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Enrichment of big-leaf mahogany (*Swietenia macrophylla* King) in logging gaps in Bolivia: The effects of planting method and silvicultural treatments on long-term seedling survival and growth

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ABSTRACT

To insure adequate regeneration and future timber yields of mahogany (*Swietenia macrophylla* King), many logged forests will have to be restocked through enrichment planting and managed using silvicultural techniques that maintain this species' long-term survival and growth. This study compared the effects of planting method and two silvicultural treatments on the survival and growth of mahogany seedlings in logging gaps in Bolivia. We tested the hypotheses that survival and growth will be higher among transplanted seedlings than seedlings established from sown seeds and higher in silvicultural treatments that reduce competing vegetation and increase light. The first silvicultural treatment consisted of gaps logged 6 months prior to planting, gaps logged just prior to planting, and gaps treated with herbicide prior to planting. The second treatment, applied 12 months after planting, consisted of manual vegetation cleaning around mahogany seedlings in half of the gaps. The first hypothesis was supported in terms of initial seedling growth but not survival, which was similar between planting methods during the 12–92 months after planting. Transplanted seedlings grew significantly faster than those established from sown seeds during the first year, but this growth advantage disappeared by the second year. Although transplants were 84 cm taller than seed-sown seedlings by the end of the study, this height gain was probably not worth the cost of growing and transplanting seedlings. The second hypothesis was supported in terms of both survival and growth. A significantly greater proportion of seedlings survived in herbicide (62%) compared to 6-month-old (46%) and recent gaps (18%) and in cleaned (51%) versus control gaps (39%). Seedlings initially grew faster in herbicide and recent gaps than in 6-month-old gaps. These differences among silvicultural treatments were largely explained by canopy cover, which, throughout the study, was at least 14% lower in herbicide gaps and 9% lower in cleaned gaps relative to their respective alternatives. By 64 months growth diminished to near zero and no longer differed among gap treatments, despite lower canopy cover in herbicide gaps. By 92 months, saplings in herbicide gaps were only 145 and 77 cm taller than those in recent and 6-month-old gaps, respectively. To maximize survival and growth of mahogany seedlings in logging gaps while minimizing costs, silvicultural strategies should focus on direct seed sowing and appropriately timed interventions (i.e. manual cleaning) to control competing vegetation.

1. Introduction

As one of the most commercially valuable timber species in Latin America, big-leaf mahogany (*Swietenia macrophylla* King) has been severely locally depleted throughout much of its range. By the mid 1990s in Mesoamerica, deforestation and over harvesting had reduced mahogany's original geographic range to roughly one third (Calvo and Rivera, 2000). In South America, the commercial range of mahogany has been reduced to an estimated 94 million hectares, or 34% of the historic range (Grogan et al., 2010). In both regions many natural populations of mahogany have been so

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depleted by legal and illegal logging as to be commercially and, in some cases, ecologically unviable (Veríssimo et al., 1995; Kometter et al., 2004; Grogan and Schulze, 2008; Schulze et al., 2008; Grogan et al., 2010). Although mahogany's adaptability to a wide range of ecological conditions suggests greater resilience to logging than is generally acknowledged (Mayhew and Newton, 1998; Brown et al., 2003; Grogan et al., 2003a), mahogany seedlings are usually scarce or absent from heavily logged forests (Lamb, 1966; Dickinson and Whigham, 1999; Grogan et al., 2003b; Grogan and Galvão, 2006). Instead, a dense cover of secondary species with low commercial value prevails (Pariona et al., 2003). To insure adequate regeneration and future timber yields of this highly valuable species, many logged, low-volume forests will have to be restocked through enrichment planting (Negreros-Castillo et al., 2003; Park et al., 2005; Grogan et al., 2005,2008).

As one of the principal bottlenecks in mahogany production, regeneration has been the focus of most studies investigating strategies to improve mahogany establishment and growth (Mostacedo and Fredericksen, 1999; Grogan et al., 2008; Cámara-Cabrales and Kelty, 2009). Natural regeneration in gaps has been investigated as an alternative to plantations, where seedlings are highly susceptible to attack by the mahogany shoot borer (*Hypsipyla grandella* Zeller) throughout mahogany's native range (Mayhew and Newton, 1998). However, lack of seed trees and low early survival under closed canopies are major limitations to natural regeneration in logged forests (Dickinson and Whigham, 1999; Grogan et al., 2003b, 2005; Pariona et al., 2003; Grogan and Galvão, 2006). To overcome limited seed production and dispersal, enrichment planting has been conducted either by sowing seeds or transplanting seedlings in gaps created by selective logging (Lopes et al., 2008) or railroad tie extraction (Negreros-Castillo and Mize, 2008). However, germination of mahogany seeds depends mainly on soil moisture (Morris et al., 2000), which tends to be higher under a closed canopy due to reduced evaporation rates than in gaps, although root water extraction can have a confounding effect (Marthews et al., 2008). Seedling survival and growth are limited by low light conditions created by the rapidly growing competing vegetation characteristic of gaps (Negreros-Castillo et al., 2003; Snook and Negreros-Castillo, 2004; Lopes et al., 2008). As these bottlenecks become better understood, silvicultural strategies are becoming increasingly refined to minimize the tradeoffs between mahogany germination, establishment, and growth.

To overcome microsite limitations to early survival and growth, particularly low light, several studies have implemented techniques to control competing vegetation. For example, Grogan et al. (2005) demonstrated that experimentally opening the forest canopy increased the survival and growth of naturally established seedlings in 2–3-year old logging gaps. Other studies have combined direct seeding or seedling restocking with treatments that control competing vegetation (Ramos and del Amo, 1992). For example, Snook and Negreros-Castillo (2004) found that survival and growth of transplanted seedlings was significantly higher in treatments that removed large areas of the overstory and limited initial and subsequent competition (slash and burn and clearing by machine) compared to a treatment that removed the overstory but allowed vigorous resprouting (fell and leave) and the control. Few studies, however, have investigated the effect of different planting methods and silvicultural techniques simultaneously. Negreros-Castillo et al. (2003) found that germination of buried seeds was significantly higher than that of surface-sown seeds, and survival but not height differed significantly among clearing treatments. A prevailing lesson from these studies is that because light is the principal limiting factor for mahogany seedlings, competing vegetation should be controlled in space and time to ensure seedling establishment and maximize early growth. A greater understanding of the factors that limit survival and growth of mahogany seedlings at different stages will help managers design practices that optimize regeneration while minimizing costs.

In this study, we simultaneously compare the effects of enrichment planting method and silvicultural treatments that control competing vegetation on the survival and growth of mahogany seedlings in gaps created by selective logging. We test two main hypotheses:

(1) Given the advanced establishment of roots, shoots and leaves, transplanted seedlings will exhibit higher survival and growth than seedlings established from directly sown seeds.
(2) As a shade-intolerant species, mahogany seedlings will experience higher survival and growth in silvicultural treatments that reduce competing vegetation and increase light availability relative to other treatments and to a control.

We also examine how the planting method and silvicultural treatments used here affect height outcomes and exposure of seedlings to attack by the mahogany shoot borer.

2. Methods

2.1. Study area

This study was conducted in a 100,000-ha forestry concession managed by Agroindustria Forestal La Chonta Ltda., located 30 km northeast of Ascensión de Guarayos in the Department of Santa Cruz de la Sierra, Bolivia (15° 47′S, 62° 55′W, 250 m elevation, Fig. 1). Mean annual precipitation is 1562 mm, with <10% falling between May and September, and mean annual temperature is 25.3 °C (Gil-López, 1998). Dominant soils are oxisols, ultisols, and inceptisols and the topography is rolling to flat.

Forests of the study area are seasonally dry humid tropical forests, containing a mix of species characteristic of the Amazon Basin and the drier Chiquitano forests to the south, which are predominately evergreen with a deciduous component (Park et al., 2005). The entire concession has been subjected to selective logging, which began in 1974, and over one third of the area burned in both 1995 and 2004 and has been undergoing succession ever since (Gil-López, 1998; Verwer et al., 2008). More than 150 tree species have been identified at the site. Mahogany and Spanish cedar (*Cedrela fissilis* Vell.) were the principal species extracted until 1997, but their increasing scarcity has shifted focus to a group of 13 additional species (Park et al., 2005). The most commercially important of these are *Ficus boliviana* C.C. Berg, *Cariniana ianeirensis* R. Knuth., *Hura crepitans* L., *Schizolobium parahyba* (Vell.) S.F. Blake, and *Terminalia oblonga* (Ruiz & Pav.) Steud. Approximately 2370 ha are selectively logged in the concession each year according to a 30-year harvest cycle (Gil-López, 1998).

2.2. Experimental design

The experiment compared the effects of two planting methods (directly sown seeds and transplanted seedlings) and two rounds of silvicultural treatments applied at different times (Fig. 2) on the survival and growth of mahogany seedlings in logging gaps. Fifty-five gaps created by recent logging were randomly selected from a 1760-ha stand based on harvest maps. Gaps containing a relatively closed canopy and advanced regeneration of commercial species were avoided. Mahogany seeds and seedlings were planted in the area that had been scarified by a skidder during the extraction process, which was equivalent among all gaps and left the soil bare of most vegetation. At the time of planting in December 2001, the experimental design consisted of the following three silvicultural treatments, hereafter called the "gap treatments":