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Soil conditions and sheltering techniques improve active restoration of degraded *Nothofagus pumilio* forest in Southern Patagonia

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ABSTRACT

Nothofagus pumilio forests in the Southern Patagonia region of Chile are highly degraded because of clearing for human settlements, extensive livestock grazing, and more recently, the impact of coal mining operations. Most of these legacy areas have remained as extensive meadows of non-native grasses and legumes with limited *Nothofagus pumilio* forest recovery due to dry soil moisture conditions and exposure to high wind and solar radiation. Therefore, active reforestation is needed to reclaim *Nothofagus pumilio* forests from abandoned grassland or disturbances caused by surface mine operation. In this study, a surface coal mine operation and an abandoned meadow established in the 1950 s needed to be restored back to *N. pumilio* forest on Riesco Island, in Southern Chilean Patagonia. We compared the establishment success of *Nothofagus pumilio* seedlings on replicated blocks under two conditions (experimental treatments): (i) four blocks of meadow previously disturbed by livestock grazing, (MS), and (ii) four blocks where a deep layer of the soil profile was removed, mixed, and then replaced simulating recommendations used for reclaiming surface coal mines (RS). To improve *Nothofagus pumilio* establishment and protection at each block under both soil conditions, seedlings were planted both unprotected and protected from wind and solar radiation using four different types of shelters: shade cloth, irregular log piles, white polypropylene shelters, and woody branches. Soil physical and chemical properties, seedling survival and growth, leaf water potential, and stomatal conductance were measured. Results at the end of the first and fourth growing seasons showed better conditions for seedling growth in the RS treatment. Mean survival rates began to be different following the second growing season with values of 84.7 ± 2.9% in RS and 60.2 ± 3.2% survival in MS treatments, respectively. At the end of the study, the difference between the treatments was even geater with values of 75.4 ± 5.5% and 32.2 ± 7.1%. Soil removal and replacement significantly changed soil physical properties, but values were still adequate for vegetation development. The use of shelters significantly influenced four-year survival rates of seedlings planted on the disturbed MS treatment with 60 ± 8.2% survival in plastic shelters and less than 25.5 ± 6.5% for all other shelters. The effects of the shelters were less clear in the RS treatment. Our study showed that *Nothofagus pumilio* restoration on abandoned grassland and reclaimed mine sites in Patagonia is a feasible option when soil conditions and planting techniques improve soil water availability, and when seedling are protected against excessive solar radiation and wind.

1. Introduction

In Southern Patagonia, forest composition is mostly dominated by *Nothofagus pumilio* (Poepp. et Endl.) Krasser (*N. pumilio*), along with *Nothofagus antarctica* (G. Forster) Oerst., and *Nothofagus betuloides* (Mirb.) Blume in some areas. The frequency of each species is associated with changes in topography, canopy protection, leaf litter, and site variability (Martínez Pastur et al., 2011a). Large extensions of this forest have been under disturbance since European colonization in the late nineteenth century. With the use of fire, forestland was replaced by

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exotic herbaceous species used for livestock grazing (Fajardo and Gundale, 2015). By the 1950s, the portion of Southern Patagonia covered by forest shrank by an estimated 2.8 million ha (López Bernal et al., 2012; Martinic, 2006). Within the same area, the presence of lignite coal seams has led to the development of a coal mining industry beginning in the 1930s, with an abrupt increase in the size of the operations and environmental impacts beginning in the mid-1980s (Martinic, 2006). Conversions of native forest to grassland and mining operations drastically changed the local forest landscape in ways that could take many decades to recover via natural processes (Holl and Aide, 2011).

More than 3 million ha of *N. pumilio* forest has been distributed from 35.35°S to 55°S in Chile and Argentina (Schmidt and Lara, 1985; Veblen et al., 1996). *N. pumilio* ecological requirements and dynamics have been previously described by other authors (Schmidt and Urzua, 1982; Veblen et al., 1980, 1996). *N. Pumilio* is a deciduous, semi-tolerant, shelterwood species (Donoso, 1987) that regenerates under low light and mesic moisture conditions. Regeneration occurs in small gaps that are normally caused by snow or wind felling old trees (Veblen et al., 1996; Martínez Pastur et al., 2011a). However, reforestation success with *N. pumilio* in open and degraded areas is reportedly very limited (Bava and Rechene, 2005; Henn et al., 2014).

In Southern Patagonia, passive forest restoration is not a viable option because seedlings are exposed to the effect of animal grazing that leads to the development of compacted soils, herbaceous ground cover, and other harmful microclimatic conditions that inhibit the establishment of *Nothofagus* spp. (Ledgard and Davis, 2004; López Bernal et al., 2012; Paritsis et al., 2015; Paz and Raffaele, 2012; Promis et al., 2010; Wiser et al., 1997). Reforestation experience with *Nothofagus* spp. in the southern hemisphere has shown limited success in highly disturbed open areas (Donoso et al., 2015; Ledgard and Davis, 2004). Changes in soil water condition, effects of herbaceous plants, and livestock impacts create unfavorable conditions for regenerating *N. pumilio* either naturally or by planting (Blackhall et al., 2008; Mermoz et al., 2005; Quinteros et al., 2017; Sánchez-Jardón et al., 2014).

The use of ecotechnologies in reforestation has been proposed to mimic the natural responses of vegetation and improve microsite conditions to reduce environmental stress (Piñeiro et al., 2013). Several facilitation technologies can affect the early establishment on disturbed sites by reducing excessive solar radiation or by improving soil water and nutrient availability (Callaway, 2007; Cortina et al., 2011; Lortie et al., 2004; Pausas et al., 2004). The use of physical shelters, like plastic tubes and nurse shrubs, minimizes transplant shock and therefore increases early seedling survival and physiological performance (Oliet et al., 2015; Piñeiro et al., 2013; Valenzuela et al., 2016). On sites disturbed by fire or livestock, the use of ecotechnologies can improve microsite conditions for *Nothofagus* seedling establishment by minimizing the negative impacts of excessive solar radiation, temperature, and wind thereby providing an effective tool for the early establishment of *Nothofagus* forests (Heinemann and Kitzberger, 2006; Valenzuela et al., 2016; Veblen et al., 2004).

Guidelines for restoring forest on surface-mined land emphasize the use of salvaged topsoil, selection of species compatible with the native ecosystem, and enhancing conditions that encourage natural plant communities (Burger et al., 2005; Grant and Koch, 2007; Zipper et al., 2011). Native topsoil utilization has been a particularly useful tool for mine reclamation, rehabilitation of roads, and post-fire reclamation due to the conservation of many soil properties that promote vegetation establishment (Burger and Zipper, 2011; Koch and Samsa, 2007; Ledgard and Davis, 2004). When soil materials are properly handled, the effects of soil manipulation on rainfall infiltration, surface erosion, soil aeration, and moisture are minimal (Burger et al., 2005; Torbert and Burger, 2000; Zipper et al., 2011). These reforestation guidelines have been applied on mine sites in North America, Europe, and Australia (Koch and Samsa, 2007; Macdonald et al., 2015). More recently, surface coal mine operations in Southern Patagonia acknowledged the need of similar mine reclamation protocols, recognizing the necessity of a more complex reforestation model adapted for *N. pumilio* forests (Smith-Ramírez et al., 2015; Valenzuela et al., 2015).

This study focuses on soil conditions and the use of ecotechnological tools to assess their combined effect during forest reclamation with *N. pumilio* on two types of disturbance where anthropogenic impacts have led to a variety of site conditions that limit reforestation efforts (Coopman et al., 2008; Donoso et al., 2013; Walters, 2005). The purpose of this paper is to improve and expand reforestation techniques for sites affected by mining and livestock grazing across Southern Patagonia within a sustainable reclamation paradigm (Burger et al., 2011).

On our study site, a large overburden pile needed to be reclaimed using salvaged and replaced topsoil. Additionally, abandoned meadows that were established by burning the native forest decades ago needed to be restored back to a *N. pumilio* forest. The specific objectives of the study were to (i) evaluate the performance of *N. pumilio* seedlings planted on replaced native mixed soil (RS) and abandoned meadow (MS), and to (ii) test ecotechnological approaches (sheltering techniques) as a complementary facilitation tool. Our hypothesis was that replacing the mixed soil profile following established forest reclamation guidelines (Burger et al., 2005; Burger and Zipper, 2011) would create conditions for successful establishment of *N. pumilio* seedlings on mined sites, and that their performance would be equal to that of seedlings planted on sites previously disturbed by livestock. For both site/soil conditions, sheltering techniques are expected to stimulate changes in early survival and growth irrespective of the type of disturbance. An above-ground shelter would improve establishment conditions for seedlings, particularly for treatments that mimic suitable light and wind regulation for *N. pumilio* during early establishment.

2. Materials and methods

2.1. Study site

The study site was located at the Invierno Ranch on Riesco Island, owned by Mina Invierno Coal Mine Company S.A (52°86′S and 71°60′W). The island is located 130 km northwest of Punta Arenas in the Magallanes Region in Southwestern Chilean Patagonia (Fig. A.1). The region has a temperate-cold climate with absolute minimum and maximum annual temperatures of −9 °C in July and 15 °C in January, respectively. The area receives moderate precipitation (700 mm year^{-1}) and strong winds during summer with an average wind speed of 65 km h^{-1} (INIA, 2015). Rainfall and temperature in the study zone for four growing seasons (September to February 2013–2017) were collected from records provided by *Centro de Ciencia del Clima y la Resiliencia* (CR2, 2017) (Fig. A.1). The other meteorological data, including photosynthetic photon flux density (PPFD) and wind velocity (k h^{-1}) were obtained from a Watch Dog 2000 meteorological station installed on the study site from September 2013 to February 2017 (Spectrum Technologies Inc., Aurora, USA). The PPFD mean data were 1600 ± 320 μmol m^{-2} s^{-1} at midday, and 20.56 ± 6.3 km h^{-1} (gusts above 60 km h^{-1}) for wind velocity during the growing season. Soils on the study site are sandy-loam to loam and are above a heavier substrate of fluvial-glacial origin. Soil penetration resistance and bulk density at 20 cm depth were 0.6 MPa and 1.65 g cm^{-3}, respectively, in the meadow sites disturbed by livestock (Valenzuela et al., 2015, 2016).

The study site is a representative sample of a legacy meadow sites that dominate the rural landscape in the region (Huber and Markgraf, 2003). A shrubland community with *Berberis microphylla* and *Empetrum rubrum* along with native herbaceous *Acaena magellanica* and *Acaena pinnatifida* dominates the vegetation. These plants coexist with scattered patches of *N. pumilio* and naturalized herbaceous species such as *Avena Fatua* L., *Bromus hordeaceus* L., *Holcus lanatus* L., *Dactylis glomerata* L., *Lolium perenne* L., *Poa pratensis* L., *Trifolium repens* L., *Rumex acetocella* L. These vegetation records were consistent with other studies