Influence of fire recurrence on CO₂ sink and soil composition in Holm oak forests

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Abstract

During the last few decades thousands of hectares of Holm oak (*Quercus ilex* subsp. *ballota*) forests have burned in Spain due to the increase in the number of large forest fires. This species is able to resprout after disturbance, so a high density coppice stand regenerates naturally after a fire. In SE Spain, a wildfire affected a Holm oak forest in August, 1993, and another fire occurred in July, 2001. A study was carried out to assess the influence of fire recurrence on the CO₂ sink capacity of this forest but also the influence on the soil composition. For this research, several plots were defined and set in the burned area. All resprouts within plots were measured (diameter at 30 cm above ground) and selected individuals were subjected to destructive tests to estimate biomass (above and below ground). By applying allometric relationships to all resprouts, the biomass of the different plots was estimated. To estimate the annual CO₂ sink in the study plots, the dry biomass obtained was multiplied by determined conversion factors. A large resprouting event occurred 3 months after the last fire and the estimated biomass suggested that recurrent fires could be negatively related to the vitality of the Holm oak shoots. Results also showed the important contribution of these coppice forests as a CO₂ sink. However, fire recurrence decreased the presence of the main soil components and it was not significantly affected by treatments. These results allowed us to establish that the CO₂ sink capacity is negatively affected by successive fires. This tendency could be changed by silvicultural treatments aimed to improve growth, vitality and adequate reproduction. Management models of coppice Holm oak stands are needed in order to improve CO₂ sink capacity.

Keywords: resprouting, quercus ilex, coppice forest.

1 Introduction

Holm oak (*Quercus ilex* ssp. *ballota*) is a mature successional hardwood species of the Mediterranean region and one of the most important evergreen tree species in Spain. Coppice forest stands have been the most commonly burnt forests in Spain (in addition to other conifers such as *Pinus halepensis*). They have adapted traits to fire-prone habitats [15], for example by resprouting. Therefore, post-fire communities usually show a high tree density which negatively influences the growth and increases the fire risk [9].

Post-fire forest management has proved to be an effective method in increasing the growth of the remaining trees [7] due to the decrease in competition and nutrient redistribution [2, 13], but there is an information gap on how to calculate the increase in biomass and CO₂ sink. For high forests, several methodologies have been developed to relate silvicultural tools and allometric relationship variability depending on site [17], density [5] or weather conditions [12, 23].

Thus, the main objectives of this study were to contribute to the knowledge of the carbon sink in young coppice stands and obtain allometric relationships. Additionally, this study aims to examine the influence of thinning on the growth and net primary productivity depending on the intensity of the treatment.

2 Material and methods

2.1 Study area

The study site was located in Campillo de Altobuey (Cuenca province, 1° 51' W, 39° 40' S, 1020 m amsl), southeastern Spain. In summer 1993, a fire burned about 500 ha and after eight years, in 2001, about 55 ha were burned again. The mean annual rainfall and temperature for the last thirty years (1977–2007) was 517 mm and 12.67 °C. The soil texture was Sandy Loam and the soil type was a Lithic Leptosol associated with Chromic Luvisol [18]. The natural vegetation consisted of evergreen oak resprouts and other shrubs, such as *Juniperus communis*, *Sideritis incana*, *Thymus vulgaris*, *Helianthemum cinereum*, *H. hirtum*, *Santolina chamacyparissus* and *Bupleurum fruticosens* and herbaceous plants such as *Linaria glauca*, *Bombycilaena erecta*, *Wangenheima lima*, *Euphorbia exigua*, *Erophila berna*, *Petrorrhagia nanteuillii*. This was a naturally regenerated community coming from a high forest which was managed and overgrazed over the last four decades. The main tree species in the post-fire community consisted of an even-aged Holm oak stand due to the resprouting ability of *Quercus* species. Twelve rectangular plots (15 x 20 m) were designed in the study site. They were visually homogenous and had no slope.

2.2 CO₂ sink

A factorial design with thinning intensity as the factor was carried out. In late 1999, we applied four thinning intensities: T_m (medium thinning: to a final

density of 5000 trees/ha), T_d (drastic thinning: to a final density of 1800 trees/ha), T_f (total felling) and C (control, i.e., without thinning). There were three randomly selected plots for each treatment (replicate treatments). To estimate aboveground biomass and leaf area of resprouts, allometric relationships (trunk diameter 30 cm above ground (D30)) were applied to predict the selected variable. To define the allometric relationships, a destructive test was carried out in late 1999 and early 2001. After thinning, five resprouts were selected to be sampled. The entire resprouted tree was weighed (fresh weight) and the leaves were removed and weighed. In the laboratory, both wood and leaves were dried (85° C for 24 h) and weighed again (dry weight). To estimate SLA (ratio leaf area and leaf dry biomass), ten leaves were randomly sampled and their projected leaf area was measured (with camera and a digital image analyzer software).

The total biomass estimate (including leaves, stems and roots) was obtained in relation to D30 by defining two different allometric relationships for each age and treatment. Their ratio estimates [4] were obtained from the measured samplings. The mean annual productivity (MAP), the last annual productivity ($LAP_{\text{trees+respr}}$) and the total annual productivity (TLAP, including biomass extracted by treatments) were calculated. To estimate annual CO_2 sink of resprouts, dry biomass was multiplied by conversion factors. We hypothesized that the content on C for the wood was 0.5 t per t of dry wood biomass [4]. To calculate the leaf content we used a different conversion factor depending on fire recurrence [13]: 0.345 t per t of leaf dry biomass of resprouts in stands with high fire-recurrence and 0.225 t per t of leaf dry biomass of resprouts in the stands burned only in 2001. Finally, to obtain total CO_2 , carbon content was multiplied by 3.67 (ratio of molecular weight of CO_2 to molecular weight of C).

2.3 Soil characteristics

To check the effects of high fire recurrence on soil, we measured the physical and chemical characteristics of the soil. Soil samples were taken in each plot 5 months before new fire (February 2001) and 6 months later (February 2002). A soil sample at a depth of 20 cm consisted of four sub-samples taken in each plot corner and another taken in the plot center. That analysis included total Nitrogen (N, %, Kjeldahl method), assimilable Phosphorus (P, ppm, Olsen method), Potassium (K, ppm, extracted with ammoniac acetate), total Carbonates (Cab, %), organic Carbon (C, %, oxydable organic matter), C/N ratio, pH (1/2.5 in H_2O) and electric conductivity (1/5 H_2O at 25 °C, mmhos/cm). Texture, i.e., sand (S), loam (L) and clay (CL) percentages were also measured.

2.4 Statistical analysis

In order to test whether continuous variables fit a normal distribution, data were examined using a normal probability plot, standardized skewness and kurtosis, and the Kolmogorov-Smirnov test. In order to check the similitude of groups of plots (that will be subjected to different thinning intensities) before thinning treatments were carried out, a multivariate ANOVA (MANOVA) was used [16].

The aim was to check for significant differences between groups for multiple variables simultaneously. In addition, simple and multifactor ANOVA were used to compare means between groups. Fisher's least significant differences (LSD) test at a 95% confidence interval was used to check which means are significantly different from the other variable means. All analyses were conducted at $p < 0.05$. If data did not complete the homocedasticity of the variances, then data were log transformed before carrying out the ANOVA analysis. Results are shown without log transformation.

To check the variability on the SLA (specific leaf area) depending on different factors (date, crown position, treatment and leaf age), a multiple regression analysis was carried out using dummy variables for the levels of these factors. All models were simplified using the forward stepwise regression method, based on the general linear test statistic (F-test) [16]. The best models were chosen selecting the highest R^2 , lowest lack of colinearity of the predictor variables (low variance inflation factor), and based on an analysis of the residuals examining both graphs of residuals and the Durbin-Watson statistic.

3 Results

3.1 CO₂ sink

Table 1 summarizes growth and productivity according to the proposed biomass basis. The mean annual productivity (MAP) before treatments ranged between 0.84 and 1.49 t.ha⁻¹y⁻¹ and no significant differences were found between treatments. The last annual productivity (LAP_{trees+respr}) was always higher than the MAP, with no thinning dependency. T_d and T_f showed a last annual productivity smaller than the MAP. This table also shows that TLAP in young resprouts ranged from 4.14 to 4.76 t.ha⁻¹y⁻¹, independently of thinning intensity, with a slightly higher value for thinned plots than for control plots (although there were no significant differences). The contribution of these coppice forest stands to the sink of greenhouse gases (CO₂), ranged between 2.8 and 7.3 t.ha⁻¹yr⁻¹ of CO₂ (for full thinning and control plots respectively).

3.2 Soil characteristics

All physical and chemical parameters measured in the soil (except pH and conductivity) showed significant differences ($p < 0.001$, $n=24$) before and after the new fire (Figure 1). However, almost all treatments and the interaction between age and treatment did not show significant differences. The mean values for N and K were considered normal for this kind of soil. Six months before the fire (Feb-01), they were 0.17% and 416 ppm, respectively. Phosphorus showed a very low concentration, 3.58 ppm. About one year later (i.e. six months after the fire), the concentrations decreased to 0.09% of N, 0.72 ppm of P and 320 ppm of K, which are very low values for this soil type. Before the fire, the total carbonates, the organic matter and the C/N ratio were 4.53%, 3.52% and 13.83 ppm respectively. After the fire, they came down to 2.84%, 1.82% and

Table 1: Mean annual productivity (in equivalent fixed CO₂) in a *Quercus ilex* coppice stand. The values were recorded four years after the last fire. MAP (t ha⁻¹.year⁻¹): mean annual productivity (from 1999 to 2005); LAP (t.ha⁻¹.year⁻¹): last annual productivity (late 2005); TLAP,(t ha⁻¹.year⁻¹): total annual productivity.

Thinning Intensity		B _{thinning}	MAP _{tree}	LAP _{tree}	LAP _{respr}	LAP _{tree+respr}	TLAP
Equivalent CO ₂	C	0.000a	2.673a	7.340a	0.012a	7.352a	7.352a
	T _m	1.792b	1.567a	3.742a	2.303b	6.045ab	7.837a
	T _d	3.650b	1.588a	0.596b	3.873b	4.469ab	8.119a
	T _f	4.582b	1.524a		2.805b	2.805b	7.381a

MAP_{tree}: Mean annual productivity of young trees (since 1993 to 1999) before treatments were carried out (equals to total stocks of young trees divided by 6).

B_{thinning}: biomass of young trees felled when thinning treatments were applied (t/ha).

LAP_{tree}: Last annual productivity of young trees (Dec-99 to Febr-01).

LAP_{respr}: Last annual productivity of resprouts (Dec-99 to Febr-01).

LAP_{tree+respr}: Last annual productivity of young trees plus resprouts (Dec-99 to Febr-01).

TLAP: Total annual productivity (include LAP_{tree+respr} and B_{thinning}).

The same letters for each variable and different thinning intensities means there were no significant differences (Fisher LSD test at p=0.05).

11.59 ppm respectively. The C/N ratio drop indicated low nitrogen release due to the high temperatures reached. The pH and electrical conductivity did not show significant differences before or after the new fire (7.7 and 0.26 in Feb-01 respectively and 7.6 and 0.24 in Feb-02). This indicates a basic and non-saline soil.

There were significant differences among granulometric composition for clay, loam and sand before and after the new fire (Figure 2). The differences were not found when treatments or interactions were compared. In general, the clay and loam content increased as a consequence of the fire and sand content decreased. Before the new fire, the mean percentages of clay, loam and sand were 8.7%, 15.6% and 75.7% respectively. After fire the values were 11.0%, 24.3% and 64.7% respectively. Before the fire, the values were similar when treatments were compared but afterwards, they were different (although not significantly).

4 Discussion

The post-fire resprouts experienced fast growth because of high water and nutrient availability and the fact that the ratio leaf area/root area increased after the fire [11]. Since the root biomass is alive (in a similar manner for all the

Figure 1: Means and confidence intervals (95%, LSD interval) of the physical and chemical soil characteristics (N, P, K, Carbonates, Organic matter, C/N ratio, Electrical Conductivity and pH), for the two dates of study and for four thinning treatments.

treatments), the methodology applied to estimate belowground biomass (estimating allometric relationships) is not valid after treatments or post-fire. To correct this, we applied the same root biomass values before and after the disturbances. After that, we calculated the aboveground biomass adding the annual root increase.

Figure 2: Means and confidence intervals (95%, LSD interval) of the granulometric composition of the soils (% dry matter, clay, loam and sand), for the two dates of study and for four thinning treatments.

For CO₂ storage, our results suggested that the allometric relationships could be changing according to the silvicultural treatment. López-Serrano et al. [12] reported the same results. The relationship varied according to the homogeneity of the stand. The total CO₂ stocks, six years after the fire, showed very low values (5-9 t/ha) in comparison to similar coppice forest stands. This variability could depend on stand age, site quality, disturbances and forest management [8].

In general, thinning improved growth and increased biomass production after recurrent fires. The effects of silvicultural treatments on CO₂ storage reported 1.27 t/ha aboveground dry biomass in a 32 year-old Holm oak coppice stand [19]. Our results showed that total felling is not advisable due to low biomass production (similar to burned and unmanaged plots). The last annual productivity ($LAP_{\text{trees+respr}}$) was always higher than the MAP, with no thinning dependency, according to general theory of growth in early stages of the forest stands [6]. Optimal management should be a medium or drastic thinning.

Fire recurrence reduced the soil properties. The changes were mainly in the physico-chemical and granulometric properties. As expected just after fire, N, P, K, organic matter, carbonates and C/N ratio decreased [6, 22]. P and N can be volatilized as a consequence of high temperatures [22], although there are some threshold values on forest fire intensity to produce significant changes [10]. In addition, loam and clay elements increased but sand decreased. The high temperatures could transform soil properties due to structural decomposition [21]. After the fire, the burned vegetation provides nutrients to the soil, increasing the pH and the conductivity but our results disagreed with this pattern. One possible reason would be that soil was washed away by autumn rainfalls [3]. Nonetheless, soil changes are typically short-term and soil properties are usually recovered in five to ten years after a fire [1, 20].

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