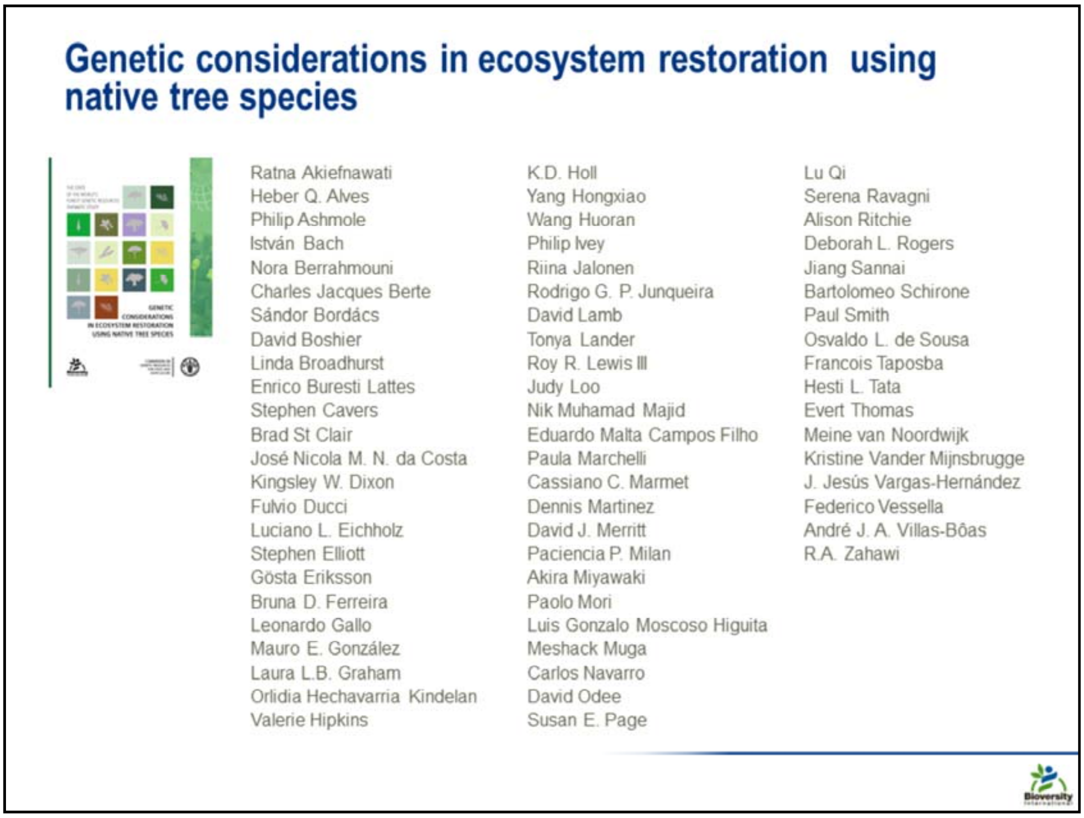
Restoring forest landscapes is recognized as one of the strategies for tackling some of the major environmental problems of our time, notably climate change, loss of biodiversity and desertification. The latest strategy of the UN Convention on Biological Diversity (2011-2020) sets the bold goal of restoring at least 15% of the world's degraded ecosystems by 2020. The huge scale of this undertaking presents opportunities and risks. The restoration of vast areas of wastelands that currently provide minimal economic or ecological value to landscapes producing goods and environmental services represents an opportunity to increase our productive land area. However, to create these transformations requires addressing and overcoming risks of failure, many of which are associated with the qualities and the composition of planting materials, and the processes needed to restore a self-sustaining ecosystem.

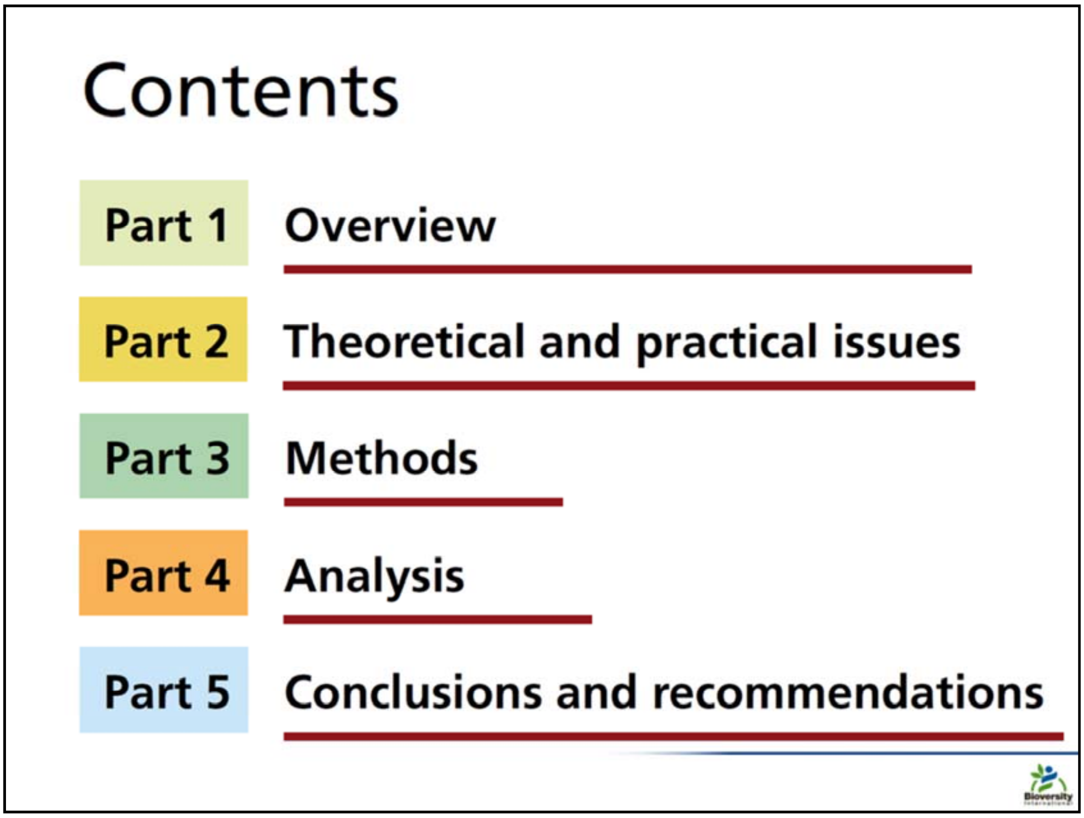
The value of using native tree species in ecosystem restoration is receiving growing recognition among practitioners and policymakers. Native species are well-adapted to local environments and should support native biodiversity and ecosystem resilience to a greater extent than would exotic planting material. However, restoration requires more than just planting the right species. The genetic composition of reproductive material significantly affects the success of restoration both in the short and the long term. Matching seed sources within species to site conditions is essential for short term success.



Bioversity scientists coordinated the thematic study on 'Genetic considerations in ecosystem restoration using native tree species' as an input to the first report on The State of the World's Forest Genetic Resources.

Bozzano, M., Jalonen, R., Thomas, E., Boshier, D., Gallo, L., Cavers, S., Bordács, S., Smith, P. & Loo, J., eds. 2014. *Genetic considerations in ecosystem restoration using native tree species*. State of the World's Forest Genetic Resources – Thematic Study. Rome, FAO and Bioversity International.

The 280-page book presents the scientific foundations and evidence for the importance of genetics in restoration. This scientific review, carried out by Bioversity International and co-published with the Food and Agriculture Organization of the UN (FAO), provides practical recommendations for researchers, policymakers and restoration practitioners to maximize the potential for success in ecosystem restoration. It can be downloaded free at the following link: www.fao.org/3/a-i3938e.pdf

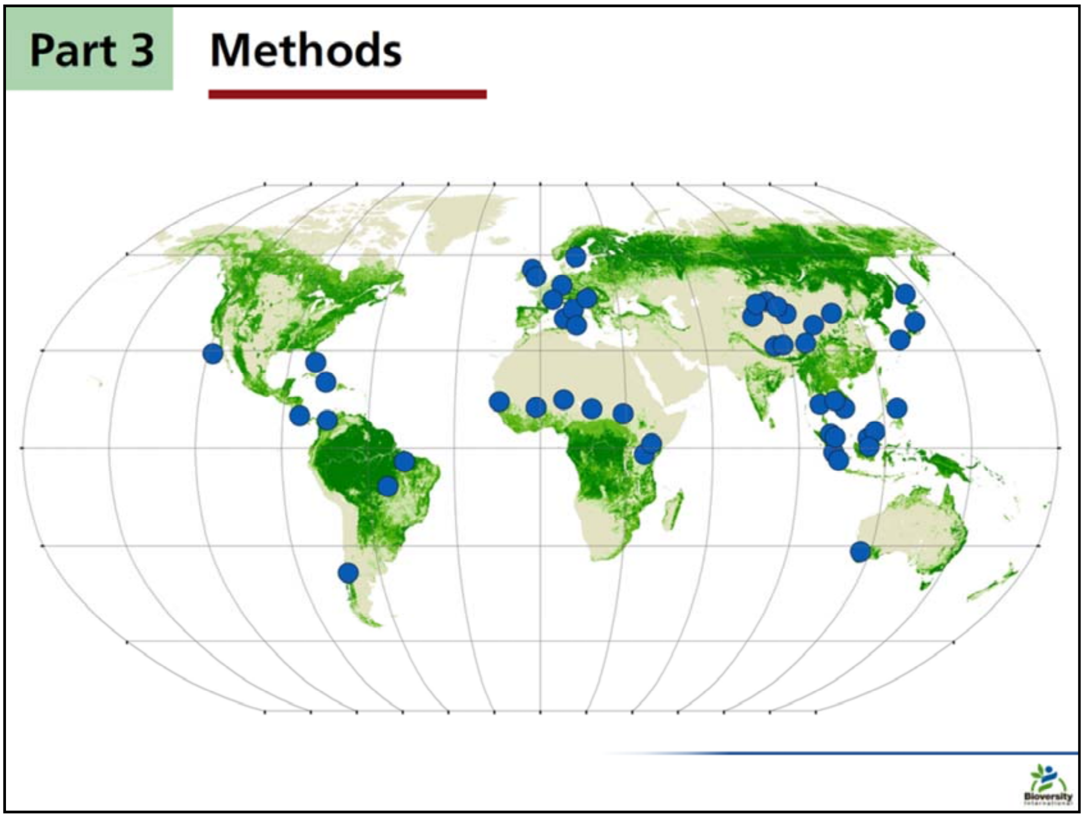


Scope

This thematic study includes a review and syntheses of experience and results; analysis of successes and failures in various systems; definition of best practices including genetic aspects; and identification of gaps in knowledge and needs for further research and development efforts.

Abstract

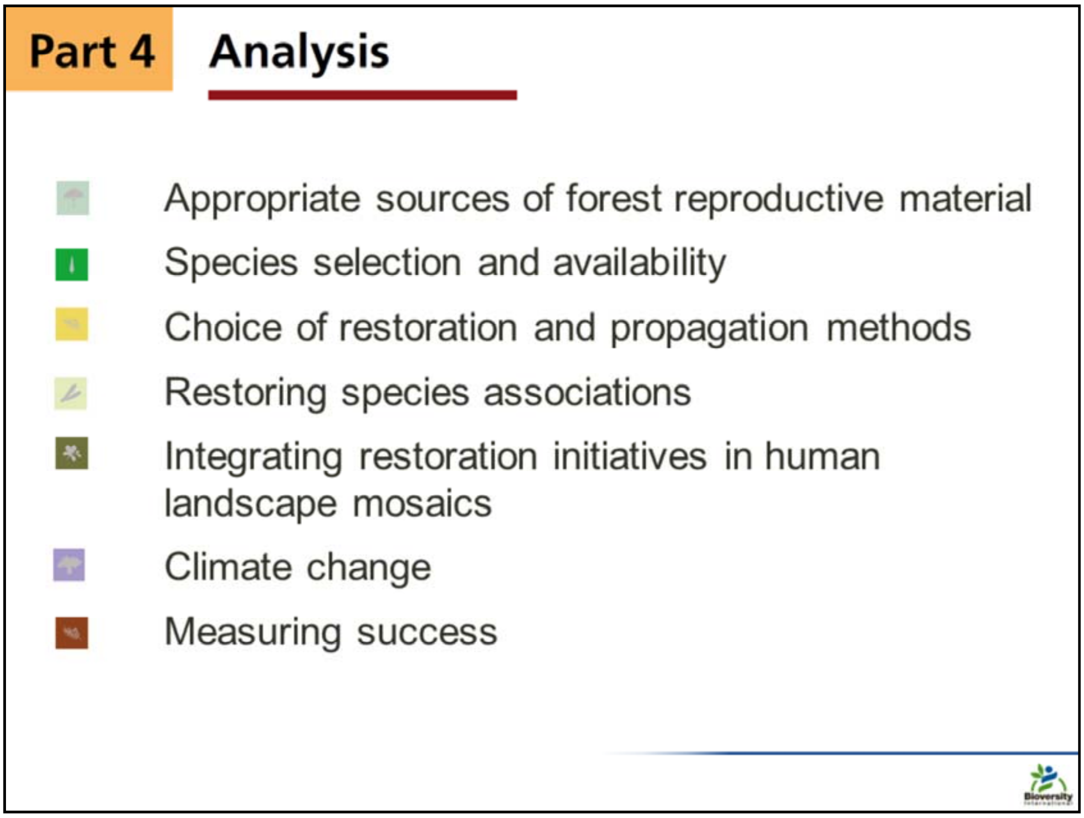
There is renewed interest in the use of native tree species in ecosystem restoration for their biodiversity benefits. Growing native tree species in production systems (e.g. plantation forests and subsistence agriculture) can also ensure landscape functionality and support for human livelihoods. Achieving these full benefits requires consideration of genetic aspects that are often neglected, such as suitability of germplasm to the site, quality and quantity of the genetic pool used and regeneration potential. Understanding the extent and nature of gene flow across fragmented agro-ecosystems is also crucial to successful ecosystem restoration. We review the role of genetic considerations in a wide range of ecosystem restoration activities involving trees and evaluate how different approaches take, or could take, genetic aspects into account, leading towards the identification and selection of the most appropriate methods.



Methods + Survey

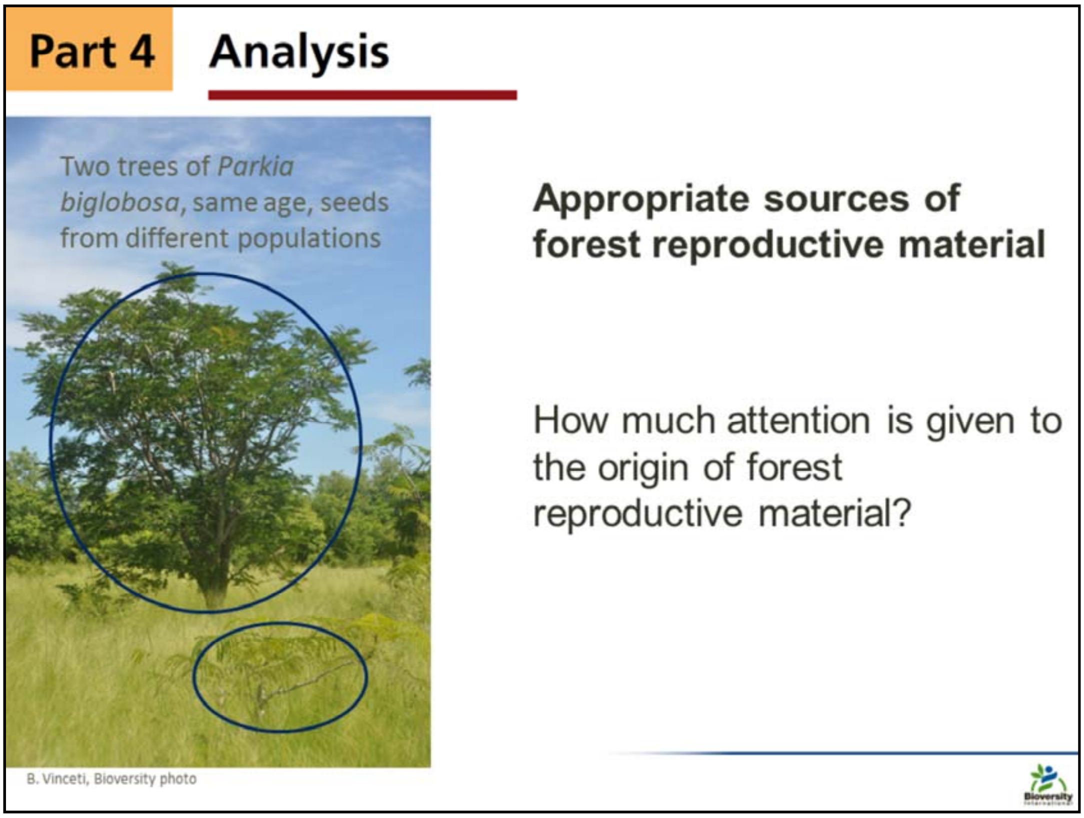
Many restoration approaches and methods focusing on native species have been developed and fine-tuned over the years, reflecting the diversity of species and ecosystems, degradation factors, stages and socio-economic contexts. In this section, some of the scientists who have developed these approaches or have been most active in promoting them describe some of the most widely applied and studied methods and their principles. In many cases these descriptions are complemented by case studies.

Authors of the methods were surveyed to collect additional information about the genetic considerations in restoration methods presented. The survey included questions about species composition, source of propagation materials and practical details of the design and implementation of each method



Chapter 4 of the thematic study discusses genetic aspects of current practice for ecosystem restoration using native tree species.

Practical implications for the viability of the restored tree populations are analysed, and options are presented for improving restoration success by applying genetic principles. To this end, the restoration methods and approaches presented in Part 3 (Methods) were analysed from a genetic perspective, based on the theoretical and practical issues of ecosystem restoration. Authors of the methods described in Part 3 were surveyed to collect additional information about the genetic considerations of the restoration methods presented. The survey included questions about species composition, source of propagation materials, and practical details of the design and implementation of each method. In total, 23 survey responses were received. Most of the respondents carry out applied research, developing and testing a range of restoration approaches and methods that use native species. A rigorous quantitative analysis of the survey results was not undertaken, as the methods and experiences included do not represent a random sample of ecosystem restoration efforts globally. Nevertheless, the responses can be considered indicative of general trends in ecosystem restoration with respect to genetic aspects, and provide useful information to guide the incorporation of genetic considerations in restoration projects.



Appropriate sources of forest reproductive material

Survey results: *Only half of the restoration methods incorporated guidelines or recommendations for the collection of forest reproductive material (FRM). Such recommendations were clearly more common for approaches aimed at conserving or restoring populations of particular tree species than for approaches that focused on restoring habitats or ecosystems in general. Sourcing FRM locally or from similar ecological conditions was considered ideal for nearly all restoration approaches. For approaches focusing on ecosystem restoration, distance of the source of FRM ranged between a few hundred metres to approximately 100 km from the restoration site, but typically FRM originated from within a few kilometres of the restoration site. Half of the respondents indicated that lack of populations of the target species in the vicinity of the restoration area very often limited the availability of FRM.*

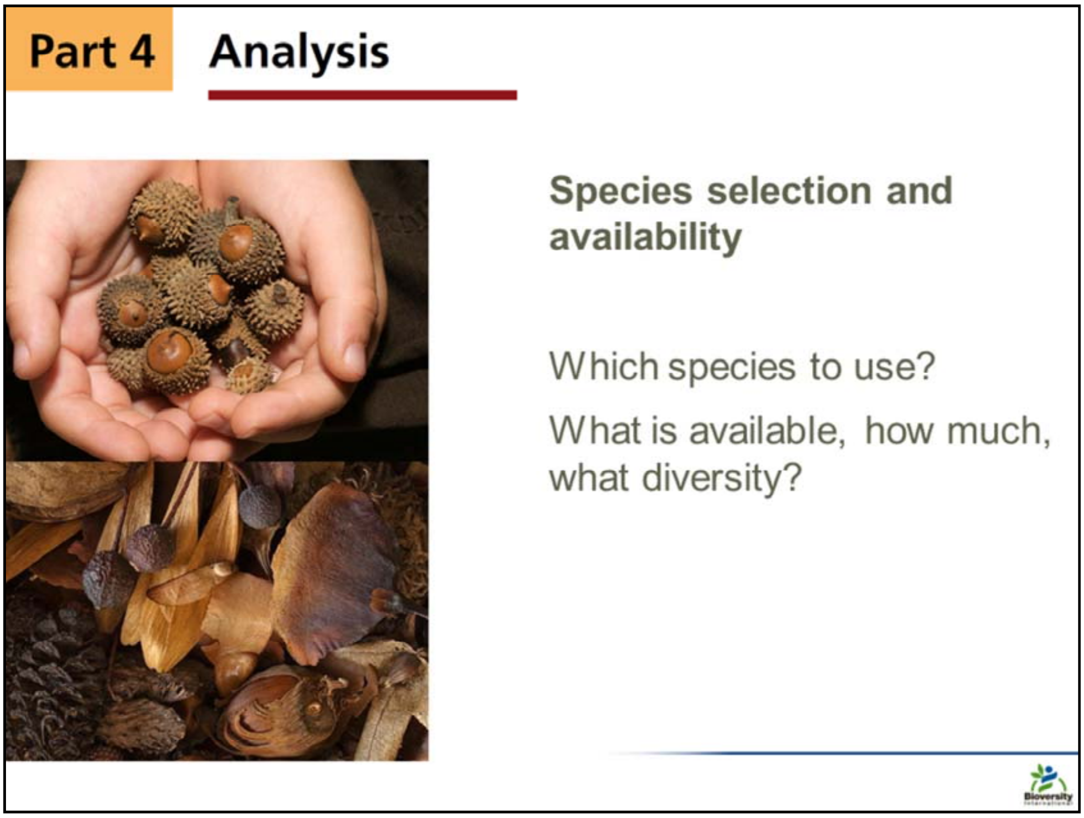
Needs for research, policy and action

Quantify the risks associated with genetic mismatching resulting from use of narrow or exotic genetic diversity, including long-term studies. Identify the critical thresholds for genetic diversity in restoration material and the key variables for well-matched sources of FRM. Studies should be initiated in systems that are simple in terms of species and structural diversity to facilitate understanding of genetic and ecological interactions.

Develop and promote decision-support tools for collecting germplasm for restoration that consider the variation in genetic patterns among tree species and ways of predicting it for lesser-known species based on life-history traits of species. Such tools should allow determination of whether remaining populations of a species in the landscape are likely to contain adequate diversity for sourcing good-quality FRM, and how to identify alternative or complementary sources of FRM when necessary.

Create wider awareness among restoration practitioners about the risks of using FRM with a narrow genetic base. Promote the adoption of national or international certification schemes, standards and guidelines for collecting FRM and documenting its origin.

Promote awareness of the potential of individual restoration projects to contribute to species conservation and serve as future seed sources, especially for rare, endemic and endangered tree species. Develop approaches and tools for planning, coordination and communication of restoration activities that support these objectives.

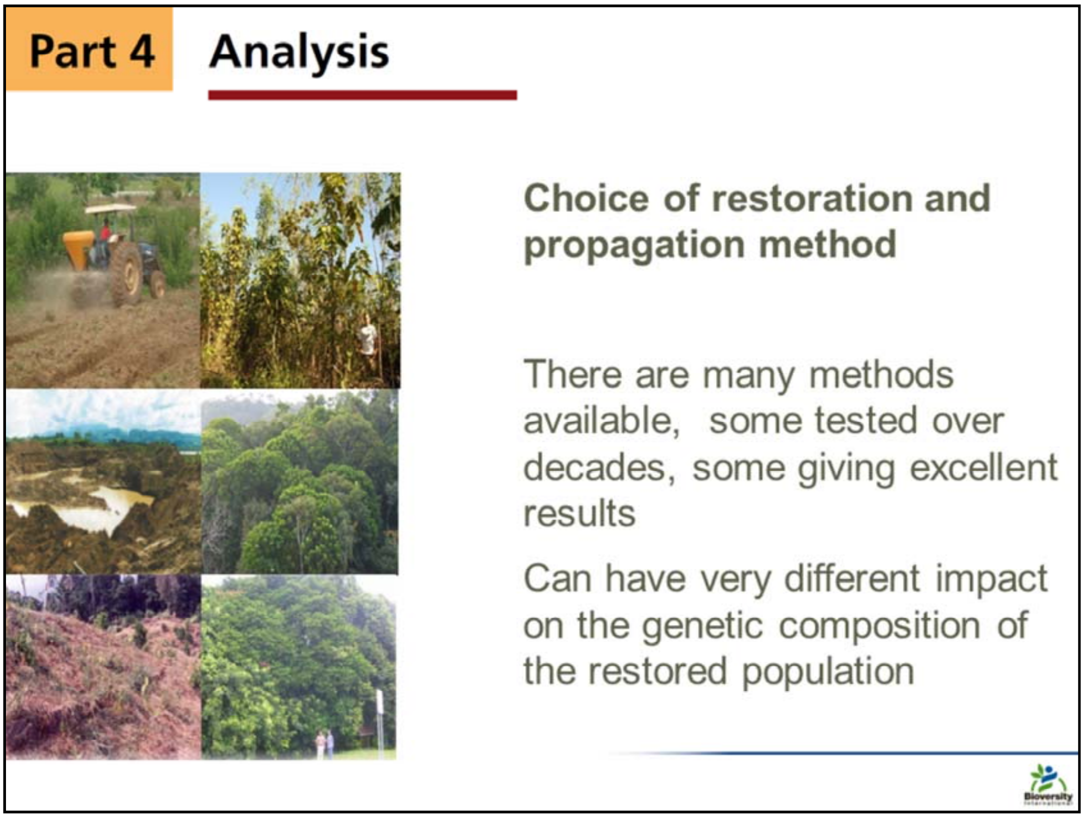


Species selection and availability

Survey results: *Lack of FRM of native tree species was the most common constraint to the wider application of the various restoration methods. Availability of FRM was limited, above all, by lack of knowledge of species biology (e.g. phenology or propagation methods) and lack of populations of the target species in the vicinity of the restoration area. Availability of FRM and ease of propagation and cultivation were the most important reasons for the choice of species after the successional characteristics of the species, and were considered more decisive than, for example, functional characteristics or conservation status of the species. Most respondents implied that FRM was collected and nursery seedlings were raised as part of the restoration effort. One out of four respondents reported that exotic species were regularly used. The most common reasons for the use of exotic species were their functional characteristics or product preferences.*

Needs for research, policy and action

Conduct applied research to understand the potential of native species to achieve various restoration objectives in assorted states of site degradation and ecological and socio-economic contexts. Analyse the ecological and socio-economic trade-offs related to the use of exotic versus native species, and the factors that currently constrain wider use of native species. Develop knowledge-based decision-support tools for identifying the conditions under which the use of exotic species in ecosystem restoration can be considered beneficial and justified, or risky and best avoided. Improve access to information that is relevant for the restoration community, particularly data on the biology and ecology of native species. Encourage restoration researchers and practitioners to share information and contribute results to publicly available databases, and develop new decision-support tools for facilitating the selection of species and restoration methods. Ensure access to information by local restoration practitioners, farmers and other stakeholders by developing and promoting appropriate communication technologies and products and provision of information in locally relevant languages that uses easily understandable terminology and accessible formats. Raise awareness among restoration practitioners of the need for early planning of appropriate and adequate germplasm supplies of desired species, including the associated time and costs. Envisage best ways to embed collection of FRM and nursery production in projects from the outset. Improve documentation of collection and propagation of FRM as well as communication channels, cooperation and feedback loops between seed suppliers, nurseries and restoration projects. Analyse the needs and options for support and regulatory frameworks tailored to the restoration of forested ecosystems and production and supply of FRM. Such frameworks should explicitly address the role and use of native species and the minimum set of genetic considerations that should be taken into account, the role and knowledge of local communities and other stakeholders, and capacity strengthening of local nurseries and seed companies, as appropriate. Develop and implement the frameworks based on needs analysis, ensuring adequate financing for the activities.



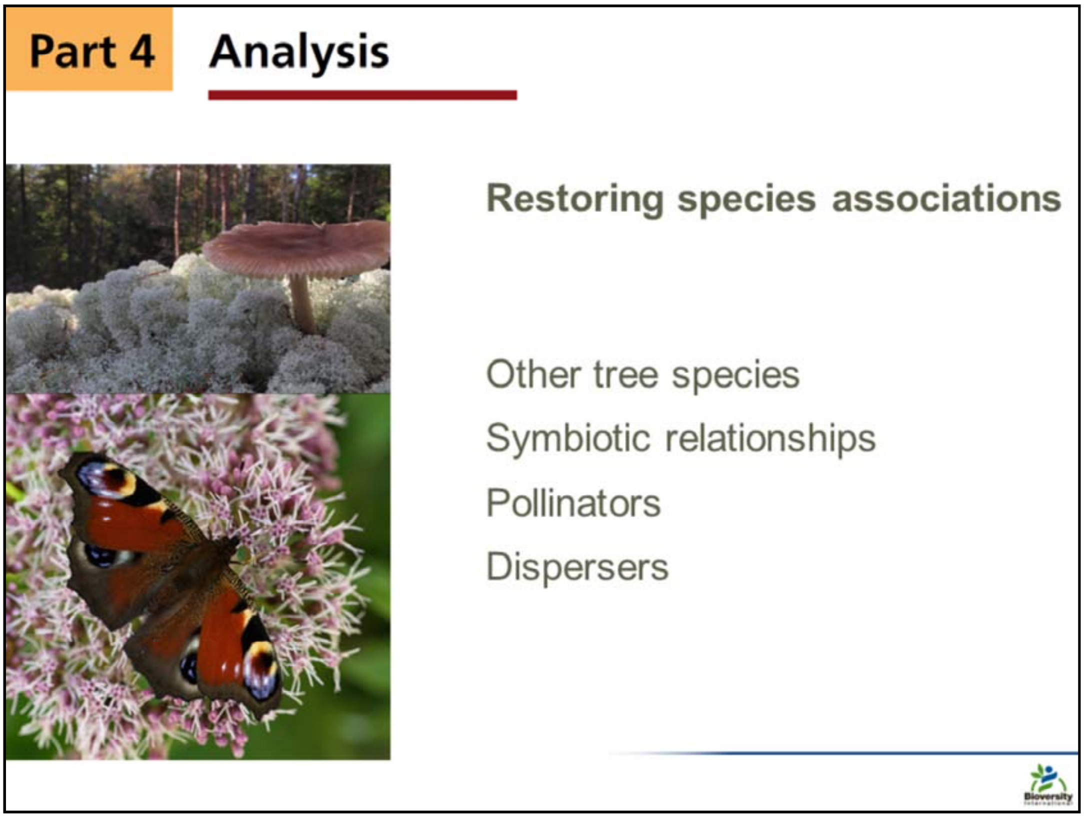
Choice of restoration and propagation method

There are many restoration Methods available, some tested for more that 30y, some giving excellent results

Survey results: *Nursery seedlings were by far the most common FRM used across the range of restoration methods, followed by wildings and seeds. With few exceptions, the respondents indicated that nursery seedlings were very often used as FRM in the restoration method they presented. Wildings were also used as FRM in most of the cases, and in half of the cases direct seeding was sometimes applied. Although vegetative propagation was mentioned it was not often used. There was a reliance on natural regeneration when constraints to regeneration (e.g. excessive grazing) were solved.*

Carry out research to develop and test suitable restoration and propagation methods and decision-making tools for a variety of native tree species and states of site degradation. Research should include analysing the genetic composition of tree populations restored through different approaches and comparisons with existing tree populations in the surrounding landscape or in similar conditions further away to help ensure the genetic integrity of the restored plant communities. Phased analysis to track the development of genetic diversity at restored sites over multiple generations would help to refine guidance for good nursery practice, for example by assessing the long-term fitness consequences for different species of using seedlings produced under the relaxed selective environment of the nursery.

Create awareness of the importance of carefully evaluating site conditions as a basis for choosing the restoration approach that best addresses the causes of degradation and the types of FRM that are most likely to ensure successful establishment of viable tree populations and most efficient in terms of use of resources.

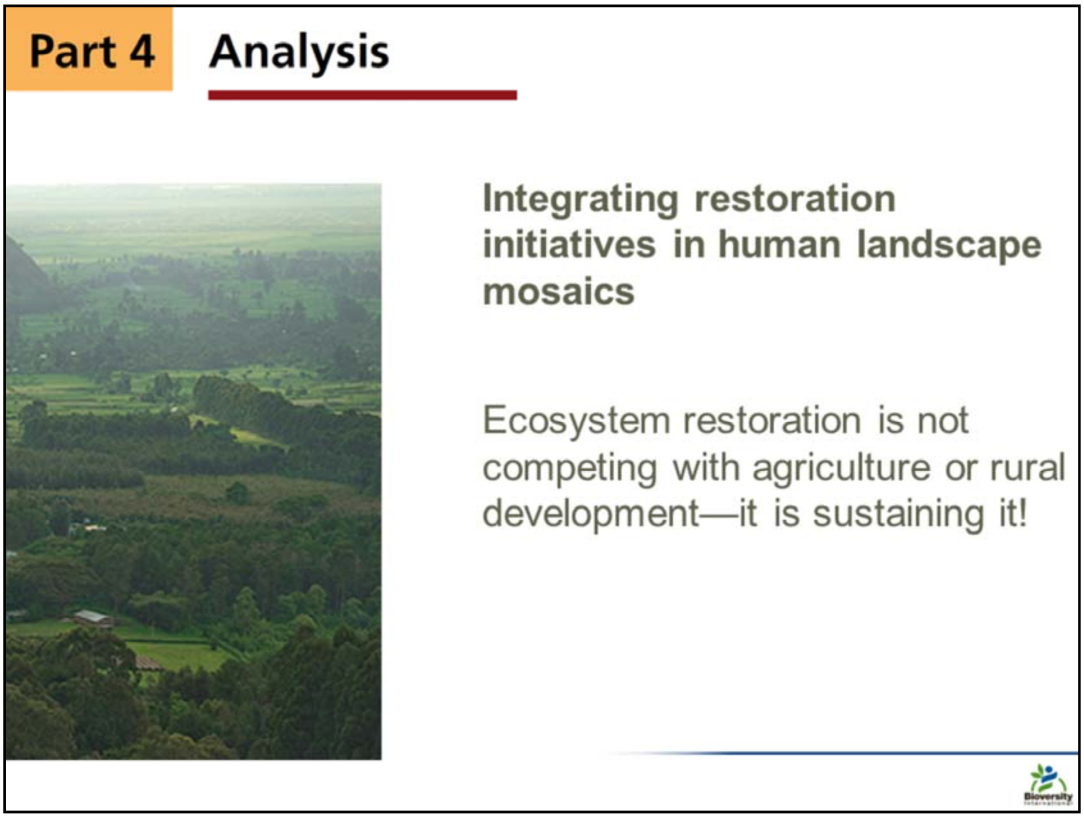


Survey results: *Only a third of the respondents indicated that the restoration methods they had used deliberately considered restoration of species associations or symbiotic relationships.*

Needs for research, policy and action

Analyse the importance and strength of relationships among foundation species, associated organisms and their genotypes and the implications of the relationships for successful establishment of diverse and viable tree populations. Identify success factors and develop practical approaches and guidelines for restoring species associations using different restoration methods and in different ecosystem and landscape contexts. Develop and test models for predicting the likely benefits of restoration to plant-community relationships, biodiversity conservation and ecosystem function and resilience.

Raise awareness of the importance of species associations for the successful restoration of ecosystem functions and promote the consideration of species associations in the planning and design of restoration projects.



Restoring species associations

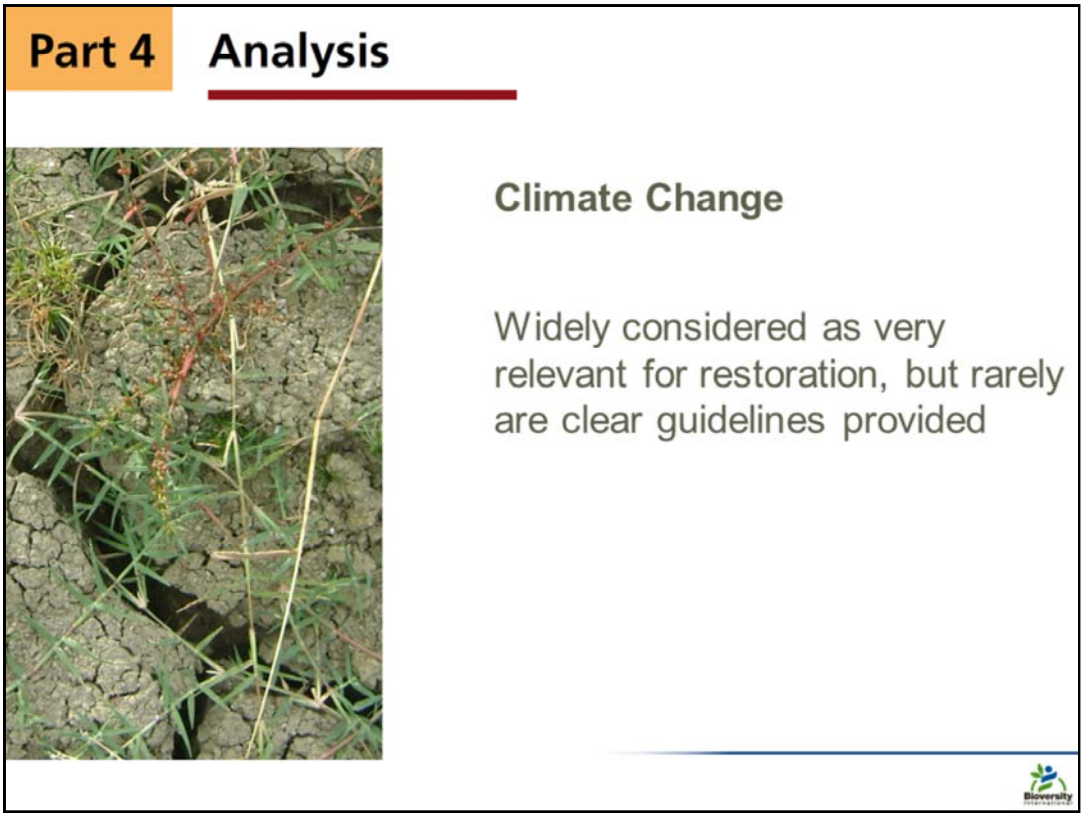
***Survey results**. Area of application varied widely within and among methods, but the most typical size reported for restoration actions was about 10 ha. Two out of three respondents indicated that landscape connectivity needs to be considered when applying their restoration method. Landscape considerations were most commonly associated with seed dispersal distances from surrounding forests to the restoration site. The majority of respondents considered carbon sequestration and restoration of habitats for flora and fauna as the most common benefits expected from restored forests, while production of timber, fodder or fuelwood were considered important by only half of the respondents. Half of respondents reported that the restoration methods they used could in some cases be applied to agroforestry or other land-use types, integrating livelihood aspects.*

Needs for research, policy and action

Consistently plan restoration efforts at a landscape scale and seek to integrate them into the surrounding land-use matrix or existing networks of habitat corridors. The presence of existing tree populations of target species needs to be explicitly taken into account to facilitate establishment and maintenance of viable tree populations. Develop and promote tools and opportunities for learning, coordination, communication and joint decision-making among landowners and users on the allocation of restoration efforts.

Carry out research on the best approaches for ensuring that individual restoration projects benefit from the landscape context and add value to it in terms of ecological and genetic connectivity, land uses and livelihood strategies. Transform the main findings into practical decision-support tools for landscape planning. Researchers should seek to consolidate the role of production systems and on-farm conservation in providing ecosystem goods and services while contributing to landscape connectivity, and should analyse the genetic impacts of different management practices and land-use patterns on tree populations.

Advocate among politicians for policy measures and decisions in favour of landscape-scale restoration of degraded forest ecosystems.



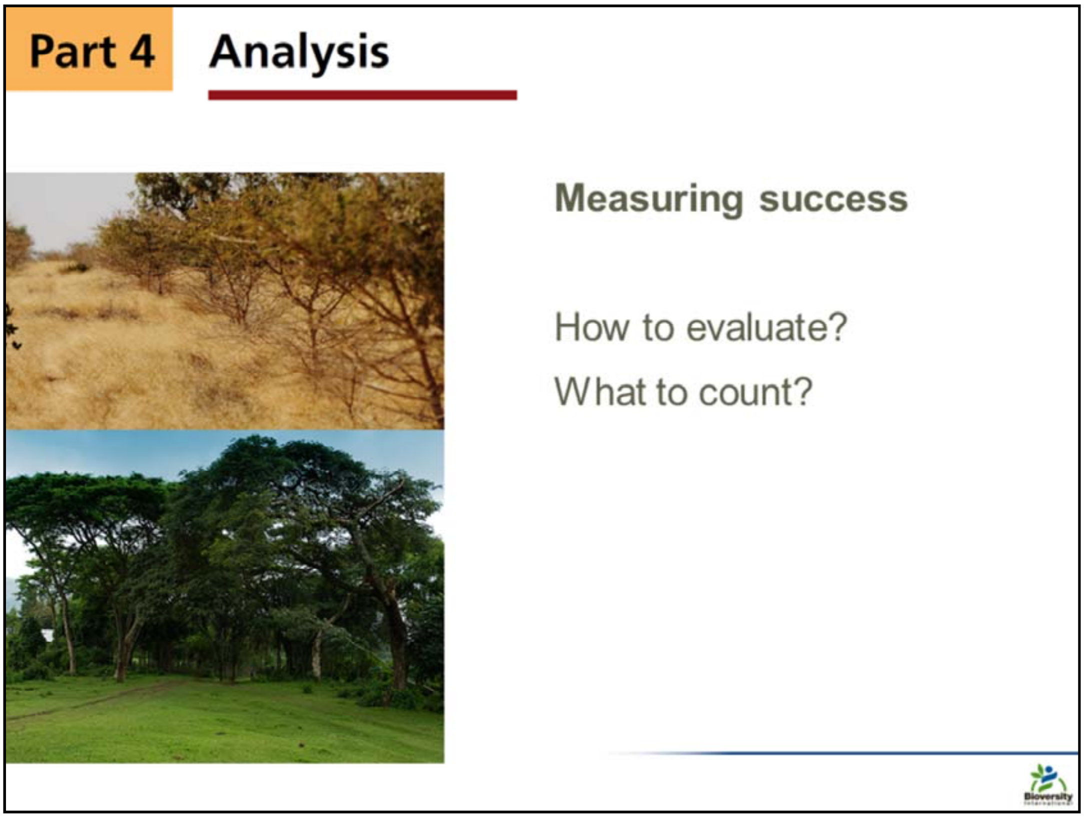
Climate Change

Survey results*: Two out of five respondents indicated that the restoration methods they use consider effects of climate change at least to some extent. At the same time, only two of the 23 respondents provided explicit approaches for anticipating climate impacts. Climate change was most commonly related to changes in species composition, with only two respondents explicitly mentioning intraspecific effects.*

Needs for research, policy and action

Given the uncertainty of future climate predictions, the most prudent approach to preparing for climate change for most restoration efforts is to use as much as possible of the genetic and species diversity available near the restoration site or in sites with similar (macro)environmental conditions, which will allow natural selection to take its course and move the restored population in the required direction. Restoration projects should collect forest reproductive material from a large number of parent trees and from as many sites as possible with locally varying (microenvironmental) habitat conditions. Such approaches should be used in combination with planning and management strategies explicitly designed to promote gene flow and facilitate species migration. In cases where genetic diversity is lacking and where impacts of climate change are already stressing the ecosystem, assisted migration may be necessary, taking precautions to match changing environmental conditions as closely as possible and to avoid possible associated risks to local biodiversity in target areas.

Conduct research on the extent and distribution of plasticity and adaptive capacity in native tree species, particularly in areas that are especially vulnerable to climate change, in order to identify appropriate FRM for restoration that also maximizes resilience. Develop and test practical approaches and decision-support tools for improving ecosystem resilience through restoration. Establish provenance trials using seed sources collected from a stratified sample across the species' distribution range, on sites across environmental gradients within and beyond current species distributions. Research should also be designed to test the feasibility of assisted migration. Modelling approaches that take into account genetic diversity and selection seem a promising approach to yield timely and relevant results.



Measuring success

Evaluating the success of any action requires a clear definition of objectives or baselines against which performance can be judged. Possible objectives of ecosystem restoration are at least as diverse as its definitions, ranging from restoring tree cover, original vegetation structure and biodiversity, to ecosystem functions, services or provision of livelihoods. One of the proposed, more holistic goals for restoration is restoring ecological integrity, defined as "maintaining the diversity and quality of ecosystems, and enhancing their capacity to adapt to change and provide for the needs of future generations" (Mansourian 2005). Another, probably more dynamic definition by lead members of the International Society of Ecological Restoration emphasizes "reinstating autogenic ecological processes by which species populations can self-organize into functional and resilient communities that adapt to changing conditions while at the same time delivering vital ecosystem services" (Alexander *et al.* 2011b).

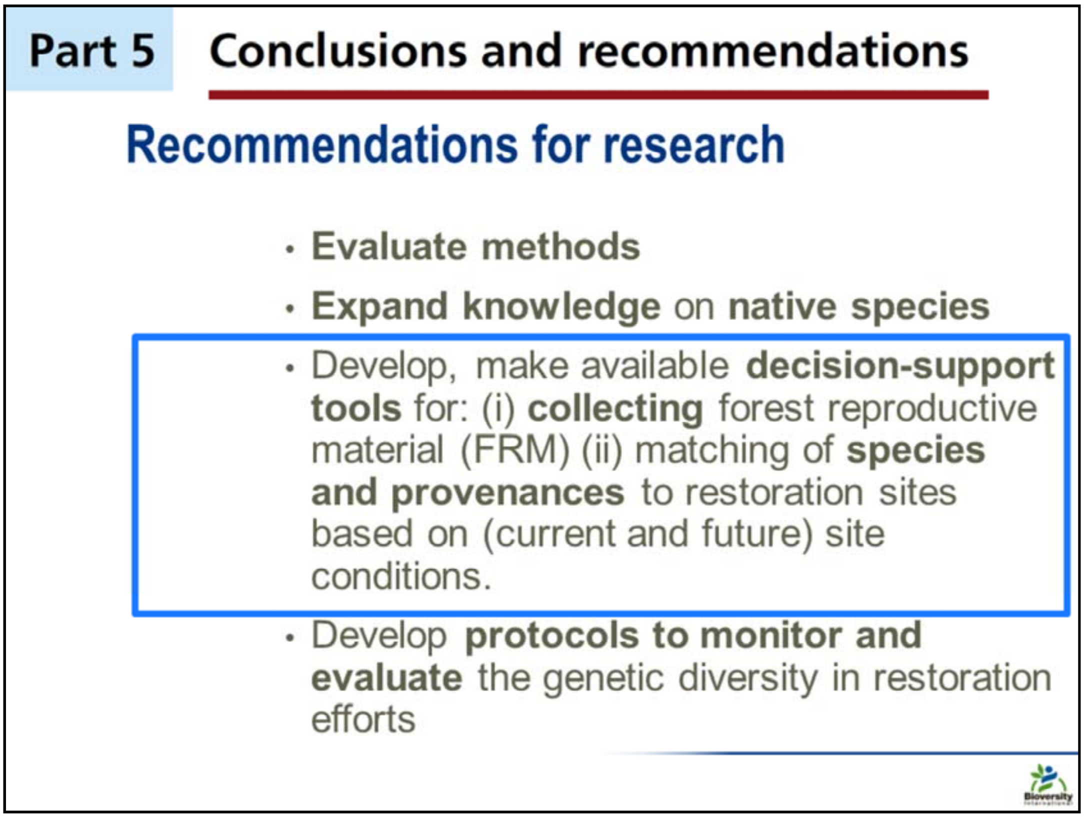
Needs for research, policy and action

Conduct research for different combinations of native species, degradation states and restoration methods to understand how various biological, genetic, ecological and management processes interact and affect ecosystem functions and the resilience of genetic diversity during restoration. Develop protocols for collecting related baseline information that are widely applicable to different species and contexts, as well as sets of genetic and surrogate indicators that allow assessment of the viability and resilience of restored tree populations.

Through the collaboration of researchers and policy-makers, compile compelling evidence and advocate for the need to measure success in restoration projects in ways that reflect ecosystem functioning and long-term resilience. Foster collaboration between restoration researchers and practitioners to compile information, conduct meta-analyses and generalize good practices for ensuring viability of restored tree populations for functional and resilient ecosystems.

Part 5 Conclusions and recommendations

- Recommendations for research
- Recommendations for restoration practice
- Recommendations for policy



Recommendations for research

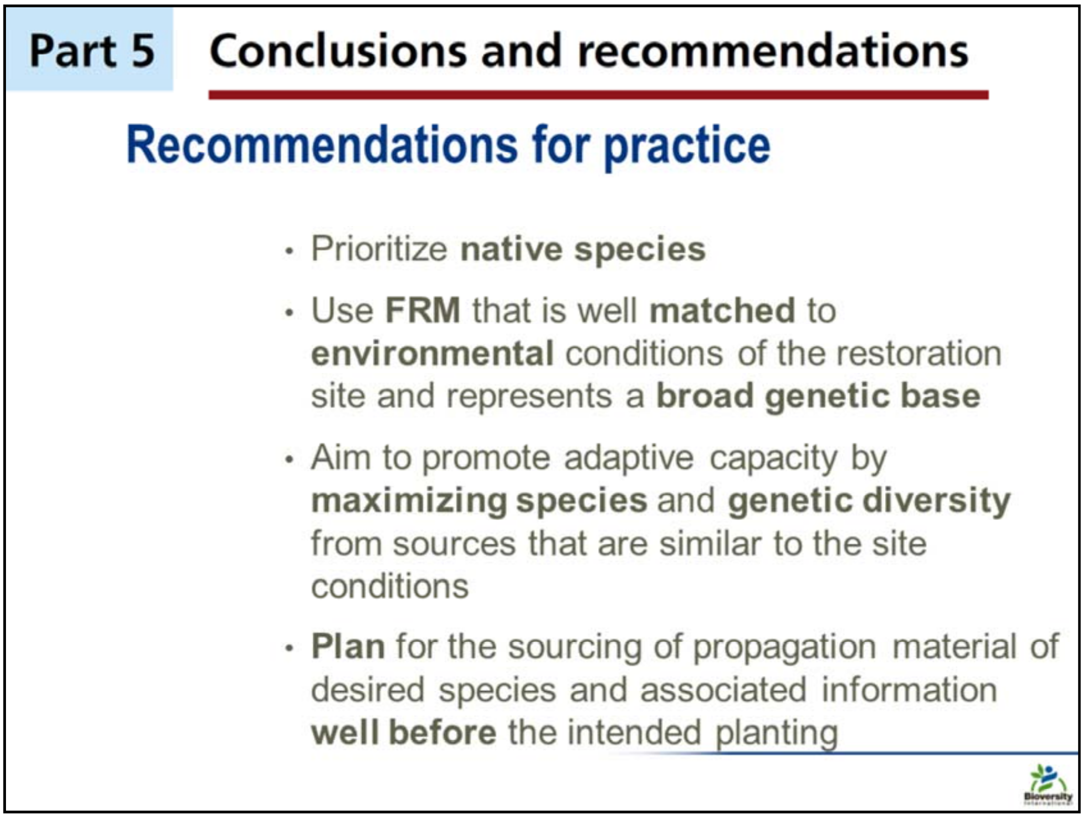
Evaluate the impact of different restoration methods on the genetic diversity of restored tree populations.

Expand knowledge on native species, particularly with respect to their ecological and livelihood importance, propagation methods and genetic variability and identify ways to overcome constraints that limit their use in restoration.

Develop, make available and support the adoption of decision-support tools for: (i) collecting and propagating germplasm in a way that ensures a broad genetic base of restored tree populations; (ii) matching of species and provenances to restoration sites based on (current and future) site conditions, predicted or known patterns of variation in adaptive traits and availability of seed sources; and (iii) landscape-level planning in restoration projects.

Develop protocols and practical indicators to monitor and evaluate the genetic diversity of tree populations in restoration efforts as an indicator of the viability and resilience of ecosystems.

Intensify research on the ecology of mycorrhizal and bacterial symbiotic systems, focusing on the most commonly used tree species and their symbiotic partners to increase the resilience of plant associations in restoration against biotic and abiotic stresses.



Recommendations for restoration practice

Give priority to the use of native tree species in restoration projects.

Strive to use Forest Reproduction Material (FRM) that is well matched to the environmental conditions of the restoration site and represents a broad genetic base.

Given the uncertainty of predictions of future climate, aim to promote resilience by maximizing species and genetic diversity from sources that are similar to the site conditions, encouraging gene flow and generational turnover and facilitating species migration to allow natural selection to take place.

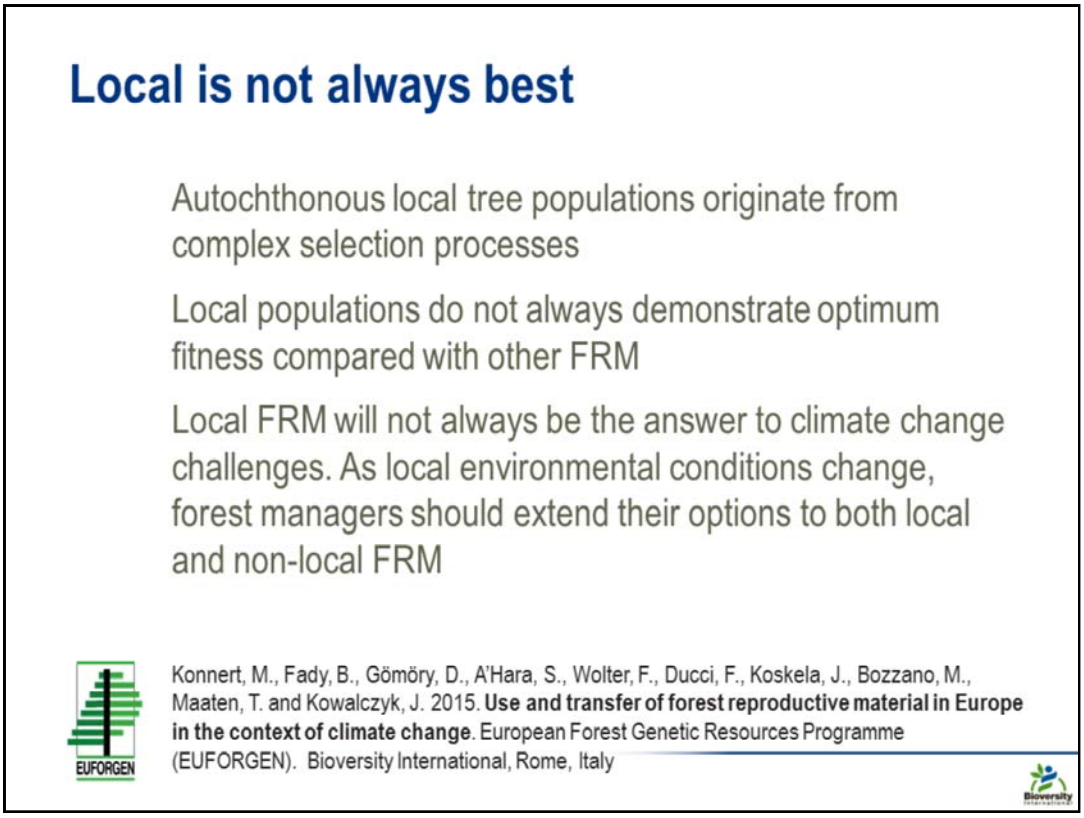
Plan for the sourcing of propagation material of desired species and associated information well before the intended planting or seeding time to ensure that optimal material for the site and restoration objectives can be identified and produced.

Consistently plan restoration efforts in the landscape context and seek to integrate them into the surrounding landscape matrix.

Why are genetic considerations important in ensuring effective forest restoration?

Genetic considerations are important in ensuring effective forest restoration

- to define appropriate **provenances**
- **to conserve local populations** and species
- to restore **adaptive capacity**
- to increase **long-term** success of restoration over generations
- **to provide ecosystem services** in short and long term

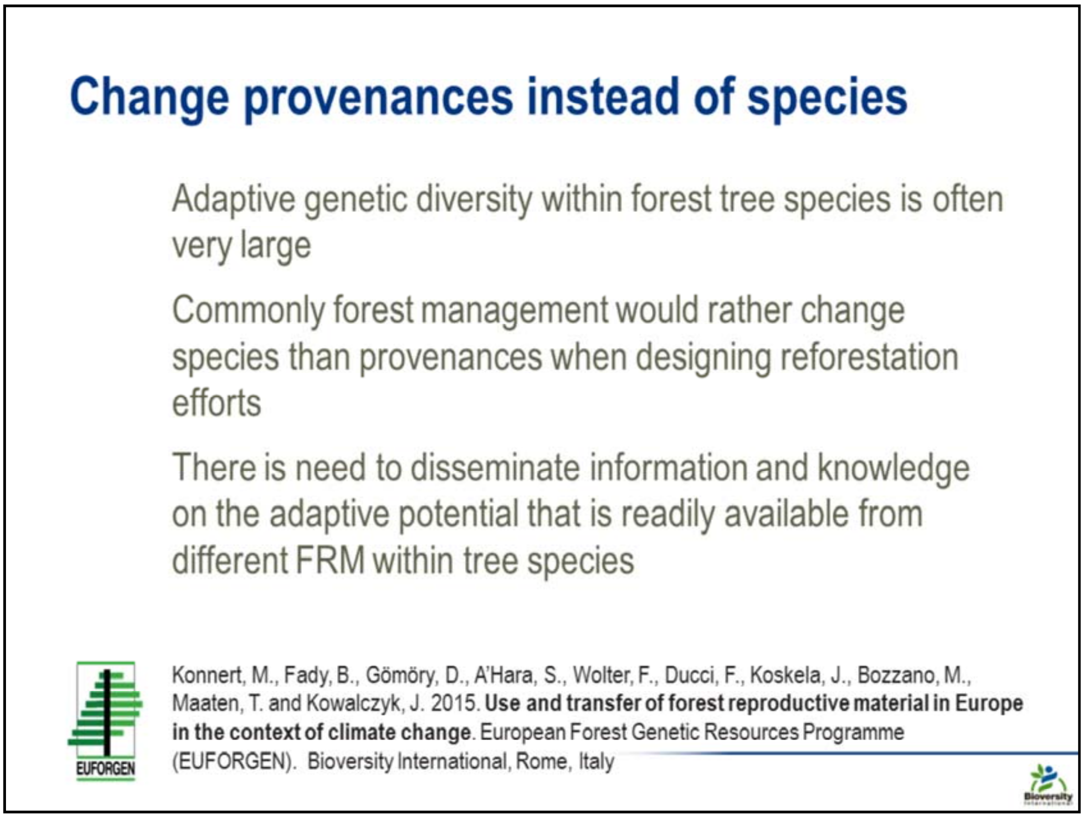


***Recommendations derived from a recently published report on "*Use and transfer of forest reproductive material in Europe in the context of climate change" of the European Forest Genetic Resources Programme (EUFORGEN).**

Konnert, M., Fady, B., Gömöry, D., A'Hara, S., Wolter, F., Ducci, F., Koskela, J., Bozzano, M., Maaten, T. and Kowalczyk, J. 2015. **Use and transfer of forest reproductive material in Europe in the context of climate change**. European Forest Genetic Resources Programme (EUFORGEN). Bioversity International, Rome, Italy

Local is not always best

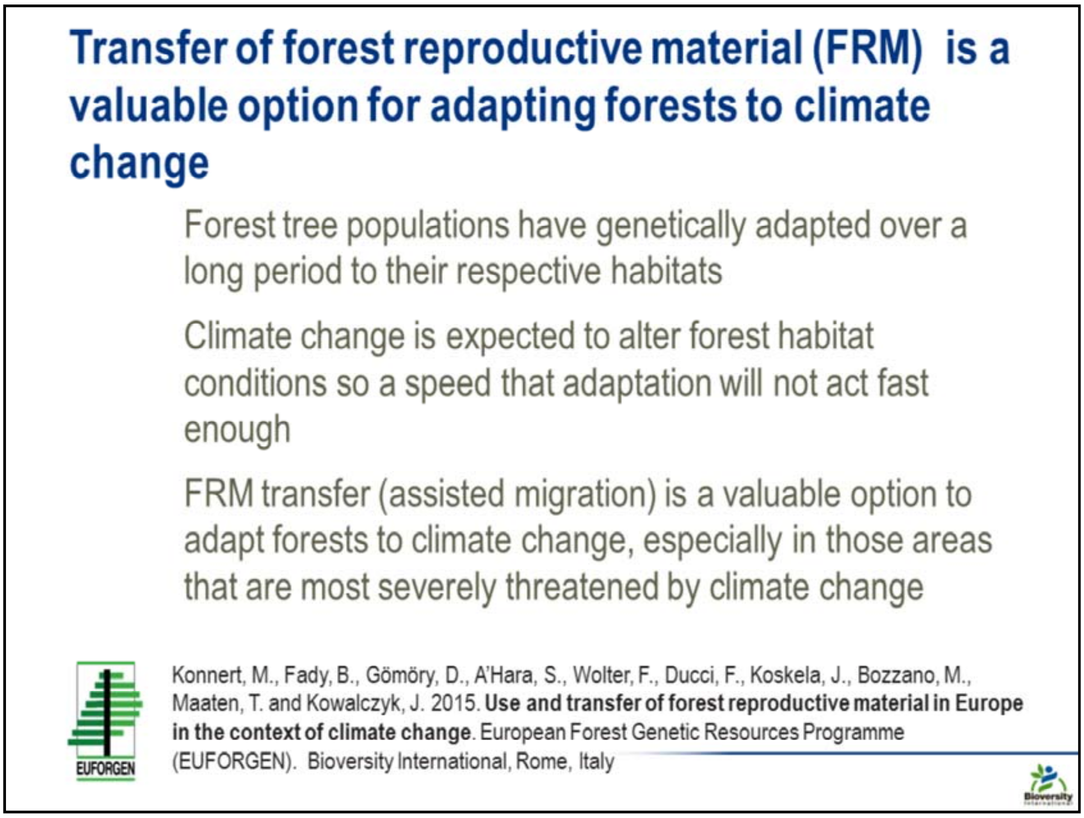
Autochthonous local tree populations originate from complex selection processes acting on a restricted regional gene pool. For various biotic and abiotic reasons, local populations do not always demonstrate optimum fitness compared with other FRM in common-garden experiments. In addition, in Europe, locally found populations often originate from historical FRM transfer but for which passport data are lost. Local FRM will not always be the answer to climate change challenges. As local environmental conditions change, forest managers should extend their options to both local and non-local FRM.



Recommendations derived from a recently published report on "**Use and transfer of forest reproductive material in Europe in the context of climate change" of the European Forest Genetic Resources Programme (EUFORGEN).**

Use provenances instead of species in assisted migration schemes

Science has repeatedly shown that adaptive genetic diversity within forest tree species is often very large and yet it seems that, under the pressure of climate change, forest management would rather change species than provenances when designing reforestation efforts. Therefore, there is an urgent need to disseminate information and knowledge on the adaptive potential that is readily available from different FRM within tree species.



***Recommendations derived from a recently published report on "*Use and transfer of forest reproductive material in Europe in the context of climate change" of the European Forest Genetic Resources Programme (EUFORGEN).**

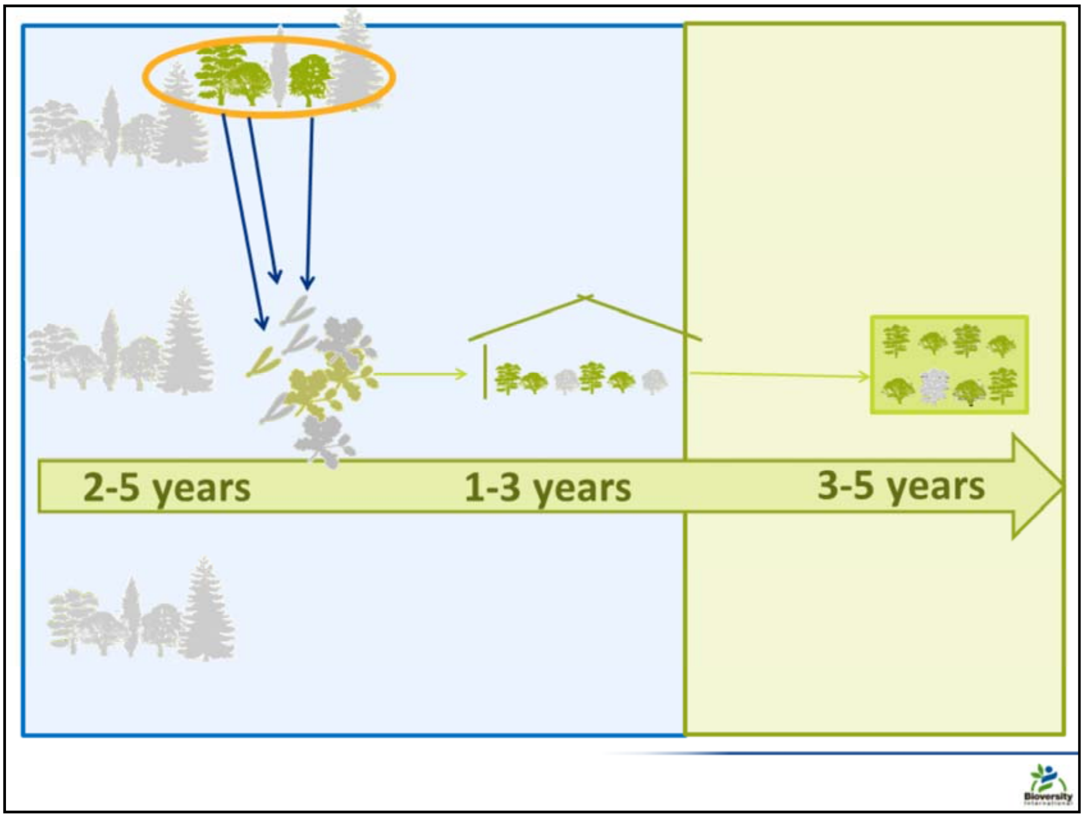
FRM transfer is a valuable option for adapting forests to climate change

Forest tree populations have (genetically) adapted over a long period (and are still adapting) to their respective habitats and, as a result of this adaptation, formed so-called provenances. Climate change is expected to alter forest habitat conditions in Europe at such a pace that the natural processes (selection, gene flow, migration) that drive evolution and adaptation will not act fast enough. Therefore, human intervention in the form of FRM transfer (assisted migration) is a valuable option to adapt forests to climate change, especially in those areas that are most severely threatened by climate change.

Transfer of FRM also has its limits

With increasing temperature and periods of drought there is an increasing demand from forestry for provenances from warmer southern regions. As long as extreme events such as late frosts occur, these provenances can be recommended only in exceptional cases, and the transfer of the material used has to be well documented. Short- rather than long-distance transfers will often be more ecologically relevant and should be preferred. The conservation of local genetic resources should be taken into account when assisted migration is being considered. Forest managers should protect particularly threatened FRM (mostly peripheral populations from rear edges of geographical distributions) that could be of use in other, more suitable, locations.

Why are genetic considerations often neglected?



Restoration seed chain

Restoration starts many years before site preparation

Genetic considerations are often neglected because the most severe bottlenecks are outside the usual timeframe of restoration projects

Time

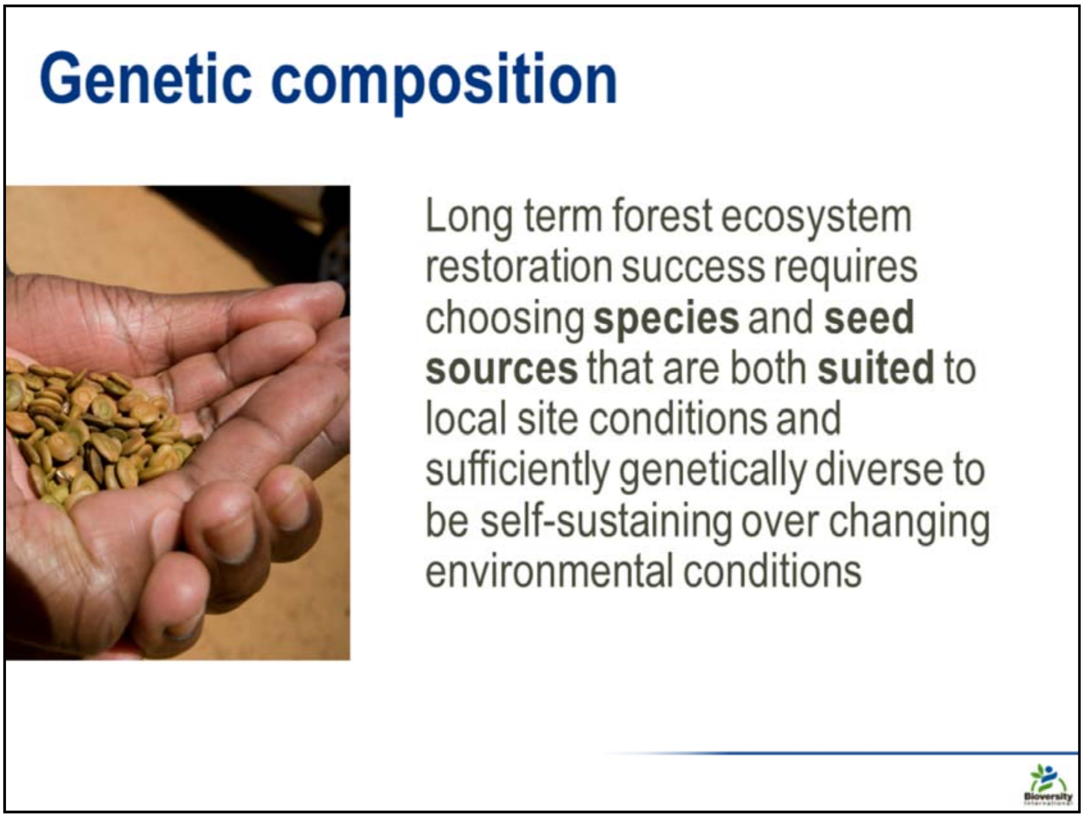
Successful restoration requires a variety of stakeholders carrying out multiple steps over a number of years.

This includes defining **objectives**, identifying planting locations and **sources** of planting material, setting up nurseries, managing planting stock, planting, monitoring...

One single project may not be feasible

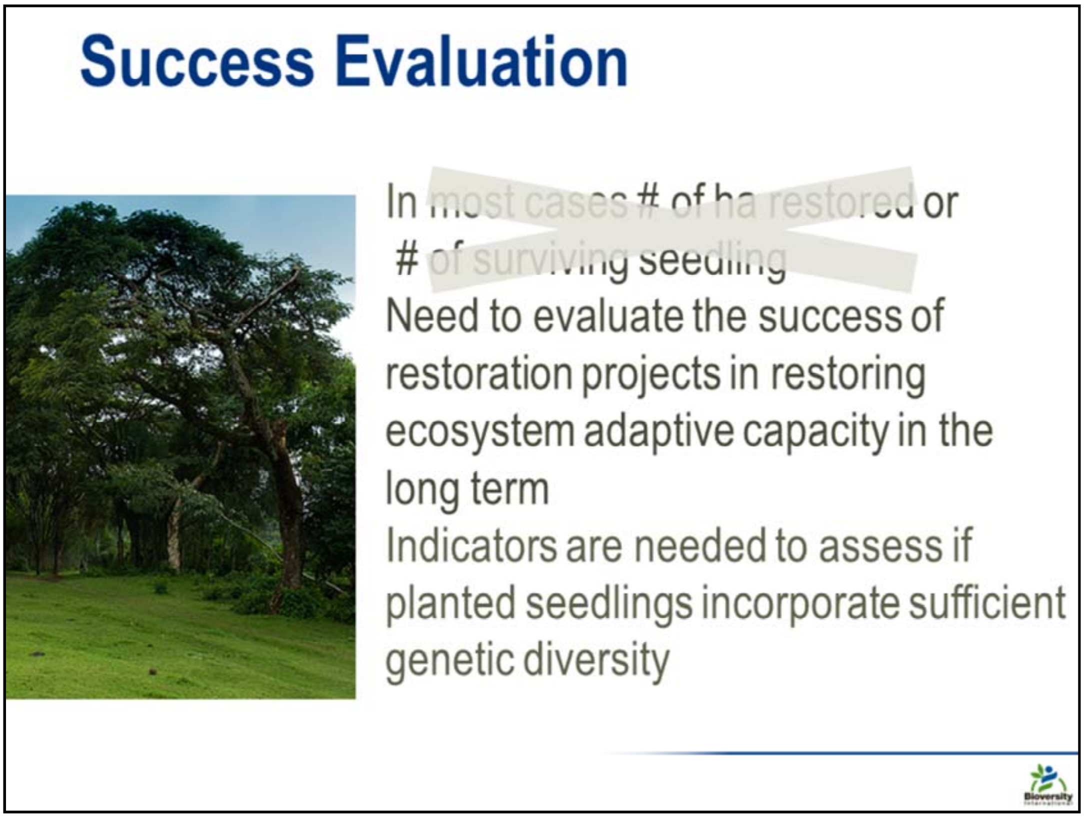
Need to develop long-term strategies funded "step-by-step"

Forest landscape restoration initiatives that aim to establish self-sustaining forest ecosystems, including planted trees, require multiple phases, spanning years. Countries and restoration implementing agencies need long-term strategies to ensure success. The starting point varies between countries, but for some, it will be determining seed collection zones for target species, based either on ecological classification or field (provenance) trial results, to ensure that planting material can be matched to planting sites. After identifying and characterizing sites for restoration, seed collection from large, healthy, diverse populations of target species must be planned and carried out with ample time to collect target species when seed production is high and to grow seedlings in local nurseries. New local nurseries may be necessary to produce the required volume of native tree seedlings. Seed must be collected from enough (20–50) trees per population of each species to ensure adequate levels of genetic diversity. Nursery practices must ensure that the diversity is not inadvertently lost by discarding the slower growing or smaller seedlings. Monitoring success after out-planting also adds years. The timeline for restoration projects must be long enough to take each step into account.



Because trees are long-lived, appropriately adapted planting material must be able to survive today's conditions as well as the predicted environmental conditions of the future. High diversity among planted seedlings allows natural selection to choose adapted individuals as conditions change. This means that seed must be collected from a large enough number of trees of each species (20 – 50 per population) to ensure that they comprise sufficient diversity to adapt to changing conditions.

If only a few trees remain in a forest patch, pollination between related trees becomes more likely. This often results in inbreeding, which reduces the viability of seed and seedlings and, thus, their probability of survival. Even if the seed is not inbred when it is collected, if it is collected from only a few individual trees per species, it is likely to lead to inbreeding in the future. This may not be detected until planted trees reach maturity, possibly after 30 years, but the next generations will reveal low viability of seeds and reduced vigour of seedlings, reducing the potential for self-sustaining ecosystems across generations. Changing climatic conditions and corresponding changes in the abundance, distribution or virulence of pests and diseases means that restoration planning must also integrate sufficient seed diversity so that the next generation has the potential to adapt and survive these new challenges.



Restored sites must be monitored using standards to ensure that investments are achieving their goals. Too often, restoration success is measured by counts of hectares treated, numbers of seedlings planted or short-term survival rates. None of these measures can detect problems associated with inbreeding or low diversity. Indicators are needed that can show that the planted material comprises sufficient diversity to reproduce, adapt and thrive through generations to come. Practical tools and protocols are needed to monitor the suitability of planted trees to planting sites and the adaptive potential of restored seedlings. Standards, indicators and monitoring protocols should be developed through a broad consultative process.

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