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Impact of protection methods and abiotic factors on *Nothofagus pumilio* seedlings mortality in Torres del Paine National Park, Chile

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Abstract: National parks (NP) are the last refugia of forests dominated by the *Nothofagus* species in Chile. However, frequent, careless human-caused fires are destroying these forests even within the national parks. After large-scale fires, *N. pumilio* stands are unable to recover naturally neither in generative nor in vegetative ways and artificial regeneration must be resorted to in order to maintain their extent. However, even artificial regeneration is not successful without protection against browsing. Therefore, the aim of this study was to experimentally test a range of repellents and other methods of mechanical protection of seedlings against browsing. Five replicates of plots were placed in Torres del Paine NP, in different habitat conditions and with different methods of protection against browsing (11 repellents, wire mesh, plastic tube and control). In each plot, 12 seedlings were treated with each type of protection. In our experiment, only 8% of the seedlings were damaged by browsing, while the mortality rate was 38%. The results indicate a more significant effect of abiotic factors (mainly frost, drought or wind) on seedling mortality than browsing. In parallel, however, it is clear that, compared with the control, six of the eleven repellents used in the experiment showed a significantly positive effect. We suggest the use of plastic tubes as the best option to protect seedlings, which, in addition to providing 100% protection against browsing, are likely to provide more favourable microclimatic conditions for seedlings, similar to leaving the burned snags.

Keywords: browsing; forest fires; guanaco; lenga; repellents

Nothofagus forests represent the southernmost forests in the southern hemisphere and include to the temperate deciduous forest and antiboreal forest zones of the Southern Hemisphere (Haemet-Ahti 1986). In the antiboreal zone (Veblen et al. 1996a) we find forests with deciduous species of *N. pumilio* and *N. antarctica* and the evergreen species *N. betuloides.* Natural forests dominated by *N. pumilio* represent the last stage of postglacial succession (Armesto et al. 1992).

The spatial structure of such a forest is a mosaic of even-aged patches with long intervals of low or no rejuvenation. Episodes of rejuvenation of *N. pumilio*, as a heliophytic woody plant,

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are conditioned by natural disturbance of most of the canopy (Veblen et al. 1996b). The opening of the canopy floor stimulates natural regeneration by changing soil conditions and light availability (Pastur et al. 2016). The most common natural disturbances are windstorms, floods, landslides, avalanches (Armesto et al. 1992; Veblen et al. 1996b), but also fires caused by lightning or volcanic origin (Veblen et al. 1996b). The potential for natural regeneration is mainly generative. Seed rain is highly variable from year to year, ranging from a few hundred thousand to several million seeds per ha (Schlegel et al. 1979; Rusch 1993; Esteban et al. 2010), with germination rates as high as 30% in *N. pumilio* (Rocuant 1984). Seedlings are often found at densities of several hundred thousand individuals per hectare, most often on exposed mineral soil; in natural stands, seedlings are also often found on fallen trunks and under canopy openings (Veblen et al. 1981).

Negative factors in natural regeneration are insufficiently moist soils (Rusch 1992), drying winds (Schmidt, Urzua 1982) or frost (Pastur et al. 2016, 2017). One of the most important factors negatively affecting natural as well as artificial regeneration of *Nothofagus* forests has been identified as browsing by game (*Lama guanicoe*) or cattle (Pastur et al. 2016).

However, since the colonisation of southern Chile in the 19th century, human-managed conversions of natural forests to pasture have fundamentally affected the evolution of *Nothofagus* forests. This has resulted in their fragmentation and a concomitant significant loss of area. Up to 70% of the area of *Nothofagus* forests is used in a silvo-pastoral way (Bahamonde et al. 2013). Human-caused fires have also caused a significant reduction in their area, with Bizama et al. (2011) reporting a 23% loss of natural forests in the Aysén River Basin (Patagonia Chilena) between 1900 and 1998.

National parks (NP) such as Torres del Paine are thus some of the last refuges of natural *Nothofagus* forests. According to paleoenvironmental research, fires are a frequent natural phenomenon in the park (Sepúlveda 2009), but in the last 40 years, 48 large forest fires exceeding 10 ha have been recorded in the national park caused by tourists. Particularly catastrophic for Torres del Paine National Park were the three largest forest fires in 1985, 2005, and 2011, which together affected more than 46 000 ha of forest and non-forest ecosystems (Vidal 2012).

N. pumilio (Lenga) stands are unable to recover naturally after large-scale fires, neither generatively nor vegetatively, and artificial regeneration is necessary to maintain their extent. However, plantations are being decimated by wild populations of guanaco llamas and the introduced hare (*Lepus europaeus*), whose diet is represented by woody plants at 5% (Ernst et al. 2021). Thus, without protection against browsing, restoration of fire-damaged forests is problematic. The aim of this work was therefore to compare different methods of seedling protection against browsing and to identify the most effective method that could subsequently be used in the restoration of forest ecosystems beyond Torres del Paine NP.

MATERIAL AND METHODS

Study area. Torres del Paine is a Chilean national park, founded in 1959, which was declared a UNESCO Biosphere Reserve in Chilean Patagonia at 51° south latitude in 1978. There are four vegetation altitudinal zones in the park: Patagonian steppes dominated by fescue (*Festuca gracillima*), pre-Andean scrubland dominated by *Mulinum spinosum*, *Escalonia rubra*, and *Berberis buxifolia*, the Magellanic subpolar forest of interest consisting of *Nothofagus pumilio* and *N. antarctica* species, and Andean deserts already found above the forest boundary (Armesto et al. 1992).

The study area is situated in a sector of the Laguna Azul National Park, in the zone affected by the 2005 fire. According to the cartographic classification of Gajardo (1994), the vegetation of this zone includes two vegetation formations: the Magallan deciduous forest and the Magallan Patagonian steppe.

Laguna Azul is located in a moderately cool rainy climatic zone with no dry season, with an annual rainfall of 400 mm and an average annual temperature of 5 °C (CONAF 2020). In terms of temperatures, this zone is characterised by the occurrence of low temperatures, with average monthly temperatures not exceeding 15 °C in the hottest month of summer (January) and with an average minimum monthly temperature in the coldest month (July) that does not fall below –2.5 °C (Mora 2006; CONAF 2007).

Research design and data acquisition. To test the efficacy of repellents and mechanical protection against the browsing of Lenga seedlings by the

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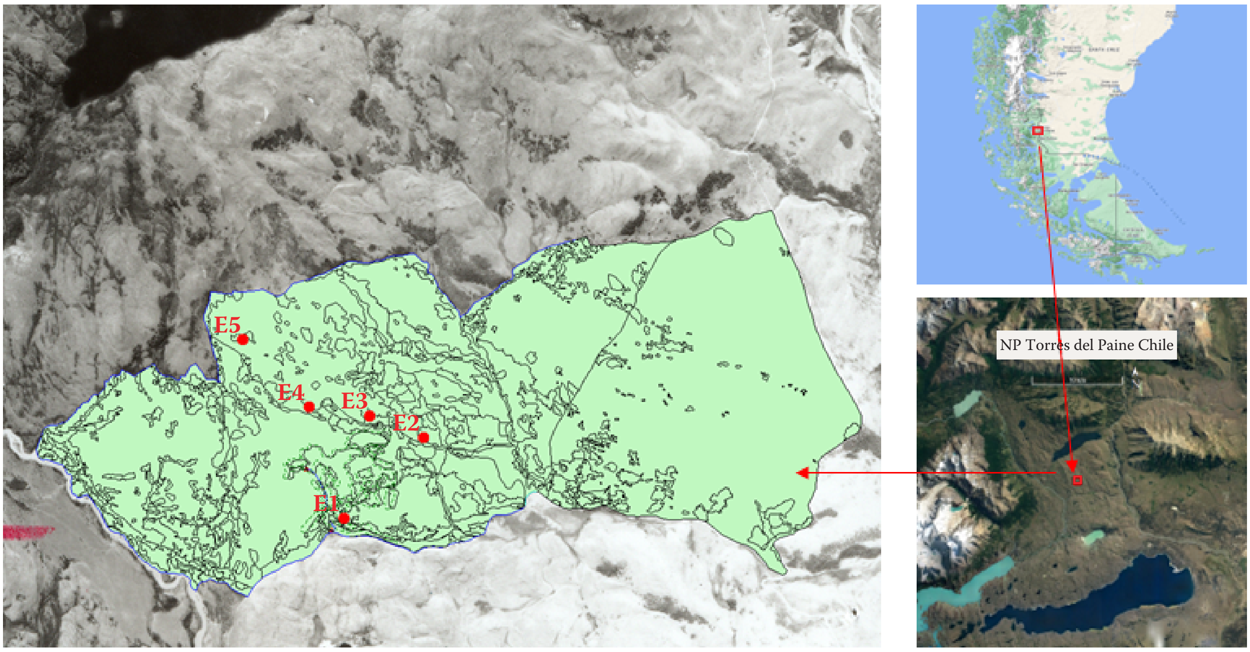

Figure 1. Location of research plots in Torres del Paine National Park (NP)

guanaco llama and hare, five different habitats were selected in the area designated by the Torres del Paine NP administration (Figure 1) to represent the environmentally wide range of habitats of the area. Plot E1 was located on a steep southeast-facing slope falling within Cañon Macho. Plot E2 was located on a plateau at the edge of the burned area. Plots E1 and E2 had nearly all standing burned logs cut down, and are habitats particularly exposed to high winds. In addition, plots E1 and E2 were most frequently visited by large groups of guanaco llamas. Plots E3 and E4 were located in burned Lenga stands, but where standing burned snags remained. These plots are located at the base of the slope and are protected from the wind. Plot E5 was placed in exposed habitat on a slope facing the Paine River valley, with burned snags remaining only on the edge of the plot. Each plot was marked with a stake in the field in the NW corner and stabilised with a coordinate.

The design of the research plots (Table 1) and the methodology were approved by both the Torres

Table 1. Scheme of the research plots

Species: Lenga, *Nothofagus pumilio* (Poepp. et Endl.) Krasser				1	2	3	4	5	6	7	8	9	10	11	12
Line No.	repellent type	abbreviation	distance (m)	spacing 2 × 1 m, plot 12 × 28 m = 3.36 ar											
1	Aversol	AV	–12	x	x	x	x	x	x	x	x	x	x	x	x
2	Cambilan	CA	–10	x	x	x	x	x	x	x	x	x	x	x	x
3	Cervacol Extra	CE	–8	x	x	x	x	x	x	x	x	x	x	x	x
4	Lavanol	LA	–6	x	x	x	x	x	x	x	x	x	x	x	x
5	plastic tube	TP	–4	x	x	x	x	x	x	x	x	x	x	x	x
6	Pelacol	PE	–2	x	x	x	x	x	x	x	x	x	x	x	x
7	control	C	0	x	x	x	x	x	x	x	x	x	x	x	x
8	Morsuvin	MO	2	x	x	x	x	x	x	x	x	x	x	x	x
9	Neoponit	NE	4	x	x	x	x	x	x	x	x	x	x	x	x
10	Nivus	NI	6	x	x	x	x	x	x	x	x	x	x	x	x
11	Recervin	RE	8	x	x	x	x	x	x	x	x	x	x	x	x
12	Sanatex	SA	10	x	x	x	x	x	x	x	x	x	x	x	x
13	wire mesh	TA	12	x	x	x	x	x	x	x	x	x	x	x	x
14	Lentacol	LE	14	x	x	x	x	x	x	x	x	x	x	x	x

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Table 2. Types of seedling protection (mechanical and chemical) used in the experiment

Name	Producer	Abbreviation
Aversol	Tora, spol. s r.o., CZ	AV
Cambilan	Eko Cheming, CZ	CA
Cervacol Extra	Avenarius Agro, GMBH, Austria	CE
Lavanol	Eko Cheming, CZ	LA
Pellacol	NUFAM GMBH & Co KG, Austria	PE
Morsuvin	NeraAgro, spol. s r.o., CZ	MO
Neoponit	Agro Radomyšl, a.s., CZ	NE
Nivus	NeraAgro, spol. s r.o., CZ	NI
Recervin	NeraAgro, spol. s r.o., CZ	RE
Sanatex	Tora, spol. s r.o., CZ	SA
Lentacol	NUFAM GMBH & Co KG, Austria	LE
Wire mesh	–	TA
Plastic tube	–	TP
Control without protection	–	C

del Paine NP administration and the state organisation Servicio Agrícola y Ganadero (SAG), which is responsible for the approval of all chemical products for agriculture and forestry in Chile.

Four research plots (E1–E4) were planted according to the approved scheme (Table 1), with Plot 5 being the only exception where Cervacol Extra (CE), plastic tube (TP), and wire mesh (TA) were not planted due to a mistake of local labourers. Three-year-old seedlings with an approximate height of 15 cm were used. Seedlings were planted in evenly spaced lines according to the repellent or mechanical control applied at the end of the 2009 growing season. In each line, 12 seedlings were evaluated according to the scheme (Table 1). Repellent applications were made prior to planting.

The following types of browsing control were chosen to protect seedlings against game (Table 2).

Both the mesh and the plastic tube (Figure 2) were 60 cm high and were attached to the ground with a wooden stake. The plastic used for the tube contained a UV filter. One line was always the control without protection (C).

In the laboratory of the Universidad de Magallanes, tests have been carried out on the environmental impact of repellents, specifically soil pH, macro and micro nutrient content in the soil, heavy metal content, micro and macro nutrients in plants, and the effect on biodiversity communities was also tested (Teneb, Ríos 2011), after which they were only approved for use for research in Torres del Paine NP.

Figure 2. Mechanical protection with a plastic tube

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For the evaluation of seedlings, which was carried out at the end of the 2010 growing season, the following categories were established: (*i*) live seedlings without damage (N) – live seedlings with standard crown development, green leaves and intact terminal bud and lateral branches; (*ii*) live seedlings with dry terminal (ZS) – live seedlings with dry terminal or side branches (frosting due to immaturity); (*iii*) seedlings browsed (K) – live seedlings with signs of browsing of terminal or lateral branches by a llama or hare; (*iv*) dead dry seedlings (S) – seedlings that have died due to various mainly climatic causes (drought, frost); (*v*) missing seedling (CH) – a seedling not found on the site according to the given scheme.

Data analysis. Habitat (environmental factors) impact assessment. Plots were described by factors that characterised vegetation, topographic, climatic, soil, and disturbance conditions (Table 3). The resulting dataset contained 67 rows (5 plots with 14 repellent treatments = 70 rows, but three rows were not planted, see explanation above, i.e. 804 samplings in total) and 9 environmental factors (Table 3) and 5 damage type factors (N, ZS, K, S, CH, for explanation see above).

We used the principal components analysis (PCA) to interpret principal components (PCs) (gradients in environmental space) associated with important environmental and other, e.g. disturbance factors. Correlation types of a cross-products matrix (data were centralised and standardised) and an orthogonal rotation option were used to get independent, mutually uncorrelated PCs (Lattin et al. 2003). We checked the dataset for outliers in PC-ORD software (Version 6.0, 2011). Significance of PCs was tested using a Monte Carlo randomisation test with 1 000 runs. We calculated the linear (parametric Pearson's r) and rank (nonparametric Kendall's tau) correlation coefficients (loadings) as relationships between the ordination scores (axes) and the environmental factors. We set the threshold for r and tau > 0.4 (e.g. Hair et al. 2013). We used PC-ORD software for the PCA analysis.

We checked the variable importance within the plots with the Random Forests supervised discrimination (RF) (Breiman 2001) to: (*i*) discriminate among the classes, and (*ii*) identify factors that were significantly associated with PC. These factors were ranked in the RF variable importance function according to mean decrease accuracy (*MDA*) and mean decrease gini (*MDG*) (Liaw, Wiener 2002). The best RF solution was revealed by the lowest 'out-of-bag' estimate of error rate as a measure of a general RF misclassification (Cutler et al. 2011). We used R software (Version 3.0.0, 2014) for the RF analysis.

Probability of occurrence of each type of damage. The effect of protection method on probability of occurrence of specific damage category was modelled using Bayesian generalised linear mixed models for binary data (family = Bernoulli) in R package, 'brms' (Bürkner 2018). Models were run separately for each damage category (K, ZS, S, CH, N) with site treated as a random effect. The differences between the individual protection methods and the control were tested using probability of direction. Probability of direction varies between 50% and 100% and can be interpreted as the probability (expressed in percentage) that a parameter (described by its posterior distribution) is strictly positive or negative (whichever is the most probable) (Makowski et al. 2019a). The probability of direction was then converted to a P-value using one-sided method. The probability of direction with its conversion to P-value were run in 'bayestestR' (Makowski et al. 2019b) R package.

Table 3. Environmental factors describing the research plots

Plot	Slope (%)	Aspect	Topogr	S_depth	S_water	Mineral	Cover (%)	Guanaco (m)	Windexp
E1	90	SW	slope centre	moderately deep	no	skeletal	5	1 550	moderately exposed
E2	15	SW	flat area	deep	no	bouldery	0	1 030	extremely exposed
E3	25	SE	slope centre	shallow	no	bouldery	40	1 500	moderately exposed
E4	15	S	slope base	moderately deep	no	skeletal	50	2 020	protected
E5	80	W	slope centre	shallow	no	skeletal	65	2 800	extremely exposed

Slope – slope inclination; aspect – slope exposure; topogr – position within the slope; s_depth – soil depth; s_water – presence of the additional soil water; mineral – content of the skeleton; cover – cover of burned snags; guanaco – distance from the closest gathering place; windexp – exposure to the wind

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RESULTS

Habitat (environmental factors) impact assessment. The PCA ordination of the dataset resulted in three significant PCs (P = 0.001), explaining 67% of the total variance within the 14 factors (Figure 3). The most important principal component PC1 was characterised by dry-dead *Nothofagus* plants, associated with the presence of dry old tree cover, the distance from the llama guanaco concentration, soil depth and the area of a mineral bare ground after the fire. PC1 was interpreted as a gradient of seedling mortality. PC2 was characterised by a dry terminal and lateral branches of *Nothofagus* plants, associated with wind exposure and the area of a mineral bare ground after. PC2 was interpreted as a gradient of climatic seedlings damage. PC3 was associated only with aspect factor; we interpreted it as a radiation gradient (Table 4, Figure 3).

The RF analysis revealed 0% of a general misclassification rate for the discrimination among the plots. Important site-specific and disturbance factors influencing the performance of *Nothofagus* plants were identified in order of *MDA*/*MDG* (in parenthesis): cover (19.1/8.7), guanaco (18.8/8.1), slope (18.1/7.9), and s_depth (17.5/7.6). Other factors were significantly less important (Figure 4).

Probability of occurrence of specific type of damage depending on the method of protection. The probability of browsing (K) was statistically significantly lower compared to the control (C) for the LA, TA, TP protection methods (Figure 5). The probability of occurrence of dried terminal (ZS) was lowest when plastic tubes (TP) were used. On the other hand, protection types LE, MO, NE, NI, PE, SA, CE showed higher probability of occurrence of dried terminal compared to control (Figure 5). The probability of occurrence of dry seedlings (S) was statistically significantly higher when CA, CE, NE, TA were used. The probability of missing seedlings (CH) was statistically significantly lower for the following protection types (CA, CE, LA, MO, NE, NI, RE, SA, TA, TP) compared to the control. The opposite view provides the probability of occurrence of completely intact seedlings (N), which was significantly higher in the following protection

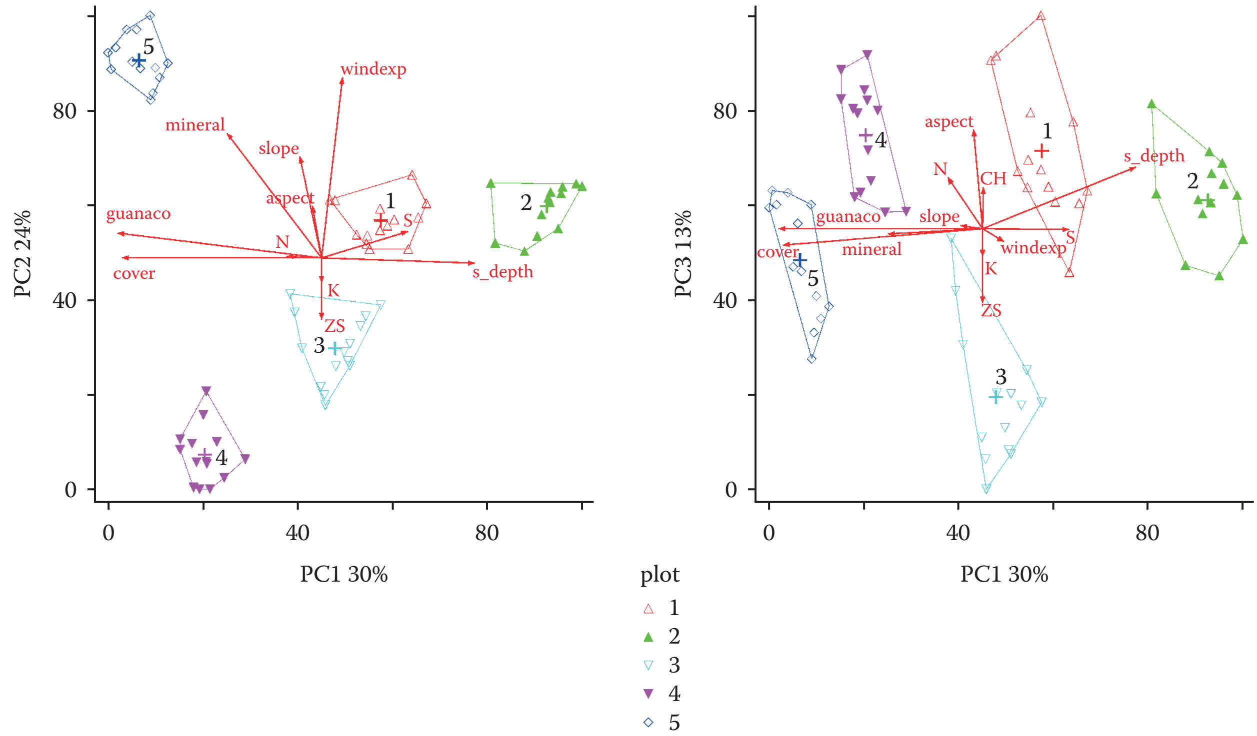

Figure 3. A biplot of sample plots and environmental and disturbance factors with significant gradients PC 1–3 in the principal components analysis (PCA) ordination for the study area

Aspect – slope exposure; CH – missing seedling; cover – cover of burned snags; guanaco – distance from the closest gathering place; K – seedlings browsed; mineral – content of the skeleton; N – live seedlings without damage; S – dead dry seedlings; s_depth – soil depth; slope – slope inclination; windexp – exposure to the wind; ZS – live seedlings with dry terminal

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Table 4. Correlations as relationships between the ordination axes (gradients) and the environmental-disturbance factors, expressed by the linear (Pearson's *r*) and rank (Kendall's tau) correlation coefficients (loadings)

Factors	Gradient 1			Gradient 2			Gradient 3		
	r	r^2	tau	*r*	r^2	tau	*r*	r^2	tau
N	–0.38	0.15	–0.31	0.08	0.01	0.05	0.46	0.22	0.34
ZS	0.02	0.00	0.06	**–0.51**	**0.26**	**–0.41**	–0.56	0.31	–0.35
K	0.02	0.00	0.06	–0.32	0.11	–0.27	–0.34	0.12	–0.18
S	**0.60**	**0.36**	**0.45**	0.33	0.11	0.30	–0.07	0.01	–0.09
CH	0.06	0.00	0.01	0.00	0.00	0.01	0.42	0.17	0.35
Slope	–0.30	0.09	–0.12	0.65	0.43	0.34	0.12	0.01	–0.04
Aspect	–0.19	0.04	–0.15	0.47	0.22	0.39	**0.65**	**0.42**	**0.44**
Windexp	0.30	0.09	0.20	**0.87**	**0.76**	**0.74**	–0.23	0.05	–0.21
Cover	–0.92	0.84	–0.88	–0.02	0.00	–0.12	–0.27	0.07	–0.11
S_depth	**0.80**	**0.64**	**0.70**	–0.15	0.02	–0.05	0.51	0.26	0.29
Mineral	–0.63	0.40	–0.57	**0.72**	**0.52**	**0.57**	–0.14	0.02	–0.21
Guanaco	**–0.93**	**0.86**	**–0.74**	0.32	0.10	0.06	–0.01	0.00	0.07

Bold – significant figures; N – live seedlings without damage; ZS – live seedlings with dry terminal; K – seedlings browsed; S – dead dry seedlings; CH – missing seedling; slope – slope inclination; aspect – slope exposure; windexp – exposure to the wind; cover – cover of burned snags; s_depth – soil depth; mineral – content of the skeleton; guanaco – distance from the closest gathering place

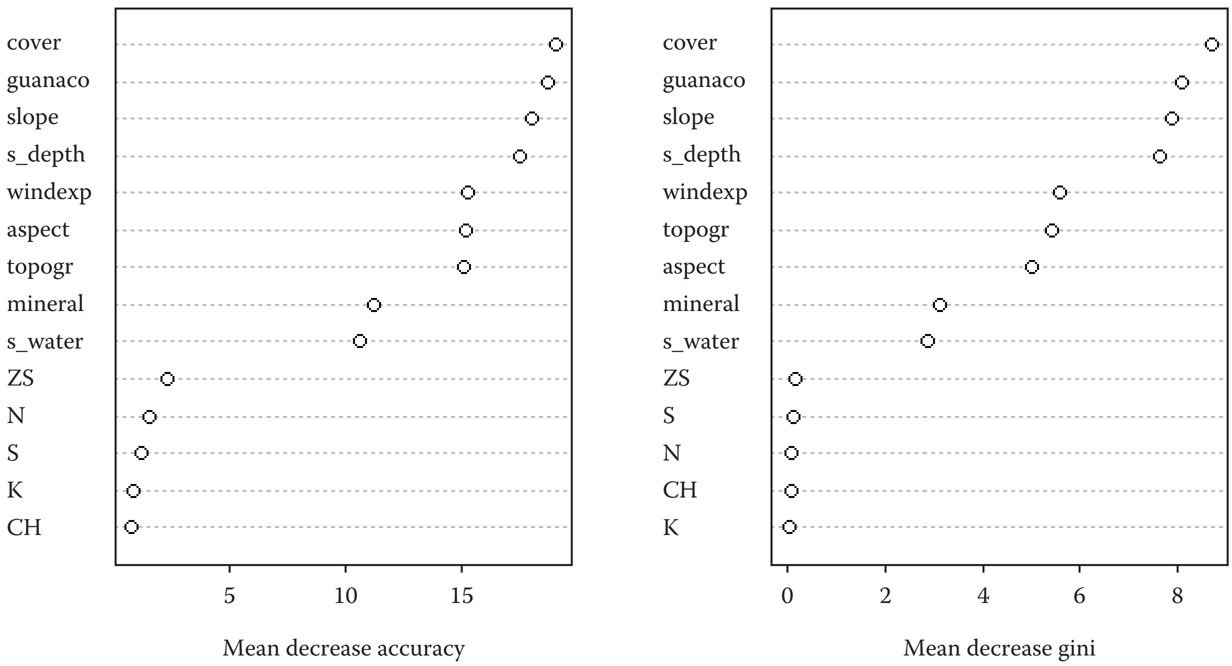

Figure 4. The analytical factors (Table 3) ranked in the Random Forest according to mean decrease accuracy (*MDA*) and mean decrease gini (*MDG*)

Cover – cover of burned snags; guanaco – distance from the closest gathering place; slope – slope inclination; s_depth – soil depth; windexp – exposure to the wind; aspect – slope exposure; topogr – position within the slope; mineral – content of the skeleton; s_water – presence of the additional soil water; ZS – live seedlings with dry terminal; N – live seedlings without damage; S – dead dry seedlings; K – seedlings browsed; CH – missing seedling

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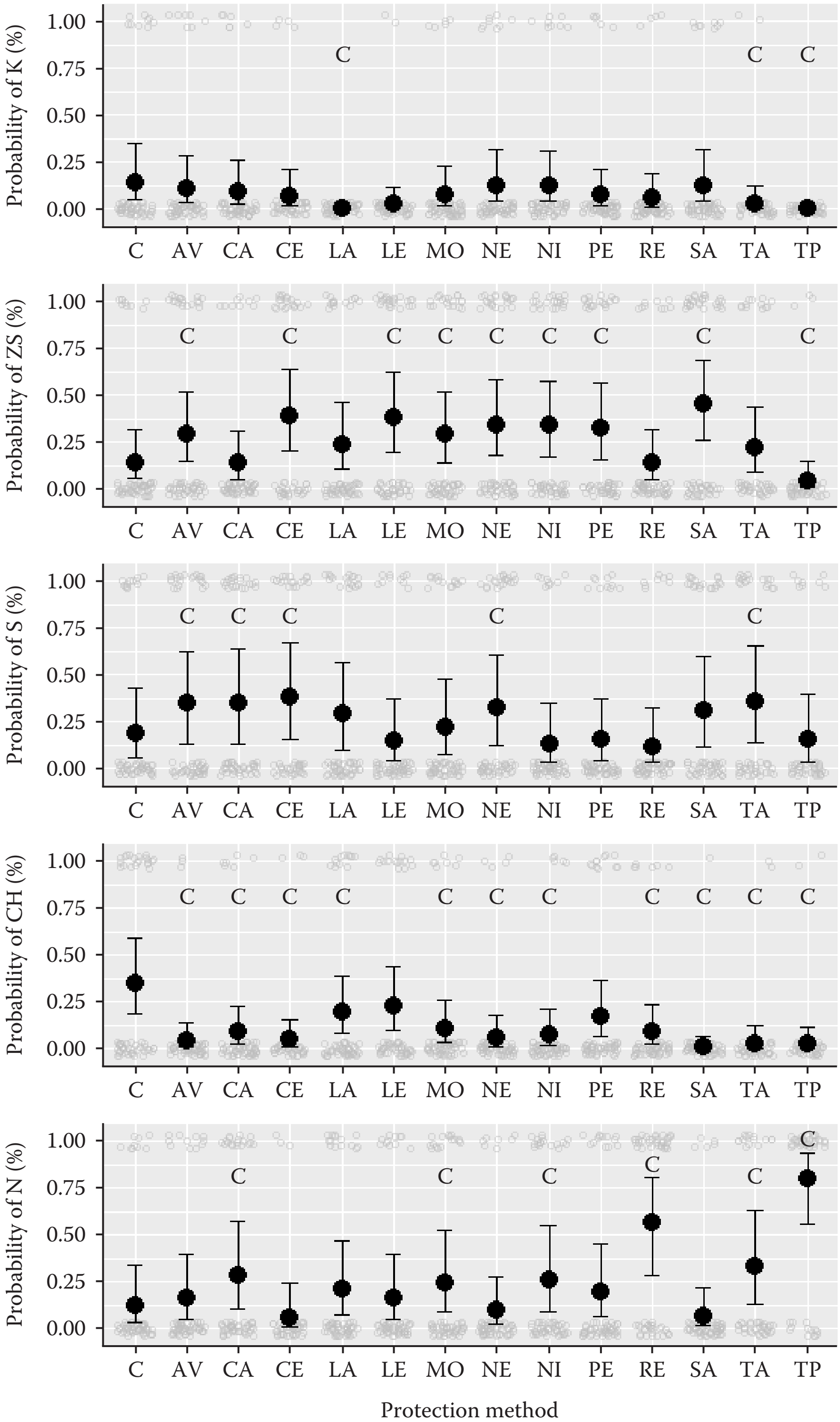

Figure 5. Plot showing the probability of individual types of damage (K, ZS, S, CH, N) occurrence in relation to protection method (Table 2)

Dark points – modelled values; whiskers depict 95% confidence interval; small circles (slightly jittered to avoid overplotting) – observed values; C – statistically significant differences of individual protection method from control; K – seedlings browsed; ZS – live seedlings with dry terminal; S – dead dry seedlings; CH – missing seedling; N – live seedlings without damage; C – control; AV – Aversol; CA – Cambilan; CE – Cervacol Extra; LA – Lavanol; LE – Lentacol; MO – Morsuvin; NE – Neoponit; NI – Nivus; PE – Pelacol; RE – Recervin; SA – Sanatex; TA – wire mesh; TP – plastic tube

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types (CA, MO, NI, RE, TA, TP) with the most positive effect of plastic tube (TP), see Figure 5.

Overall, it is clear [see Table S1 of the Electronic Supplementary Material (ESM)] that on average only 8% of seedlings were damaged by browsing (irrespective of the type of repellent). Seedling mortality (dry or missing seedlings) was much higher on average (38%). Thus, after the first year of planting, the success rate of reforestation (damage categories N, ZS, K), as verified accurately in the plots, was 62%.

The ESM also shows that the best results were achieved with the application of Recervin repellent (23% mortality, 7% browsed), while the same mortality was achieved for seedlings treated with Nivus repellent, but with a lower proportion of undamaged seedlings due to higher browsing (23% mortality, 13% bite). Excellent results were achieved with the use of plastic tubes, which achieved low mortality (21%) together with zero browsing. A browsing rate below 10% was still found with the repellents Cervacol, Pellacol, Lentacol, Morsuvin, and with the use of wire mesh. However, these products had high mortality rates (44%, 35%, 40%, 35%, and 42%, respectively). In the case of the repellent Lavanol, even no browsing was detected, but high mortality (52%). Control unprotected seedlings were browsed at 15% and mortality reached 55%.

DISCUSSION

In recent years, there has been concern about the increasing scale, frequency and severity of forest fires, combined with other human-induced disturbances such as cattle grazing, which may cause a failure of natural regeneration even in ecosystems that are adapted to fire (Clason et al. 2022). Thus, tree planting after fire becomes an important method of forest restoration. According to paleoenvironmental research, fires are a frequent natural phenomenon in Torres del Paine National Park (Francois 2009). In the last 40 years, 48 large forest fires caused by tourists exceeding 10 ha have been recorded in the national park. Particularly catastrophic for Torres del Paine National Park were the three largest forest fires in 1985, 2005, and 2011, which together affected more than 46 000 ha of land and 5 730 ha of forest ecosystems (Cifuentes 2017; Cafourek et al. 2021).

Nothofagus forests have coexisted with herbivores such as the guanaco llama for several thousand years (Pastur et al. 2016). However, problems with seedlings browsed by wild and domestic herbivores during the restoration of *Nothofagus* forests have recently been reported by a number of authors (Echene, Bava 2005; Pastur et al. 2016, 2017). Pastur et al. (2016) found no difference in seedling density between fenced and unfenced areas, but browsing negatively affected seedling height growth. Fencing and reducing llama densities by hunting can shorten the recovery phase by 30–50% (Pastur et al. 2016). Seedlings in the first four years of life are the most susceptible (Pastur et al. 2017).

The use of mechanical or chemical protection of seedlings against browsing is therefore a prerequisite for the successful restoration of *Nothofagus* forests in Torres del Paine NP. For the use of repellents in Torres del Paine National Park, it was necessary to verify the environmental friendliness of the repellents used. For this reason, an analysis of their ecological safety was carried out in collaboration with the Universidad de Magallanes. According to the results, no negative impact of the repellents on the ecosystems of Torres del Paine National Park was found (Teneb, Ríos 2011).

Our experiment was designed as trial plots with all types of protection together. We followed a design of blocks similar to those used by Santili et al. (2004) for the evaluation of three repellents for the prevention of damage to olive seedlings by deer. Some of the repellents used in our experiment are attractive not only by their taste but also by their smell, such as Cervacol or Morsuvin, and therefore it could raise concerns about mutual influence or synergistic effect on control raw. However, control raw gave us the worst results regarding the survival success of seedlings, and what is more, the browsing was not the main issue of seedling survival rate compared with the influence of abiotic factors.

In our experiment, only 8% of the seedlings were damaged by browsing on average, whereas the mortality rate due to climatic extremes reached 38% (Table S1, ESM). Thus, similar to Pastur et al. (2017), our results indicate a more significant effect of abiotic factors (mainly frost, drought or wind) on seedling mortality than biotic factors, i.e. browsing (Figures 3–5). In parallel, however, it is clear that, compared to the control (15% of seedlings browsed), six of the eleven repellents used in the experiment show good efficacy (less than 8% of seedlings browsed) in protection against browsing (Table S1, ESM). In this context, however, it is worth mentioning the statistically significant negative effect of the

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use of some repellents on the drying of terminals (ZS) or whole seedlings (S; Figure 5). The question is whether this is indeed a causal relationship or just a randomly proven phenomenon. Obviously, browsing was best eliminated by mechanical protection with plastic tubes (0% of the seedlings browsed) and wire mesh (4% of the seedlings browsed).

Fires create large numbers of standing dead trees (Holden et al. 2006). Leaving standing dead trees after a disturbance is ecologically important in terms of promoting tree seedlings or forest regeneration (Jonášová, Prach 2004). As evidenced by our results, seedling mortality was significantly lower in plots E3 and E4 with standing burned snags left compared to the other plots (Figure 3, Table S1, ESM). Standing burned snags provided at least minimal protection to seedlings from microclimatic extremes. Thus, it can be concluded, in line with the results of similar studies from other ecosystem types (Jonášová, Prach 2004; Kupferschmid et al. 2006; Svoboda et al. 2010; Wild et al. 2014), that the removal of standing dead tree torsos is inappropriate from the perspective of forest regeneration. In addition, leaving standing dead trees increases biodiversity by creating microhabitats for many species of organisms (Perry, Thill 2013; Baeza, Santana 2015; Ganey 2016).

On the basis of our experiment, we can claim that the best option for seedling protection is the use of plastic tubes (Figure 5, Table S1, ESM) which, in addition to providing 100% protection against browsing, are likely to provide more favourable microclimatic conditions for the seedlings. This fact is confirmed in a number of studies (Campo et al. 2006; Oliet, Jacobs 2007; Devine, Harrington 2008). The wider use of plastic tubes, at the time of the project, encountered several problems. First and foremost was the negative attitude of the Torres del Paine NP administration towards the wider use of this protection due to the negative visual effect in tourist-exposed places. This view has now been reconsidered and plastic tubes are used as protection at many tourist sites. Plastic pollution is another issue (Alvarez-Risco et al. 2020) as the tubes need to be collected after use, or bio-degradable material should be used. Another issue is the higher overall labour intensity. Due to the extreme winds, the original tubes imported from the Czech Republic had to be cut to about one third of their height and anchored firmly to a wooden stake in the ground. This also entails higher costs for this type of protection (Salinas et al. 2022). However, a significant advantage is the rapid development and growth of seedlings inside the tubes. The height growth of the seedlings inside the tubes was many times higher than the growth of the seedlings outside the tubes according to the ocular inspection. Such conclusions are confirmed by other authors (Delisle 1999; Ponder 2003).

CONCLUSION

The results of the field experiment showed that in the post-fire conditions in Torres del Paine National Park, extreme climatic factors (38% losses) had a greater influence on the recovery success of *Nothofagus pumilio* than damage by guanaco llama and hare browsing (8%). The use of plastic tubes, which also protect the seedlings against climatic extremes and thus contribute to rapid seedling development and growth, has proved to be a very effective method of protecting seedlings in the first years after planting, completely preventing damage to seedlings by browsing. The disadvantages of this method are the higher cost and labour involved in the installation and subsequent disposal of plastic residues if non-biodegradable tubes are used. The use of repellents is particularly suitable in locations where plastic tubes cannot be used, e.g. extremely exposed habitats or poorly accessible locations. The advantage is the possibility of applying the repellent in the nursery and planting already treated seedlings. Of the range of repellents tested, Recervin proved to be the most effective, with a mortality rate of 23% and only 7% seedling browsing damage. The repellents Lentacol and Lavanol can be recommended as the next most effective repellents for application. Both repellents had a browsing rate below 10%.

A comparison of mortality results at five different sites showed that at the two sites where burned snags remained, seedling mortality was significantly lower than at sites where trees were cut or missing. There was a positive effect of retained burned snags on the microclimate, especially on exposed sites. It can therefore be recommended to the Torres del Paine National Park authority to leave standing torsos until they decay also in other similar cases.

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