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Post-fire regeneration of the critically endangered *Nothofagus alessandrii* Espinosa in the Maule Region of central Chile

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Abstract

The ruil (*Nothofagus alessandrii* Espinosa) forest is one of the most endangered forest ecosystems in central Chile whose regeneration is critically threatened. In this study, we sampled 36 plots (625 m^2 each) in the distribution range of *N. alessandrii* and quantified regeneration of the species from seed after a catastrophic large-scale fire event occurred in 2017. By means of logistic regression and contingency tables, we related ruil's seedling regeneration with vegetative cover, number of ruil individuals, richness of native species, density of *Pinus radiata* D. Don seedlings, and fire severity. Results indicate that fire severity was the most important variable explaining the probability of regeneration of *N. alessandrii*. Seedling recruitment was high in sites with low fire severity, but the opposite was true for sites severely burned by fire. Our results suggests that after a severe fire the restoration efforts of *N. alessandrii* should be concentrated on reforestation activities, but in low burned areas, efforts must be focused on the management and protection of the new recruits.

Keywords: Ruil, fire severity, seedling regeneration, endangered species recovery

Introduction, scope and main objectives

Nothofagus alessandrii Espinosa (ruil) is a Critically Endangered (Barstow et al. 2017) and endemic species from the Mediterranean zone of Chile whose origin may be as ancient as 42–61 million-years (Knapp et al. 2005). Forests of the species are degraded and fragmented, and today they are surrounded and invaded by the exotic *P. radiata* (Gómez et al. 2019), influencing presumably growth and survival of *N. alessandrii*. The species has low seedling recruitment, and its seed has low viability (7-14 %) and germination capacity (lower than 8.7 %) (San Martín et al. 2006). In addition, the devastating fires that occurred in Chile during 2017 (De la Barrera et al. 2018) burned almost half of the c.a. 314 ha of remnant forests of the species (Valencia et al. 2018). These factors raise concerns about the ecological restoration of such ecosystems and calls for a better understanding of factors affecting its natural regeneration.

Regeneration of *N. alessandrii* depends on gap dynamics, allowing regeneration to prosper when a canopy opening is produced after mature trees fall (Donoso 1993). Similarly to *Nothofagus antarctica* (G. Forst.) Oerst. (Veblen et al. 1977), it has been observed that *N. alessandrii* can resprout after being burned. However, sexual reproduction is scarce, and information about the presence of seedlings and juveniles after a fire is lacking. It is known that low intensity fires stimulate seed germination in some species (Mbalo et al. 1997) but severe fires are known to provoke drastic and negative changes in the soil (Boyd and Davies 2010) and in seed germination

(Auld and O'Conell 1991). According to González et al. (2010) and Assal et al. (2018) fire is an important driver controlling regeneration of *Nothofagus* species. In this context and considering that fire has become a common environmental stress during summer in Mediterranean sites, we aimed to evaluate how the post-fire sexual regeneration of *N*. *alessandrii* is affected by different microsite conditions and by fire severity.

Methodology/approach

We surveyed sexual regeneration of *N*. *alessandrii* in seven fragments in central Chile (Fig. 1), with different intensities of fire damage. In November 2018, i.e., 20 months after the mega-fire of 2017, a total of thirty-six 20 × 25 (625 m^2) plots were measured in natural forests of *N*. *alessandrii* within the native range of the species. A complete search for regeneration was conducted in the 625 m^2 plots and *N*. *alessandrii* seedlings (height < 50 cm) encountered were tallied. To corroborate that the individuals were from seeds, a sample of plants was extracted, and it was verified that they had individual roots. Additionally, in each of the 625 m^2 plots we assessed richness of native plant species (as the number of species per plot), vegetative cover percentage, number of ruil individuals, density of *P*. *radiata* seedlings, and fire severity. To estimate the density of *P*. *radiata* seedlings, we sampled three 1 m^2 sub-plots and counted all seedlings of *P*. *radiata*. Then, the mean of the three sub-plots was extrapolated to the 625 m^2 plot. The vegetative cover percentage was visually inspected following the guidelines proposed by the Foresty Agency of Japan (2011). The fire severity was estimated in March 2017 based on the Composite Burn Index (CBI). We measured CBI values at the 36 plots following the field protocol by Key and Benson (2006). Briefly in each plot, five vertical strata were considered and ordered into a hierarchical structure (De Santis and Chuvieco 2007), namely soil, herbs, shrubs, intermediate trees, and big trees. At each stratum, we assessed visual attributes such as changes in color by fire, litter and surface fuels, alterations in the canopy cover, and vegetation mortality (De Santis and Chuvieco 2009). CBI values were classified as low (little change in cover and little mortality of vegetation), medium (a mix between unchanged and high change in cover) and high severity (high to complete mortality of vegetation). The mean of the values for every attribute was taken to compile a CBI for each plot (Key and Benson 2006).

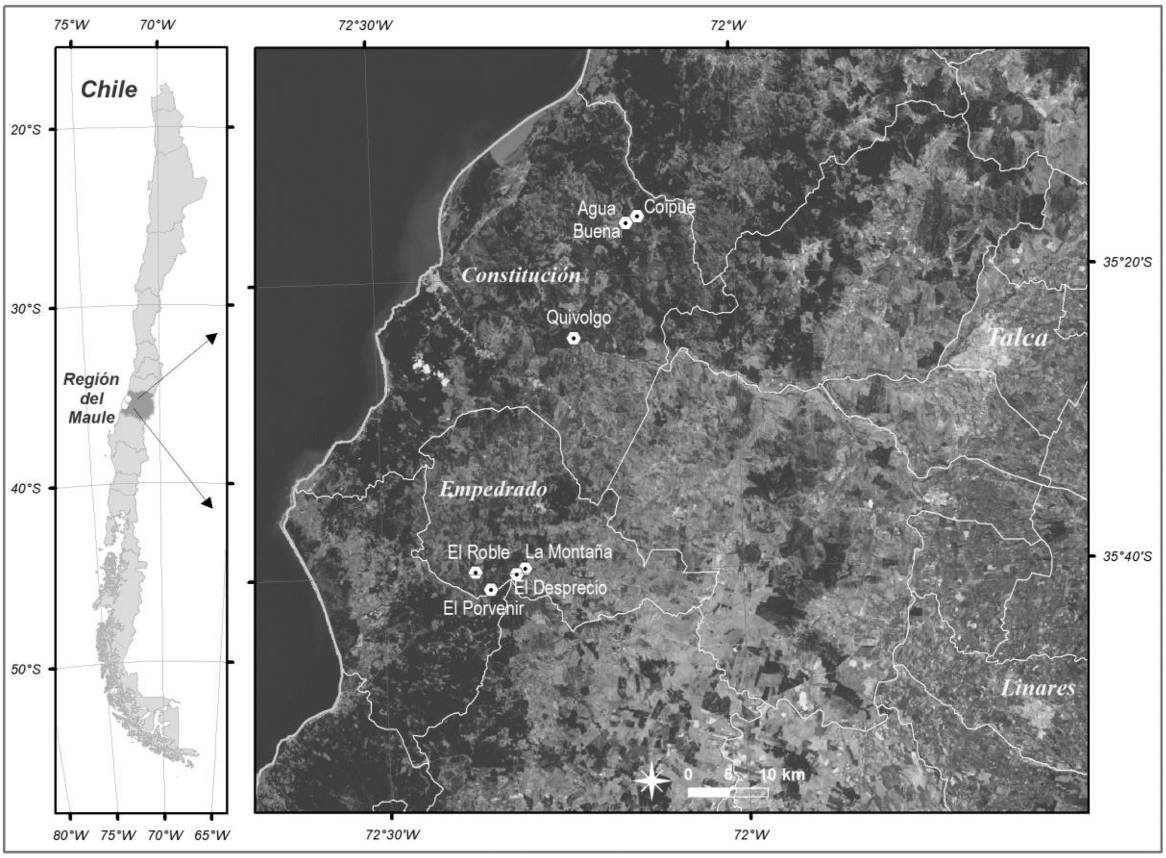

Fig. 1 Location of the seven fragments for *N*. *alessandrii* surveyed for seedling regeneration.

The following logistic regression model was fitted to explain the predicted seedling presence of *N*. *alessandrii* in each plot.

$$\mathrm{P} = \frac{1}{1+\mathrm{e}^{-(\beta_0+\beta_1\mathrm{COV}+\beta_2\mathrm{RUI}+\beta_3\mathrm{RAD}+\beta_4\mathrm{RICH}+\beta_5\mathrm{CBI})}} \quad (1)$$

where P is the probability of seedling presence of *N*. *alessandrii* (as a binary dependent variable i.e., 1 = present, 0 = absent) within a 625 m^2 plot. The independent variables were vegetative cover (COV, %), the number of ruil individuals (RUI), the density of *P*. *radiata* seedlings (RAD), the number of different native species (RICH), the fire severity in each 625 m^2 plot (CBI; low 1, medium 2, high 3). Next, and based on results from the logistic regression, we assessed the association between explanatory variables selected in the logistic regression with *N*. *alessandrii* seedling regeneration by means of contingency tables and the Chi-square test. These analyses were performed with SPSS version 18.0 software (SPSS Inc, Chicago, Illinois, USA), procedures BINARY LOGISTIC and CONTINGENCY TABLES.

Results

The result of the logistic regression indicates that the relationship between the presence of *N. alessandrii* seedlings and the variables COV, RUI, RAD, and RICH was non-significant ($P > 0.05$). Thus, the saturated model (Equation 1) was reduced to a model indicating that the probability of presence of *N. alessandrii* seedling was explained by the fire severity (CBI) ($\beta_0 = 1.63$, $\beta_1 = -1.88$, $P = 0.030$, Wald = 4.713). The estimated probability of presence of ruil individuals is reduced with increasing fire severity i.e., 44, 11, and 2 % in low, medium, and high fire severity plots, respectively. The contingency tables corroborated the strong association between the presence of *N. alessandrii* seedlings and CBI ($Chi^2 = 13.16$, $P = 0.001$). In those plots with low fire severity the probability of seedling presence reaches 60%, while in those plots with high fire severity, this chance is reduced to 0%. As expected, the average number of seedlings was high in plots with low fire severity, but there was a weak association between SEED with CBI ($R^2 = 0.00$, $P = 0.278$).

Discussion

Nothofagus species can tolerate harsh conditions and disturbances such as fires, which would usually contribute to the persistence of the species. For example, *N. antarctica* produces root suckers (McQueen 1976) and adventitious roots on partially buried branches (Veblen et al. 1977), and after a fire it vigorously resprouts from the base (Veblen and Lorenz 1988; Burns 1993). Similarly, species such as *Nothofagus dombeyi* (Mirb.) Oerst. and *Nothofagus obliqua* (Mirb.) Oerst. have the capacity to resprout and recruit from seeds after a fire (Burns 1993; Veblen 1985; Armesto et al. 2009). In the case of *Fagus sylvatica* L.; a species related to the *Nothofagus* genus, fires of medium intensity favors seedling recruitment (Ascoli et al. 2013). Thus, in our study, the temperature of the fires in the low fire severity plots, though not measured, might have been appropriate to break dormancy in *N. alessandrii* and promote seed germination and seedling emergence. By visual inspection in our field campaigns, we did not find abundant mother trees with available seeds by February 2018, or if there were remaining mother trees, they had been partially or totally consumed by fire in 2017. We surveyed the plots in November 2018, i.e., 20 months after the fire and the seed release from remnant mature seed-bearing trees (February in the case of *N. alessandrii*), and we only found seedlings with heights lower than 50 cm that were presumably germinated in August that same year. From a conservation point of view, our results suggests that the efforts to increase the regeneration and restoration of *N. alessandrii* after a fire must be driven by the site disturbance provoked by fire severity. Those sites with low fire severity would probably not need intense revegetation actions because there are remaining seed-bearing trees that promote seedling recruitment and efforts should focus on the facilitation of new recruits and reforestation of open areas in which there is absence of seed sources. However, in situations of high fire severity it seems that *N. alessandrii* is not able to recover because most seed sources, resprouts, and root suckers (if any), are consumed by fire. According to Donoso (1993), in those forests where the severity of fire is high, the recovery of the system is more complex. In this situation, we believe the most suitable action to recover the species is reforestation instead of management of the scarce natural regeneration. The lack of regeneration in these sites might be due to drastic changes in soil properties. Severe fires are known to cause losses of organic matter and nutrients, to increase soil erosion and spatial variation of the soil properties (Certini 2005), and to decrease plant growth and survival (Chambers 2000; Boyd and Davies 2010).

The results from the logistic regression did not directly relate *N. alessandrii* seedling regeneration with *P. radiata* abundance, but the opportunistic prior establishment of this exotic species might have had some influence on *N. alessandrii* regeneration by modifying the light intensity intercepted by small seedlings with its dense cover and fast growth, favoring shade-tolerant species (Guerrero and Bustamante 2009). *N. alessandrii* is classified as shade- intolerant, but its regeneration requires semi-shade conditions provided by canopy gaps (Bustamante and Castor 1998) and the growth and survival of the species is negatively affected when it grows under high irradiances (Acevedo et al. 2020). It is not yet clear what is the direct effect of *P*. *radiata* invasion on *N*. *alessandrii* regeneration; however, it is known that this exotic species is highly invasive (Higgins and Richardson 1998) and has successfully invaded the Maulino Forest and the *N*. *alessandrii* remnant forests due to its serotinous cones that release seeds in response to high temperature and fire (Richardson and Brown 1998). This situation can cause that remnants of *N*. *alessandrii* located in burned areas surrounded by *P*. *radiata* plantations might evolve with this exotic species as the dominant species (Bustamante and Castor 1998). Thus, maintaining lower *P*. *radiata* cover in those areas may assist to minimize the damage of this aggressive invader.

Conclusions/ wider implications of findings

Our results indicates that low intensity fires favor seedling regeneration of *N*. *alessandrii*. The effect of *P*. *radiata* invasion on *N*. *alessandrii* regeneration is not clear yet, thus new studies are needed to resolve this question. This calls for a long-term monitoring of the new recruits in order to understand the ecological regeneration of the species.

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