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Genetic considerations in ecosystem restoration using native tree species

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ABSTRACT

Rehabilitation and restoration of forest ecosystems are in growing demand to tackle climate change, biodiversity loss and desertification—major environmental problems of our time. Interest in restoration of ecosystems is increasingly translated into strong political commitment to large-scale tree planting projects. Along with this new impetus and the enormous scale of planned projects come both opportunities and risks: opportunities to significantly increase the use of native species, and risks of failure associated with the use of inadequate or mismatched reproductive material, which though it may provide forest cover in the short term, will not likely establish a self-sustaining ecosystem. The value of using native tree species in ecosystem restoration is receiving growing recognition both among restoration practitioners and policy makers. However, insufficient attention has been given to genetic variation within and among native tree species, their life histories and the consequences of their interactions with each other and with their environment. Also restoration practitioners have often neglected to build in safeguards against the anticipated effects of anthropogenic climate change. Measurement of restoration success has tended to be assessments of hectares covered or seedling survival in a short timeframe, neither of which is an indicator of ecosystem establishment in the long term. In this article, we review current practices in ecosystem restoration using native tree species, with a particular focus on genetic considerations. Our discussion is organised across three themes: (i) species selection and the sourcing of forest reproductive material; (ii) increasing resilience by fostering natural selection, ecological connectivity and species associations; and (iii) measuring the success of restoration activities. We present a number of practical recommendations for researchers, policymakers and restoration practitioners to increase the potential for successful interventions. We recommend the development and adoption of decision-support tools for: (i) collecting and propagating germplasm in a way that ensures a broad genetic base of restored tree populations, including planning the sourcing of propagation material of desired species well before the intended planting time; (ii) matching 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.

1. Introduction

Ecosystem restoration is of increasing global interest as part of broader strategies to tackle climate change, loss of biodiversity and desertification, major environmental problems of our times. This emerging interest was formalized with the adoption of the revised and updated Strategic Plan of the UN Convention on Biological Diversity (CBD) for 2011–2020, which aims for the restoration of at least 15% of degraded ecosystems by 2020 (Aichi Target 15). As approximately 2 billion hectares of land are estimated to have potential to benefit from restoration (GPFLR, 2011; Laestadius et al., 2012), achieving Target 15 would imply the restoration of 300 million hectares, in this time frame.

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Large-scale restoration has been initiated in many parts of the world. In the 1970s, the "Green Wall" was started in China; in early 2000 a similar effort was launched in Africa.[1] Many other large-scale commitments have been made recently, such as: the Bonn Challenge, a core commitment to restore 150 million hectares of lost forests and degraded lands worldwide by 2020; Brazil's Atlantic Forest Restoration Pact (15 million hectares)[2]; and India's Green Mission (5 million hectares).[3] Considering that many restoration projects achieve limited success or fail completely (e.g. Wuethrich, 2007), it is imperative that future projects, representing massive investments be carried out in such a way as to be sustainable and resilient. The reasons for failures in forest restoration practice are often not well understood but include planting material that is inadequately matched to the environmental conditions at the restoration site and inappropriate silvicultural approaches and techniques (Kettle, 2010; Godefroid et al., 2011; Le et al., 2012; Wenying et al., 2013).

One of the proposed, holistic goals of ecological restoration by lead members of the International Society of Ecological Restoration emphasises "reinstating autogenic ecological processes by which species populations can self-organise into functional and resilient communities that adapt to changing conditions while at the same time delivering vital ecosystem services" (Alexander et al., 2011b). An important consideration in achieving the goal of self-sustaining ecosystem restoration is the genetic composition of reproductive material which affects the success of restoration both in the short and the long term. Genetic diversity is positively related not only to the fitness of tree populations (Reed and Frankham, 2003; Schaberg et al., 2008; Breed et al., 2012) but also to wider ecosystem functioning and resilience (Gregorius, 1996; Elmqvist et al., 2003; Kettenring et al., 2014; Muller-Starck et al., 2005; Thompson et al., 2010; Sgrò et al., 2011). For example, significantly reduced growth was observed in second and third generation seedlings of *Acacia mangium* compared to the mother trees originally introduced to Sabah (Malaysia) from Australia in 1967 which represented genetically reduced sub-samples (Sim, 1984). Self-sustainability of tree populations depends on adaptive genetic variation, combining the potential for survival and good growth and resistance to changing biotic and abiotic stresses (Aitken et al., 2008; Pautasso, 2009; Dawson et al., 2011; Schueler et al., 2012; Tooker and Frank, 2012). Furthermore, the extent of gene flow across landscapes over subsequent generations is important for the successful long-term restoration of ecosystems and tree populations (Céspedes et al., 2003; Navascues and Emerson, 2007; Ritchie and Krauss, 2012; Cruz Neto et al., 2014).

To our knowledge, the success of restoration in terms of establishing tree populations that are genetically diverse and appropriate to the restoration site has rarely been rigorously evaluated. In the few studies we found that were aimed at evaluating the appropriateness of germplasm collection practices in restoration efforts, mismatching of germplasm to site conditions (Sinclair et al., 2006; Liu et al., 2008; Krishnan et al., 2013), and genetic bottlenecks, were common problems. In the case of genetic bottlenecks, source populations for germplasm collection were either declining (Broadhurst et al., 2006; Broadhurst, 2011), or if they were large and presumably diverse, collection practices failed to capture this genetic diversity (Burgarella et al., 2007; Navascues and Emerson, 2007; Kettle et al., 2008; Salas-Leiva et al., 2009; Li et al., 2012; Krishnan et al., 2013).

In this paper we review current practices in ecosystem restoration using native tree species, focusing on the influence of genetics on long- and short-term success. We build on a thematic study on genetic considerations in forest ecosystem restoration methods that was developed to support the FAO's 2014 State of the World's Forest Genetic Resources report (Bozzano et al., 2014). The importance of genetic considerations in restoration practice is presented in the context of three themes: (i), selecting sources of forest reproductive material among and within species; (ii) increasing resilience by fostering natural selection, ecological connectivity and species associations; and (iii) measuring the success of restoration activities. We identify when and how genetic factors should be considered in the various stages of forest ecosystem restoration, pose key research questions, and conclude by providing practical recommendations for the communities of researchers, policy makers, and restoration practitioners to improve the potential for the long-term success of restoration efforts.

2. Species selection and the sourcing of forest reproductive material (FRM)

2.1. Native vs exotic and local vs non-local

In sites with low to intermediate levels of degradation, where soils are largely intact and there are sufficient germplasm sources for the next generation (e.g. mature trees or soil seed bank), natural regeneration may be the best choice (Chazdon, 2008). This bypasses some of the risks associated with introducing germplasm, by promoting the maintenance of genetic integrity and the recruitment of well-adapted seedlings. However, in sites where (i) diverse native seed sources are lacking or insufficient, (ii) seed sources suffer from genetic erosion, and/or (iii) active planting is envisaged, the introduction of forest reproductive material from off site may either be advantageous or the only solution, at least in the short term.

The first decision with respect to planting material concerns species selection. In order to restore self-sustaining ecosystems and their services, native species are generally preferred over exotics, although exotic species may be useful or even necessary in some cases, e.g. as nurse crops to ameliorate the microenvironment on very degraded sites (Montagnini and Finney, 2011; Newton, 2011; Lamb, 2012; Thomas, 2014). Native species are expected to be adapted to local biotic and abiotic conditions and thus support native biodiversity and ecosystem function to a greater degree than exotics (Tang et al., 2007). In addition, evidence is growing for the importance of choosing tree species that are representative of different functional groups based on adaptive traits (Davis et al., 2011; Aerts and Honnay, 2011; Laughlin, 2014). However, selecting native species on the basis of functional group requires more knowledge than is currently available about traits associated with their reproductive biology, phenology, and propagation. This knowledge gap may often compromise the optimal selection and use of native species for restoration and result in the selection of better documented, but less suited, exotic species (Boshier et al., 2009; Newton, 2011; Godefroid et al., 2011).

Species choice is followed by the identification of appropriate sources of planting material. If FRM is not adapted to site conditions, there may be severe consequences such as low initial survival or high mortality before reaching reproductive age (Bresnan et al., 1994). Alternatively, and probably more typically, maladaptation to site conditions may be expressed gradually, for example through reduced growth, low competitiveness and poor seed set. Johnson et al. (2004) described another common expression of maladaptation which appeared years after planting. In their example, *Pseudotsuga menziesii* provenances in Oregon, USA, performed well from 1915 to 1955 and then were hit with an unusual and prolonged cold period that local sources survived but off-site sources were either badly damaged or killed. Similarly, 30,000 ha

[1] http://www.fao.org/partnerships/great-green-wall.

[2] http://www.pactomataatlantica.org.br/protocolo.aspx.

[3] http://www.indiaenvironmentportal.org.in/category/34854/thesaurus/national-mission-for-green-india-gim/.