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Cost-efficiency analysis of seedling introduction *vs.* direct seeding of *Oreomunnea mexicana* for secondary forest enrichment

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ABSTRACT

Among recovery strategies for secondary and degraded tropical forests, the introduction of tree species is one of the most commonly used. This is achieved particularly through the planting of nursery-grown seedlings (i.e. seedling introduction). Another less common technique, but one that could prove efficient, is sowing seeds (i.e. direct seeding) in the forest floor. However, very few comparisons have been made in the literature in terms of the ecological and economic costs and benefits between these two techniques. This study presents a cost-efficiency analysis of the introduction of seedlings and seeds of *Oreomunnea mexicana* (a threatened species in Mexico) in a secondary Tropical Montane Cloud Forest in central Veracruz, evaluating (1) the performance of the seedlings derived from each of the two practices, (2) the relationship of their performance with the environmental variables at the microsite level, and (3) the ecological and economic cost-efficiency of each practice. At the end of the experiment, survival was higher in the nursery-grown than in the direct-seeded seedlings (97% *vs.* 22%, respectively); however, the relative growth rate in height was lower for the planted than the emerged seedlings (0.02 ± 0.002 *vs.* 0.03 ± 0.002 cm cm^{-1} month^{-1}). Relative growth rate in diameter was similar in seedlings introduced by either technique. No predation of seeds or seedlings was registered. The cost-efficiency analysis revealed that, considering the costs of production and plantation, introducing seedlings was almost two times more expensive compared to direct seeding. Results suggest that recovery of this species is feasible with combined practices depending upon the life stage of the plant and the conditions of the microsite. Improvements to these techniques, such as protection of the seed plumules, could confer even greater ecological and economic advantages for the introduction of *O. mexicana* in tropical secondary forests.

1. Introduction

The establishment of enrichment plantations is one of the strategies for the recovery of secondary and degraded tropical forests. This practice involves the selective introduction of key species (e.g. threatened, facilitators of succession, of restricted distribution, of high specialization or with little or null dispersion), in order to maintain their populations, accelerate the natural recovery process, increase local biodiversity and ensure the permanence of ecosystem services (Adjers et al., 1995; Montagnini et al., 1997; Lamb and Gilmour, 2003; Lamb et al., 2005; Paquette et al., 2006; Rappaport and Montagnini, 2014).

The enrichment of secondary and degraded tropical forests can be achieved through the introduction of nursery-grown seedlings (e.g. Ramos and del Amo, 1992; Montagnini et al., 1997; Peña-Claros et al., 2002; Keefe et al., 2009; Sovu et al., 2010; Millet et al., 2013; Rappaport and Montagnini, 2014), translocation of juveniles (e.g. Adjers et al., 1995; Quintana-Ascencio et al., 2004), propagation of stem cuttings (e.g. Zahawi, 2005, 2008; Zahawi and Holl, 2009; Kettle, 2010) or sowing seeds (direct seeding) (e.g. Woods and Elliott, 2004; Bonilla-Moheno and Holl, 2010; Hossain et al., 2014; Bertacchi et al., 2016). Given the fact that the choice of technique is crucial and represents one of the most important challenges for the successful recovery of tropical forests (Zahawi and Holl, 2014), it is important to determine the ecological and economic advantages and disadvantages of each method through a cost-efficiency analysis (Douterlungne et al., 2015).

While seedling introduction has been the most commonly used technique in secondary and degraded tropical forests, it is costly in terms of the production, maintenance and planting (Montagnini et al., 1997; Peña-Claros et al., 2002; Douterlungne et al., 2015). Furthermore, the practice is often limited by the availability of certain species present in the nurseries. Where this is the case, the long-term viability

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of the plantations depends on the performance of the species, as well as the environmental conditions of the forest and of the plantation microsite.

Previous studies show that direct seeding could represent a viable and low-cost method for enrichment of secondary and degraded tropical forests (e.g. Engel and Parrota, 2001; Camargo et al., 2002; Hooper et al., 2002; Doust et al., 2006; Sampaio et al., 2007; Cole et al., 2011). It has also been reported that the direct seeding of late successional species can represent an effective technique in sites where the successional process has begun and there is already a certain quantity of canopy coverage present (Bonilla-Moheno and Holl, 2010; Cole et al., 2011). However, various factors have been found to limit the success of this technique, including low seed viability, lack of information regarding the regeneration niche of certain species, seed depredation and low survival of recently emerged seedlings, as well as competition with the adjacent vegetation (Ceccon et al., 2016; Meli et al., 2017).

Implementation of either of these techniques, introduction of seedlings or direct seeding, implies trade-offs in terms of economic costs, labor investment and individual survival (Zahawi and Holl, 2014) and a combination of both would probably be the best strategy to successfully introduce the species and accelerate tropical forest recovery. Despite the fact that knowledge of the net costs and benefits of these practices would be of great importance in meeting restoration objectives at the lowest possible cost, their evaluation requires effort, time and money, as well as many logistical considerations (Palma and Laurance, 2015). The purpose of this study was therefore to evaluate the ecological and economic cost-efficiency of the early establishment of *Oreomunnea mexicana*, a threatened but little-studied species of the Tropical Montane Cloud Forest, comparing the enrichment practices of direct seeding and introduction of seedlings. This study is one of the few to have compared the two practices simultaneously and the first to use the same species for both techniques. The results provide valuable information for consideration on choosing the most suitable strategy for the enrichment of secondary tropical forests and a useful methodology for comparing these two practices.

2. Methods

2.1. Study area

The study was conducted in a 30 ha fragment of secondary Tropical Montane Cloud Forest (TMCF) located in Xalapa, Veracruz, Mexico. The area forms part of the "Santuario de Bosque de Niebla" (SBN) reserve (19°30′47.80″N, 96°56′15.93″W; 1250 m asl) and has a temperate humid climate, with a mean annual temperature of 18.7 °C and mean annual precipitation of 1671 mm. The soil is classified as Andisol (Williams-Linera et al., 2013). At the beginning of the 1940 s, part of the understory was replaced with plantations of coffee and citrus; however, over the last 40 years, these plantations were removed and some patches have been undergoing a process of regeneration. The arboreal vegetation currently presents a range of successional stages, and is dominated by *Quercus xalapensis*, *Q. germana*, *Carpinus tropicalis*, *Clethra macrophylla*, *Liquidambar styraciflua* and *Turpinia insignis* (Williams-Linera et al., 2013). Experiments for this study were conducted in the remnants of the oldest forest available (*ca.* 80 years of age), where the dominant canopy trees were never replaced (Williams-Linera et al., 2016).

2.2. Species selection

Oreomunnea mexicana (Standl.) J. F. Leroy subs. *mexicana* (Juglandaceae) is a tree species native to the TMCF. The species is classified as endangered due to its discontinuous and restricted distribution in Central America and the southern mountainous regions of Mexico (Rzedowski and Palacios-Chávez, 1977; González-Espinosa et al., 2011). Over the past 10 years, it is estimated that more than half of the populations of the species in Mexico have been reduced (González-Espinosa et al., 2011), probably due to changes in land use, selective extraction and climate change (González-Espinosa et al., 2011; Rojas-Soto et al., 2012; Naranjo-Luna, 2014; Alfonso-Corrado et al., 2017). Indeed, it is been estimated that distribution of the species in Mexico will decrease to 36% of its potential ecological niche by the year 2050 (Alfonso-Corrado et al., 2017).

2.2.1. Seed and seedling selection

Seeds were collected in January 2014 from two parent trees (located approximately 1200 m apart) from a small population in central Veracruz, Mexico (19°30′0.86″N, 97°0′31.14″W). This low number of parent trees was due to the inaccessibility of the site and the lack of synchronization among individuals in terms of fruit production, which must be mature at the moment of collection in order to ensure seed germination. Fruits were collected from branches and cleaned by removing the bracts. The seeds were mixed and stored in plastic bags at room temperature for three weeks until use (February 2014), considering that this species remains viable for less than three months (Niembro et al., 2010). We discarded all seeds that showed signs of damage or floated in water (Gribko and Jones, 1995; Ramírez-Marcial et al., 2008).

Nursery-grown seedlings were purchased in January 2014. The seeds used to propagate these nursery-grown individuals, as well as those used for the direct seeding experiment, came from the same tree population in Veracruz. Seedlings were two years old when purchased and 2.4 years old when transplanted in June 2014. Prior to transplantation, the seedlings were placed in the nursery of the "Instituto de Ecología" (INECOL; located at 1340 m asl) under the canopy of TMCF trees, providing 31 ± 0.35% of light incidence (ceptometer AccuPAR LP-80), and watered every third day in order to homogenize conditions. Seedlings were then selected based on their height (40.77 ± 0.77 cm) and apparent vigor.

2.3. Experimental design and data collection

2.3.1. Site preparation

Each microsite consisted of a 50 × 50 cm plot, where seeds or seedlings were introduced; leaf litter and herbaceous plant coverage were removed before introduction. At each common location, the seed and seedling microsites were located between 5 and 10 m apart.

2.3.2. Direct seeding

In February 2014, 600 seeds were sown distributed across 60 microsites (10 seeds × site) located along the length of an approximately 600 m transect in the SBN reserve. Sowing sites were selected based on a visual estimate of the canopy coverage (intermediate to high) and high soil moisture content. In each microsite, the 10 seeds were sown in a 2 × 5 spatial pattern, at a distance of 2 cm apart. Seeds were sown directly into the soil at a depth of 1–2 cm, with no pre-germinative treatment applied. After sowing, the emerged seedlings (i.e. those in which the plumule reached a height of 0.5 cm above the soil surface) were marked. Seedling survival was calculated as the percentage of seedlings that survived from the total number that initially emerged. Where possible, we recorded the causes of mortality (e.g. desiccation, physical damage or undetermined). Seedlings were considered dead when their leaves and inner stem appeared brown and dry.

2.3.3. Seedling introduction

In June 2014, 100 nursery-grown seedlings were planted. Sixty of these were introduced in 60 the common location of the direct seeding microsites; the remaining 40 seedlings were planted in 40 new microsites selected every 100 m along the transect completing a total transect length of 1000 meters. These 40 additional microsites were chosen in order to increase sample size and facilitate exploration of the relationship between performance and the environmental variables of