APPLIED ECOLOGY

Positive site selection bias in meta-analyses comparing natural regeneration to active forest restoration

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Several recent meta-analyses have aimed to determine whether natural regeneration is more effective at recovering tropical forests than active restoration (for example, tree planting). We reviewed this literature and found that comparisons between strategies are biased by positive site selection. Studies of natural forest regeneration are generally conducted at sites where a secondary forest was already present, whereas tree planting studies are done in a broad range of site conditions, including non-forested sites that may not have regenerated in the absence of planting. Thus, a level of success in forest regeneration is guaranteed for many studies representing natural regeneration, but not for those representing active restoration. The complexity of optimizing forest restoration is best addressed by paired experimentation at the same site, replicated across landscapes. Studies that have taken this approach reach different conclusions than those arising from meta-analyses; the results of paired experimental comparisons emphasize that natural regeneration is a highly variable process and that active restoration and natural regeneration are complementary strategies.

How and where to restore tropical forests have become topics of global importance for addressing the interrelated challenges of climate change, biodiversity loss, and desertification (*1–3*). A suite of recent meta-analyses have attempted to advance the state of the science by comparing active forest restoration or reforestation approaches (for example, tree planting) to natural regeneration (that is, forest regeneration with little or no intervention by humans) (*4–6*). On the basis of comparisons across many studies, these meta-analyses find little to no advantage in actively intervening to catalyze forest succession. For example, Crouzeilles *et al.* (*6*) determined that naturally regenerated tropical forests have higher plant diversity, tree density, and tree height than forests established by active restoration, and they concluded that tropical forest restoration is more successful using the former approach. However, this and other meta-analytical data sets contain an inherent, positive selection bias for naturally regenerated forests that casts doubt on the robustness of these conclusions.

The bias in these meta-analyses arises from a mismatch between the pool of studies that contain data about active forest restoration and the pool of studies that contain data about natural forest regeneration (Fig. 1). With few exceptions, studies of natural regeneration and active restoration have been conducted at separate locations. Most studies evaluating natural regeneration, for instance, occurred in sites where secondary forest was present at the start of the study [for example, (*7–10*)]. In contrast, active tree planting studies are typically initiated on entirely deforested sites [for example, (*11–13*)], including sites that likely would not have established at all without assistance (for example, strip mines). Hence, many natural regeneration studies focus on forests that have already passed through a filter that excludes less resilient, more degraded sites where forest succession would be slow or stalled. Active restoration studies are not exposed to the same site selection filter, so it is hardly surprising that active restoration should perform weakly in meta-analyses when compared to secondary forests that had already established.

For example, take a tree plantation where seedlings were planted on degraded agricultural land, and compare that plantation to a 10-year-old secondary forest discovered on post-agricultural land. All else being equal, the plantation has the opportunity to fail to establish, but if the secondary forest had not already established it would never have been considered as a study site.

Documented cases of slow or arrested forest succession are widespread throughout the tropics [for example, (*14–18*)]. These and other studies attribute slow or stalled recovery to a suite of factors including the severity of prior land use, the distance to propagule sources, and the intrinsic resilience of species that make up a given community (*19*). Meta-analyses comparing active restoration and natural forest regeneration have sometimes attempted to statistically control for some of these factors, but what limits forest growth at a given site can be idiosyncratic and there may not be enough replication in the literature to conduct a rigorous meta-analysis. A few of these factors include soil quality (*20*, *21*), fire (*22*), presence of seed-dispersing animals (*23*), competition from exotic grasses (*24*), and herbivory (*25*). Moreover, statistical controls still fail to establish a counterfactual; a rigorous meta-analysis would have to select only those natural regeneration studies in which failed regeneration was a possibility.

In some cases, meta-analyses are further complicated by questionable categorizations of actions that qualify as active restoration or natural regeneration. For instance, Parrota and Knowles (*26*) evaluated a restoration treatment at a bauxite mine in Brazil that included using

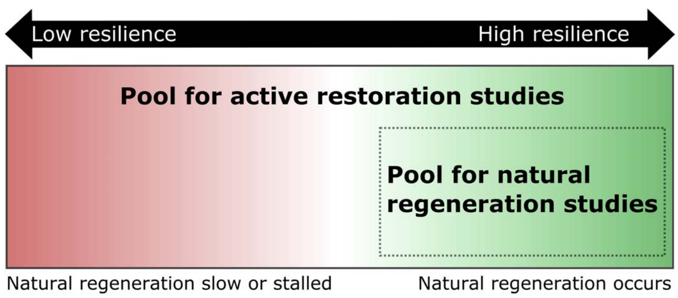

Fig. 1. Positive selection bias in recent meta-analyses comparing active restoration to natural regeneration.

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heavy machinery to level the overburden and replace 15 cm of topsoil and woody debris from a stockpile. This treatment was considered to be "natural regeneration" by Crouzeilles *et al.* (*6*), but without this expensive human intervention, it is doubtful that forest would have regenerated on the bare, mined surface. Likewise, Crouzeilles *et al.* (*6*) considered plantations of exotic, agroforestry trees to be active restoration (*27*, *28*) and compared these to the rapid, natural regeneration of selectively logged forests (*29*); neither treatment is widely representative of projects seeking to restore native tropical forests.

The complexity of conditions that can influence whether natural regeneration will be slow or stalled highlights the need for paired evaluations of active restoration and natural regeneration at the same site (*30*). The relatively small number of studies where this has been done highlights the fact that the process of natural regeneration can be highly variable, sometimes producing a secondary forest quickly (*31*) and sometimes not (*32*). Similar conclusions are reported from a large-scale analysis of >2000 Brazilian forest restoration projects spanning nearly 700,000 ha. Comparing passive and active restoration at sites that were all initially deforested, Brancalion *et al.* (*33*) found that, although active restoration and natural regeneration both had variable outcomes, tree planting generally increased canopy cover and tree and shrub diversity. Given the discrepancies between meta-analyses and site-based comparisons, definitive evaluation of the effects of tree planting on the pace of tropical forest recovery would benefit from a systematic review using formal quality assessment (*34*).

For restoration practitioners seeking evidence-based management strategies, a take-home message from the empirical literature is that it is often worthwhile to observe natural forest recovery for a year or two to assess if natural regeneration will accomplish management objectives before deciding whether some form of active intervention is needed (*19*). If an adaptive management process indicates that action is warranted, possible interventions range from low-intensity assisted natural regeneration to higher-intensity plantations (*35*). Despite the implication by recent meta-analyses that active restoration and natural regeneration are competitive and mutually exclusive strategies, in reality, human interventions to restore tropical forests fall on a continuous gradient of intensity and are often synergistic.

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