Forest Ecology and Management 262 (2011) 759–769

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Synergistic effects of past historical logging and drought on the decline of Pyrenean silver fir forests

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ARTICLE INFO

Article history:
Received 25 March 2011
Received in revised form 4 May 2011
Accepted 5 May 2011
Available online 1 June 2011

Keywords:
Abies alba
Dendroecology
Drought stress
Pyrenees
Radial growth
Releases

ABSTRACT

The causal factors and effects of forest declines are not well understood in temperate conifer forests. Most studies have focused on climatic and environmental stressors and have obviated the potential role of historical forest management as a predisposing factor of decline. Here, we assess if the recent silver fir (*Abies alba*) decline observed in the Spanish Pyrenees was predisposed by historical logging and incited by warming-induced drought stress. We analysed a dataset of environmental, structural, and historical variables at the tree and stand level including 32 sites with contrasting degrees of defoliation distributed over 5600 km^2. We followed a dendroecological approach to reconstruct historical logging and to infer the effects of warming-induced drought stress on growth. The silver fir decline was more severe and widespread in western low-elevation mixed forests dominated by trees of small size and slow growth. These sites were subject to higher water deficits than eastern sites, where late-summer rainfall as the key climatic variable controlling silver fir growth was higher. Declining sites showed more frequent growth releases induced by historical logging than non-declining sites. Historical logging and warming-induced drought acted as long-term predisposing and short-term inciting factors of silver fir decline in the Pyrenees, respectively. We suggest that biomass increases caused by past intense logging affected the vulnerability of silver fir against late-summer water deficit. Future research in declining temperate conifer forests should consider the interacting role of predisposing historical management and inducing climatic stressors such as droughts.

1. Introduction

Forests store approximately 45% of terrestrial carbon, but huge carbon emissions may occur rapidly from sudden mortality episodes linked to forest decline (Breshears and Allen, 2002). Recently, numerous cases of forest decline have been reported worldwide and related to warming-linked drought stress (Allen et al., 2010). Warming-induced forest decline in drought-stressed environments is linked to rapid defoliation and selective mortality of overstory trees (McDowell et al., 2008). Nevertheless, in temperate conifer forests, the environmental factors causing forest decline are not as well studied as in dry woodlands (van Mantgem and Stephenson, 2007).

Forest decline is still poorly understood because of the interaction of several stress factors acting at different spatio-temporal scales, which complicates the disentangling of lagged cause-effect relationships (Manion, 2003). In addition, few long-term assessments of the potential stressors involved have been carried out. Many decline episodes have been studied following Manion's (1981) conceptual model, which includes predisposing, inciting, and contributing stress factors causing a decline in tree vigor. Predisposing factors such as site conditions reduce a tree's vigor over the long term (Suarez et al., 2004), whereas inciting factors such as drought lead to a strong and short-term reduction in tree vigor (Bigler et al., 2006). Contributing factors such as mistletoe, insects, and fungi may lead to tree death acting as secondary stress factors. Historical land-use factors such as past logging may predispose forests to decline (Linares et al., 2009). However, few studies have assessed the role of historical logging on the decline of temperate conifer forests despite most of them have been intensively managed (Frelich, 2002).

The different natures of interacting factors such as land-use legacies (e.g., historical logging) and climatic extremes (e.g., severe droughts) have precluded considering the interactions between them. For instance, historical effects have persisted for decades and centuries shaping the current structure of most temperate conifer forests in Europe (Kirby and Watkins, 1998). Therefore,

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doi:10.1016/j.foreco.2011.05.009

any link between the historical management and warming-induced drought stress may be highly relevant for understanding past and current episodes of forest decline (Foster et al., 2006). A retrospective approach based on long-term tree growth data may provide historical information to infer the links between past forest use, drought stress, and forest decline.

Decline episodes of silver fir forests (*Abies alba* Mill.) in central Europe were systematically reported in the 1970s (Skelly and Innes, 1994). In the 1980s, silver fir decline was also observed in the Central Spanish Pyrenees (Aragón Pyrenees, Fig. 1), being more severe in western stands where up to 50% of trees showed severe defoliation (Camarero et al., 2002). Therefore, it may be hypothesized that drought stress has recently increased due to climate warming and a regime shift in precipitation causing silver fir decline. In addition, most of these forests were logged to extract timber up to the 1970s when their management ceased due to rural migration to cities (Cabrera, 2001). In this study, we addressed the following questions: (1) How did silver fir growth change in the Aragón Pyrenees during the twentieth century, and how was this growth variability related to the recent pattern of defoliation and decline? (2) Did historical logging, reconstructed using historical information and dendrochronological dating of growth releases, and warming-induced drought synergistically act as predisposing and inducing factors of the recent silver fir decline? To answer these questions we analysed a detailed dataset of environmental, structural, and historical variables at the tree and stand level, including sites subjected to contrasting climatic conditions, combined with tree-ring data and assessments of crown defoliation.

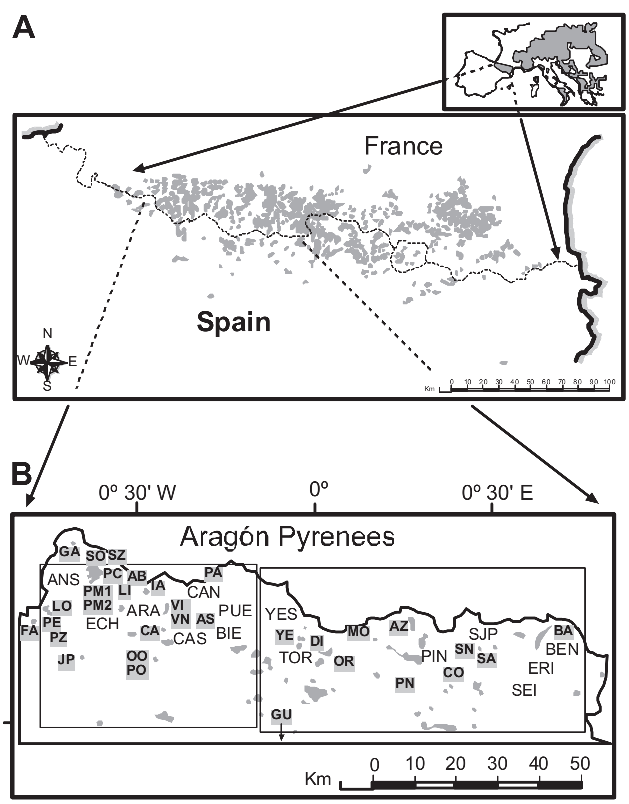

Fig. 1. Distribution of *A. alba* in Europe (A) and study sites in the Aragón Pyrenees (B), northeastern Spain (site codes with bold letters, see Table 1). The two rectangles in the lower figure delineate the two homogeneous climatic sub-regions based on local data from the displayed climatic stations (3 letter codes): Western (WAP) and Eastern (EAP) Aragón Pyrenees (see Supplementary data S1).

2. Material and methods

2.1. Study area

The Pyrenees constitute a transitional area between more humid conditions in their northern margin and drier conditions southwards (Vigo and Ninot, 1987). This gradient overlaps with a longitudinal gradient caused by the location of the range between the Atlantic Ocean and the Mediterranean Sea. According to meteorological data from nearby stations, the climate in the study area is continental with oceanic (western sites) or Mediterranean (eastern and southern sites) influences (Supplementary data S1). The westward oceanic influence leads to greater precipitation in winter and a smaller temperature range than eastwards, where the Mediterranean influence prevails being characterized by higher precipitation in summer, as expressed in percentage relative to the annual precipitation, than westwards.

The studied silver fir populations are located in the Aragón Pyrenees, NE Spain (Fig. 1). The main geographic and topographic characteristics of the 32 sampled stands appear in Table 1. In the Aragón Pyrenees, silver fir stands are usually found at humid sites on north-facing slopes, where they form pure or mixed stands with *Fagus sylvatica* L. or *Pinus sylvestris* L. Silver fir forests in the study area may experience summer-drought stress in August despite a total annual precipitation between 900 and 2000 mm, which usually increases with elevation. Most studied stands are located on marls and limestones, which generate basic soils, or on moraine deposits with rocky but deep soils. The most frequently used method of timber harvesting in the study area was diameter limit cutting, which mostly affected fast-growing and big trees (Aunós and Blanco, 2006). According to historical data (Cabrera, 2001), logging intensity during the 20th century in the Pyrenees was greatest in the 1950s but no data are available on how widespread logging in this region was and how it affected the current structure and dynamics of different stands.

2.2. Climate data

Because local climatic records are inadequate to study the spatiotemporal variation of mountain climates, we created regional climatic records averaging the longest and most complete local climate records available from the study area (see methods in Supplementary data S1). We used monthly climatic data (mean temperature, total precipitation) to delineate two relatively homogeneous climatic areas within the Aragón Pyrenees, hereafter abbreviated as WAP (western Aragón Pyrenees) and EAP (eastern Aragón Pyrenees) sub-regions. We preferred to use local climate data instead of gridded or interpolated climatic datasets because local data captured more climatic variability among sites than gridded data. We obtained mean temperature and precipitation data for each sub-region for the period 1940–1999. Finally, we calculated annual and cumulative monthly water deficits for both climatic sub-regions using a modified Thornthwaite water-budget procedure (Supplementary data S2).

2.3. Field sampling

Sampling was conducted beween 1999 and 2001. We sampled at least one silver fir stand (forests with at least 10 ha of area and silver fir cover >50%) in each 10-km^2 grid in the Aragón Pyrenees (Fig. 1). The sampled stand in those grids with multiple stands was selected randomly. More stands in those 10-km^2 grids with more defoliated trees were sampled because we were mainly interested in discerning the causes of forest decline. We sampled 21 and 11 sites within the WAP and EAP sub-regions, respectively. At each