging seeds, as well as processing space, but the size and details of the workspace are not specified in our method of calculation. We estimated the capacity of this generalized seed bank at 8 million seeds at any given time, and 53 million seeds over 10 years of active restoration (see Appendix for details).

For each theoretical "need for seeds" scenario, we calculated:

i. Number of seeds needed per hectare of RP. This was calculated as:

$$\frac{\text{Number of plants needed per hectare of restoration}}{\text{Total survival rate after losses from germination + planting}}$$

ii. Number of seed banks needed per million hectares (Mha) of RP, based on the capacity of the generalized, small restoration seed bank (Box 4). This was calculated as:

$$\frac{\text{Number of seeds needed per hectare of restoration} \times \text{1M}}{\text{53.3M (capacity per seed bank over 10 years)}}$$

iii. Number of hectares supported by a single seed bank. This was calculated as:

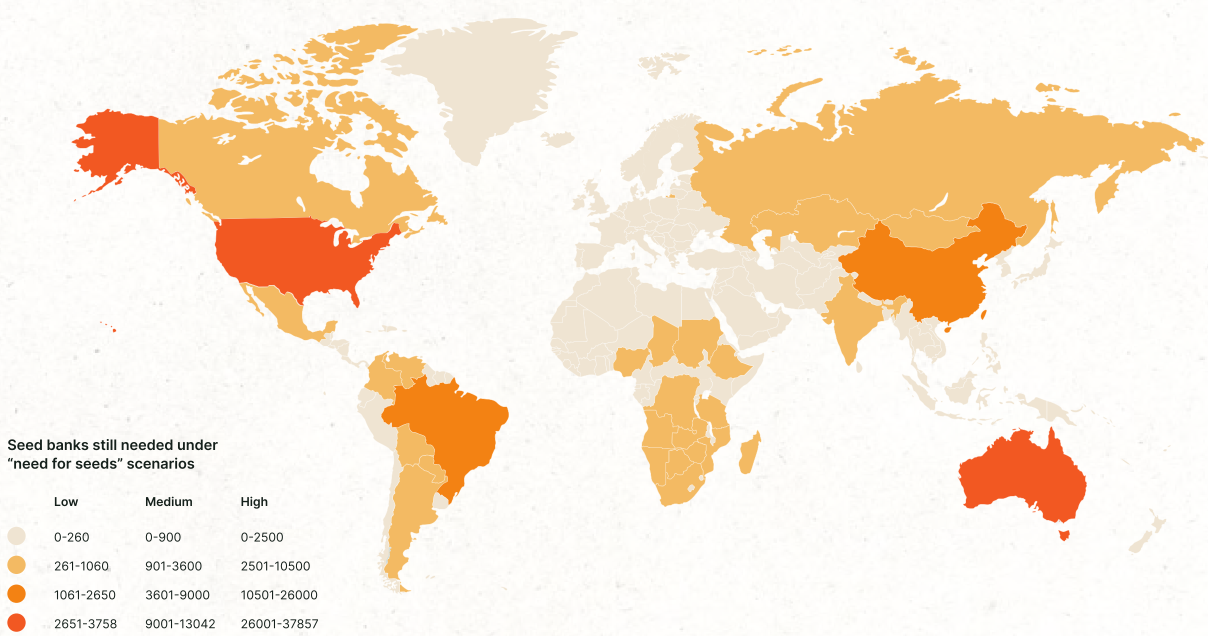
$$\frac{\text{53.3M (capacity per seed bank over 10 years)}}{\text{Number of seeds needed per ha of restoration}}$$

Table 1. Areas of RP (in hectares and acres) that a small restoration seed bank could serve, and number of seed banks needed per Mha of RP, based on the three middle "need for seeds" scenarios.

'Need for seeds' scenario	Area of RP per seed bank (ha)	Area of RP per seed bank (acres)	Number of seed banks per Mha
Low	21739	53718	46
Medium	6410	15839	156
High	2222	5491	450

By assessing the existing seed banks and the global RP, and determining how much land area each seed bank could support in order to meet the global RP over a period of 10 years, we then calculated how many seed banks would be needed in each country if the total global RP were realized within the next decade (Map 3).

Nearly all countries need seed banks to fulfill the global restoration potential



Map 3. Estimated number of seed banks still needed per country based on low, medium, and high "need for seeds" scenarios. For example, Brazil needs 1061–2650 seed banks in the low scenario, 3601–9000 seed banks in the medium scenario, and 10501–26000 seed banks in the high scenario.

BOX 4

Why did we estimate how many seed banks are needed, instead of how many seeds?

We calculated an estimated range of seeds needed for restoration. There is substantial variation in every factor and few published studies available to estimate those factors. Therefore, we presented the estimates under five scenarios (see Appendix). The total number of seeds needed to meet the global RP is likely between 2 and 17 trillion (based on the middle three scenarios), but the data do not currently exist to make a more accurate estimate.

To provide a more accurate estimate of total seeds needed to meet global RP, one would need to account for the spatial variation of RP across different biomes and ecosystems, and variations in planting density, seed germination, and plant survival rates — across species, landscapes, restoration techniques, and socioeconomic conditions. This requires extensive data collection and complex modeling, and we highlight this as an excellent opportunity for future research. Our study is meant as a foundational analysis for more detailed investigations and hypothesis testing.

Seed size also varies immensely. One million seeds of one species might fill a small jar or a large freezer. However, species diversity is critical in restoration. Due to variation in seed size and proportions of species' seeds stored over time, seed banks have flexible capacity. Restoration seed banks that support active planting also vary in turnover time, or the speed at which seeds are withdrawn, used for planting, and replenished in storage, which influences capacity within a time range, such as the decade calculated in this analysis (see Appendix).

We linked seed banks with an estimated area of RP (Table 1). Although we used a small restoration seed bank to estimate capacity, we expect the actual seed banks established across the world to vary in capacity and coverage, based on species, ecosystems, and other local factors. Large restoration seed banks could efficiently meet a significantly higher proportion of the overall seed supply need if they are well equipped, staffed, and resourced — and are certainly called for[60]. However, many organizations may need to start small, and local seed banks empower communities with seed sovereignty. This variation in seed bank capacity helps compensate for the high variation in the number of seeds needed.

BOX 4 Continued

Using the number of seed banks is a more accurate estimation of what is needed on the ground to address differing seed supply challenges in each region. Outliers are rounded off; for instance, average seed size will be similar among seed banks, despite high variation among species. Counting seed banks allows us to better estimate average local capacity to host a diversity of species, across life forms and ecosystems. The number of seeds needed in restoration will also change over time (even in one location) as technology improves and landscapes change.

For any "need for seeds" scenario, seed banks are the units where most processes necessary to ensure native seed supply can be carried out safely and efficiently. There are also innate variables, such as seed dormancy, and external, environmental variables that affect seed quality, which are overlooked or difficult to account for when only considering the number of seeds to be collected. These frequently reported challenges can often be alleviated in a seed bank, strengthening the seed supply chain and even reducing the number of seeds needed for restoration.

Regardless of fluctuations in seeds needed over space and time, seed banks (in a variety of forms) will be the primary infrastructure needed for sustainably transitioning seeds from natural areas to restored ecosystems.

What We Found

To fulfill the global RP, we need seed banks almost everywhere. Seed banks would be beneficial in all countries, except for very small countries or administrative regions that already have 1–2 seed banks to support their RP. A generalized, small restoration seed bank can support an estimated 2,200 to 22,000 hectares of planting, and an estimated 46 to 450 seed banks are needed per million hectares of RP, depending on the "need for seeds" scenario. The main finding of our analysis is that a global network of tens of thousands of restoration seed banks would be needed to sustainably fulfill the global RP within 10 years. However, the work already being done by the 410 existing seed banks is incredibly valuable, and even adding a few more seed banks in each region would have a high impact, in many cases doubling or tripling existing seed banking capacity.

The four countries that need the most seed banks to meet their RP within 10 years (United States of America [USA], Australia, Brazil, and China) are among those that already have the most seed banks.

> **"Even though we need a somewhat smaller number of seed banks per country in tropical and subtropical regions, each seed bank will have a greater impact on restoration outcomes for climate change and biodiversity.**

Three of these — USA, Brazil, and China — are among the four countries that contain half of the world's forests[61] and are also among the countries with the largest land area, which strongly influences the country-level results of this study. Though these are important countries for expanding seed bank infrastructure to fulfill RP, in prioritizing and allocating resources for establishing new seed banks, we also need to consider biodiversity, sustainability, and long-term climate stability.

Seed banks will have high impacts in the tropics. Even though they may have less area per country, many countries in the tropical and subtropical regions could still use hundreds or thousands of seed banks to support their RP. Most ecologists agree this region is the highest priority for restoration, considering factors such as biodiversity, carbon sequestration potential for climate change mitigation, ongoing land degradation, and cost effectiveness[62]. While tropical areas are more likely to have some seeds that do not tolerate storage, researchers have predicted that over 80% of tropical species can be stored in seed banks (Appendix section 4.g.ii)[63]. In other words, even though we need a somewhat smaller number of seed banks per country in tropical and subtropical regions, each seed bank will have a greater impact on restoration outcomes for climate change and biodiversity.

Small numbers of seed banks have huge benefits for biodiversity hotspots. For example, the south and east Mediterranean region (North Africa and the Middle East) needs fewer seed banks than most of the world, but it is a global biodiversity hotspot. There are at least 888 Important Plant Areas (defined as internationally significant sites for plants and their habitats, based on standardized criteria) in this region, of which 75% are home to endemic plants found only in one country and nowhere else in the world, while over a third of these areas are threatened by deforestation and other human impacts[64]. Seed banks can empower these regions to preserve species from Important Plant Areas and incorporate them into restoration projects to reverse the devastating effects of land degradation.

In addition to supporting restoration, seed banks can preserve biodiversity. While our analysis shows that some countries have a lower need for restoration seed banks, we want to emphasize that approximately 40% of the world's plants are at risk of extinction, many existing as small populations of few individual plants, often under enormous pressure due to habitat destruction[65]. Additionally, one in three species of trees is threatened with extinction[66], including rare tree species with high carbon capture potential. Therefore, the potential of restoration seed banks expands beyond the need to achieve net zero emissions and can contribute to biodiversity conservation as well.

Additional Benefits of Restoration Seed Banks

Restoration seed banks improve restoration outcomes and contribute to scientific knowledge. Long-term research seed banks test seeds for viability, but rarely quantify germination success and seedling survival[67]. Restoration seed banks can empower the monitoring of success from germination all the way through to survival of plants in the field — a major gap in scientific knowledge.

Restoration seed banks can also help fill gaps in knowledge of seed storage behavior. These types of data can be informative even after just a few years of storage, and studies are especially lacking in the tropics[68], where there is a need for more seed banks. As this research helps identify which species' seeds cannot be stored, this can help develop alternative genetic storage methods such as seed farming for restoration, and/or conservation in botanical gardens and other specialized methods.

Thus, seed banks build an essential connection between research and restoration practices on the ground, connecting local, regional, national, and international stakeholders who develop the knowledge base for seed conservation and restoration.

They support the expansion of native seed farming. To meet UN Decade on Ecosystem Restoration commitments, the next bottleneck to address will be sustainable wild seed sources. Our estimated number of needed seed banks does not consider the natural seed sources available within a country, or the capacity of wild plant populations to provide seeds in the required quantity.

To ensure no harm to intact ecosystems, sustainable seed collecting following international standards is a priority[69]. In many regions, there is or will soon be a need to establish seed farms or seed production areas (SPAs) to increase quantities of common native species used in restoration. Such SPAs can be established in diverse locations, such as Indigenous communities, botanical gardens, and large-scale operations. Establishing SPAs is essential, both to meet restoration goals and to avoid over-harvesting and other negative effects on wild ecosystems that are critical for biodiversity conservation[70,71].

However, it is important to distinguish an SPA for restoration from SPAs for commercial purposes, which may focus on traits such as speeding up or synchronizing germination. While this makes it easier to grow plants, it eliminates the natural genetic diversity found in wild plants, which causes the plants to be poorly adapted to natural conditions in restoration sites. In addition, even restoration SPAs face risks to genetic diversity resulting from too few seed collections from mother plants, or from the process of cultivation, so it is critical to plan and manage SPAs carefully[72,73].

Just like collecting seeds from the wild, producing seeds in SPAs will also require seed bank support to ensure seeds remain viable until they are planted, to avoid waste of seeds and other valuable resources, and to increase the seed supply on hand for restoration and emergency response.

Seed banks that preserve seed quality can also empower seed farmers with improved livelihoods. We can proactively prepare for this next phase by establishing the needed infrastructure.

They support conservation of threatened plants and ecosystems. Seed banks are considered an *ex situ* (off-site) method of conservation — preserving species away from their natural environment, while *in situ* (in-place) conservation preserves species and ecosystems in the wild. *In situ* conservation is the first priority for primary forests and other intact ecosystems, because preventing their destruction and degradation has the highest impact on climate resilience and biodiversity. However, seed banking is one of the most critical *ex situ* methods to help prevent species extinctions and preserve biodiversity in natural areas. It also supports conservation of entire ecosystems, because millions of seeds representing the natural genetic variability and species diversity of a site can be stored in a relatively small space.

Storing seeds from rare species provides a backup source of locally adapted plants, in case natural disasters or changing environmental conditions damage or destroy wild populations. While some seeds may be sent to large, centralized seed banks for long-term storage (several decades or more), restoration seed banks can also support *in situ* conservation projects locally, supporting Target 8 of the Global Strategy for Plant Conservation: "At least 75 per cent of threatened plant species in *ex situ* collections, preferably in the country of origin, and at least 20 per cent available for recovery and restoration programmes"[74]. Restoration seed banks' laboratory conditions enable immediate processing and drying of seeds after they are collected, maximizing viability and longevity.

> **"It also supports conservation of entire ecosystems, because millions of seeds representing the natural genetic variability and species diversity of a site can be stored in a relatively small space.**

Some seeds can be stored locally for 10 to 20 years or more. This longer-term storage of threatened species can support active *in situ* projects on the ground, such as population augmentation, or growing more plants of threatened species and planting them within natural populations to bolster their numbers, genetic diversity, and resilience. Restoration seed banks can support this critical work while also facilitating research, restoration of degraded land, and other goals important to governments, local organizations, and communities.

They can benefit local and Indigenous communities. Seed banks can support the SDGs, particularly Gender Equality (Goal 5), Decent Work and Economic Growth (Goal 8), and Reduced Inequalities (Goal 10), by producing jobs, particularly for women, who are often already stewards of local plants and seeds but frequently have limited job opportunities[75]. Seed banks can provide and/or support a variety of economic models that may be applicable in different communities, such as seed banking as a service to other local organizations, sales of seeds and/or plants for restoration (if appropriate for local distribution), ecotourism opportunities, academic study and cultural learning opportunities, and sustainable agroforestry and sale of non-timber forest products. Even if seed banks are physically located outside Indigenous or local communities, regional seed banks nearby can provide the long-term storage and quality control needed to successfully market native seeds as a product, supporting community seed supply networks of collectors and farmers. Additionally, seed banks that enable rapid scaling up of restoration help improve ecosystem services that benefit local communities, such as clean water and air, healthy soils, pollinators to support food security, ecosystem resilience, and much more.

Conclusions

Seed banks are needed around the world if we are to fulfill the global restoration potential. A small seed bank can support an estimated 2,200 to 22,000 hectares of planting, and an estimated 46 to 450 seed banks are needed per million hectares of restoration potential, depending on the "need for seeds" scenario. Tens of thousands of seed banks globally would greatly benefit restoration goals and planting commitments that collectively aim to address climate change and biodiversity loss. Establishing larger regional seed banks could help meet the need for seeds more efficiently.

Though greater numbers of seed banks are needed to support restoration in larger countries, seed banks are extremely impactful in countries in the tropics and subtropics, as well as other biodiversity hotspots, where each seed bank can have an especially high positive impact on biodiversity preservation, climate change mitigation, cost effectiveness of restoration, and benefits to society.

A hub-and-spoke network of restoration seed banks has enormous potential to support the UN's Decade on Ecosystem Restoration and the planting commitments of hundreds of countries and organizations, while empowering biodiversity preservation and fulfillment of SDGs. The following are some actions we can take to realize this potential.

Calls to Action

Local restoration organizations can greatly benefit from seed banking.

Effective climate action will come from multiple stakeholders working together across a diversity of solutions. However, starting from the grassroots with people who are already growing plants and doing restoration on the ground is ideal for nature-based solutions. Seed banking can help restoration teams efficiently scale up their work, providing new local livelihoods and economic opportunities, while accelerating the restoration of healthy, productive environments that improve quality of life.

Government support has major potential to help scale up seed supply systems.

While grassroots-driven change is powerful, government support at local, regional, national, and international levels can have a huge impact on scaling up restoration efforts. Government provision of centralized seed banks could enable long-term storage at larger scales, and backup storage, especially for species from legally protected areas or those threatened with extinction. Government investment in a hub-and-spoke network of seed banks could also empower critically needed localized restoration with adapted, resilient seeds at finer scales.

Businesses play a critical role by investing in restoration practices.

Corporate social responsibility is no longer just a compliance concern; many businesses now actively prioritize sustainability within their strategic plans, budgets, and supply chains, in many cases aligned with the SDGs. Seed banks are a tangible product with measurable benefits that directly support SDGs, ecological restoration, and climate change mitigation. Corporate sponsors can catalyze restoration by providing this important foundational infrastructure.

Everyone can help raise awareness of seed banking as a critical restoration tool.

Much of the public conversation around restoration focuses on tree planting, which is certainly important. However, it matters where those trees and other plants come from. Seed banks are the most efficient and effective way to preserve and track biodiverse sources of plant material for both active and future restoration. Climate fluctuations and environmental stressors are rapidly depleting native seed sources, but a network of well-positioned seed banks can dramatically reduce seed waste, promoting sustainable harvests and protecting ecosystems while also building capacity and empowering local communities. Sharing this message is essential if the world is to achieve planting goals while also restoring biodiversity and working to reverse climate change. Seeds transport the natural genetic diversity of plants from one generation to the next, through space and time. We can save the future of our planet by conserving one of our most valuable natural resources — the seeds.

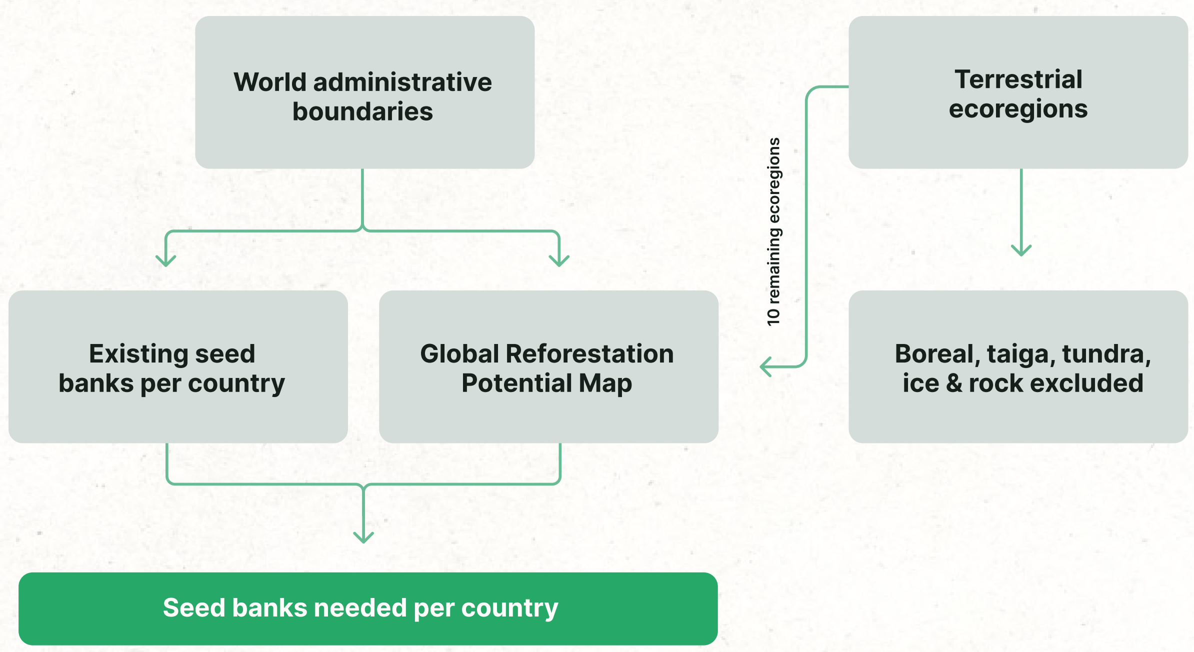
Appendix

Detailed Methods for the Global Seed Bank Index

Goal

The overall goal of our analysis was to calculate how many seed banks would be needed per country to meet the global restoration potential (RP) in 10 years, based on the land area (in Mha; 1 Mha = 2.471 million acres) designated as having RP and the number of existing seed banks per country.

This appendix details the overall methodology we used to create the Global Seed Bank Index. A general structure of the methodology is presented in Appendix Fig. 1.



Appendix Figure 1. Methodology for calculating the number of seed banks needed per country for the Global Seed Bank Index.

We took the following steps:

01

We used the world administrative boundaries by the UN World Food Programme[76], which is a publicly available data source. It encompasses 256 countries that are grouped into 22 geographic regions and was last modified on April 26, 2019.

A. Once we downloaded the data in a shapefile format, we used the open-source GIS software QGIS[77] to merge island or other non-contiguous territories with their mainland or sovereign country they belong to. However, like other communities, each territory may want to consider having a seed bank for local restoration and conservation.

02

We estimated the current number of seed banks in each country.

A. Methods

i. We gathered data on existing seed banks from the following sources:

1. IUCN SSC Seed Conservation Specialist Group, Seed Conservation Directory of Expertise, key words: 'cold' or 'cool' seed storage

⟶ seedconservationsg.org/seed-conservation-directory-of-expertise)

2. Botanic Gardens Conservation International (BGCI) GardenSearch Database, key word: 'seed bank'

⟶ tools.bgci.org/garden_search.php?action=Find&ftrCountry=All&ftrKeyword=seed+bank&x=0&y=0)

3. Millennium Seed Bank Partnership (MSBP) Data Warehouse, seed banks that have contributed to the database

⟶ brahmsonline.kew.org/msbp/SeedData/DW)

4. US Center for Plant Conservation

⟶ saveplants.org/search/?category=institutions

5. The Crop Wild Relative Project

⟶ cwrdiversity.org/project-partners/

6. Australian Seed Bank Partnership

⟶ seedpartnership.org.au

7. European Seed Conservation Network

⟶ enscobase.maich.gr/total_inst.tml

8. Italian Network of Germplasm Banks

⟶ reteribes.it/

9. Colombian Network of Seed Banks

⟶ reporte.humboldt.org.co/biodiversidad/2019/cap3/301/#seccion4

10. Indonesian Botanic Garden Seed Banks and Indonesian Institute of Sciences

⟶ iopscience.iop.org/article/10.1088/1755-1315/298/1/012006/pdf

11. Alpine Seed Conservation and Research Network

⟶ alpineseedconservation.eu/index.php/partners/

12. Personal knowledge, information from seed banking partners and colleagues, and internet searches using Google Chrome with keywords of the names of possible seed banks

ii. The databases that did not specify whether institutions had seed banks were checked using an internet search, and institutions were only included if the search confirmed an existing seed bank that met our criteria.

iii. Lists of seed banks by country were cross-checked across all sources, including checking for names listed differently in different sources or other duplications.

B. Criteria for inclusion of seed banks in our list

i. The seeds stored include native species, but may also include non-native species (excluding seed banks that only store agricultural or horticultural seeds).

ii. The seeds are stored for any length of time (short- to long-term storage), but drying methods are used.

iii. The seeds are used in any way (including conservation, restoration, research, botanical garden management, etc.).

iv. The seed bank is of any size.

C. Assumptions for the analysis of existing seed banks

i. Seed banks that currently store native species, even if not currently supporting restoration, have the potential, in terms of facilities and expertise, to support restoration, and thus are conservatively counted in this analysis.

ii. Each seed bank is counted once, regardless of size, and assumed to have the potential to support restoration in a similar capacity to a generalized, small restoration seed bank, with approximately 1700 liters (60 cubic feet) of storage space for seeds, and a space with controlled temperature and relative humidity for drying and packaging seeds. However, the size, shape, and other characteristics of the workspace are flexible and not specified in this estimation. While existing seed banks vary substantially in size, we conservatively counted each one as a small restoration seed bank (Box 4).

D. Large seed banks

i. We identified 4 large seed banks that hold seeds from > 5000 plant species and in > 10,000 accessions (individual collections of seeds accepted by the seed bank).
ii. Each was still counted as 1 seed bank to...

E. Limitations and future research directions

i. We have likely missed some seed banks that are not connected with larger networks or databases and may not have a presence online. We invite institutions holding seed banks, and anyone with seed banking expertise, to add themselves to the Seed Conservation Directory of Expertise at

→ seedconservationsg.org/seed-conservation-directory-of-expertise

ii. Physical capacity and drying/storage conditions vary dramatically, and in many cases the ability of existing seed banks to support restoration was unknown. Some undoubtedly support more or less restoration than a generalized, small restoration seed bank. All these variables are also dynamic, constantly changing.

iii. For these reasons, we used generalizations and conservative assumptions for this foundational analysis, which aims to provide a baseline for future, more nuanced investigations into conditions and restoration capacity of existing seed banks.

03

We estimated the area of RP in each country.

A. Units: 1 million hectares (Mha; equivalent to 2.471 million acres)

B. Datasets

i. We used the global tree RP map created by the Crowther Lab at ETH Zurich[78,79]. The dataset is in raster format with a resolution of 1 km^2 and is calculated as the difference between the total potential tree cover of the planet, and current tree cover, cropland, and urban areas (assuming that croplands and urban areas are unlikely to be reforested). Each pixel on the map represents the potential for tree restoration in percentage, based on a combination of five climatic (WorldClim2), two topographic (SRTM), and three edaphic variables (SoilGrids): annual mean temperature, mean temperature of the wettest quarter, annual precipitation, precipitation seasonality, precipitation of the driest quarter, elevation, hillshade, soil organic carbon, soil sand content, and the depth to bedrock.

ii. Next, we used the World Wildlife Fund map of Terrestrial Ecoregions of the World (Biomes) to exclude boreal, ice and rock, taiga, and tundra biomes, and extract the remaining pixels within each country boundary[80].

C. Limitations and future research directions

i. There are likely other spatial variables which could be taken into consideration when estimating global RP, including, but not limited to, global population growth and projected future increases in agricultural and urban land size.

ii. We see the potential to build on the current analysis by adding these, as well as factors related to restoration prioritization[81], into a model which weights the importance of each, hence providing a more nuanced view on the global RP.

04

We estimated the number of seed banks needed in each country.

A. To determine how many seed banks are needed per country, we estimated the number of seed banks needed per Mha (2.471 million acres) of RP (Appendix Table 1), using the following factors (data from the literature cited below):

i. Number of plants needed per hectare (2.471 acres) of restoration[82,83,84]. Since quantitative data are so limited in the literature, we also spoke directly with representatives from numerous restoration projects around the world to help inform the variation in planting density.

ii. Estimated average germination rate across a suite of local species[85,86]. Since quantitative data are so limited in the literature, we used a wide range of germination rates across the five scenarios.

iii. Estimated plant survival rate across a suite of local species[87,88,89,90,91,92,93]

B. For each of these three factors, we calculated five "theoretical need for seeds" scenarios: extra-low, low, medium, high, and extra-high, based on ranges found in the scientific literature on restoration practices and survival rates. We excluded the extra-low and extra-high scenarios from this analysis as being unrealistic on a global scale.

Appendix Table 1. Calculation of five theoretical "need for seeds" scenarios to estimate the number of seed banks needed per Mha of restoration potential.

	Theoretical 'Need for Seeds'				
Factor	**Extra-Low**	**Low**	**Medium**	**High**	**Extra-High**
Number of plants needed per hectare of restoration	500	1200	2500	3600	5000
Estimated average germination rate across suite of local species	0.80	0.70	0.60	0.50	0.40
Estimated average plant survival rate across suite of local species	0.90	0.70	0.50	0.30	0.1
Total survival rate after losses from germination and planting	0.72	0.49	0.30	0.15	0.04
Number of seeds needed per hectare of restoration	694	2449	8333	24,000	125,000
Number of seed banks needed per Mha of restoration potential	**13**	**46**	**156**	**450**	**2344**

i. Extra-low scenarios are unlikely to be used alone, but rather in combination with other restoration techniques. For seedling transplantation, the survival rate is between 31% and 94%[94,95,96,97] ranging between the extra-low and high scenarios. However, the extra-low scenario is likely unrealistic because at extra-low density, enrichment planting is typically needed in following years, making it closer to the low scenario.

ii. Extra-high scenarios most likely represent direct-seeding techniques, where seeds are broadcast directly over the landscape, rather than seedlings being transplanted. In direct seeding, the germination plus survival rates of suites of plants is reported as 0% to 33%[98,99,100,101,102] ranging from medium to extra-high scenarios, but skewed toward extra-high. A similar pattern appears in references on seed weight used in restoration[103,104,105]. The "need for seeds" is so high mostly because of low survival and high loss of seeds. We generally recommend planting in most restoration projects. However, we recognize the utility of direct-seeding techniques in certain appropriate situations.

iii. Planting density and plant survival rate could have an inverse relationship, as theoretically shown here. Germination rate most likely does not have a direct relationship with either (it is more likely driven by taxonomy and ecosystem), but here it is simply scaled from best to worst, or lowest to highest need for seeds. This is another reason the middle scenarios are more likely realistic.

C. We calculated the number of seeds held per seed bank for restoration over 10 years.

i. For a generalized, small restoration seed bank (described in Appendix section 2.c.ii; Box 4), a conservative estimate of capacity, giving equal portion of the total capacity to five size classes of seeds, is 8M seeds at any given time.

ii. Assuming one-third of the capacity is held for longer-term storage and two-thirds of the capacity is used for cycling seeds annually to support active restoration, over 10 years the restoration capacity is 53.3M seeds.

iii. For actual seed banks, we expect variation both in seed storage capacity and seed turnover rates.

D. For all five theoretical "need for seeds" scenarios, we calculated:

i. Number of seeds needed per hectare of RP. This was calculated as:

$$\frac{\text{Number of plants needed per ha of restoration}}{\text{Total survival rate after losses from germination + planting}}$$

ii. Number of seed banks needed per million hectares of RP, based on the capacity of the generalized, small restoration seed bank (Box 4). This was calculated as:

$$\frac{\text{Number of seeds needed per ha of restoration} \times 1\text{M}}{\text{53.3M (capacity per seed bank over 10 years)}}$$

iii. Number of hectares supported by a single seed bank. This was calculated as:

$$\frac{\text{53.3M (capacity per seed bank over 10 years)}}{\text{Number of seeds needed per ha of restoration}}$$

E. We calculated the number of seed banks needed per country based on their RP (point 3 above) for the low, medium, and high "need for seeds" scenarios. We are treating these needed seed banks as roughly equivalent to a generalized, small restoration seed bank (described in Appendix section 2.c.ii; see Box 4).

F. We subtracted the number of seed banks currently available in each country (point 2 above) from the total number of seed banks to support the RP in each country under each scenario to determine the number of seed banks needed in each country, represented in Map 3.

G. Limitations and future research directions

i. Each of the factors estimated in this analysis is highly variable. Restoration practices are often not quantified, with only limited studies reported in the scientific literature. Germination and survival rates of seeds are highly species- and site-dependent, often not published, and vary substantially across restoration methods.

Therefore, we calculated estimates for the wide range of five scenarios, to help encompass some of that broad variation across these factors. Future research that uses modeling to account for the spatial variation of RP across different biomes and ecosystems, and variations in the factors above — across landscapes, restoration techniques, and socioeconomic conditions — would be highly valuable to inform restoration practices and decision-making.

ii. Although seeds of an estimated 8% of species globally and 18.5% in the tropics are considered “recalcitrant” or desiccation-sensitive[106], and cannot be stored using conventional seed bank methods, we did not remove these seeds from the analysis. Like numerous other factors, data on recalcitrant seeds are limited and not consistent at the country level. Data on seed storage behavior of species can also conflict among sources. Additionally, variation in the number of seeds a seed bank can store is dependent upon numerous other factors such as seed size, seed germinability and viability, climate, ecosystem, and seasonality of the region, among others. For this study, we chose a generalized, small restoration seed bank to calculate capacity (Box 4).

iii. Seed banks are also highly variable in shape, size, staffing, and capacity, both for existing seed banks and no doubt for future seed banks. However, this variation is expected within our current analysis. The flexibility of seed banks’ capacity in different locations helps compensate for the extreme variation in estimated number of seeds based only on currently available literature. Future research with more complex modeling and multivariate statistical analyses would greatly benefit the fields of restoration and seed conservation.

iv. Software and technology are rapidly improving to enable organizations to better monitor and track results of their restoration projects, and more restoration projects are set up in ways that facilitate the collection of data that can inform future efforts. We strongly encourage this practice among restoration projects, and we see this as an important direction for future research on the global need for seeds, seed supply systems, and seed banks.

Endnotes

1. IPCC (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. In Press.
2. Pörtner, H.O. et al. (2021). IPBES-IPCC Co-Sponsored Workshop Report on Biodiversity and Climate Change; IPBES and IPCC.
3. https://www.decadeonrestoration.org/
4. Alves et al. (2022). The Role of Assisted Natural Regeneration in Accelerating Forest and Landscape Restoration: Practical Experiences from the Field. Practice Note. São Paulo: WRI Brasil.
5. Bannister et al. (2018). Major Bottlenecks for the Restoration of Natural Forests in Chile. *Restoration Ecology, 26*(6), 1039–1044.
6. Fargione et al. (2021). Challenges to the Reforestation Pipeline in the United States. *Frontiers in Forests and Global Change, 4*.
7. Jalonen et al. (2018). Forest and Landscape Restoration Severely Constrained by a Lack of Attention to the Quantity and Quality of Tree Seed: Insights from a Global Survey. *Conservation Letters, 11*(4), 1–9.
8. Nyoka et al. (2015). Tree Seed and Seedling Supply Systems: A Review of the Asia, Africa and Latin America Models. *Small-Scale Forestry, 14*(2), 171–191.
9. Palma & Laurance (2015). A Review of the Use of Direct Seeding and Seedling Plantings in Restoration: What Do We Know and Where Should We Go? *Applied Vegetation Science, 18*(4), 561–568.
10. Sommaruga & Eldridge (2021). Avocado Production: Water Footprint and Socio-Economic Implications. *EuroChoices, 20*(2), 48–53.
11. Palma & Laurance (2015).
12. Jalonen et al. (2018).
13. Jalonen et al. (2018).
14. Macqueen & Mayers (2020). Unseen Foresters—An Assessment of Approaches for Wider Recognition and Spread of Sustainable Forest Management by Local Communities. WWF.
15. Swamy et al. (2018). The Future of Tropical Forests Under the United Nations Sustainable Development Goals. *Journal of Sustainable Forestry, 37*(2), 221–256.
16. United Nations Forum on Forests (2021). Global Forests Goal Report 2021. United Nations Department of Economic and Social Affairs.
17. https://sdgs.un.org/goals
18. https://www.cbd.int/gspc/targets.shtml
19. https://www.ser.org/
20. Merritt & Dixon (2011). Restoration Seed Banks—A Matter of Scale. *Science*, 332, 21–22.
21. https://www.unccd.int/
22. Walters & Pence (2020). The Unique Role of Seed Banking and Cryobiotechnologies in Plant Conservation. *Plants, People, Planet, 3*(1), 83–91.
23. Wyse & Dickie (2017). Predicting the Global Incidence of Seed Desiccation Sensitivity. *Journal of Ecology, 105*(4), 1082–1093.
24. https://seedconservationsg.org/
25. Fargione et al. (2021).
26. León-Lobos et al. (2012). The Role of Ex Situ Seed Banks in the Conservation of Plant Diversity and in Ecological Restoration in Latin America. *Plant Ecology and Diversity, 5*(2), 245–258.
27. Jalonen et al. (2018).
28. Palma & Laurance (2015).
29. De Vitis et al. (2020). Seed Storage: Maintaining Seed Viability and Vigor for Restoration Use. *Restoration Ecology, 28*(S3).
30. Di Sacco et al. (2021). Ten Golden Rules for Reforestation to Optimize Carbon Sequestration, Biodiversity Recovery and Livelihood Benefits. *Global Change Biology*, *27*(7), 1328–1348.
31. Merritt & Dixon (2011).

32. Pedrini et al. (2020). Collection and Production of Native Seeds for Ecological Restoration. *Restoration Ecology, 28*(S3), S228–S238.
33. Vernooy et al. (2017). Community Seed Banks: Concept and Practice. Alliance of Bioversity International and CIAT, Rome, Italy.
34. Kimani et al. (2021). Strengthening Community Seed Banks in East and Southern Africa in Times of Covid-19. Alliance of Bioversity International and CIAT, Rome, Italy.
35. Urzedo et al. (2022). Indigenous and Local Communities Can Boost Seed Supply in the UN Decade on Ecosystem Restoration. *Ambio*, 51, 557–568.
36. IPCC (2022).
37. Kijowska-Oberc et al. (2020). Adaptation of Forest Trees to Rapidly Changing Climate. *Forests, 11(2)*, 123.
38. Scheffers et al. (2016). The Broad Footprint of Climate Change from Genes to Biomes to People. *Science*, *354*(6313), aaf7671.
39. IPCC (2022).
40. Turner et al. (2016). The Restoration Seed Bank Initiative: A Focus on Biodiverse Restoration in the Semi-Arid Pilbara of Western Australia. *BGjournal, 13*(2), 20–23.
41. De Vitis et al. (2020).
42. Di Sacco et al. (2021).
43. Merritt & Dixon (2011).
44. León-Lobos et al. (2012).
45. Vernooy et al. (2017).
46. Camhi et al. (2019). Market-Based Opportunities for Expanding Native Seed Resources for Restoration: A Case Study on the Colorado Plateau. *Journal of Environmental Management*, 252, 109644.
47. Urzedo et al. (2022).
48. https://www.decadeonrestoration.org/
49. USDA Forest Service (2022). National Forest System Reforestation Strategy: Growing and Nurturing Resilient Forests. U.S. Department of Agriculture Forest Service, FS-1198.
50. Note on country-level planting commitments: While there are numerous international restoration, conservation, and other planting initiatives, most do not specify country-specific target metrics. We considered using country-level planting commitments such as those listed in Lewis et al. 2019, Table S1, but only 24 countries have specific listed restoration commitments. Lewis et al. (2019), Restoring Natural Forests Is the Best Way to Remove Atmospheric Carbon, *Nature*, *568*(7750), 25–28.
51. https://www.keybiodiversityareas.org/
52. https://www.iucnredlist.org/
53. https://unstats.un.org/sdgs/unsdg
54. https://restor.eco/
55. Bastin et al. (2019). The Global Tree Restoration Potential. *Science, 365*(6448), 76–79.
56. https://www.arcgis.com/apps/View/index.html?appid=d60ec415febb4874ac5e0960a6a2e448
57. Betts (2000). Offset of the Potential Carbon Sink from Boreal Forestation by Decreases in Surface Albedo. *Nature*, 408, 187–190.
58. Griscom et al. (2017). Natural Climate Solutions. *Proceedings of the National Academy of Sciences*, *114(44)*, 11645–11650.
59. Helbig et al. (2020). The Biophysical Climate Mitigation Potential of Boreal Peatlands During the Growing Season. *Environmental Research Letters, 15*(10), 104004.
60. Merritt & Dixon (2011).
61. FAO & UNEP (2020). The State of the World's Forests 2020: Forests, Biodiversity and People.
62. Strassburg et al. (2020). Global Priority Areas for Ecosystem Restoration. *Nature*, 586, 1–6.
63. Wyse & Dickie (2017).
64. Radford et al. (eds.) (2011). Important Plant Areas of the South and East Mediterranean Region: Priority Sites for Conservation. IUCN, Gland, Switzerland and Malaga, Spain.
65. Antonelli et al. (2020). State of the World's Plants and Fungi 2020. Royal Botanic Gardens, Kew.
66. BGCI (2021). State of the World's Trees.
67. Wortley et al. (2013). Evaluating Ecological Restoration Success: A Review of the Literature. *Restoration Ecology, 21*(5), 537–543.

68. Chau et al. (2019). Seed Freeze Sensitivity and Ex Situ Longevity of 295 Species in the Native Hawaiian Flora. *American Journal of Botany, 106*(9), 1248–1270.
69. Zinnen et al. (2021). Seed Production Areas Are Crucial to Conservation Outcomes: Benefits and Risks of an Emerging Restoration Tool. *Biodiversity and Conservation, 30*(5), 1233–1256.
70. Nevill et al. (2016). Seed Production Areas for the Global Restoration Challenge. *Ecology and Evolution, 6*(20), 7490–7497.
71. Pedrini et al. (2020).
72. Nevill et al. (2016).
73. Zinnen et al. (2021).
74. https://www.cbd.int/gspc/targets.shtml
75. https://unstats.un.org/sdgs/unsdg
76. https://geonode.wfp.org/
77. https://qgis.org/
78. https://restor.eco/
79. Bastin et al. (2019).
80. https://www.arcgis.com/apps/View/index.html?appid=d60ec415febb4874ac5e0960a6a2e448
81. Strassburg et al. (2020).
82. Brancalion et al. (2016). Balancing Economic Costs and Ecological Outcomes of Passive and Active Restoration in Agricultural Landscapes: The Case of Brazil. *Biotropica, 48*(6), 856–867.
83. Williams-Linera & Alvarez-Aquino (2010). Tropical Dry Forest Landscape Restoration in Central Veracruz, Mexico. *Ecological Restoration, 28*(3), 259–261.
84. Personal communications.
85. FAO (2014). Genebank Standards for Plant Genetic Resources for Food and Agriculture.
86. Chau et al. (2019).
87. Camargo et al. (2002). Rehabilitation of Degraded Areas of Central Amazonia Using Direct Sowing of Forest Tree Seeds. *Restoration Ecology, 10*(4), 636–644.
88. Ceccon et al. (2016). Is Direct Seeding a Biologically Viable Strategy for Restoring Forest Ecosystems? Evidences from a Meta-Analysis. *Land Degradation and Development, 27*(3), 511–520.
89. James et al. (2011). Demographic Processes Limiting Seedling Recruitment in Arid Grassland Restoration. *Journal of Applied Ecology, 48*(4), 961–969.
90. Palma & Laurance (2015).
91. Pérez et al. (2019). Direct Seeding and Outplantings in Drylands of Argentinean Patagonia: Estimated Costs, and Prospects for Large-Scale Restoration and Rehabilitation. *Restoration Ecology, 27*(5), 1105–1116.
92. Vora et al. (2008). Multi-Species Planting and Other Practices to Restore Forest Diversity in Northeastern Minnesota. *Ecological Restoration*, *26*(4), 340–349.
93. Williams-Linera et al. (2010).
94. Palma & Laurance (2015).
95. Perez et al. (2019).
96. Vora et al. (2008).
97. Williams-Linera et al. (2010).
98. Camargo et al. (2002).
99. Ceccon et al. (2016).
100. James et al. (2011).
101. Palma & Laurance (2015).
102. Perez et al. (2019).
103. Campos-Filho et al. (2013). Mechanized Direct-Seeding of Native Forests in Xingu, Central Brazil. *Journal of Sustainable Forestry*, *32*(7), 702–727.
104. Merritt & Dixon (2011).
105. Urzedo et al. (2020). Seed Networks for Upscaling Forest Landscape Restoration: Is It Possible to Expand Native Plant Sources in Brazil? *Forests*, *11*(3), 259.
106. Wyse & Dickie (2017).

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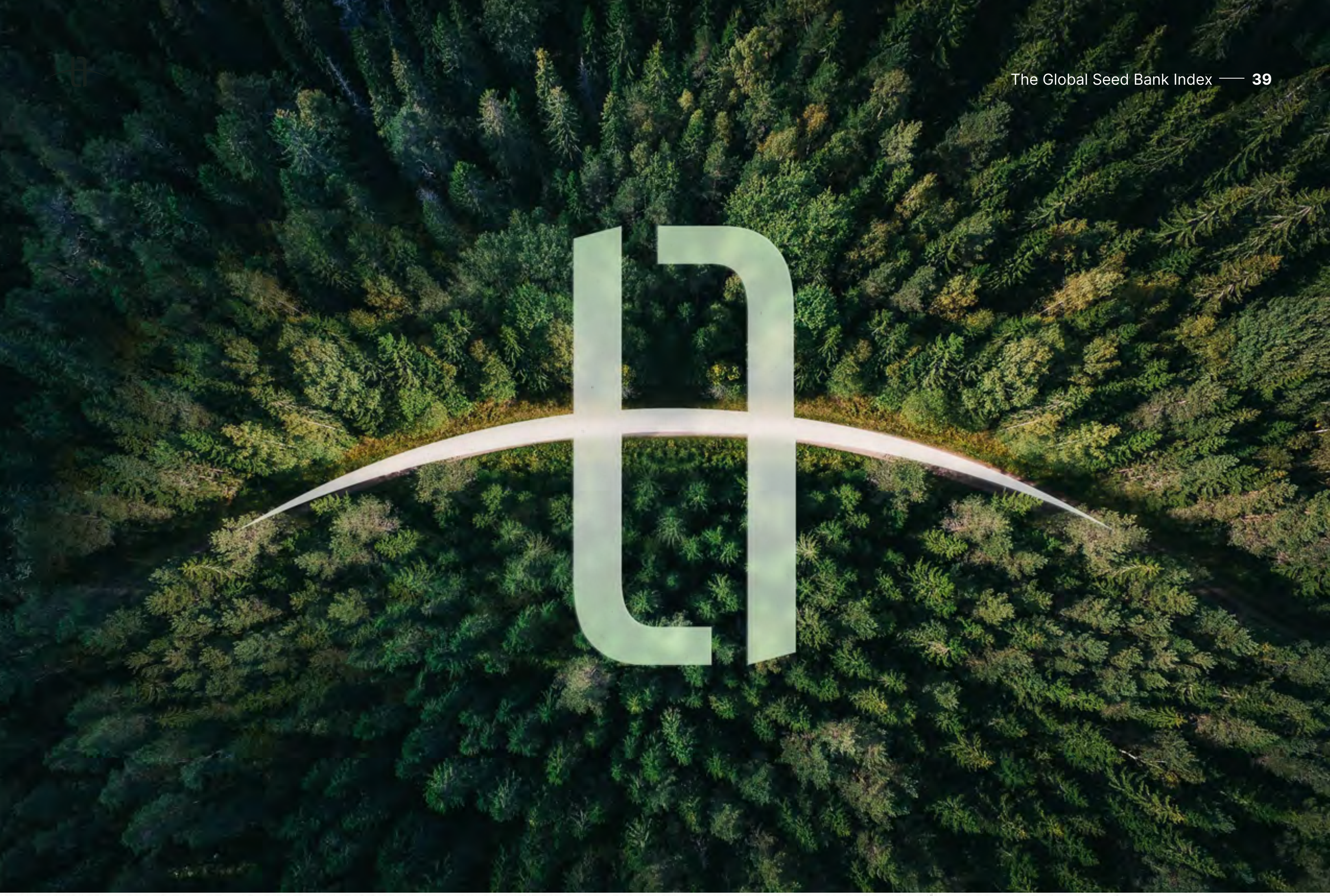

About Terraformation

Terraformation is dedicated to restoring the world's forests to stabilize our climate, revive ecosystems, and build thriving communities.

The company hosts a forest carbon accelerator, supporting early-stage forestry teams to launch, build, and scale biodiverse reforestation projects. In addition to producing high-quality, verified carbon credits, these projects generate complementary sustainable revenue streams to support local economies.

Terraformation's current partner network spans five continents and includes diverse landowners and organizations. It was founded in 2019 by Yishan Wong, former CEO of Reddit.

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