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Thinning increases tree growth by delaying drought-induced growth cessation in a Mediterranean evergreen oak coppice

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ABSTRACT

The Mediterranean evergreen oak coppices of Southern Europe are increasingly vulnerable to drought because of both the ongoing climate change that increases drought length and intensity, and the lack of forest management that induces a structural aging of the stands. Decreasing stand density through thinning has been widely regarded as a means to improve the resistance of evergreen oak forests to climate change by decreasing the competition for water amongst the remaining stems.

Data from a 30-years thinning experiment, that includes a control and four thinning intensity treatments (from 25% to 80% of basal area removed), in a coppiced holm oak (*Quercus ilex* L.) forest of southern France, was used to quantify the effects of thinning on stem growth. Building on the 'sink limitation' paradigm, which proposes that tree growth is controlled by phenology and climatic constraints and decoupled from carbon assimilation, we investigated if the effect of thinning on stem growth was explained by a delayed drought-induced growth cessation. Using a water balance model, we simulated the date of drought-induced growth cessation, previously found to correspond to the day of the year when water potential drops below a threshold of −1.1 MPa, and used it to predict growth in the different treatments of the thinning experiment.

Thinning increased long-term growth at the stem level but decreased the wood biomass at the stand level. Decreasing stem density, and hence the leaf area index, was simulated to delay the date of drought-induced growth cessation. A growth model based on the date of growth cessation explained 85% of the effect of thinning on stem growth over the 30-year period of the study, and 95% for the first five years after thinning.

The canopy density for which the effect of thinning is the most beneficial was found to maximize the growth duration without lifting completely the water limitation in summer. Moderate thinning had a sustained beneficial effect on the growth of all stem size classes, whereas stronger thinning intensities increased the size asymmetry of competition and their overall effect dropped faster. Our simple predictive model based on the simulation of the water balance as a function of stand density opens the way to providing management guidelines for the optimization of tree density as a function of water limitation in Mediterranean evergreen woodlands.

1. Introduction

The forest ecosystems around the Mediterranean basin have long been shaped by human activities, which influenced their distribution, structure and species composition (Blondel and Aronson, 1999; Quézel and Barbero, 1990). After a reduction of the Mediterranean forests cover to half of their potential area during the 19th century (Quézel, 1976), the deep socio-economic changes that occurred in the northern Mediterranean during the 20th century (e.g. the rural depopulation, the shift toward fossil fuels, the agriculture mechanisation and the Common Agricultural Policy) triggered an extensive spontaneous afforestation of abandoned fields (Mouillot et al., 2005; Poyatos et al., 2003; San Roman Sanz et al., 2013; Serra et al., 2008) as well as changes in forest structures (Poyatos et al., 2003; Quézel and Barbero, 1990). Holm oak

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(*Quercus ilex* L.) forests cover more than 6 Mha in the Mediterranean Basin, mostly in its western part (Ducrey, 1992) and about 350,000 ha in southern France where they were traditionally coppiced on short rotations (from 7 to 30 years; Ducrey, 1988) for charcoal or tannins production (Terradas, 1999). These coppices have been generally abandoned and under-logged since the second half of the 20th century, which resulted in alterations of the forests structure mainly due to aging (Barbero et al., 1990) and increased the forests sensitivity to perturbations such as pests, fire and drought (Ducrey, 1992; Rodríguez-Calcerrada et al., 2011).

General Circulation Models forecast a global increase in temperatures and local shifts in precipitation patterns (IPCC, 2014) and, although regional projections in climate change are still uncertain, it is likely that the Mediterranean region will be particularly exposed to increased temperatures and decreased precipitations (Giorgi and Lionello, 2008). The Mediterranean basin climate is characterized by mild wet winters and hot and dry summers that induce strong water limitations on the vegetation. Mediterranean forests will therefore probably undergo substantially stronger water limitations by the end of the 21st century (García-Ruiz et al., 2011; Ruffault et al., 2013a), which has already been observed in the south of France during the four last decades (Ruffault et al., 2013b) and raises the question of holm oak forests vulnerability in the future.

In this context, thinning has been considered as a way to address the structural aging (Ducrey, 1988) and, more recently, to mitigate the impact of climate change on holm oak forests (Rodríguez-Calcerrada et al., 2011). Thinning has a positive effect on growth and vigour of seasonally dry forests by decreasing the stand density and leaf area, and therefore releasing the competition for water amongst trees (Bréda et al., 1995; Keyser and Brown, 2014; Moreno and Cubera, 2008; Rodríguez-Calcerrada et al., 2011; Sohn et al., 2016). The subsequent increased water availability to the remaining trees is expected to improve their water status and hence their carbon assimilation (Limousin et al., 2010). Furthermore, a decreased seasonal water stress allows trees to sustain cell turgor and therefore to maintain the meristematic and cambial activity (Fatichi et al., 2014). Whether tree growth is limited by carbon assimilation (i.e. source limitation) or cambial activity (i.e. sink limitation) is still unclear and likely depends on the locally most limiting resource (Guillemot et al., 2015), but in either case growth should be favoured by thinning. In strongly water-constrained ecosystems such as Mediterranean forests, sink activity appears to be more limiting than carbon supply and to be the main driver of tree growth (Lempereur et al., 2015). Stem growth in holm oak forests has been reported to depend mainly on climatic variables, and especially on winter temperatures and on summer precipitations and temperatures (Corcuera et al., 2004; Gutiérrez et al., 2011). Lempereur et al. (2015) further proposed that holm oak growth could be predicted by the duration of spring growth, which onset depends on winter temperatures and which cessation is controlled by a water potential threshold. Here we hypothesize that thinning improves tree growth by decreasing water competition and consequently delaying the drought-induced summer growth cessation.

To test this hypothesis, we applied a daily water balance model to simulate the date of drought-induced growth cessation and predict tree growth in a *Quercus ilex* forest in which several thinning intensity treatments were conducted and followed over a 30-year period. The specific objectives of our study are to (i) quantify experimentally the long-term effect of thinning on tree growth and wood production in a Mediterranean *Q. ilex* coppice and (ii) verify the growth duration hypothesis proposed by Lempereur et al. (2015) in stands with a wide range of tree densities, using a modelling experiment.

2. Material and methods

2.1. Site description

The study site is located 35 km northwest of Montpellier, Southern France, in the state forest of Puéchabon (43°44′29″N, 3°35′45″E, 270 m a.s.l). This forest has been managed as a coppice for centuries with a clear-cut frequency of approximately 25 years, but its exploitation stopped in the first half of the 20th century. Depending on the plots, the last clear cut took place in 1928 or 1942 and no fire or management occurred since then.

Q. ilex is the dominant species and forms a dense canopy at an average height of 5.5 m. The average stand density was 4700 stems ha^{-1} in 2014 and the average diameter at breast height (DBH, measured at 1.30 m) was 8.4 cm. The main understory species are *Buxus sempervirens*, *Juniperus oxycedrus*, *Pistacia lentiscus*, *Pistacia terebinthus*, and *Phyllirea latifolia* and form together a sparse shrubby layer with less than 25% of coverage.

The shallow bedrock has a Jurassic limestone origin and the volumetric fraction of rocks in the soil is 75% in the top 0–50 cm and 90% below, making a limited soil reserve of extractable water around 140 mm. The stone-free fine fraction of the top-soil (within 0–50 cm) is a homogeneous silty clay loam (USDA texture triangle; 38.8% clay, 35.2% silt and 26% sand). Most of the root biomass is located in the top horizon, however *Q. ilex* roots have been observed to extract water up to a depth of 4.50 m.

The climate is Mediterranean with a mean annual rainfall of 924 mm over the period 1984–2014. Approximately 80% of the annual precipitation falls between September and April, and the summer months are characterized by an important water deficit. The mean annual temperature over the same period is 13.3 °C, the coldest month being January (5.5 °C) and the hottest month July (22.9 °C). A meteorological station located on-site since 1984 provides daily recordings of precipitation and minimum and maximum air temperature.

2.2. Thinning experiment

The thinning experiment started in 1986 and is composed of 15 plots of 1000 m^2 each, divided into 3 blocks. The last clear-cut occurred in 1942 for the blocks 1 and 2, and in 1928 for the block 3. Selective thinning from below (*sensu* Assman, 1970), which consists in removing the smallest stems to the benefit of the biggest ones, was applied in March 1986 when stems were 44 years old in the blocks 1 and 2 and 59 years old in the block 3. Five thinning intensities were applied where approximately 0%, 25%, 45%, 60% and 80% of the basal area was removed, hereafter named Control, T25%, T45%, T60% and T80%, respectively. Each treatment level was applied to a 1000 m^2 plot and replicated in each of the three blocks. The number of stems that were removed varies between 55%, for T25% and 90% for T80%.

The Diameter at Breast Height (DBH) of each *Q. ilex* stem was measured during two full inventories in 1986, before and after thinning. The Control and T80% plots of the block 1 were fully inventoried again in 2015. In each of the 15 plots, the DBH of a sub-sample of trees (45 stems in the thinned plots and 60 stems in the control plots) was measured annually from 1986 to 1991 and then again in 2013 and in 2015. DBH was consistently measured in winter during dry conditions using a diameter tape, at a location on the stem identified by a painted mark in order to minimize the error between repeated measures. In the thinned plots, the sampled stems were selected to be representative of the diameter distribution within each plot, whereas in the control plots more of the larger stems were selected in order to include stems of similar diameter than in the thinned plots. The characteristics of this sampling are summarized in Table S 1.