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Managing stand density to enhance the adaptability of Scots pine stands to climate change: A modelling approach

Aitor Ameztegui[a,b,*,1], Antoine Cabon[a,b,1], Miquel De Cáceres[a,b], Lluís Coll[a,b,c]

[a] CREAF, Cerdanyola del Vallès, 08193, Spain
[b] Forest Sciences Center of Catalonia (CEMFOR-CTFC), Ctra. Sant Llorenç km.2, Solsona, 25280, Spain
[c] Department of Agriculture and Forest Engineering (EAGROF), University of Lleida, Lleida, 25198, Spain

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ABSTRACT

In the Mediterranean region most climatic forecasts predict longer and more intense drought periods that can affect tree growth and mortality over broad geographic regions. One of the silvicultural treatments that has gained currency to lessen the impacts of climatic change is the reduction of stand density by thinning. However, we lack information on how the response of forest stands to different thinning treatments will be affected by climate change, and on the post-thinning temporal dynamics of water balance, specifically blue and green water. We adopted a modelling approach to explore the long-term effects of different thinning intensities on forest dynamics and water balance under climate change scenarios, coupling an individual-based model of forest dynamics (SORTIE-ND) with a mechanistic model of soil moisture dynamics and plant drought stress. We used as a case study three Scots pine plots across a gradient of climatic conditions, and we assessed the effect of site, three climatic scenarios and eight thinning intensities on tree growth, stand productivity, tree drought stress and blue water. The best thinning intensity in terms of stand productivity was obtained when between 20 and 40% of the basal area was removed, whereas the final stand stock rapidly decreased at higher thinning intensities. Moreover, the decrease in final basal area occurred at lower thinning intensities the drier the site conditions. Moderate and heavy thinnings (>30%) doubled basal area increment (BAI) of the following years in all the plots, although the effect vanished after 30–40 years, independently of the site and climate scenario. As expected, thinning was simulated to have an overall positive effect on the blue water yield and tree water status, which increased and also tended to last longer for higher thinning intensities. However, the magnitude of this effect on tree water status was most dependent on the site and climatic scenario, as drier conditions generally raised stronger and longer lasting reductions in drought stress for a given thinning intensity. Furthermore, our results highlight the existence of a site- and climate-dependent trade-off between the gain in stand productivity and the improvement in tree water status obtained by thinning, particularly for moderate or heavy thinning intensities. Our simulations suggest that thinning is a useful management tool to mitigate climate change but strongly argue against the application of general recipes across sites and appeals for carefully taking into consideration local climatic trajectories for management planning.

1. Introduction

In the Mediterranean region most climatic models forecast reductions in the total amount of rainfall and increases in the seasonality (IPCC, 2014), leading to longer and more intense drought periods that can strongly affect tree growth and mortality over broad geographic regions (Carnicer et al., 2011). Moreover, climatic changes have the potential to bring about modifications in runoff and streamflow of forested landscapes, and in the balance between blue water (the water exported via runoff or drainage to saturated layers, i.e. ultimately going to streams and lakes) and green water (the part that flows through the plant before returning to the atmosphere, hence contributing to vegetation growth; Avila et al., 1996). Since water resources are highly dependent on land cover and vegetation type (see for example Gracia et al., 1999; Llorens and Domingo, 2007 or Vicente-Serrano et al., 2016), hydrology-oriented

* Corresponding author at: Aitor Ameztegui, CEMFOR-CTFC, Ctra. Sant Llorenç de Morunys km.2., Solsona, 25280, Spain.
E-mail address: ameztegui@gmail.com (A. Ameztegui).
[1] Authors who equally contributed to this work.

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silviculture is increasingly considered as an option to attenuate the effects of water shortage on vegetation drought stress and streamflow, although a better understanding and quantification of its effects on the water fluxes is required (del Campo et al., 2014).

One of the silvicultural treatments that has gained currency to diminish impacts of climatic changes is the reduction of stand density by thinning (Linder, 2000; Kolström et al., 2011). Thinning treatments have been long-time applied as a means of increasing the quality and value of timber and the health of trees and stands. In some contexts, thinning can also lead to higher cumulative timber volume, i.e., the sum of extracted and stocking timber (del Río et al., 2008; Magruder et al., 2013). In a context of climate change, thinning has been praised due to its positive effect on tree vigour (López et al., 2009; Rodríguez-Calcerrada et al., 2011), water use efficiency (Gebhardt et al., 2014), resilience to drought events (D'Amato et al., 2013), and soil water content (Ganatsios et al., 2010). The positive effects of stand density reduction on the water balance of forests are mediated by three processes: First, it diminishes interception losses, increasing the amount of water that infiltrates into the soil (Mazza et al., 2011; Molina and del Campo, 2012). Second, it reduces water losses due to lower stand transpiration (Zhang et al., 2001). Third, the amount of water available in the soil is apportioned among fewer trees (Martín-Benito et al., 2010; Magruder et al., 2013). However, the release in growth accelerates post-thinning canopy closure, so the effects of thinning on the stand and soil water balance are transient, and its duration dependent on thinning intensity and environmental or site conditions (Aussenac and Granier, 1988; D'Amato et al., 2013; Elkin et al., 2015).

Given the ecological and economical importance of Scots pine (*Pinus sylvestris* L.), many thinning trials have been conducted on forests of this species, including some with long-term observations examining mainly its effects on growth (Chroust, 1979; del Río et al., 2008; Montero et al., 2001; Peltola et al., 2002), but also on resistance and resilience to drought episodes (Giuggiola et al., 2013; Sohn et al., 2016). Nevertheless, we lack information on how the response of forest stands to different thinning treatments will be affected by climate change. Moreover, we are still far from a thorough understanding of the post-thinning temporal dynamics of blue and green water, or the trade-offs between increasing resilience to drought stress and increasing forest productivity. The main limitation lies on the difficulty of setting field experiments that include several thinning intensities and that are monitored for a sufficient amount of time to observe the long-term effects on water budget, tree growth and resilience to drought stress. The use of ecological models to forecast long-term post-thinning effects may help to overcome the limitation of experimental data, and their ability to evaluate future scenarios may provide adequate recommendations for the management of forests in the predicted context of environmental uncertainty.

Here, we adopt a modeling approach to explore the long-term effects of different thinning intensities on forest dynamics and water balance under climate change scenarios. Specifically, we coupled an individual-based model of forest growth and dynamics (SORTIE-ND; Canham et al., 2005), with a mechanistic model of soil moisture dynamics and drought stress in individual forest stands (De Cáceres et al., 2015). This integration allowed us to evaluate the effects of a wide array of thinning intensities, and to assess the combined effects of thinning intensity, site conditions and climate change on forest production, water balance and tree drought stress. Previous studies have shown that the effects of thinning on forest growth and tree drought stress are greater and last longer for heavy thinning treatments, but we expect this trend to be affected by initial site conditions and climate scenario. Moreover, we expect to find a trade-off between the benefits obtained by thinning in terms of stand productivity and water balance, which could have important implications for management.

2. Material and methods

2.1. Study area and species

We used as a case study Scots pine stands of Catalonia (NE Spain). Scots pine is a shade-intolerant widespread species that in this region covers more than 240,000 ha (17% of the forested area), two thirds of which are monospecific stands. It is one of the most productive species, providing yearly more than 160,000 m^3 of timber, which represents >25% of the total annual timber volume harvested in the region (IDESCAT, 2014). Scots pine thrives in Catalonia from the humid valleys at the northern slopes of the Pyrenean range, with annual precipitation exceeding 1000 mm, to the semiarid meridional mountains in the Catalan Pre-Coastal Range, where annual precipitation drops to ~500 mm. There, the species is close to its distributional boundary and its populations are currently suffering drought-induced decline in the most xeric sites (Martínez-Vilalta and Piñol, 2002; Galiano et al., 2010). Climate change predictions in the region include increases in temperature and slight reductions in precipitation (Barrera-Escoda and Cunillera, 2011), with an increase of precipitation concentration leading to more intense and longer drought periods. Therefore, drought-induced declines are expected to continue and even expand into other parts of its distribution in the near future.

2.2. Site conditions and climatic scenarios

We selected three plot locations representative of the gradient of climatic conditions experienced by *P. sylvestris* in Catalonia (humid, mesic and xeric; see Table 1). For each of the three locations we defined three climatic scenarios, each encompassing 90 years. In a first scenario we assumed no trend in temperature and precipitation during the 90 years (no climate change; NoCC). The second and third climatic scenarios corresponded to the climate forecasts according to the IPCC emissions scenarios B2 and A2 on the period 2011–2100 (IPCC, 2014). Historic and projected climatic data were extracted from raster maps developed using the methods of the Climatic Atlas of the Iberian Peninsula (Ninyerola et al., 2000) from information provided by the Spanish National Meteorological Agency (AEMET). Table 2 shows a summary of climatic changes predicted between 2010 and 2100 under scenarios B2 and A2 for the three studied sites. Temporal series of mean annual temperature and precipitation for the three scenarios can be found in Appendix A in Supplementary material.

2.3. Initial structure and thinning intensity

We created individual tree datasets describing the initial stand configuration on each of the three site conditions (Table 1). The size of each plot was set to 1 ha and the three virtual stands had an initial mean diameter (d) = 12.5 cm, the diameter at which thinning is usually first applied in the region (Piqué et al., 2011a,b). We then determined the initial stem density for each stand using the modification of the Stand Density Index (SDI) proposed by Condés

Table 1
Mean climatic and stand characteristics of the studied plots of Scots pine (*Pinus sylvestris*) before the application of thinning treatments.

	Humid	Mesic	Xeric
Mean annual temperature (°C)	8.7	12.0	12.5
Mean annual rainfall (mm)	828.0	714.3	564.3
Martonne Index	44.3	32.5	25.1
Quadratic mean diameter (cm)	12.6	12.6	12.6
Initial Stem density (stems ha^{-1})	2510.0	2377.0	2278.0
Initial Basal Area (m^2 ha^{-1})	31.4	29.7	28.6