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High diversity mixed plantations of *Eucalyptus* and native trees: An interface between production and restoration for the tropics

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ABSTRACT

Despite the high diversity of trees in the tropics, very few native species have been used in plantations. In a scenario of high international demand for nature conservation, ecological restoration and for the provision of forest products, mixed species forestry in the tropics emerges as a promising option. In this study, we examine three large experiments in the Atlantic Forest region of Brazil that combine early *Eucalyptus* wood production with a high diversity (23–30 species) of native tree species. We tested the following hypotheses: (1) *Eucalyptus* growth and survival is higher in mixed plantations than in monocultures, while that of native species is lower when intercropped with *Eucalyptus*; (2) The diameter of target native trees is influenced by the size and by the identity of neighboring trees; (3) The negative effect of competition from *Eucalyptus* on native species is directly related to their growth rate. We compared mixtures of *Eucalyptus* and a high diversity of native tree species with *Eucalyptus* monocultures and with plots containing only native species, replacing *Eucalyptus* by ten native species. To test our hypotheses, we examined inventory data considering the stand- and the tree-levels. We calculated survival rate, diameter and height growth and basal area of whole stands and groups of species. We also used a neighborhood index analysis to separate the effect of total competition (i.e. stand density) and the influence of groups of species (intra- and inter-specific competition). The *Eucalyptus* trees in high diversity mixtures grew larger and yielded nearly 75% of the basal area produced by *Eucalyptus* monocultures even though this genus accounted for only 50% of seedlings in the mixtures. In the mixtures, *Eucalyptus* negatively affected the growth of native species proportionate to the native species' growth rate. With some exceptions, the mixed plantations had no overall negative effect on tree survival or height growth. We conclude that mixtures of *Eucalyptus* and a high diversity of native tree species are feasible and represent a potential alternative for establishing multipurpose plantations, especially in the context of forest and landscape restoration.

1. Introduction

Tropical forests host the vast majority of tree species on Earth (Beech et al., 2017; Slik et al., 2015), but this potential remains underutilized as modern tropical silviculture is still dominated by monospecific plantations of a few genera, especially *Eucalyptus*, *Pinus*, *Acacia*, and *Tectona* (Kelty, 2006). Apart from being simplified from a biodiversity perspective, monocultures can also have a lower capacity to provide the ecosystem goods and services provided by diverse forests (Bauhus et al., 2017a; Lindenmayer et al., 2012) in the context of forest landscape restoration. The combined outcomes of providing ecosystem services while delivering timber and non-timber products may be improved when production and conservation objectives are balanced and integrated. However, a complex set of factors currently hinder the adoption of alternative systems (Puettmann et al., 2015).

New forestry systems could be designed as stable mixes where species do not outcompete each other and may result in plantations that have ecological and economic resilience (Lamb, 2005). Commercial mixed plantations usually comprise two to four species and are often only preferred when they produce a higher quantity or quality of wood

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(or biomass) than monocultures (Kelty, 2006). Together with the demand for timber products, there is growing international demand for forest and landscape restoration and for forests that can be used to achieve multiple objectives (Brancalion and Chazdon, 2017; Chazdon et al., 2017; FAO, 2016). In this scenario, mixed species forestry in the tropics emerges as a promising option to meet international demands for production and conservation at the stand and landscape scales while contributing to restoration objectives and serving as complementary forest habitat for wild species (Lamb, 2005).

In this study, we explore a silvicultural option for the tropical region of Brazil that intercrops a fast-growing species of *Eucalyptus*, widely used by the industry and farmers in the tropics, with a high diversity of native tree species. In other tropical regions, mixtures of native tropical species, sometimes including *Eucalyptus*, have demonstrated that these systems can result in greater individual tree and stand productivity than monocultures and that the diversity of tree species is reflected in the diversity of growth responses and in the flexibility of potential silvicultural regimes (Erskine et al., 2006, 2005; Montagnini et al., 1995; Nguyen et al., 2014). For example, *Eucalyptus* can reduce establishment costs by providing early income from wood production, while planting native species can potentially enhance the conservation value of plantations and serve as an option for high value timber exploitation in the longer term (Brancalion et al., 2012).

An important challenge for the design of this new type of mixture is to prevent the seedlings of the native species from becoming suppressed by *Eucalyptus*, which may result in reduced growth and/or high mortality, thus compromising the potential of mixed plantings to reestablish diverse tree communities. The use of a fast-growing *Eucalyptus* species in this system aims to provide a rapid economic return due to its relatively short cycle but is a challenge for its conservation viability. *Eucalyptus* species have been subject to extensive genetic improvement programs and are managed under intensive silvicultural regimes to achieve high biomass yield (Gonçalves et al., 2013), which is associated with a high demand for local resources. Commercial varieties of *Eucalyptus* might be, in comparison to native fast-growing trees, more efficient in acquiring and using the available water, light and nutrients. Native species have not gone through breeding programs and show a wide range of growth rates. This genetic diversity is desired for conservation purposes but may compromise the use of native trees in plantation forestry. It is necessary to understand how *Eucalyptus* and native species interact in these mixed plantations and to further improve these systems to minimize competition while maximizing both wood production and restoration outcomes.

In this study we examined mixed plantations of *Eucalyptus* and a high diversity of native species using large experiments controlled for species diversity, stand density, age, disturbance regime and site characteristics such as soil type, topography and climate. We analyzed inventory data at the stand and tree levels from three different experimental sites in eastern Brazil containing (i) mixed plantations of *Eucalyptus* and a high diversity of native trees (23–30 species), (ii) *Eucalyptus* monocultures, and (iii) plantations composed exclusively of native trees, in which ten additional native tree species replaced *Eucalyptus* in the design of mixed plantings. To investigate the silvicultural viability of these mixtures both to produce high yields of *Eucalyptus* wood in mixed plantations and establish plantation stands with a high diversity of native tree species, our objective was to answer the following questions: What are the silvicultural consequences of intercropping *Eucalyptus* and native species? Do the size and identity of neighboring trees influence target tree diameter? How do different native species respond to the intercropping with *Eucalyptus*? We tested the following hypotheses: (1) *Eucalyptus* growth and survival is higher in mixed plantations than in monocultures, while that of native species is lower when intercropped with *Eucalyptus*; (2) The diameter of target native trees is influenced by the size and by the identity of neighboring trees; (3) The negative effect of competition from *Eucalyptus* on native species is directly related to their growth rate.

2. Material and methods

2.1. The mixed forests and the control treatments

We implemented three experimental sites with three treatments, where mixture plots (hereafter MIX) contained rows of clonal *Eucalyptus* alternating with high diversity rows comprising of 23–30 native tree species (hereafter, diversity group); monospecific *Eucalyptus* stands (hereafter EUC) as the control for *Eucalyptus*; and plots planted with native species (hereafter NAT), as the control for native tree species, in which we used the same 23–30 native species (diversity group) that were intercropped with *Eucalyptus*, but *Eucalyptus* rows were replaced by rows containing a mix of 9–10 fast-growing, wide-canopy native tree species (Supplementary Fig. 1). All seedlings in each experimental site were planted at the same time and were cultivated with the same silvicultural techniques commonly used in short-rotation *Eucalyptus* plantations in the region. This includes fertilization according to *Eucalyptus* nutritional demands for the local soil conditions, grass control with glyphosate spraying, ant control with insecticide baits and replanting after very low mortality within 1–2 months. All treatments of a given experimental site had the same spacing between the rows and between trees within rows. The mixtures that intercrop *Eucalyptus* and a high diversity of native tree species were conceived as a strategy to provide early income from the exploitation of *Eucalyptus* wood to offset part of the costs of plantation and maintenance in tropical forest restoration but may also serve as a permanent production system. Although, for areas where ecological restoration is the final objective (and where *Eucalyptus* is exotic), *Eucalyptus* may remain as part of the system during one or a few rotations and then be harvested and replaced by several native species to increase diversity.

2.2. Study sites and experimental design

We implemented three experimental sites within the Atlantic Forest region along the Brazilian East coast, located in Aracruz, ES, Mucuri, BA, and Igrapiúna, BA. The geographic distribution of the experimental sites represents a gradient of latitude, altitude, precipitation and temperature (Supplementary Table 1; Table 1). To control for the variability of ecological interactions, each native species was planted in the same position within all plots. The list of species used in each treatment is shown in Supplementary Table 2. Stand development is illustrated in Fig. 1 and the visual difference between mixtures and native species plots is shown in Fig. 2.

2.3. Data collection

We measured the survival rate while considering planted trees of any size. The Diameter at Breast Height-DBH (cm) and total height (m) were measured for all planted trees ≥ 1.3 m tall. Dead trees were not measured. In the experimental sites of Aracruz and Mucuri, trees that branched below 1.3 m had up to five of the largest stems measured. In Igrapiúna, we measured up to three of the largest stems. Height data was not available for the experiment in Igrapiúna. We inventoried the experiment in Aracruz at 38, 51 and 57 months after planting; the one in Mucuri at 48 months; and the one in Igrapiúna at 31, 45, 53 and 60 months after planting.

2.4. Data analysis

We divided species into different functional groups within each site according to their taxonomic identity and growth rate. These included *Eucalyptus*, fast-growing, wide-canopy native tree species, and all other native species grouped in terms of fast- (DBH $>$ 10 cm), intermediate- (DBH between 5 and 10 cm), and slow-growth rates (DBH $<$ 5 cm). Native species growth-rate classification was based on the mean diameter of native species intercropped with fast-growing, wide-canopy