Capítulo 5

Effects of vegetation clearing, soil preparation and reforestation methods on the recovery of burned *Pinus nigra* forests: A multi-criteria evaluation

Introduction

Extensive tree regeneration failure after large wildfire events is becoming one of the major factors threatening the conservation of many forests ecosystems in the West Mediterranean Basin (Moreno et al. 1998). In spite of the well known resilience of Mediterranean species to fires through effective regeneration mechanisms such as resprouting or seeding (see among others: Keeley & Zedler 1978), increasing occurrence of large and intense wildfires in non fire-prone Mediterranean areas (Terradas 1996) may compromise the future of species lacking efficient post-fire regeneration mechanism (e.g. Piussi 1992; Alcahud et al 1995; Riera & Castell 1997). In those areas, extensive and massive crown fires result on homogeneous burned landscapes where the absence of surviving trees and the distance to the edge can severely difficult the arrival of propagules and the possibilities of a successful regeneration process (Retana et al. in press). In Catalonia (NE, Spain) large wildfire events (> 1000 ha) have accounted for 0.41% of the total number of fires but 75.1% of the total burned surface from 1975 to 1999 (Salvador et al. 2000). Moreover, since 1990, 35.3% of the total surface burned by large wildfires has affected middle-montane and sub-mediterranean areas destroying more than 25% of the whole range area occupied by Black pine *(Pinus nigra* Arnold.) forests (Gracia et al. 2000). *P.nigra* lacks of serotinous cones and, due the early release of pinions at the beginning of spring, does not maintain a seed bank when summer wildfires occur (Habrouk et al. 1999). For these reasons, this species has very low or nil post-fire regeneration (Trabaud & Campant 1991; Retana et al. in press).

P. nigra forests have both economic importance and ecological significance (e.g. *P.nigra* forests are included in the EU Endangered Habitats directive). For this reason, the lack of successful regeneration in these forests has arisen major concern about the best alternatives to recover them throughout suitable artificial reforestation programs (Espelta 1999). In the West Mediterranean Basin, water stress has been envisaged as the most limiting factor for ecosystem reconstruction, with soil fertility achieving a secondary importance (Vallejo et al. 2000). Thus, successful reforestation with *P. nigra* in Mediterranean areas should work out the chronic water shortage of the Mediterranean climate, due to the existence of low and highly irregular precipitation per year, hot and dry summers, and frequent out-of-season droughts, all those traits occurring in soils usually with low infiltration and water holding capacity (Vallejo & Alloza 1998). Moreover, recently established seedlings may particularly suffer from water stress (Sachs et a. 1994), because they have not developed yet a root system able to replace water lost through transpiration. In that framework, site preparation before reforestation, including both vegetation clearing and soil preparation, may have a paramount importance to increase the outcome of seedlings established (Graham et al 1989; Flemming et al. 1996). Vegetation clearing has been reported to diminish competence for water and nutrients, thus ameliorating the survival rates of planted seedlings (Ashby 1997; Harvey et al. 1996) and encouraging germination and establishment after seedling (Nilsson et al. 1996). On the other hand, soil preparation by plowing may increase water availability for seedlings through reducing runoff losses, increasing the total water stored in the profile and decreasing the penetration resistance of the soil (Querejeta et al. 2001; Serrada 1990).

Present-days existing methods to clear vegetation (e.g. mechanical, controlled burning, herbicides or livestock grazing) as well as soil preparation techniques (e.g. ripping, spot tillage) may differ largely in their economic cost, the effects on seedlings survival and growth, and even the promotion of undesired indirect ecological impacts on the local fauna and flora (Peman & Navarro 1996). Although the benefits of different site preparation techniques in reforestation programs has been thoroughly documented elsewhere, very few studies have taken into account not only their effects on the plantation performance but also their economic cost as well as possible negative ecological consequences. Notwithstanding, a general consensus has been growing up about the necessity that insights from ecology and economy, as well as social awareness about management of natural resources, be brought together if restoration efforts are to succeed on a large scale (Edwards & Abivardy 1997; Holl & Howard 2000). The comparison of the different reforestation alternatives to elucidate the best way to increase plantation performance with the minimum economic cost and ecological impact, may benefit from advanced multi-criteria decision-support tools. These methods may facilitate the comparison of the different alternatives, as they can hold information arising from this complex system where each criteria (plantation performance, economic cost and ecological impact) may be expressed in a different way (e.g. quantitative or non-quantitative) or subjected to different types of uncertainty (e.g. stochastic or “fuzzy”) (see, among others: Ducey & Larson 1999; Martinez- Alier et al. 1998; Munda 1995)

In the framework of assessing the best alternatives to reforest extensive burned *P. nigra* forests in Mediterranean areas, the main objectives of this study are: i) to evaluate the combined effects of three different methods of vegetation clearing (controlled burning, livestock grazing and mechanical clearing), two types of reforestation strategies (seeding, planting) and two soil preparation techniques (ripping, spot tillage) in the establishment, survival and growth of *P. nigra* seedlings into burned areas in Catalonia (NE Spain) and ii) to compare this array of contrasting alternatives in light of their economic cost, plantation performance and ecological impact using a recently developed multi-criteria decision-support tool (NAIADE: New Approach to Imprecise Assessment and Decision Environment; Munda 1995).

Material and methods

Study area

This study was carried out at the regions of Bages and Berguedà (41^{o} 45’ to 42^{o} 6’ N; 1^{o} 38’ to 2^{o} 1’ E, Catalonia, NE Spain). Climatic conditions vary from dry-subhumid to subhumid Mediterranean climate (according to the Thornwaite index), with mean annual temperature of 11 ^{o}C and mean annual precipitation of 600 mm. These regions were affected by the largest historically recorded wildfire in NE Spain, the Bages-Berguedà (hereafter BB) wildfire, which burned ca. 24.300 forested ha in July 1994. According to the data provided by the Forest Ecological Inventory of Catalonia (IEFC) and the Spanish Second National Forest Inventory (IFN2) carried out before the fire events (1993), the area was covered extensively by forests (71%). The main forest tree species before the fire events was *Pinus nigra* Arnold (75%) while other tree species present in the area were *Pinus halepensis* Mill, *Pinus sylvestris*, *Quercus ilex* L. and *Quercus cerrioides* Wk. et Costa (Gracia et al., 2000). After the fire event, and due to the failure of *P. nigra* regeneration (see Habrouk et al. 1999; Retana et al., in press), regeneration of tree species in a large portion of the burned area was almost nil, and these areas became grasslands or open shrublands dominated by *Brachipodium phoniecoides* with scattered shrubs *(Pistacea lentiscus, Rosmarinus officinalis, Quercus coccifera*). These areas without natural regeneration of tree species accounted for a large part of the surface covered by the previous *P. nigra* forests (39%).

Experimental design and data analysis

The study was carried out in three sites that burned in the BB fire, Can Armengol, Viladasses and Soler de Jaumas located on calcareous limstones (Figure 1). It started in 1998, i.e. 4 years after the fire event. In each experimental area, 14 plots of one ha each were settled down to test different methodologies of: i) vegetation clearing, ii) reforestation, and iii) soil preparation.

Before the start of the experimental treatments, cover and height of the vegetation was determined in each plot (sampling 1). To do so, ten transects of 25 m each were laid per plot. In each transect, species composition and vegetation height were measured at each meter. At this time, no significant differences were found among experimental treatments for vegetation cover (range of mean values per plot: 83-86%) and height (range: 38-43 cm), while the three zones differed in vegetation cover (Mean±Standard error: 91±1%, 89±1%, and 77±1%, for Viladasses, Can Armengol and Soler de Jaumas, respectively), but not in vegetation height (Viladasses: 48±2 cm; Can Armengol: 41±2 cm; Soler de Jaumas: 33±2 cm).

In each study area, four different treatments of vegetation clearing were carried out (Figure 2):

- *Livestock grazing* (hereafter, G) . Four plots per site were grazed by domestic animals, such as sheep (in Soler de Jaumas and Viladasses) and cattle (in Can Armengol) during the spring and fall of 1998. According to the observed levels of tips and leaves consumption, as well as the light browsing of low palatable shrubs present in the area, the grazing pressure could be classified as moderate (following Etienne et al. 1996).

- *Prescribed burning* (hereafter, B) . The vegetation of four plots per site was burned in December 1998 by a controlled fire. Prescribed burning was carried out by the SARPIF (Servei Rural d'Agents Rurals i Prevenció d'Incendis Forestals, Generalitat de Catalunya).

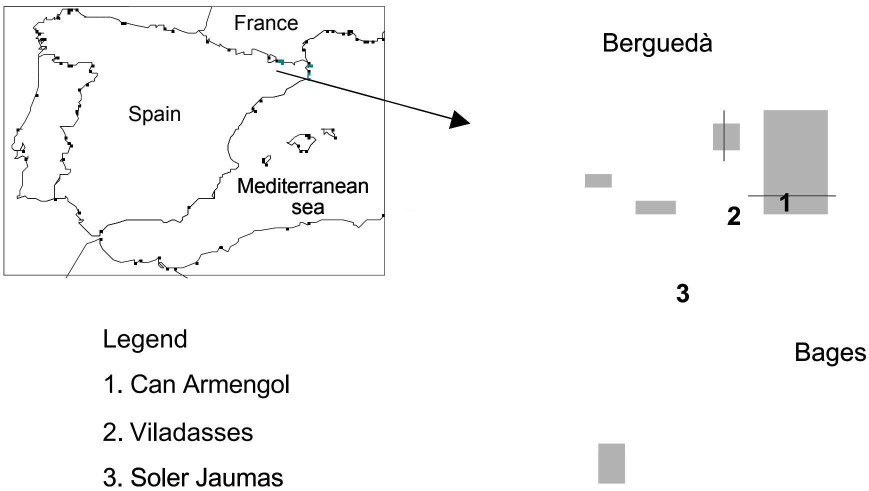


Figure 1. Geographical location of the sites sampled in this study along the area of Bages and Berguedà regions affected by the large wildfire of 1994.

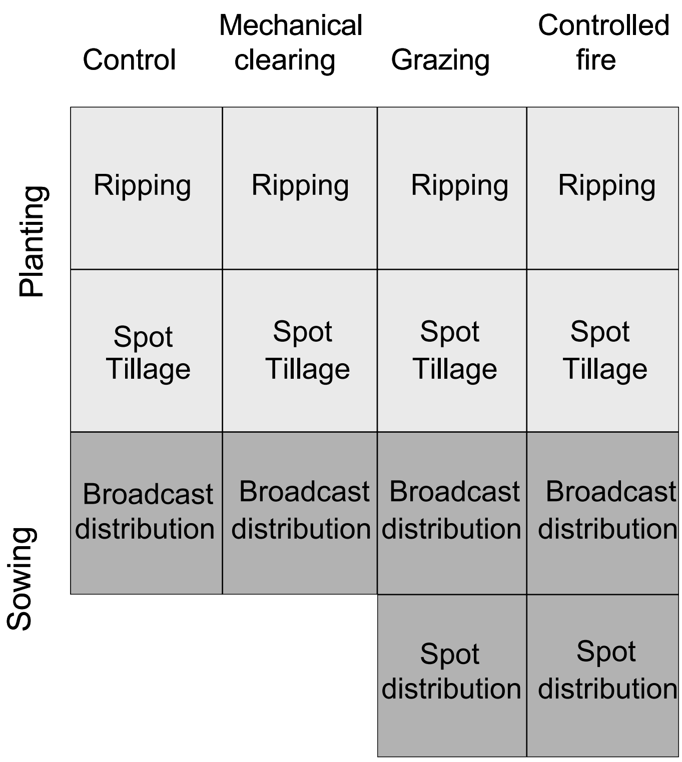


Figure 2. Experimental design carried out in each study area. The design evaluates the combined effects of four different methods of vegetation clearing (control, mechanical clearing, livestock grazing and controlled fire), two types of reforestation strategies (planting, seeding), two soil preparation techniques before planting (ripping, spot tillage), and two sowing methodologies (broadcast distribution and spot distribution).

- *Mechanical clearing* (hereafter MC). The vegetation of three plots per site was cleared by rolling chains pulled behind a tractor, that chopped and crushed all shrubs, leaving the debris scattered about the site.
- *Control* (hereafter C). The vegetation of three plots per site was kept intact and these plots were considered as control.

To evaluate the effect of these clearing treatments on the suppression of the vegetation measured before the fire (sampling 1), the same ten transects per plot of sampling 1 were monitored again after vegetation clearing in March 1999 (sampling 2), and one year later, in March 2000 (sampling 3). The increase (or decrease) in vegetation cover (or height) per transect between sampling 1 and 2 was the variable used to analyse the ability of the different clearing treatments to eliminate vegetation, while the increase (or decrease) per transect between sampling 1 and 3 was the variable that allowed us to evaluate the ability to suppress vegetation re-growth during a longer period of time. The variations of these variables with vegetation elimination treatment and zone were analysed by ANOVA models.

In the three experimental areas, the two reforestation methodologies contrasted consisted on plantation of (1+0) *P. nigra* seedlings (eight plots) and sowing of *P. nigra* seeds (six plots). In the eight plots were *P. nigra seedlings* were planted, two soil preparation methodologies were carried out for contrasting purposes (Figure 2):

- *Ripping* (hereafter, R). In four plots, each one with a different treatment of vegetation clearing, ploughing of planting lines where seedlings were afterwards planted, was carried out using a double teeth subsoiler mounted at the rear of a bulldozer, which opened two parallel rips of 70-90 cm depth.
- *Spot tillage* (hereafter, ST). In four plots, each one with a different treatment of vegetation clearing, seedlings were planted in small spots (40x40 cm) up to 50 cm depth. These spots were carried out with an excavator fitted with an articulating arm.

Initial seedling density planted per plot (1ha) was 1400 seedlings/ha regularly distributed. Survival of seedlings were checked one and two years after plantation, in six subplots of 25 seedlings (total 150 seedlings) per plot. Height growth of five seedlings per subplot was also monitored in the 6 subplots laid down per plot. Height growth of seedlings was established as the difference between their initial height (measured just after plantation) and their height at the end of the first and second year after the start of the experiment.

The effects of the vegetation clearing treatment, soil preparation, zone and time after plantation on seedling survival and seedling height growth were analysed by repeated-measures ANOVA models. Inspection of residuals was carried out to check for normality and homoscedasticity. The sequential Bonferroni method was employed to control the group-wide type

I error rate (Rice 1989). The individual values of the different levels of each variable were compared with a post-hoc test (Fisher's protected least significant difference).

Reforestation seeding involved two different methodologies to sow *P. nigra* seeds:

- Broadcast distribution treatment. A total of 0.5 kg of *P. nigra* seeds (c.f. 25000 seeds per ha) were broadcasted in the whole surface of each 1-ha plot. This treatment was applied in four plots per site, one per treatment of vegetation elimination.

- Spot distribution treatment In this case, 0.25 kg of *P. nigra* seeds were used per 1-ha plot. A total number of 1400-1500 small spots per ha were regularly distributed in each plot. In each spot, 6-8 seeds were sown. This treatment was only applied in two plots per site, one grazed by livestock and the another burned. We specifically applied this type of seedling under those two vegetation clearing methods, because they both do barely leave any debris above the soil, in contrast with the mechanical clearing or the uncleared (control) plots, and thus we wanted to compare the possible benefits of a broadcast or a spot seed distribution under those circumstances.

P. nigra seeds used in this part of the study were previously cleared by a mixture of water and 2% lye during 2 min and imbibed in water during 4 hours. To avoid or minimize predation after sowing by birds and small rodents, seeds were lightly dusted with two commercial and widely used repellents (Morkit ® and Mesurol ®)

Since plots for all combinations of vegetation elimination treatment x seeding methodologies were not present in the field design, we were forced to carry out two different complementary ANOVA analysis instead of the complete design: a one-way ANOVA of the effect of the four vegetation elimination treatments on seedling establishment for the broadcast distribution treatment, and a two-way ANOVA of the effect of the two seed distribution treatments and two of the vegetation elimination treatments (grazed and burned plots) on seedling establishment. In both cases, seedling establishment (density of seedlings per ha) was log-transformed.

To asses a possible negative ecological impact of the treatments applied, the dynamics of the community of small mammals were evaluated. We selected this animal group as it can be considered highly sensitive to the treatments used to clear vegetation and prepare soil for planting (Barrett & Peles, 1999). Five surveys were carried out from November 1998 (before the experimental treatments) to January 2000. Two tramping transects were placed in each plot. Each transect was composed of 7 Sherman traps at a distance of 10 m one each other. Captures included two consecutive nights revised every 12 h to minimise trap mortality) to obtain an animal abundance index (number of animals caught per trap and night) in each plot (according to Jones et al. 1996). The total effort applied was 1680 trap-nights and animals captured were 514 of one insectivorous species (O. Insectivora) and four rodent species (O. Rodentia): Greater White-Toothed Shrew (*Crocidura russula*), Woodmouse (*Apodemus sylvaticus*), House Mouse (*Mus musculus*), Algerian Mouse (*Mus spretus*) and Garden Dormouse (*Eliomys quercinus*). Two variables were used for describing the community of small mammals in each plot: Total density (i.e., the total number of animals captured per plot and survey), and small mammal diversity (computed as the Shannon diversity index: $H = -\sum(p_i \cdot \ln p_i$, where p_i is the proportion of animals of the i^{th} species in traps during the period of time considered). In our study we only used those final results but more information on the effects of the different reforestation methods on the dynamics of the community of small mammals are described in Comas et al. (in prep.).

Multicriterial analysis of the different reforestation practices

The evaluation of the benefits and advantages of the different reforestation alternatives was undertaken through a multicriteria analysis taking into account not only the success of the practices in terms of survival and growth of *P. nigra* seedlings, but including their economic cost and an estimation of their ecological impact. This analysis was done with the NAIDAE (New Approach to Imprecise Assessment and Decision Environments) method (Munda, 1995). NAIADE is a multicriteria evaluation method which performs the comparison of alternatives on the basis of a set of criteria. It allows the use of information affected by different types and degrees of uncertainty, thus the values assigned to the criteria for each alternative may be expressed in the form of either crisp, stochastic, fuzzy numbers or linguistic expressions. This is a discrete method (the set of alternatives is finite) that does not use traditional weighting criteria and that generates a ranking of alternatives using a pairwise comparison technique (JRC-Ispra site, 1996). NAIADE multicriteria analysis is based on a comparison algorithm made up by the following steps (see, Munda 1995, Froger and Munda 1998, for further details on the NAIADE method):

1) Completion of the criteria/alternatives matrix.
2) Pairwise comparison of alternatives using preference relations.
3) Calculation of an aggregation algorithm of the credibility indexes leading to a preference intensity index of one alternative with respect to another.
4) Ranking of alternatives based on the preference intensity indexes.

In this multicriteria analysis we only tested the different planting alternatives (8 possible combinations of vegetation cleaning and plantation), but excluded the seeding treatments, as their large failure of seedling establishment (see, Results) made them worthless comparable.

To run the multicriteria analysis of the different plantation practices conducted in our experiment, we used seven different criteria, mixing both economical and ecological data sets:

1- *Economic cost*: monetary cost of the different combinations of vegetation clearing, soil preparation and plantation methods conducted, computed during the different phases of treatment application.
2- *Reduction of vegetation cover:* percentage of reduction of vegetation cover at the end of the experiment by means of the different clearing techniques employed.
3- *Reduction of vegetation height*: percentage of reduction of vegetation height at the end of the experiment by means of the different clearing techniques employed.
4- *Survival of P. nigra seedlings*: density of *P. nigra* seedlings surviving at the end of the experiment (two years after plantation).
5- *Height growth of P. nigra seedlings*: absolute mean height growth of *P. nigra* seedlings between the start and the end of the experiment (two years after plantation).
6- *Diversity of small mammals*: computed as the Shannon diversity index per plot at the end of the two years study, see above.
7- Density of small mammals: Abundance of small mammals captured per plot at the end of the experiment

The set of criteria used in the multiple comparison had clearly a different form: economic cost was a numerical criteria, while vegetation cover reduction, *P. nigra* survival and *P. nigra* growth were used as fuzzy criteria because there were interactions among the different factors analysed (vegetation cleaning, soil preparation and zone, see below). Thus, we integrated this variability assigning to each alternative cell the observed value but including a fuzzy function determined by this value and the maximum range of variability observed. On the other hand, reduction of vegetation height could simply be considered a numerical criteria as no interaction was observed among the different experimental factors. For these six criteria, we estimated the thresholds defining *indifference*, *slight indifference*, *slight preference* and *high preference* according to our previous experience and enquires with landowners and governmental departments in charge of restoration programs. As it was impossible to define realistically such thresholds for diversity and density of small mammals, we used a linguistic expression to define its outcome (an advantage of the NAIDADE method). In the frame of the comparison of alternatives, economic costs were clearly considered a trend to minimize while, shrub cover and height reduction, survival and height growth of *P. nigra* seedlings, and the diversity and density of small mammals have been considered trends to maximize. See Table 1 for a summary on the form, thresholds and trends of the different criteria used in the analysis.

We run two different analysis, one including only the economic costs and survival of *P.nigra* seedlings and the second including the other variables, to check for potential differences between a more traditional analysis (only based on economic aspects) and an analysis including other environmental considerations. Each analysis included 10000 simulations with a minimum requirement for fuzzy variables (α=0.4).

Table 1. Expression, trend, unit and thresholds of indifference (μ ==), slight indifference (μ =), slight preference/rejection (μ <& μ>) and preference/rejection (μ <<& μ>>) for the criteria used in the multicriteria analysis. Note that preference or rejection will depend upon the trend of the criteria (respectively, maximize or minimize). Threshold values arise from personal experience and discussion with landowners and governmental technical services. Num. = number of seedlings.

Criteria	Expression	Trend	Unit	μ ==	μ =	μ <& μ>	μ <<& μ>>
Economic cost	Numeric	Minimize	Euro	60	90	105	120
Reduction shrub cover	Fuzzy	Maximize	%	10	15	20	25
Reduction shrub height	Numeric	Maximize	%	10	20	30	40
Survival of *P. nigra*	Fuzzy	Maximize	Num.	70	140	175	210
Height growth of *P. nigra*	Fuzzy	Maximize	$cm.yr^{-1}$	2	4	6	8
Diversity small mammals	Linguistic	Maximize	---	---	---	---	---
Density small mammals	Linguistic	Maximize	---	---	---	---	---

Results

Vegetation clearing

The different treatments to clear vegetation showed significant differences in the reduction of vegetation cover and height (Table 2). The highest reduction in vegetation cover was obtained with the controlled burning treatment, while the highest reduction in vegetation height was obtained with the mechanical clearing (Figure 3). The reduction in vegetation

Table 2. F values from ANOVA tests of effects of vegetation clearing treatment, zone and plot (nested within plot) on the decrease of vegetation cover and height per transect just after the elimination treatment (grazing, fire and mechanical clearing). Significant coefficients (at _=0.05 after applying the sequential Bonferroni method) are indicated in bold.

Factor	df	Vegetation cover	Vegetation height
Vegetation clearing (VC)	2	**119.3**	**52.7**
Zone (Z)	2	**8.3**	1.6
VC x Z	4	2.1	**3.8**
Plot (Zone)	3	**7.1**	1.6

cover (but not height) varied with zone (this reduction was higher in Viladasses -41%- and Can Armengol -39%- than in Soler de Jaumas -33%-). The interaction between vegetation clearing treatment and zone was also significant for vegetation height, because differences in height reduction among zones were higher for the mechanical clearing treatment than for the other two.

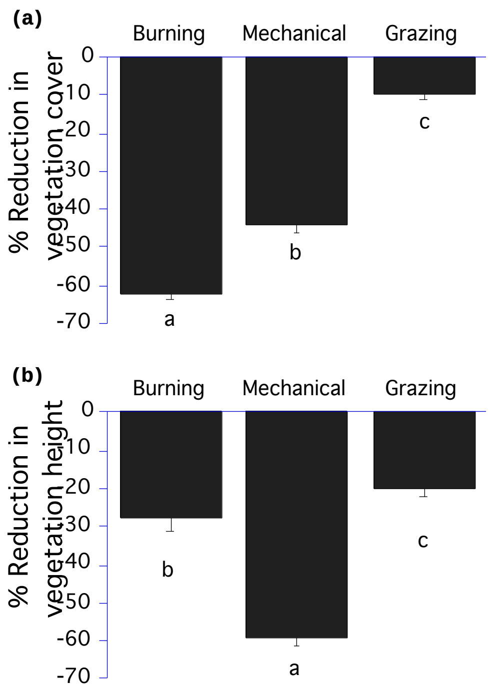


Figure 3. Reduction of (a) vegetation cover, and (b) vegetation height after the three treatments used to eliminate vegetation in the study zones. Vertical bars extend over +1 SE of the mean. Different letters indicate significant differences among treatments according to the Fisher PSLD post-hoc test.

One year after vegetation clearing, there were significant differences in vegetation recovery among experimental treatments (Table 3): the grazing treatment showed the lowest reduction in vegetation cover, and even an increase in vegetation height, in both cases higher than control plots, while plots where the mechanical clearing and burning treatments were applied showed the highest reduction compared to the initial situation (Figure 4). Zone and the interaction between zone and clearing treatment were significant for vegetation cover, because vegetation recovery for the burning treatment was higher in Can Armengol than in the other two zones, while very small differences among zones were found for the other treatments.

Table 3. F values from ANOVA tests of effects of vegetation clearing treatment (grazing, fire, mechanical clearing and control), zone and plot (nested within plot) on the decrease of vegetation cover and height per transect one year after the elimination of vegetation. Significant coefficients (at _ =0.05 after applying the sequential Bonferroni method) are indicated in bold. Data of vegetation height were log-transformed.

Factor	df	Vegetation cover	Vegetation height
Vegetation clearing (VC)	2	**7.5**	**9.9**
Zone (Z)	2	**11.0**	1.1
VC x Z	4	**3.3**	0.9
Plot (Zone)	3	**8.6**	0.2

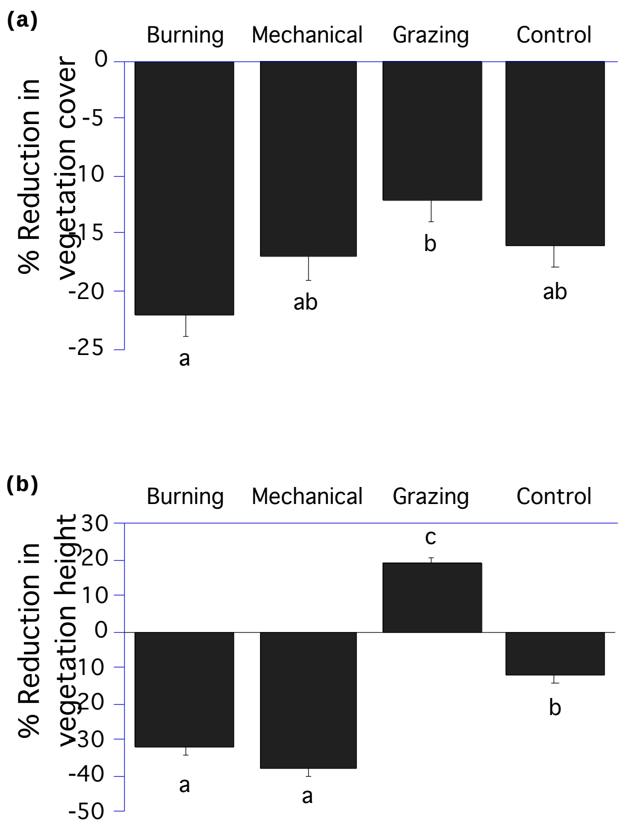


Figure 4. Increment (or reduction) of (a) vegetation cover, and (b) vegetation height one year after the elimination of vegetation by the four treatments used in the study zones. Vertical bars extend over +1 SE of the mean. Different letters indicate significant differences among treatments according to the Fisher PSLD post-hoc test.

Seedling survival and height growth in the plantation plots

All factors and most of their interactions affected seedling survival (Table 4). Thus, seedling survival was higher in plots where vegetation had been eliminated by mechanical clearing (% seedling survival±SE: 57.0±1.5%) and in control plots (55.7±1.4%), than in grazed plots (52.1±1.2%) and burned plots (50.0±1.3%). Moreover, seedling survival was higher in plots where seedlings were planted after ripping (57.0±0.9%) than in those where seedlings were planted in spots (50.3±1.0%), and was also different in the three zones included in the study. However, most of the interactions between these factors were also significant. Thus, seedling survival was higher in the ripper treatment than in the spot tillage one for all vegetation clearing treatments except the control one (Figure 5). In the control treatment there were also different

Table 4. F values from ANOVA tests of effects of vegetation clearing treatment, soil preparation treatment, zone and year after plantation (1999 and 2000) on seedling survival and seedling height growth. Significant coefficients (at _ =0.05 after applying the sequential Bonferroni method) are indicated in bold.

Factor	df	Seedling survival	Seedling height growth
Vegetation clearing (VC)	3	**7.7**	**6.0**
Soil preparation (SP)	1	**32.4**	**9.0**
Zone (Z)	2	**228.2**	**6.3**
Year after plantation (Y)	1	**1101.1**	**8.2**
VC x SP	3	**33.7**	0.1
VC x Z	6	**16.3**	2.8
SP x Z	2	**15.9**	1.7
VC x Y	3	**12.2**	0.6
SP x Y	1	1.9	4.7
Z x Y	2	**52.4**	3.4
VC x SP x Z	6	**21.8**	1.3
VC x SP x Y	3	**16.3**	3.8
VC x Z x Y	6	**7.7**	0.9
SP x Z x Y	2	**11.1**	0.1
VC x SP x Z x Y	6	2.1	0.4

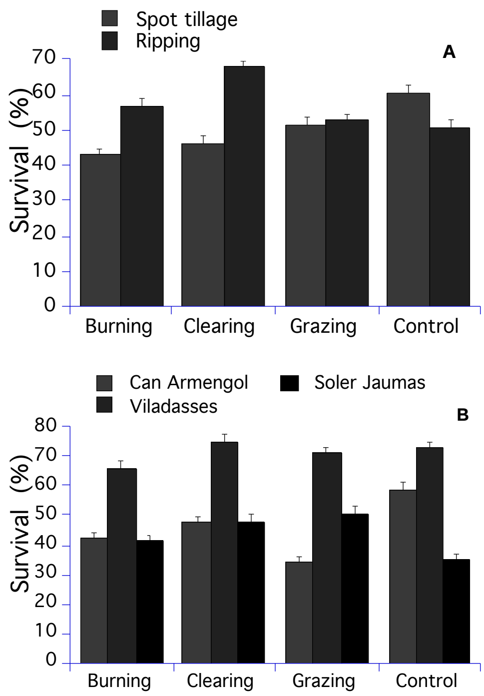
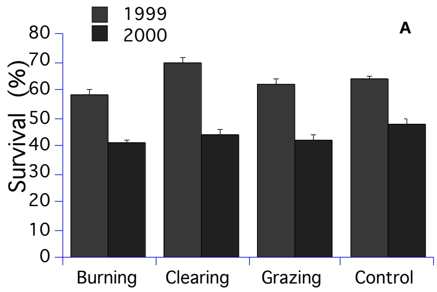


Figure 5. Variations in seedling survival in plots where vegetation had been eliminated by the different treatments according to (a) the soil preparation methodology used, and (b) the study zone considered. Vertical bars extend over +1 SE of the mean

patterns in the three study zones (Figure 5). The three zones also showed significant differences for the two soil preparation treatments, because survival was higher in the ripping treatment than in spot tillaged plots in Soler de Jaumas, while differences in the other two zones were much smaller. Seedling survival decreased from 63.6±0.9% in 1999 to 43.7±1.0% in 2000, although this factor also showed significant interactions with the other three. Thus, the highest survival was found in the mechanical clearing treatment in the first year, and in the control treatment in the second (Figure 6). There was also a lower survival in Soler de Jaumas during the second year than in the other two zones (Figure 6). The significant interactions of higher order were of difficult interpretation.

Seedling height growth also varied for three of the main factors considered (Table 4). Seedling height growth was lower in plots where vegetation had been cleared by controlled burning (height growth±SE: 6.8±0.2 cm) than in the other three types (mechanical clearing plots: 7.5±0.2 cm; livestock grazed plots 8.1±0.2 cm; and control plots: 8.1±0.2 cm); it was also lower in plots where soil preparation was carried out through ripping (7.2±0.1 cm) than in those where spot tillage was done (8.1±0.2 cm), and was also different in the three zones included in the study. There were also significant differences between years (year 1999: 7.4±0.1 cm; year 2000: 7.8±0.2 cm). The interactions between all these factors were not significant (Table 4).



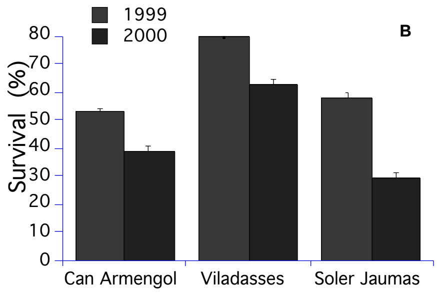


Figure 6. Variations in seedling survival in the two years of study according to (a) the treatment of vegetation elimination applied, and (b) the study zone considered. Vertical bars extend over +1 SE of the mean.

Seedling density in the sowing plots

No significant differences were found among plots with different type of vegetation clearing (two-way ANOVA, p=0.41), among zones (p=0.15) or for the interaction between both factors (p=0.92) for the broadcast sowing treatment. In these plots, seedling establishment was very low (range: 0-200 seedlings/ha). Similar results were found for the comparison between the two types of seed distribution in plots with different type of vegetation clearing: no differences were found between seed distribution types (three-way ANOVA, p=0.10; broadcast distribution: 7±4 seedlings/ha; spot distribution: 80±36 seedlings/ha), vegetation clearing treatments (p=0.18) or zones (p=0.12). None of the interactions between these variables was significant (p>0.50 in all cases).

Multicriteria analysis of the different reforestation practices

Table 5 shows the alternative x criteria matrix for the NAIDAE comparison of the different reforestation methods assayed in this study.

The first comparison and ranking of alternatives according to their economic cost and survival of *P. nigra* seedlings (Figure 7) indicated the alternative of preserving vegetation (control) and ripping (C+R) as the best one, while mechanical clearing and spot tillage (M+S) produced the worst score. Both separate rankings based on the better and much better relations (_+) and in the

Table 5. Alternative x criteria matrix used to compare the different reforestation methods essayed in the study. Numbers preceded by the symbol (a = approximately) are those of fuzzy criteria. In that case the value of the cell is the value observed in that alternative, but due to the existence of interaction with other factors (e.g. zone) it is presumed to vary according to a function shaped by this value and the minimum and maximum observed. G= livestock grazing, B=controlled burning, M=mechanical clearing, C=Control, R=ripping, S=spot tillage.

	G+R	G+S	B+R	B+S	M+R	M+S	C+R	C+S
Economic cost	1020	1500	1200	1680	1320	1800	1020	1500
Reduction shrub cover	a12	a18	a22	a22	a18	a18	a16	a16
Reduction shrub height	0	0	50	50	60	60	30	30
Survival of *P. nigra*	a560	a630	a644	a490	a798	a434	a602	a728
Growth height of *P. nigra*	a17	a18	a16	a17	a18	a20	a18	a19
Diversity small mammals	± Good	± Good	± Bad	± Bad	Bad	Bad	± Good	± Good
Density small mammals	Good	Good	± Bad	± Bad	Moderate	Moderate	Good	Good

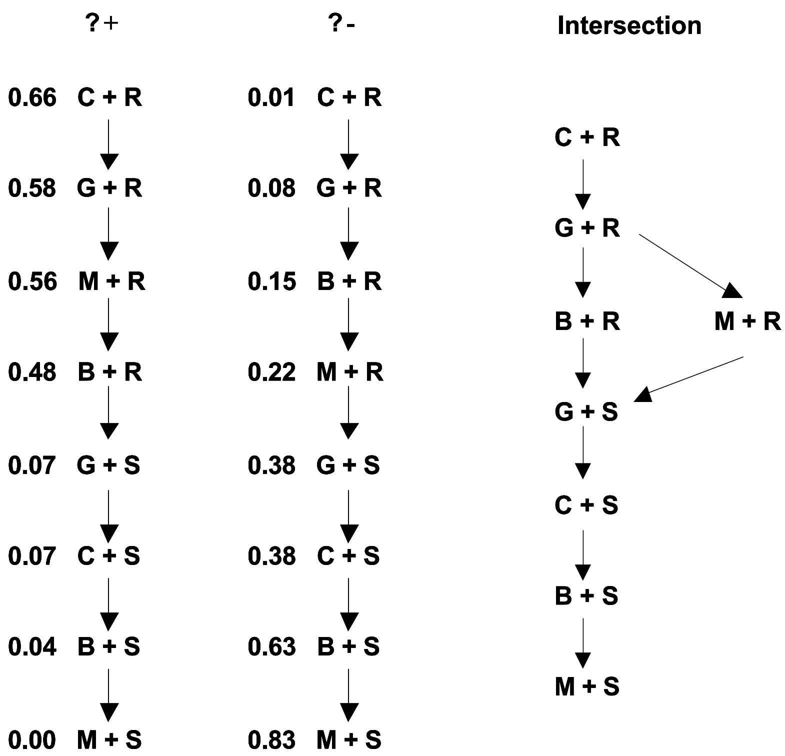


Figure 7. Ranking of alternatives according to their economic cost and survival of *Pinus nigra* seedlings. _+ = ranking based on the better and much better relations (values range from 0 to 1, indicating how an alternative is better than the rest), _- = ranking based on the worse and much worse relations (values range from 0 to 1, indicating how an alternative is worse than the rest). Intersection = Intersection of _+ and _

worse and much worse preference relations (_-) produced a similar ordination of alternatives, except for the alternatives of burning and ripping (B+R) and mechanical clearing and ripping (M+R) which appeared in a reverse order in the two rankings (Figure 7). The intersection of both rankings produced an ordination where the four most preferred alternatives were those where soil preparation was made by ripping (C+R, G+R, B+R and M+R), while the less preferred were those with spot tillage as soil preparation methodology (C+S, G+S, B+S and M+S). Due to their reverse position in the _+ and _- rankings alternatives, B+R and M+R appeared as incomparable. Since survival of *P. nigra* seedlings was relatively similar in all treatments, this ordination reflected largely the paramount importance of economic differences among treatments of ripping (cheaper) and those where spot tillage was carried out (much more expensive). Inside each group of soil preparation techniques, treatments including no cost in the vegetation clearing process (control and livestock grazing) were preferred over those (controlled burning or mechanical clearing) where vegetation clearing involved high economic expenses (Figure 7).

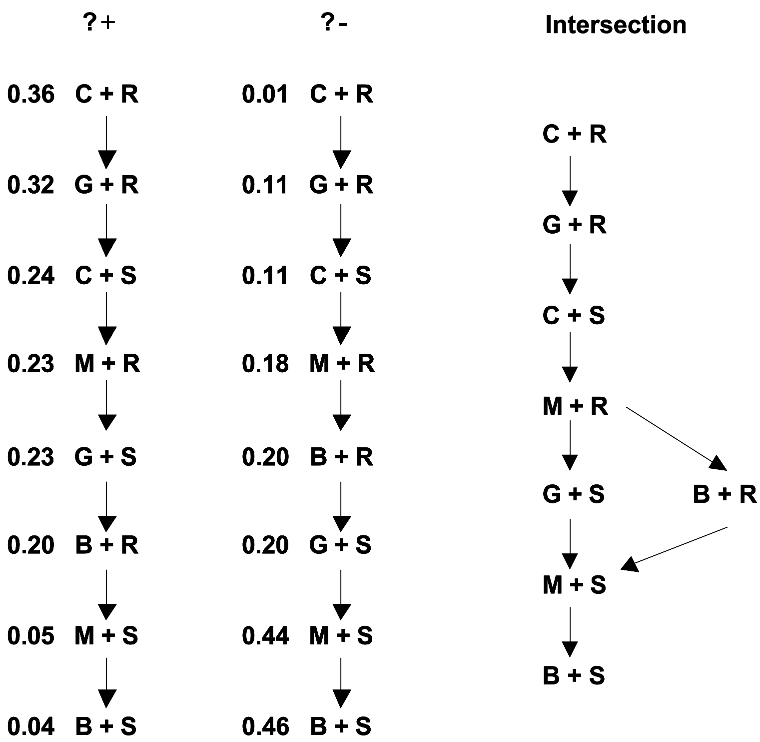


Figure 8. Ranking of alternatives according to their economic cost, survival and height growth of *Pinus nigra* seedlings, shrub cover and height reduction, impact on the diversity and density of the community of small mammals. _+ = ranking based on the better and much better relations (values range from 0 to 1, indicating how an alternative is better than the rest), _- = ranking based on the worse and much worse relations (values range from 0 to 1, indicating how an alternative is worse than the rest). Intersection = Intersection of _+ and _-

The second analysis, which included the comparison and ranking of alternatives considering other ecological criteria together with economic costs and *P. nigra* survival, produced a ordination with similarities with the first analysis but with slight differences (Figure 8). These differences were mostly due to the impact of the type of vegetation clearing on the community of small mammals. The two most preferred alternatives continued to be C+R and G+R because, for a similar shrub control and *P. nigra* survival and growth, their vegetation clearing method had a lower impact on the community of small mammals and ripping was the cheapest soil preparation method (see Table 5). On the other hand, the two less preferred alternatives continued to be B+S and M+S (see Table 5). The other alternatives remained in the middle of the ranking, although the C+S treatment obtained the third position (in spite of its higher cost it was less aggressive over small mammal populations), while alternatives including burning or mechanical clearing and ripping obtained a worst classification, as soil preparation was cheaper but the type vegetation clearing diminished small mammals diversity and density.

Discussion

In most Mediterranean countries, reforestation has been the most widespread large-scale restoration practice aimed to reduce desertification processes as well as following extensive wildfires events (Cortina & Vallejo 1999). Reforestation through seeding was the commonest way to restore pine forests till the middle seventies, when increased possibilities of mechanical site preparation as well as improved seedling quality and higher guarantees of success leaded a shift towards plantation practices (Castell & Castelló 1996; Vallejo et al. 2000). Notwithstanding, in the last years the need to reforest extensive burned areas has renewed the interest about comparing different seeding and planting strategies: the former as a low cost and large scale technique to quickly reforest large areas, in contrast with the latter, more expensive, time consuming, but rather successful (Moreno & Vallejo 1999).

In our study, the comparison of the final establishment of *P. nigra* seedlings two years after the experiment onset, ranged drastically from 7±4 seedlings/ha in the broadcast seeding treatments to 610±40 seedlings/ha in the plantation assays. Establishment of *P. nigra* seedlings in the seeding treatments was much lower than the only comparable experience we know in Catalonia; results obtained by Castell & Castelló (1996) in an aerial seeding experience with *P. halepensis* (830 - 7200 seedlings/ha) after the Garraf (Barcelona, NE Spain) 1994 wildfire. Apart from the differences among the germination rates in both species (Habrouk et al. 1999), the disagreement observed may be attributed to various sources. The reported aerial seeding was conducted immediately after the fire event in an area free of plant cover and competence, and mainly consisting of old culture terraces. This treatment was followed by a mild-wet summer and rainy autumn (Castell & Castelló 1996). On the other hand, we seeded 4 years after the fire event, once ground vegetation have achieved a cover ranging from 77% to 91% (see Material and Methods), in thinner soil layered slopes and, in this case, seeding was followed by an unusual dry summer and autumn. This high variability in edaphic and climatic conditions has been commonly reported to be the major cause of disappointing results concerning seeding treatments in Mediterranean environments (Cortina & Vallejo 1999). Moreover, although seeds of *P. nigra* were dusted with bird and rodent repellents, we observed a huge predation by granivorous ants (*Messor* spp.), which had already massively colonised the zone (pers.obs). The failure of the broadcast seeding assay points out that although it may be recommended to wait a precautionary time to observe whether natural regeneration occurs after a wildfire event (Espelta 1999), the fast recovery of ground vegetation, as well as some animal groups, severely threatens the success of broadcast seeding treatments. In that sense, other seeding experiences with *P.nigra* conducted just after a close wildfire event (in the Solsonés area in 1998), where broadcast seeding was coupled to soil raking by the removal of burned trees, revealed a much more successful establishment (241±59 seedlings/ha) (unpublished results). According to those results, seeding practices to restore *P. nigra* forests, in spite of its low cost, should be considered only in a palliative scope and carried out immediately after the fire event (see also Molina et al. 1989).

The establishment of seedlings of *P.nigra* in the plantation experiences was low in comparison to the success of plantations reported in temperate and boreal forests (Archibold et al. 2000; Gemmel et al. 1996; Russell et al. 1989), but fall in the range of other experiences carried out in Mediterranean environments (Vallejo & Alloza 1998), where the transplant-shock to a very harsh environment and the following chronic water stress usually causes low survival rates (Mesón & Montoya 1994). Mortality linked to the early post-transplant moment is specially acute in Mediterranean environments, because of the poor ability of the root system of the new established seedlings to replace water lost through transpiration (Baeza et al. 1991; Sachs et a. 1994). In that sense, plantation projects do even commonly expect an early 20% of mortality just after transplanting (Serrada 1993; Peman & Navarro 1996). In addition, survival rates usually further decrease after the first summer drought (Vallejo et al. 2000). For these reasons, although global survival of *P. nigra* seedlings two years after our plantation experiences accounted roughly for 50% of the initial density (610 seedlings/ha), this result can be considered fairly promising. According to previous studies, progressive smoothening of mortality rates once pine seedlings have been successfully established would allow us to predict, from this initial medium density, that development of *P. nigra* forests in the area will be possible at a medium term scale (see Retana et al. in press).

Survival of *P. nigra* seedlings varied depending on the vegetation clearing and soil preparation treatments. Both controlled burning and mechanical clearing were the most effective methods to suppress ground vegetation in comparison to livestock grazing. Controlled burning was more effective than mechanical clearing, as the former could even eliminate the extensive herb layer composed by *Brachypodium retusum*, which escaped the rolling chains. On the other hand, mechanical clearing significantly reduced more than burning vegetation height, as the upper part of some shrubs was only partially burned. In contrast, livestock grazing presented the poorest score, and even the browsing carried out promoted a vigorous height re-growth of the herb and shrubby layer (see similar over-compensatory effects in Aguilar et al. 1996, or Paige &

Whitman 1987) In spite of these observed patterns, the effect of vegetation clearing on seedling survival showed a rather low impact, as survival after two years was quite similar in all plots, with slightly higher values in control plots (Figure 6A). The effects of vegetation clearing prior to plantation has been thoroughly documented, although contrasting results have arisen: some studies have pointed out beneficial effects for seedling performance throughout reducing competition (Nilsson et al. 1996; Weber et al. 1995), while others have stressed the advantages of a shrubby layer protecting young established seedlings (Jobidon et al. 1998). The lack of major effects of the vegetation clearing and even some better results in the non cleared plots in our study could be linked to two factors. In the one hand, the fast re-growth of the cleared vegetation through re-sprouting leaded all plots to present after two years a rather similar and high cover (more than 75%), vanishing initial differences among treatments (less than 10% at the end). Moreover, it is important to note, that in a harsh environment such as the Mediterranean climate, this ground vegetation could act as a shelter for young seedlings, protecting them from excessive solar radiation and water stress, and thus explaining the aforementioned high survival values in the control plots (see examples of this “nursery” effect in Callaway 1992, or Jobidon et al. 1998).

Notwithstanding this general trend, the type of vegetation clearing interacted with the soil preparation method. Linear ripping has been reported as an excellent way to ameliorate water availability and nutrient release for seedlings through retaining runoff in a vast area, increasing the total water stored in the profile and enhancing the possibilities of the root systems to penetrate and obtain water and nutrients (Varelides & Kritikis 1995; Querejeta et al. 2001). However, to capture run off losses it will be important to break soil crusts and obtain regular and deep plowing ripes in all the surface (Peman & Navarro 1996). In our study areas, ripping was much more easily and regularly conducted in plots where vegetation was previously burned or mechanically cleared, in comparison to the grazed or control areas, where shrubs obstructed ripping. In contrast, in those areas the punctual spot tillage carried out by the excavator produced deep and regular planting holes. We hypothesise that these differences in soil preparation, and their possible major effect on water availability, are responsible that in the burned and mechanically cleared plots seedling survival was higher in the rips, while no differences among soil preparation methods were observed in the grazed plots and even a slight advantage of the punctual planting holes method occurred in the control plots (Figure 5A).

The previous stated differences among reforestation alternatives give us a first insight about the best way to face recovery of extensively burned *P. nigra* forests. However, possible emerging recommendations turns over when considering differences in economic cost and ecological impact throughout the NAIADE multi-criteria analysis. Thus, the first analysis carried out including only economic and plantation performance terms, revealed the paramount importance of economic costs in restoration practices. In spite of statistically significant differences in the survival of *P. nigra* seedlings, the best ranked alternatives were those cheaper, based on soil preparation through ripping in contrast to those where spot tillage was performed. On the other hand, inside both groups the most preferred alternatives were those with no cost in the vegetation clearing process (control and livestock grazing). Notwithstanding this, it is important to note that although "economic values" and "biocentric values" have been predicted to fall at the opposite extremes when dealing with restoration problems (Jackson et al. 1995), the inclusion in a second analysis of the ecological impact criteria only produced minor changes in the reported rank. Soil preparation type decreased its weight in front of a major importance of the vegetation clearing strategy, due to the deleterious effects of two of those treatments (burning and mechanical clearing) on the diversity and abundance of the small mammals community. Thus, combination of a low economic cost and low ecological impact made control or grazed plots with soil preparation through ripping to be the top ranked ones while burning or mechanical cleared plots with spot tillage were the less preferred.

Restoration represents a long term dedication of natural resources and a substantial financial commitment (Ehrenfeld 2000). Moreover, practitioners need to know how to allocate this limited funding, labor and time for maximum effect in the design of restoration programs of large scale projects (Clewell & Rieger, 1997). In that framework, our study provides some valuable insights in the different ways to face recovery of extensively burned *P. nigra* forests in Mediterranean areas. Four years after the fire event, plantation rather than seeding arises as the most suitable afforestation practice, with the observed survival of the planted seedlings allowing us to predict the continuity of *P.nigra* forests in the area. Nevertheless, it appears that vegetation clearing prior to plantation, although a common sense practice extensively reported, involves a high economic cost and ecological impact in the conservation of some animal groups and does not fit the expected benefits in plantation performance. In that sense, the multi-criteria analysis carried out provides a valuable example that although restoration activities are inextricable embedded within an economic framework (Abivardi 1997), it is possible to reconcile such scope with ecological criteria (see Holl & Howarth 2000).

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Conclusiones Generales

Conclusiones

1. El estudio de la tolerancia de las semillas de tres de las especies de pinos más importante de la Cuenca Mediterránea, *P. halepensis, P. nigra* y *P. sylvestris*, a diferentes temperaturas y tiempos de la exposición muestra que el porcentaje de germinación decrece rápidamente al aumentar la temperatura y el tiempo de exposición, aunque varía entre especies, ya que las tasas de supervivencia son altas en *P. halepensis*, disminuyen en *P. nigra* y son aún menores en *P. sylvestris.*

2. En las tres especies se muestra el importante papel de las piñas como mecanismo de protección de las semillas, ya que el porcentaje de germinación es mucho mayor en las semillas sometidas al tratamiento térmico dentro de las piñas que en las semillas libres. Conjuntamente, estos resultados sugieren que la regeneración después del fuego en estas especies podría proceder del banco de suelo o del de copa, pero difícilmente de las semillas libres en superficie. Esto, junto con la diferente fenología de dispersión de las semillas, explica la mejor regeneración post-incendio de *P. halepensis* en comparación con *P. nigra* o *P. sylvestris.*

3. El estudio de campo de la regeneración post-incendio de estas tres especies en el área afectada por el gran incendio del Bages-Berguedà de 1994 muestra importantes diferencias entre ellas, ya que *P. halepensis* tiene una elevada regeneración, mientras que *P. nigra* y *P. sylvestris* prácticamente desaparecen después del incendio.

4. Mediante un modelo sucesional se han establecido los cambios en la composición del bosque 30 años después del fuego a partir de la regeneración justo después del fuego. Las simulaciones indican que casi tres cuartas partes de las parcelas de *P. halepensis* se mantienen como tales después del fuego y que, en cambio, los bosques de las otras dos especies desaparecen como tales después del fuego, y pasan a ser comunidades dominadas por robles y encinas o, en menor medida, matorrales.

5. La comparación de la respuesta al pastoreo de los individuos rebrotados de dos *Quercus* mediterráneos, *Q. ilex* (especie perenne) y *Q. cerrioides* (especie caducifolia), que coexisten en las áreas afectadas por el gran incendio del Bages-Berguedà, indica que, a nivel de mortalidad, no hay diferencias entre ambas especies. Los efectos negativos del pastoreo sobre el crecimiento son mayores en *Q. cerrioides* que en *Q. ilex*, tanto cuando el pastoreo se inicia justo después del incendio como si lo hace varios años después.

6. En el experimento de simulación de pastoreo, las diferencias en crecimiento entre estaciones son considerables: los individuos pastoreados al final del invierno muestran menor crecimiento relativo en altura y proyección de copa que los pastoreados en las otras estaciones. Las diferencias entre especies en las diferentes épocas del año son escasas.

7. Los patrones de regeneración de ambas especies en rodales quemados de diferente calidad de estación muestran que *Q. cerrioides* y *Q. ilex* rebrotan vigorosamente después del fuego, pero de manera distinta: *Q. ilex* produce mayor número de rebrotes que *Q. cerrioides*, mientras que *Q. cerrioides* alcanza mayor crecimiento en altura, proyección de copa y diámetro basal en rodales de elevada calidad de estación, aunque no en rodales de baja calidad, donde las dos especies muestran un tamaño similar.

8. La comparación de los resultados obtenidos con los diferentes tratamientos de selección y poda de rebrotes ensayados muestra que estas prácticas hacen aumentar el crecimiento absoluto y relativo en altura y diámetro de los rebrotes dominantes reservados de ambas especies. Así, los individuos con un único rebrote reservado muestran mayor crecimiento que los que tienen tres rebrotes, que a su vez crecen más que los controles. La poda hace aumentar la proyección de copa de los individuos podados, pero no su altura o diámetro basal.

9. El número medio de nuevos rebrotes producidos después de la selección es mucho mayor en *Q. ilex* que en *Q. cerrioides,* aumentando también en los individuos en los que se reserva un único rebrote dominante frente a los que se reservan tres. Estos resultados sugieren que esta última estrategia más conservadora puede ser más adecuada, pues muestra un incremento de crecimiento parecido al de la más intensa pero reduce el crecimiento de los nuevos rebrotes.

10. Los malos resultados obtenidos en los experimentos de siembra con *P. nigra* desaconsejan el uso de esta práctica para la recuperación de los bosques de esta especie, cuatro años después del incendio de 1994. Por el contrario, la supervivencia observada en las distintas plantaciones realizadas, aunque moderada, permite predecir a medio plazo la instalación de una cubierta arbolada de *P. nigra*.

11. Los diferentes tratamientos de eliminación de la vegetación preexistente así como de preparación del suelo afectaron significativamente la supervivencia de las plántulas de *P. nigra.* La interacción entre ambos factores ha señalado como más aconsejable los subsolados en terrenos en que previamente la vegetación se ha eliminado

mecánicamente o bien mediante quema controlada, mientras que una preparación puntual del terreno aparece como más conveniente en las zonas sin desbrozar.

12. El análisis multicriterial de las alternativas de plantación ha revelado que, de acuerdo con criterios económicos y de protección de las comunidades de pequeños mamíferos y, dada la escasa relevancia de las diferencias en la supervivencia de las plantaciones, las alternativas más aconsejables son las de realizar un subsolado en zonas sin eliminar la vegetación preexistente o controlarla mediante un pastoreo moderado, y las menos aconsejables las que incluyen una preparación puntual del terreno y la eliminación de la vegetación mecánicamente o mediante una quema controlada.