Available online at www.sciencedirect.com
ScienceDirect
Forest Ecology and Management 255 (2008) 3322–3330
Forest Ecology and Management
www.elsevier.com/locate/foreco

Effects of silvicultural treatments on forest biodiversity indicators in the Mediterranean

Olga Torras [a], Santiago Saura [a,b,*]

[a] Department of Agroforestry Engineering, ETSEA, University of Lleida, Av. Alcalde Rovira Roure, 191, 25198 Lleida, Spain
[b] Forest Technology Centre of Catalonia, C/ Pujada del Seminari s/n, 25280 Solsona, Spain

Received 15 October 2007; received in revised form 11 February 2008; accepted 11 February 2008

Abstract

Biodiversity maintenance is a key management objective and a requisite for sustainable forestry. Research efforts on the effects of forest management on biological diversity are therefore increasingly needed, particularly in regions such as the Mediterranean that have been comparatively less studied in this respect. We analysed the effects of different regeneration and stand improvement treatments on six forest biodiversity indicators (snags, mature trees, shrub abundance, shrub species richness, tree species richness and tree species diversity) in the Mediterranean region of Catalonia (NE Spain) by analysing a set of 9808 plots from the Third Spanish National Forest Inventory comprising both managed and unmanaged stands.

Managed stands had significantly fewer large-diameter trees (with the exception of *Quercus suber* forests) and snags than unmanaged ones. While clearcutting decreased tree species richness, stands with selection cutting had higher shrub and tree species richness and tree species diversity, which is consistent with the intermediate disturbance hypothesis, which states that diversity is highest at intermediate disturbance levels. Stand improvement treatments increased the number of large-diameter trees, tree species richness and diversity (cleaning and thinning), and shrub species richness (pruning), while no significant negative effect was found for any of the other indicators.

Our results suggest that preventing silvicultural disturbances may not be the best solution for conserving and enhancing biodiversity in the Mediterranean forests of Catalonia, where many stands have high tree density that impedes the establishment of a variety of plant species and the transition to more developed stages. Selection cutting may be an appropriate and sustainable regeneration treatment for Mediterranean forests in this respect, but their practical implementation should avoid the systematic harvesting of the highest quality and largest trees, which is still common in many private forests in Catalonia.

Keywords: Forest biodiversity; Biodiversity indicators; Sustainable forest management; Mediterranean forests; Silvicultural treatments; Stand improvement

1. Introduction

Biodiversity maintenance is a key management objective and a requisite for sustainable forestry and it is necessary to understand the dynamics and heterogeneity of natural forests to provide guidelines for management (Spies and Turner, 1999; Lindenmayer et al., 2000). It is also important for recognising the role of disturbances as integrated features of ecosystems (White, 1979). In this context, forest management treatments can be understood as disturbances that may have a large influence on the composition, structure and biodiversity of the forest (Niemelä, 1999; Bengtsson et al., 2000). Different species are more or less benefited by the changes in environmental conditions provided by the disturbances and different silvicultural treatments therefore lead to differences in species composition and distribution. For example, several early successional tree species which were not found in undisturbed forest were present in the harvest gaps analysed by Schumann et al. (2003) through a gap dynamics approach. In recent years, research about biodiversity in managed landscapes has been motivated by species declines and habitat loss (Halpern and Spies, 1995) and the use of management practices to emulate natural disturbances and dynamics has been explored in several studies (Hansen et al., 1991; Roberts and Gilliam, 1995; Niemelä, 1999; Bengtsson et al., 2000; Atlegrim and Sjöberg, 2004). Various fundamental differences between forestry operations and natural disturbances were reported by Niemelä (1999) for boreal forests, particularly the periodicity

* Corresponding author. Tel.: +34 973 70 28 77; fax: +34 973 70 26 73.
E-mail address: ssaura@eagrof.udl.cat (S. Saura).

0378-1127/$ – see front matter
doi:10.1016/j.foreco.2008.02.013

and spatial configuration of timber harvesting, residual organic matter, the frequency of fire and the use of exotic species in regeneration practices. At the same time, new harvesting practices based on natural forest dynamics have also been developed (Hansen et al., 1991). Consequently, the compatibility of timber production and biodiversity conservation is a critical challenge (Eriksson and Hammer, 2006), not only because of societal demands but also because human-managed ecosystems are critical for maintaining biodiversity (Pimentel et al., 1992). Recent studies have analysed the influence of harvesting strategies on biodiversity, suggesting alternatives to maintain biodiversity in managed forests. Deal (2007) suggests the use of light partial cutting as an alternative to increase both stand structural diversity and enhance biodiversity in old growth forests in Alaska. The cumulative landscape-scale effects of the management strategies of different land owners could also favour biodiversity as analysed by Gustafson et al. (2007).

The intermediate-disturbance hypothesis is a nonequilibrium model of diversity postulating that maximum diversity is provided by intermediate disturbance size, frequency and intensity (Roberts and Gilliam, 1995). Species diversity should increase with increasing levels of disturbance up to a point, after which diversity declines. Based on this hypothesis, several authors (Battles et al., 2001; Schumann et al., 2003) evaluated the effect of management practices with different intensities on species in various regions, concluding that intermediate disturbances favour species diversity. However, the response of biodiversity to silvicultural treatments is not well-studied in the Mediterranean region, which is considered a biodiversity hotspot and has been subjected to human impacts for centuries.

Our study aims to assess the effects of different silvicultural practices on forest biodiversity indicators in the Mediterranean region of Catalonia (NE Spain), considering the intensity of the silvicultural treatments through the amount of removed basal area. We performed an analysis at the stand level using a large data set based on thousands of inventory plots of the Third Spanish National Forest Inventory (3SNFI; Ministerio de Medio Ambiente, 1997–2007), which have increasingly incorporated different measures related to biodiversity and now contains a large amount of valuable information on the state of the tree and shrub species in the region. Specifically, the aim of this study is to analyse the effects of regeneration cuts and stand improvement treatments on six biodiversity indicators (snags, large-diameter trees, shrub abundance, shrub species richness, tree species richness and tree species diversity) obtained from the 3SNFI plots in Catalonia. These indicators were selected because they could be estimated from the information available in the 3SNFI and because they are widely used in the literature (Marrugan, 1989; Noss, 1990; Alberdi et al., 2005). We conducted two major analyses: (i) comparing indicators of biodiversity between managed and unmanaged stands, and (ii) evaluating the effects of each of the silvicultural treatments with different intensity on the biodiversity indicators, testing the hypothesis that the intermediate disturbances resulting from management increase Mediterranean forest diversity. We conclude by discussing implications for maintaining and enhancing biodiversity when managing Mediterranean forests.

2. Materials and methods

2.1. Study area

The study was performed in the Mediterranean region of Catalonia (NE Spain). This region has a high topographical and microclimate variability with the coastline of the Mediterranean Sea in the East and the Pyrenees Mountains in the North (Fig. 1). Conditions in the region have favoured great vegetation diversity and a high number of endemic species. Forests in the Mediterranean basin have been strongly transformed by human activity for centuries and no virgin forests remain in Catalonia. Currently, forests occupy about 38% of the territory, with an additional 23% occupied by other wooded lands, due mainly to complex topography that made difficult the agricultural and demographic expansion towards the mountains (Terradas et al., 2004). According to the 3SNFI (Ministerio de Medio Ambiente, 1997–2007), the dominant forest tree species in Catalonia are *Pinus halepensis*, *Pinus sylvestris*, *Quercus ilex*, *Pinus nigra, Pinus uncinata* and *Quercus suber*, followed by *Quercus pubescens*, *Fagus sylvatica*, *Pinus pinea*, *Quercus faginea*, *Quercus petraea*, *Abies alba*, *Pinus pinaster* and *Castanea sativa*.

Nearly 81% of the forested area is privately owned in Catalonia (Terradas et al., 2004). Most of these private forests are unmanaged and only about 25% of them have an updated management plan developed in accordance with the official regulations of the Catalan Government to promote sustainable forestry (see http://mediambient.gencat.net/cat/cpf/). This is a consequence of low economic return that most owners expect to get from the management of Mediterranean forests (Terradas et al., 2004), mainly due to the slow growth and low timber yields that are characteristic in this region. In recent years there has been a considerable increase in the number of managed forests resulting from subsidies and other initiatives from the Catalan Government.

2.2. Data source and analysis

The Third Spanish National Forest Inventory (3SNFI; Ministerio de Medio Ambiente, 1997–2007) gathered information from 12,234 field plots in Catalonia from July 2000 to August 2001, which was the data source both for the forest biodiversity indicators and for the type of management carried out in each of the field plots. 3SNFI plots are located according to a systematic sampling design in the intersections of the 1 km × 1 km UTM grid that fall inside forests and other woodlands, with an average sampling intensity of one plot per 1 km^2 of land. Plots in the 3SNFI are circular and concentric, with a variable size that depends on the tree diameter at breast height (DBH), with a plot radius of 5 m for trees with a DBH from 75 to 125 mm, of 10 m for trees with a DBH from 125 to 225 mm, of 15 m for trees with a DBH from 225 to 425 mm, and a radius of 25 m for trees with a DBH of at least 425 mm.

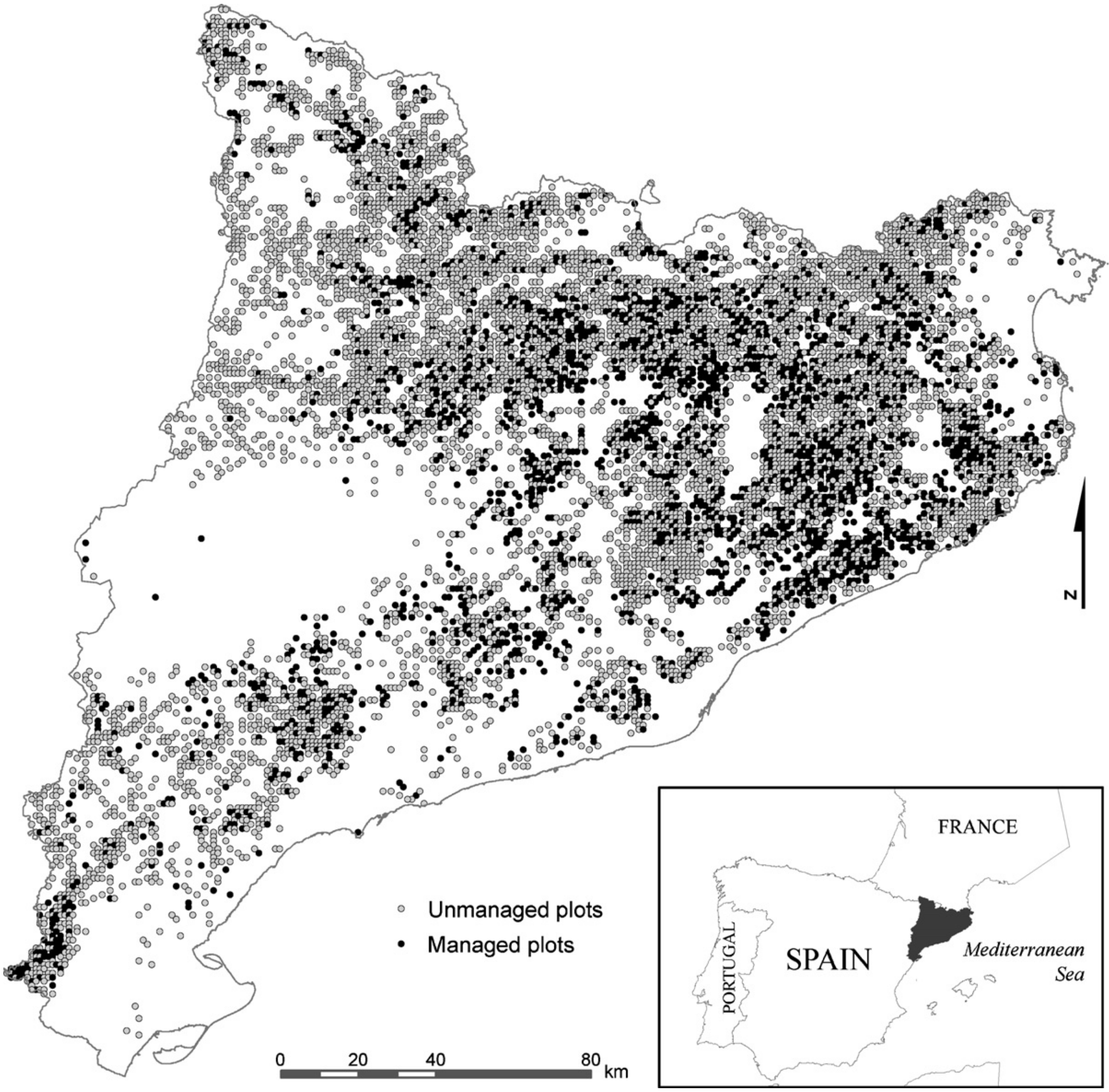

Fig. 1. Geographic location of Catalonia in the map of Spain (bottom right) and location of the 9808 plots of the Third Spanish National Forest Inventory used in the analysis, differentiating between managed and unmanaged plots.

We used only the plots where tally trees (DBH $\geq$ 75 mm) were inventoried (10,459 field plots) and discarded 288 plots in which the presence or absence of silvicultural treatments were not reported. We also excluded from the analysis 363 plots affected by forest fires that occurred between 1989 and 2000 in Catalonia according to the available official information of the Catalan Government (Department de Medi Ambient i Habitatge, 2007). We assumed that the effect of silvicultural treatments on biodiversity would be confounded with fire effects in these plots. The total number of 3SNFI inventory plots we analysed was 9808.

Six biodiversity indicators were obtained from the information of the 3SNFI plots. Only the tally trees were considered for the calculations. The indicators were calculated as (1) snags (stems/ha), (2) large-diameter (DBH > 500 mm) trees (stems/ha), as a surrogate for old-growth trees (Alberdi et al., 2005), (3) shrub species abundance, calculated by summing the abundance values of each of the shrub species present in each plot, where the abundance of a species was calculated as the product of shrub coverage (%) by height (dm), (4) shrub species richness, (5) tree species richness, and (6) tree species diversity, calculated using the Shannon index (Marrugan, 1989) based on the proportion of total basal area (m^2/ha) corresponding to each species and computed through a base e log transformation. We did not include indicators from the herbaceous layer because this information was not available in the 3SNFI plots, although we are aware of the importance of this layer in maintaining the structure and function of forests and recognise that the species diversity is highest in the herb layer among all forest strata (Roberts, 2004; Gilliam, 2007).

The 3SNFI reports the silvicultural treatments that have been performed in each of the plots, differentiating three regeneration methods (clearcutting, shelterwood, selection cutting) and four stand improvement treatments (cleaning, precommercial thinning, thinning and pruning). No soil improvement treatments were considered in this study. Most of the plots (about 73%) were unmanaged, resulting in 2616 plots in which at least one of the treatments was observed. 363 plots had both regeneration and stand improvement treatments, but these were analysed as regeneration plots because regeneration treatments have the largest influence on stand structure and diversity. The number of plots by treatment in the 3SNFI was: 81 with clearcutting, 12 with shelterwood, 1901 with selection cutting, 158 with cleaning, 67 with precommercial thinning, 283 with thinning and 114 with pruning. We estimated and ranked the intensity of each silvicultural treatment through the percentage of basal area removed in 8613 of the 3SNFI plots that had also been inventoried 10 years before in the Second Spanish National Forest Inventory (2SNFI). This percentage was calculated as the amount of basal area of those tally trees that had been inventoried in the 2SNFI but that were not present in the same permanent plots in the 3SNFI, divided by the total basal area of the stand. Although management is the main cause of tree removal from the forest, other natural disturbances different from forest fires (already excluded from the analyses) may also cause the natural mortality and loss of stems in the stands, and therefore forests without human disturbance may still lose basal area as calculated here.

To test for significant effects of forest management of different intensity on the biodiversity indicators, the mean values for the indicators on the plots with the different silvicultural treatments were contrasted with those corresponding to the unmanaged plots. Because the variables were not normally distributed, the Mann–Whitney non-parametric test was used to compare the averages. The test was performed both for all the plots (without differentiating by forest types, Table 1) and separately for the six most abundant forest types (pure stands where the dominant species provides at least 80% of total basal area) in Catalonia (Table 2). We did not perform the analysis separately for other less abundant forest types because the number of plots was too low for reporting significant differences.

3. Results

3.1. Managed versus unmanaged stands

Managed stands had significantly fewer snags and large-diameter trees than unmanaged ones (18% and 22% lower in managed stands, respectively) (Table 1). When we analysed the main forest types separately, the results were the same except for *Quercus suber* stands, where silvicultural treatments greatly increased the number of large-diameter trees (Table 2).

Managed stands in Catalonia had significantly higher values of shrub and tree species richness and tree species diversity than unmanaged ones (Tables 1 and 2). The difference was larger for tree species richness and diversity (7% and 13% higher in managed stands, respectively) than for shrub species richness (4% higher in managed stands) (Table 1). No significant effect of forest management on shrub abundance was observed when considering all the forest types together, although the mean value of this indicator was slightly lower in managed forests (Table 1).

The average removal of basal area in the managed stands in Catalonia was about 32%, more than 2.5 times larger than that caused by the loss of stems due to natural disturbances (forest fires excluded) and mortality in unmanaged stands (Table 1).

3.2. Regeneration cuts

Selection cuttings significantly increased shrub species richness, tree species richness and tree species diversity (Tables 1 and 2). The number of large-diameter trees and snags generally decreased when compared to unmanaged stands (Table 1), although an exception was found for *Quercus suber* forests (Table 2). Selection cuttings only had a significant effect on shrub abundance for certain forest types (Tables 1 and 2), increasing shrub abundance for *Quercus ilex* and *Pinus sylvestris* and decreasing shrub abundance for *Pinus uncinata* and *Quercus suber*.

Table 1
Average value of the biodiversity indicators and the removed basal area in the plots with different management practices

Silvicultural treatments	Number of plots	Removed basal area (%)	Biodiversity indicators					
			Snags (stems/ha)	Large-diameter trees (stems/ha)	Shrub abundance (canopy cover × height)	Shrub species richness (number of species)	Tree species richness (number of species)	Tree species diversity (Shannon index)
Unmanaged	7192	12.40	28.97	2.03	680.36	5.86	2.17	0.42
Managed (any treatment)	2616	32.05**	23.85**	1.58**	640.89	6.08**	2.31**	0.47**
Regeneration								
Clearcutting	81	64.19**	41.06	0.44	556.06	5.63	1.93*	0.38
Shelterwood	12	48.97**	5.01	0.00	435.83	5.67	1.75	0.39
Selection	1901	33.90**	22.60**	1.34**	644.31	6.10**	2.28**	0.46**
Stand improvement								
Cleaning	158	14.77**	26.72	3.87*	659.65	5.67	2.52**	0.54**
Pre-commercial thinning	67	33.97**	32.17	0.08**	525.57	5.76	2.21	0.43
Thinning	283	26.21**	29.27	2.91**	713.41	5.99	2.68**	0.57**
Pruning	114	11.81*	12.11	0.98	527.54	7.10**	2.05	0.39

Asterisks indicate mean values significantly different from those of the unmanaged plots ($^{*}p < 0.05$ and $^{**}p < 0.01$, Mann–Whitney test).

Table 2
Average value of the biodiversity indicators in the six most abundant forest types (pure stands with a basal area percentage for the dominant species of at least 80%) for unmanaged, managed plots (including any type of silvicultural treatment) and plots with selection cuttings

Species	Silvicultural treatments	Number of plots	Biodiversity indicators					
			Snags (stems/ha)	Large-diameter trees (stems/ha)	Shrub abundance (canopy cover x height)	Shrub species richness (number of species)	Tree species richness (number of species)	Tree species diversity (Shannon index)
Pinus halepensis	Unmanaged	1154	19.62	0.27	853.23	9.43	1.302	0.08
	Managed	349	16.56	0.19	751.13**	9.23	1.390**	0.10**
	Selection	275	16.40	0.20	780.35	9.26	1.411**	0.10**
Pinus sylvestris	Unmanaged	846	33.55	2.12	311.25	3.58	1.637	0.15
	Managed	340	29.23*	1.71*	345.45	4.22**	1.606	0.16
	Selection	282	31.11*	1.30**	368.60*	4.25**	1.574	0.15
Quercus ilex	Unmanaged	719	24.74	0.20	766.75	5.93	1.570	0.15
	Managed	146	13.61	0.14	734.08	6.00	1.856**	0.23**
	Selection	76	1.44*	0.27	924.88**	6.70*	2.026**	0.28**
Pinus nigra	Unmanaged	418	19.16	0.62	353.47	5.48	1.730	0.18
	Managed	217	30.61	0.89	382.75	5.68	1.770	0.21
	Selection	202	29.13	0.78	394.09	5.79	1.792	0.21
Pinus uncinata	Unmanaged	385	39.12	5.40	135.74	2.03	1.310	0.08
	Managed	95	45.01	2.89**	85.42**	1.68	1.368	0.11
	Selection	75	43.25	2.72**	89.37*	1.79	1.347	0.11
Quercus suber	Unmanaged	186	16.83	1.15	1753.74	7.18	1.688	0.17
	Managed	74	8.78	1.79*	1173.08*	7.00	1.878	0.22
	Selection	39	4.85	2.22*	1331.56*	7.31	1.846	0.23

Asterisks indicate mean values significantly different from those of the unmanaged plots (*$p < 0.05$ and **$p < 0.01$, Mann–Whitney test). Results for other silvicultural treatments are not included because there were too few plots to report significant differences.

Tree species richness was lower in clearcut stands than in the unmanaged ones, but no significant effects of clearcutting were found for the rest of the biodiversity indicators (Table 1). We did not find any significant effect for shelterwood treatments due to the small number of plots.

The maximum basal area removal occurred with clearcutting (about 64%), nearly double that of selection cuttings, and more than five times larger than the average of 12% caused by natural mortality and disturbances in unmanaged stands (Table 1).

3.3. Stand improvement treatments

Both cleaning and thinning showed statistically significant effects on the abundance of large-diameter trees, tree species richness and tree species diversity, with higher values of these biodiversity indicators in the treated stands compared to the unmanaged ones (Table 1). We also observed that pruning significantly favoured shrub species richness but not the other biodiversity indicators (Table 1). A low number of large-diameter trees was found in the stands with precommercial thinning (Table 1).

Both thinning and pre-commercial thinning were similar in intensity to selection cuttings, with about 30% removed basal area (Table 1). Cleaning and pruning, had percentages of removed basal area very similar to those of the unmanaged stands (Table 1).

4. Discussion

The low number of snags and large-diameter trees in managed stands reported here is expected under intensive timber production management, which precludes the existence of forests in advanced or decadent stages of development and negatively impacts the abundance of these elements that are considered critical for forest biodiversity (see McComb and Lindenmayer, 1999), as has been observed by numerous authors (Green and Peterken, 1997; Marage and Lemperiere, 2005; Rowland et al., 2005). Hansen et al. (1991) reported similar results for intensively managed forests in the Coastal Northwest United States, where they found a higher abundance of large trees and large snags in natural forests than in managed stands. The situation is different however in *Quercus suber* forests in Catalonia, where the main product and management objective is not timber but cork, with considerably longer rotations than those for timber production in other forest types, since the best quality cork comes from trees between 70 and 150 years of age (Saura and Piqué, 2006). In addition, managed stands of *Quercus suber* are much less dense than more natural stands, with a typical density for the former of about 300–350 stems per ha (Grañó and Martínez, 2001), which allows the adequate development of large-diameter trees and high quality cork.

Silvicultural treatments create gaps in the forest that increase the availability of light and other environmental changes and promote the growth of edge and pioneer species, which, depending on the intensity of the treatments, may increase the diversity of plants in a forest that otherwise, may be dominated by a few shade-tolerant species (Schumann et al., 2003). However, if the frequency of disturbance is too high, the early successional species-dominated communities are maintained, reducing plant diversity compared to unmanaged stands, as has been found here for clearcuttings, which had a negative effect on tree species richness. This result is consistent with the intermediate disturbance hypothesis; few species can persist under the intense disturbances produced by clearcutting (Roberts and Gilliam, 1995). The large clearcut areas produce new and homogeneous environmental conditions that promote a few shade-intolerant and pioneer species that rapidly recruit in the open areas, which in the Mediterranean regions are mainly *Pinus halepensis* and others like *Quercus coccifera* (Montès et al., 2004). Several studies have reported similar results. For example, Brashears et al. (2004) observed a rapid, early height growth of shade-intolerant species favoured by clearcutting, causing a shift in species composition of hardwoods in north-central West Virginia. Also, our results agree with Brokaw and Lent (1999), who stated that the simplified vertical structure in clearcut stands could explain in part the lower tree species richness observed. On the other hand, Wang and Nyland (1993) found an increase of shade-intolerant species, but in this case it produced an increase in tree species richness after clearcutting because of an initial composition based on a few dominant shade-tolerant species. An increase in tree species diversity after clearcutting was also reported by Crow et al. (2002) and in a review by Rowland et al. (2005). However, such results were usually associated with gentle terrain and productive sites that reduce the chance of serious soil degradation associated with timber removal. Such conditions are not typically found in Mediterranean forests that grow on thin soils with little water retention and low nutrient levels that receive little precipitation (Terradas et al., 2004).

Despite the absence of significant effects of clearcutting for the rest of the biodiversity indicators due to the small sample size, changes in the understory plant community could be expected by the removal of the canopy in clearcut harvesting as it mainly provides higher light availability and lower competition for other resources (Rowland et al., 2005). In the review by Rowland et al. (2005), an increase in the abundance or dominance of the residual shrubs was noted, although this effect cannot be generalized. For example, nonsignificant differences were reported by Albert and Barnes (1987) in the understory species richness and composition in clearcut stands and undisturbed areas in western Upper Michigan (USA). On the other hand, it is widely recognised that in managed forests, the amount of dead wood is reduced by harvesting and sanitation fellings (Green and Peterken, 1997), despite its importance for the biodiversity of forest ecosystems.

Selection cutting, as a regeneration system of lower intensity than clearcutting, increased the diversity and richness of tree and shrub species in Catalonia, which is consistent with the intermediate disturbance hypothesis. This type of treatment (with an average removal of basal area about 30%) falls in the range of the intermediate intensity that enhances forest diversity compared both to unmanaged and intensively-managed stands. This result is supported in part by other authors (Rowland et al., 2005; Deal, 2007). Indeed, both disturbance-resistant and superior competitor species may be present at intermediate sizes, intensities and frequencies of disturbances (Degen et al., 2005; Roberts and Gilliam, 1995). However, Decocq et al. (2004) found that in the Aisne department (France), the high frequency of selection cuttings (4–8 years, clearly above the corresponding figure for this treatment in Catalonia) may cause the elimination of the most sensitive species in the understory in the long term. If the frequency of disturbance is too high, the communities dominated by early successional species are maintained, potentially reducing plant diversity (Decocq et al., 2004).

Another key factor is the size of the canopy gap. The small gaps created by selection cutting allow the lateral expansion of the crowns of neighbouring trees into the open space; while the establishment of some shade-intolerant species can take place before canopy closure, the conditions are still adequate for shade-tolerant species in the rest of the stand, and increased species richness is therefore expected (Decocq et al., 2004). However, if the gaps exceed a critical size, a new succession based on a few light-demanding and dominating species occurs in the earliest stage (Decocq et al., 2004) resulting in low understory species richness.

Other factors conditioning changes in diversity of the forest understory have been also documented. For example, Atauri et al. (2005) concluded that the type of tree formation, the forest management practices and the plantation age simultaneously affected understory diversity in the Basque region (N Spain). The literature on the effect of selective cutting on tree diversity is scarce, although the processes occurring in gaps created by selective cuts may be similar to those just discussed for understory species. Other key structural elements to forest biodiversity (large-diameter trees, snags) were significantly reduced after selection cuttings, similar to the results observed by Atlegrim and Sjöberg (2004), who found a lower number of dead trees in stands selectively felled than in virgin forests in Sweden.

For some forest types, silvicultural treatments significantly reduced shrub abundance (*Pinus halepensis*, *Quercus suber*), which may be expected because some silvicultural treatments (e.g. cleaning) directly affect understory vegetation. However, other treatments (e.g. thinning, selection cuttings) may provide more available resources for the development of the shrub stratum (Rowland et al., 2005), which may explain the significant increase in shrub abundance after selection cuttings in *Quercus ilex* and *Pinus sylvestris* forests (Table 2). The variable and relatively weak results we found regarding this indicator agree with Gracia et al. (2007), who reported a poor correlation between overstory cover and shrub cover, with the effect of topography being much more important for shrub species abundance than the characteristics of the tree stratum.

Cleaning and thinning reduce competition and favour the development and health of the remaining stems, which was here reflected in an increase in larger-diameter trees. Increased availability of light and other resources provided by cleaning and thinning can also benefit the recruitment of new species that increase the diversity of the stand as reported here. In fact, the average thinning intensity in Catalonia is similar to that of the selection cuttings (about 30% of basal area removal), falling within the moderate-intensity management that is predicted to favour forest diversity under the intermediate disturbance hypothesis, as supported by our results in Mediterranean forests. However, we did not find a significant effect of thinning on the abundance or richness of understory species, contrary to previous studies. For example, higher understory plant cover and species richness were observed by Thomas et al. (1999) in western Washington State under intense thinning treatment. Also, Decocq et al. (2004) found an increase of overall cover of understory vegetation. However, similar results to ours were obtained by He and Barclay (2000) in British Columbia, where no apparent effects of thinning on understory cover were found.

The low density of large-diameter trees observed after precommercial thinning results from the treatment being performed only in young stands, which necessarily have fewer old trees than more mature unmanaged and managed plots. Precommercial thinning is a key management practice to enhance the yield and quality of wood production as has been widely studied (Huuskonen and Hynynen, 2006; Simard et al., 2004; Zhang et al., 2006), but there is a lack of specific studies about its effects on biodiversity. In the same way, few data exist regarding the effects of pruning on forest diversity. Here, pruning significantly favoured shrub species richness but not the other biodiversity indicators (Table 1). In general, the overall results could be also interpreted by the disturbance theory, which suggests that new environmental conditions, in this case mainly more light on the understory vegetation, start a successional process. Pruning probably has important effects by modifying structural characteristics of the forest at a small scale, taking into account that the complexity of vertical structure is a relevant attribute for the habitat of many species (Brokaw and Lent, 1999).

5. Management implications and further research

According to our results, preventing any silvicultural disturbance may not be the best solution for conserving and enhancing biodiversity in the Mediterranean forests. However, most of the Mediterranean woodlands produce low timber volumes, which, together with the rural population decline and land abandonment processes, has caused many Catalan forests to become too dense, with small diameters and with their growth and development slowed down by poor management (Saura and Piqué, 2006). Many unmanaged forests in Catalonia may be too dense for allowing the establishment of a variety of species in the stand. Similarly, reforestation carried out in Spain within the second part of the 20th century (usually single-species and dense plantations) have received little subsequent management, which may have negatively affected the flora and fauna diversity in these forests (Gil-Tena et al., 2007).

Our results show that the diversity of Mediterranean forests would benefit in general from moderate-intensity forest management both for the regeneration and the improvement of the stands. Disturbances play a major role in maintaining and favouring forest diversity by creating more heterogeneous conditions and preventing the competitive dominance of one or a few species (Roberts and Gilliam, 1995). However, not all silvicultural treatments can be considered appropriate for these purposes and forest managers need to know the potential effects of different types of treatments on diversity in order to design environmentally sound management practices (Roberts and Gilliam, 1995). While clearcutting is the most severe and intensive practice and is in detriment of Mediterranean forest diversity, selection cutting may be an appropriate regeneration treatment for forest stands in Catalonia, considering the positive effects on forest diversity reported in this study. Nevertheless, it is necessary to improve the practical implementation of this treatment to consider it as a fully sustainable management option for biodiversity in Catalonia, since negative selection cuts, in which the best and largest trees are cut systematically, are still very common in this region (Saura and Piqué, 2006). Indeed, snags and large-diameter trees are rare in forests managed for timber production (Green and Peterken, 1997; Marage and Lemperiere, 2005; Rowland et al., 2005), and this is still the case in many of the selection cuts in Catalonia.

Besides, our results show that the stand improvement treatments, especially thinning and pruning, also have positive effects on biodiversity indicators. These moderate-intensity management practices provide new environmental conditions that favour a succession process and modify the complexity of the stand vertical structure, which has been shown to be positively related to species richness and diversity (e.g. Brokaw and Lent, 1999). Apart from their benefits in terms of biodiversity, stand improvement practices also reduce the risk of forest fires and increase the carbon sequestration rates in the Mediterranean forests (Bravo et al., 2007).

No virgin forest remains in the Mediterranean and forest management is in general not too intensive in this region. For this reason, fewer differences may be expected between the managed and unmanaged forests in this study compared with other regions, such as tropical or North American regions where native forests remain but where intensive silviculture may be applied to others. This may explain why for some biodiversity indicators we did not find significant effects of management in this study. Further research with larger data sets and long-term data is as well needed to evaluate effects of management on the stand structure and biodiversity indicators in the Mediterranean, which is part of our ongoing research. More detailed and integrated research on forest biodiversity should include herbaceous species as well, since competitive interactions within the herb layer can determine the initial success of plants occupying higher strata, including the regeneration of dominant overstory tree species (Roberts, 2004; Gilliam, 2007). Specific measurements of the herbaceous layer are to be included in the next Forth Spanish National Forest Inventory.

In addition, forest management also requires a landscape perspective in order to maintain biodiversity (Franklin, 1993; McComb et al., 1993). Spatial patterns of forest ecosystems need to be considered (Crow et al., 2002; Gustafson et al., 2007) and a forest mosaic needs to be designed based on management practices with different size, intensity and frequency across the landscape. If only the intermediate disturbances were to occur all over the landscape, with no variability in the size, frequency or intensity, then landscape-level diversity would likely be reduced because species dependent on the extremes of disturbances would be eliminated (Roberts and Gilliam, 1995). However, in Mediterranean landscapes like Catalonia, forest fires play a major role as large-scale and intense disturbances may therefore not be necessary to replicate this kind of large disturbances throughout these regions. In this sense, further research from a landscape approach is needed to evaluate the effects of management on species with particular habitat requirements (Niemelä, 1999), since the number, size and arrangement of the patches in the mosaic strongly influence certain species (Franklin and Forman, 1987).

Acknowledgements

This research was funded by the *Ministerio de Educación y Ciencia* (Spain) and the European Union (FEDER funds) through the IBEPFOR project (CGL2006-00312/BOS). The information on the Third Spanish National Forest Inventory was provided by the *Dirección General para la Biodiversidad* (*Ministerio de Medio Ambiente*, Spain).

References

Alberdi, I., Saura, S., Martínez-Millán, F.J., 2005. El estudio de la biodiversidad en el tercer inventario forestal nacional. In: Saura, S., Vega, C., Piqué, M., Lobo, A., Pascual, L. (Eds.), Actas de la I Reunión de Inventario y Teledetección Forestal, Cuadernos de la Sociedad Española de Ciencias Forestales, 19, pp. 11–19.

Albert, D.A., Barnes, B.V., 1987. Effects of clearcutting on the vegetation and soil of a sugar maple-dominated ecosystem, western Upper Michigan. For. Ecol. Manage. 18, 283–298.

Atauri, J.A., De Pablo, C.L., Martín de Agar, P., Schmitz, M.F., Pineda, F.D., 2005. Effects of management on understory diversity in the forest ecosystems of Northern Spain. Environ. Manage. 6, 819–828.

Atlegrim, O., Sjöberg, K., 2004. Selective felling as a potential tool for maintaining biodiversity in managed forests. Biodivers. Conserv. 13, 1123–1133.

Battles, J.J., Shlisky, A.J., Barrett, R.H., Heald, R.C., Allen-Diaz, B.H., 2001. The effects of forest management on plant species diversity in a Sierran conifer forest. For. Ecol. Manage. 146, 211–222.

Bengtsson, J., Nilsson, S.G., Franc, A., Menozzi, P., 2000. Biodiversity, disturbances, ecosystem function and management of European forests. For. Ecol. Manage. 132, 39–50.

Brashears, M.B., Fajvan, M.A., Schuler, T.M., 2004. An assessment of canopy stratification and tree species diversity following clearcutting in central Appalachian hardwoods. For. Sci. 50, 54–64.

Bravo, F., del Peso, C., Bravo-Oviedo, A., Osorio, L.F., Gallardo, J.F., Merino, A., Montero, G., 2007. Impacto de la gestión forestal sobre el efecto sumidero de los sistemas forestales. In: Bravo, F. (Ed.), El papel de los bosques españoles en la mitigación del cambio climático. Fundación Gas Natural, Barcelona, pp. 113–141.

Brokaw, N.V., Lent, R.A., 1999. Vertical structure. In: Hunter, M.L. (Ed.), Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge, pp. 335–361.

Crow, T.R., Buckley, D.S., Nauertz, E.A., Zasada, J.C., 2002. Effects of management on the composition and structure of northern hardwood forests in upper Michigan. For. Sci. 48, 129–145.

Deal, R.L., 2007. Management strategies to increase stand structural diversity and enhance biodiversity in coastal rainforests of Alaska. Biol. Conserv. 137, 520–532.

Decocq, G., Aubert, M., Dupont, F., Alard, D., Saguez, R., Wattez-Franger, A., De Foucault, B., Delelis-Dusollier, A., Bardat, J., 2004. Plant diversity in a managed temperate deciduous forest: understory response to two silvicultural systems. J. Appl. Ecol. 41, 1065–1079.

Degen, T., Devillez, F., Jacquemart, A.L., 2005. Gaps promote plant diversity in beech forests (*Luzulo-Fagetum*), North Vosges, France. Ann. For. Sci. 62, 429–440.

Departament de Medi Ambient i Habitatge, 2007. Cartography available at http://mediambient.gencat.net/cat/el_departament/cartografia/.

Eriksson, S., Hammer, M., 2006. The challenge of combining timber production and biodiversity conservation for long-term ecosystem functioning—a case study of Swedish boreal forestry. For. Ecol. Manage. 237, 208–217.

Franklin, J.F., 1993. Preserving biodiversity: species, ecosystems or landscapes? Ecol. Appl. 3, 202–205.

Franklin, J.F., Forman, R.T.T., 1987. Creating landscape patterns by forest cutting: Ecological consequences and principles. Landsc. Ecol. 1, 5–18.

Gilliam, F.S., 2007. The ecological significance of the herbaceous layer in temperate forest ecosystems. BioScience 57, 845–858.

Gil-Tena, A., Saura, S., Brotons, L., 2007. Effects of forest composition and structure on bird species richness in a Mediterranean context: implications for forest ecosystem management. For. Ecol. Manage. 242, 470–476.

Gracia, M., Montané, F., Piqué, J., Retana, J., 2007. Overstory structure and topographic gradients determining diversity and abundance of understory shrub species in temperate forests in central Pyrenees (NE Spain). For. Ecol. Manage. 242, 391–397.

Grañó, M., Martínez, S., 2001. Una anàlisis sobre diferents models de boscos productors de suro. Catalunya forestal 52. Available at: http://www.forestal.cat/numero52/noti03.htm.

Green, P., Peterken, G.F., 1997. Variation in the amount of dead wood in the woodlands of the Lower Wye Valley, UK in relation to the intensity of management. For. Ecol. Manage. 98, 229–238.

Gustafson, E.J., Lytle, D.E., Swaty, R., Loehle, C., 2007. Simulating the cumulative effects of multiple forest management strategies on landscape measures of forest sustainability. Landsc. Ecol. 22, 141–156.

Halpern, C.B., Spies, T.A., 1995. Plant species diversity in natural and managed forests of the Pacific Northwest. Ecol. Appl. 5, 913–934.

Hansen, A.J., Spies, T.A., Swanson, F.J., Ohmann, J.L., 1991. Conserving biodiversity in managed forests: lessons from natural forests. BioScience 41, 382–392.

He, F., Barclay, H.J., 2000. Long-term response of understory plant species to thinning and fertilization in a Douglas-fir plantation on southern Vancouver Island, British Columbia. Can. J. For. Res. 30, 566–572.

Huuskonen, S., Hynynen, J., 2006. Timing and intensity of precommercial thinning and their effects on the first commercial thinning in Scots pine stands. Silva. Fenn. 40, 645–662.

Lindenmayer, D.B., Margules, C.R., Botkin, D.B., 2000. Indicators of biodiversity for ecologically sustainable forest management. Conserv. Biol. 14, 941–950.

Marage, D., Lemperiere, G., 2005. The management of snags: a comparison in managed and unmanaged ancient forests of the Southern French Alps. Ann. For. Sci. 62, 135–142.

Marrugan, A.E., 1989. Diversidad Ecológica y su Medición. Vedrà, Barcelona.

McComb, W.C., Lindenmayer, D., 1999. Dying, dead, and down trees. In: Hunter, M.L. (Ed.), Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge, pp. 335–361.

McComb, W.C., Spies, T.A., Emmingham, W.H., 1993. Stand management for timber and mature-forest wildlife in Douglas-fir forests. J. For. 91, 31–42.

Ministerio de Medio Ambiente, 1997–2007. Tercer Inventario Forestal Nacional. Dirección General para la Biodiversidad, Madrid.

Montès, N., Ballini, C., Bonin, G., Faures, J., 2004. A comparative study of aboveground biomass of three Mediterranean species in a post-fire succession. Acta Oecol. Int. J. Ecol. 25, 1–6.

Niemelä, J., 1999. Management in relation to disturbance in the boreal forest. For. Ecol. Manage. 115, 127–134.

Noss, R.F., 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conserv. Biol. 4, 355–364.

Pimentel, D., Stachow, U., Takacs, D.A., Brubaker, H.W., Dumas, A.R., Meaney, J.J., O'Neil, J.A.S., Onsi, D.E., Corzilius, D.B., 1992. Conserving biological diversity in agricultural/forestry systems. BioScience 42, 354–362.

Roberts, M.R., 2004. Response of the herbaceous layer to natural disturbance in North American forests. Can. J. Bot. 82, 1273–1283.

Roberts, M.R., Gilliam, F.S., 1995. Patterns and mechanisms of plant diversity in forested ecosystems: implications for forest management. Ecol. Appl. 5, 969–977.

Rowland, E.L., White, A.S., William, H.L., 2005. A literature review of the effects of intensive forestry on forest structure and plant community composition at the stand and landscape levels. Miscellaneous Publication 754, Maine Agricultural and Forest Experiment Station, the University of Maine.

Saura, S., Piqué, M., 2006. Forests and forest sector in Catalonia. In: Estany, J. (Ed.), Agriculture and Agri-food Production in Perspective: Profile of the Sector in Catalonia [cd-rom]. University of Lleida, Lleida.

Schumann, M.E., White, A.S., Witham, J.W., 2003. The effects of harvest-created gaps on plant species diversity, composition, and abundance in a Maine oak-pine forest. For. Ecol. Manage. 176, 543–561.

Simard, S.W., Blenner-Hassett, T., Cameron, I.R., 2004. Pre-commercial thinning effects on growth, yield and mortality in even-aged paper birch stands in British Columbia. For. Ecol. Manage. 190, 163–178.

Spies, T.A., Turner, M.G., 1999. Dynamic forest mosaics. In: Hunter, M.L. (Ed.), Maintaining Biodiversity in Forest Ecosystems. Cambridge University Press, Cambridge, pp. 335–361.

Terradas, J., Ibàñez, J.J., Vayreda, J., Espelta, J.M., Àvila, A., Gracia, C., 2004. Els Boscos de Catalunya: Estructura Dinàmica i Funcionament. Departament de Medi ambient i Habitatge, Generalitat de Catalunya, Barcelona.

Thomas, S.C., Halpern, C.B., Falk, D.A., Liguori, D.A., Austin, K.A., 1999. Plant diversity in managed forests: understory responses to thinning and fertilization. Ecol. Appl. 9, 864–879.

Wang, Z., Nyland, R.D., 1993. Tree species richness increased by clearcutting of northern hardwoods in central New York. For. Ecol. Manage. 57, 71–84.

White, P.S., 1979. Pattern, process and natural disturbance in vegetation. Bot. Rev. 45, 229–299.

Zhang, S.Y., Chauret, G., Swift, D.E., Duchesne, I., 2006. Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. Can. J. For. Res. 36, 945–952.