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

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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.

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## 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

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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 |

**Table 2**
Climatic values at the end of the simulation period (2100) for the three sites under two climatic scenarios: B2 (moderate) and A2 (severe). Values in brackets indicate the difference with respect to initial values (Table 1).

| | Humid | | Mesic | | Xeric | |
|---|---|---|---|---|---|---|
| | B2 | A2 | B2 | A2 | B2 | A2 |
| Mean annual temperature (°C) | 11.4 (+26.7%) | 13.3 (+47.8%) | 14.4 (+20.0%) | 16.3 (+35.8%) | 15.0 (+20.0%) | 16.7 (+33.6%) |
| Mean annual rainfall (mm) | 776.4 (−3.7%) | 686.8 (−14.8%) | 651.4 (−8.8%) | 592.8 (−17.0%) | 564.2 (−0.0%) | 506.3 (−10.3%) |
| Martonne Index | 36.3 (−18.0%) | 29.5 (−33.4%) | 26.7 (−17.8%) | 22.5 (−10.4%) | 22.6 (−10.0%) | 19.0 (−24.3%) |

et al. (2016), in which stand density depends on the mean quadratic diameter ($d_g$) and site aridity:

$$N_{max} = (C_0 + C_1 \cdot log(M)) \cdot d_g^{(E_0+E_1M)} \quad (1)$$

where $M$ is the Martonne's Aridity Index (P/(T+10)) and $C_0$, $C_1$, $E_0$ and $E_1$ are estimated parameters (for *Pinus sylvestris*, $C_0 = 339979$, $C_1 = -2764.14$, $E_0 = -1.9662$, and $E_1 = 0.0065$, Condés et al., 2016). To ensure some variation in the initial conditions, the diameter distribution of the virtual stands was drawn from a truncated normal distribution ($\mu = 12.5$ cm, $\sigma = 1.87$, min = 0 cm, max = 25 cm).

We defined eight different treatments of increasing thinning intensity. In the first treatment (control) no thinning was applied to the virtual stand, whereas subsequent treatments implied the removal of 10, 20, 30, 40, 50, 60 and 70% of stand basal area, respectively. In all cases, thinning was applied from below, i.e. we started removing the smallest diameter trees and worked upward through diameter classes until the specified target basal area was achieved. The details on the density and basal area removed by site, treatment and diameter class can be found in Appendix B in Supplementary material.

### 2.4. Modeling forest structure dynamics with SORTIE-ND

Growth and mortality after thinning were simulated for 90 years under the three climatic scenarios using SORTIE-ND version 7.4 (http://www.sortie-nd.org) (Canham et al., 2005). SORTIE-ND is a spatially explicit, individual-based model of forest dynamics, in which the growth of every single individual tree is influenced by its spatial context and climate according to the following equation:

$$Diam.\ Growth = PDG \cdot Size\ effect \cdot Crowding\ effect \cdot Temp.\ Effect \cdot Prec.\ Effect \quad (2)$$

where $PDG$ is the maximum potential diameter growth (in mm yr$^{-1}$), whereas size, crowding, temperature and precipitation effects are all factors that act to reduce the estimated maximum growth rate. Each of these effects is a scalar that ranges between 0 and 1. *Size effect* takes the form of a lognormal function, whereas *crowding effect* is based on the Neighborhood Competition Index (NCI, Canham and Uriarte, 2006), which states that competition exerted to a target tree by its neighbours increases with the size of the neighbours and decreases with their distance to the target tree. *Temperature effect* and *precipitation effect* are modelled using a bivariate Gaussian function. Each of the parameters needed to estimate diameter growth were obtained using likelihood methods and data from the Spanish Forest Inventory IFN (Gómez-Aparicio et al., 2011; Ameztegui et al., 2015), and the results were validated against an independent dataset. Details on the exact formulation of tree growth, the parameter values used to run the simulations and the validation can be found in Appendix C in Supplementary material.

The site characteristics defined a stand structure that was used as starting point for SORTIE-ND (Fig. 1). We ran 5 replicates of each simulation to account for the stochasticity of some processes (the position of individual trees, as well as mortality). SORTIE-ND produced annual estimates of stand structure, based on the position, diameter and growth of every individual tree in a plot.

### 2.5. Modeling water balance and drought stress

The water balance model described in De Cáceres et al. (2015) (implemented in an R package called 'medfate') was used to estimate water fluxes and stand drought stress over the 90 years for each combination of plot, climatic scenario and thinning intensity. The model follows the design principles from BILJOU (Granier et al., 1999) and SIERRA water balance submodel (Mouillot et al., 2001). The model performs daily updates of soil water content as a function of the stand structure and daily weather (radiation, temperature and precipitation). Soil water balance is the difference between processes determining water input (precipitation) and outputs (canopy interception, tree transpiration, bare soil evaporation, surface runoff and deep drainage). Details of the formulation of each of these processes are given in De Cáceres et al. (2015).

The water balance model requires stand structure to be described at the cohort level by the average height of individuals and their cumulative leaf area index (*LAI*). The diameter distribution dynamics given by SORTIE-ND were used to update the canopy evaporative surface every year by calculating *LAI* of each cohort as follows:

$$LAI = SLA \cdot 1/S \cdot \sum_{i=1}^{n} \left[ a \cdot DBH_i^b \cdot e^{c \cdot BAL_i} \cdot DBH_i^{d \cdot BAL_i} \right] \quad (3)$$

where $n$ is the number of individuals of the cohort, $SLA$ is the specific leaf area of *P. sylvestris* in Catalonia, $S$ the plot surface, i.e. 10 000 m$^2$, $DBH_i$ is the diameter at breast height of the target tree $i$, and $BAL_i$ is the basal area of trees with a larger DBH than the target tree $i$; whereas $a$, $b$, $c$, and $d$ are parameters calibrated against data from the Catalan forest inventory (Gracia et al., 2004). Soil was represented using two layers with a total depth of 50 cm, a loamy texture (USDA soil texture definition) and a rock content fraction of 10–15% in volume. The proportion of fine roots in the two layers was set assuming a conic distribution of the roots across the whole profile.

The daily water balance was simulated for each input stand structure dynamic simulated by SORTIE-ND (i.e. one for each combination of site, climatic scenario, thinning intensity and simulation replicate). In the same way as for SORTIE-ND simulations, the water balance simulations were replicated 15 times in order to account for the stochasticity of the water balance model induced by the downscaling of the monthly to daily precipitation, raising the total number of simulation replicates to $5 \times 15 = 75$.

We calculated the annual proportion of blue water ($BW_{year}$) as the annual sum of water exported via runoff and deep drainage relative to annual precipitation. Annual $BW_{year}$ values were averaged over the 90-year period to obtain a single estimate of blue water proportion ($BW$) for each combination of site, treatment, climate scenario and replicate. In order to estimate daily drought stress,

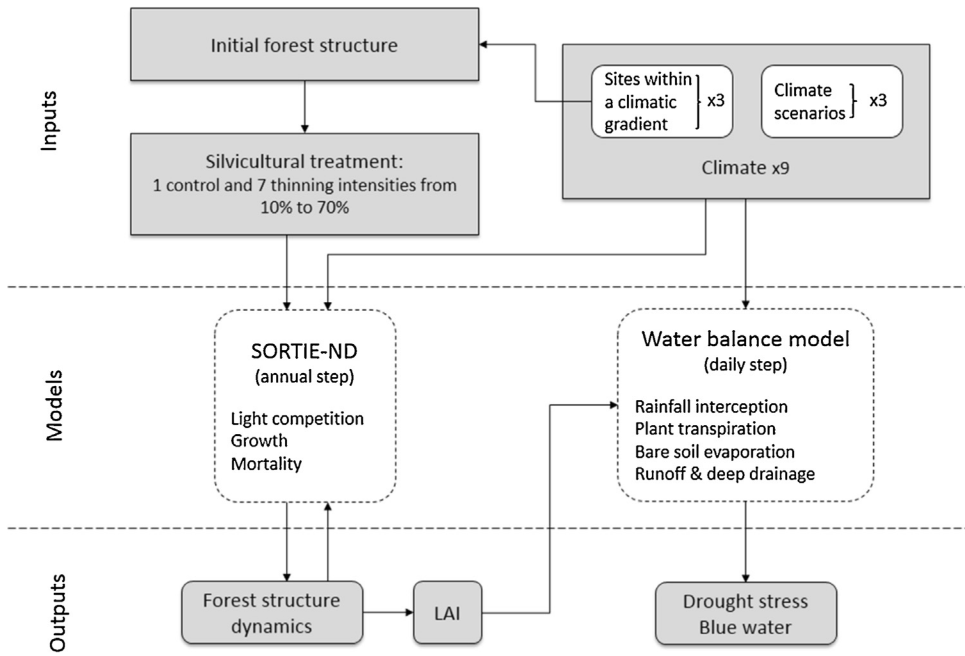


**Fig. 1.** Diagram showing the integration of SORTIE-ND and the water balance model from 'medfate' R package to simulate the effects of thinning and climate change on forest dynamics and water balance. Site characteristics define the initial forest structure, which is entered into SORTIE-ND. Competition, growth and mortality are then simulated for 90 years under three climatic scenarios. SORTIE-ND provides annual outputs of forest structure, which are subsequently used by the water balance model, together with climatic data, to estimate rainfall interception, evapotranspiration, runoff and deep drainage. Outputs from this latter model are finally used to estimate plant drought stress and blue water.

we first calculated the whole plant relative conductance ($K$) as a function of the soil water potential (De Cáceres et al., 2015):

$$K = 1/2 \cdot \sum_{k=1}^{2} \nu_k \cdot exp\left\{-ln\left(1/2\right) \cdot \left(\frac{\psi_{soil,k}}{\psi_{50}}\right)^3\right\} \quad (4)$$

where $\nu_k$ and $\Psi_{\text{soil,k}}$ are the root proportion and the soil water potential in the $k^{\text{th}}$ soil layer, respectively, and $\Psi_{50}$ is the water potential at which the relative conductance of *P. sylvestris* is equal to 50% ($\Psi_{50} = -3.61$ MPa; Choat et al., 2012). We defined a daily drought stress index ($SI_{day}$) as the complement of the whole plant relative conductance (1–$K$) and an annual drought stress index ($SI_{year}$) as the average of the daily drought stress of the 30 consecutive driest days of the year. We finally defined the drought stress corresponding to the 90 year- period of each simulation ($SI$) as the average of the $SI_{year}$ of the driest 5 consecutive years.

The effect of thinning on $SI_{year}$ was calculated for every thinning treatment and timestep as the difference in $SI_{year}$ between the thinned stands and the control. We thereafter defined the duration of the effect ($T_{50,stress}$) as the number of years for which the effect of thinning was clear, i.e. at least 50% of the initial effect on $SI_{year}$ (average of the 5 first years after thinning). Similarly, the duration of blue water surplus ($T_{50,BW}$) was calculated as the number of years for which the surplus in $BW_{year}$ was at least 50% of the initial surplus (the difference between thinned and unthinned stands for the first 5 years after thinning).

## 3. Results

### 3.1. Effects of thinning intensity, site conditions and climatic scenario on tree growth and stand productivity

The maximum final basal area was obtained at different thinning intensities depending on site conditions and climatic scenario (Fig. 2A). At the humid site, maximum basal area was obtained at intensities between 20 and 30%. For the mesic and xeric sites, early timber extraction through low or moderate thinnings (<30%) was offset by a greater growth of the residual stands but barely exceeded the final basal area of the control treatment (i.e., no thinning) (Fig. 2A). In all cases the final stand stock rapidly decreased at higher thinning intensities (>40%). Moreover, the decrease in final basal area occurred at lower thinning intensities the drier the site conditions. Differences among climatic scenarios in terms of the thinning intensity corresponding to maximum final basal area were small (Fig. 2A). Thinning intensity exerted an immediate positive effect on basal area increment (BAI, expressed as the annual increase in stand basal area). Moderate and heavy thinnings (>30%) had comparable effects on BAI, which doubled during the first years in all the plots (Fig. 2B), whereas light thinnings caused a much smaller effect. In any case, the initial positive effect of thinning on BAI vanished after 30–40 years, independently of the site and climate scenario (Fig. 2B).

### 3.2. Effects of thinning intensity, site conditions and climatic scenario on tree drought stress and blue water

Average blue water ($BW$; i.e., the proportion of precipitation lost via runoff or deep drainage, averaged across years) increased non-linearly with thinning intensity at all sites (Fig. 3A). Although $BW$ tended to represent a higher proportion of total rainfall the more humid the site conditions and the milder the climatic scenario, the differences among climate scenarios were small and tended to decrease with thinning intensity. At the highest thinning intensity, $BW$ represented ~50% of total precipitation for all sites and climatic scenarios. Average tree drought stress ($SI$) was higher the more xeric the site and for the most severe climatic scenario (A2), whereas there were almost no differences between scenarios B2 (moderate climate change) and NoCC (no climate change). For the unthinned stands, $SI$ was always <0.5 (i.e. the simulated percentage of loss of conductivity was inferior to 50%) at the humid site, but always exceeded this value at the xeric site. The mesic site exhibited an intermediate behaviour, with $SI$ of unthinned stand

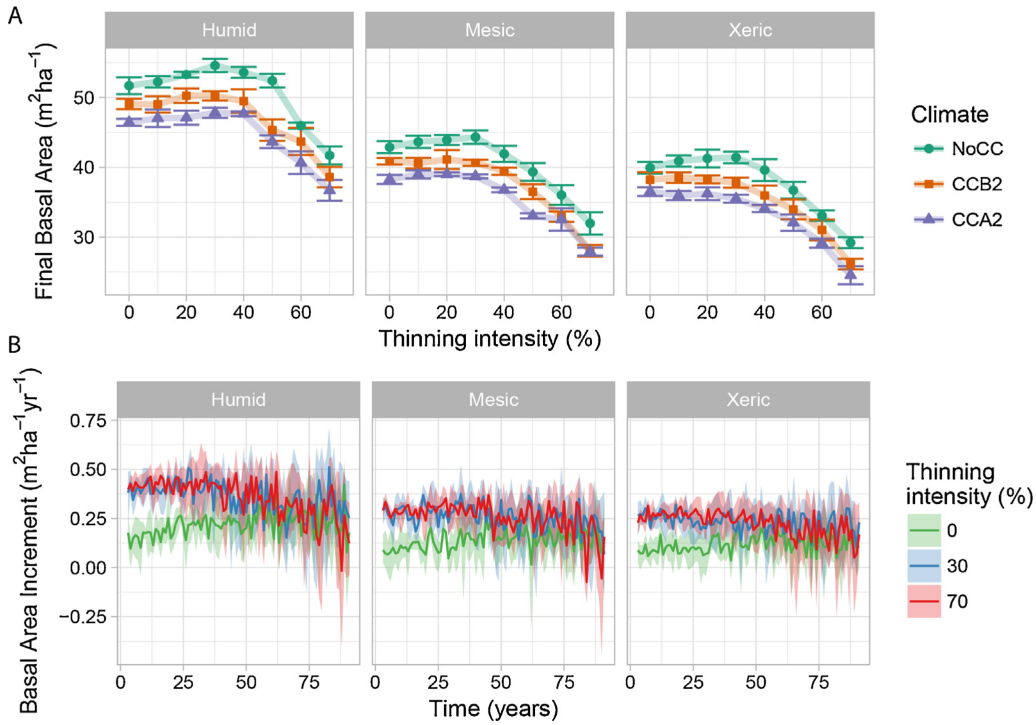


**Fig. 2.** Effects of thinning intensity and climatic scenario on final stand basal area (a), and temporal dynamics of basal area increment as a function of thinning intensity (b) for three plots of Scots pine (*Pinus sylvestris*) across a range of initial climatic conditions. In (a), points and error bars represent the mean ± 1 SD of SORTIE-ND simulation replicates (n = 5). In (b), solid lines represent the basal area increment averaged across replications (n = 5) and shaded areas represent the range between the 5th and 95th centile. For (b), only the scenario with no climate change is shown.

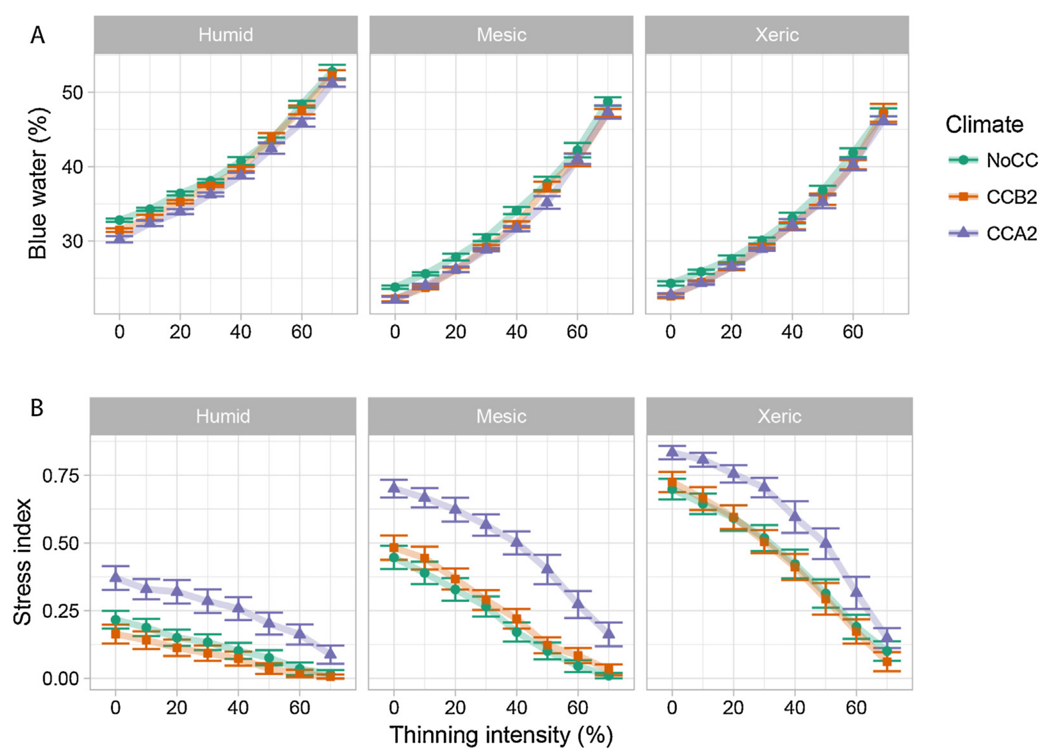


**Fig. 3.** Effects of thinning intensity (in percentage of removed BA) and climatic scenario on (a) the 90-year average blue water expressed in percentage of annual precipitation (*BW*) and (b) stress index (*SI*), i.e. the average of the $SI_{year}$ for the driest 5 consecutive years; for three plots of Scots pine (*Pinus sylvestris*) across a range of climatic conditions. Points and error bars represent the mean ± 1 SD of the simulation replicates (n = 75).

being much higher (∼0.70) under the A2 climate scenario, whereas it was slightly below 0.5 under the climate scenario B2 and NoCC (Fig. 3B). Thinning had the consistent effect of reducing *SI* for all sites and climatic scenarios, leading the differences in tree stress among scenarios to decline with thinning intensity, and *SI* was below 0.2 for all sites and climate scenarios for the strongest thinning treatment. Consequently, the decrease of drought stress with thinning intensity was the highest at the xeric site (Fig. 3B).

Heavier thinning resulted in an increase of $T_{50,BW}$, i.e. the thinning effect on $BW_{year}$ persisted more years (Fig. 4A, and see also Appendix D in Supplementary material). The increase in $T_{50,BW}$ with thinning intensity was similar across climatic scenarios. At the xeric site, there was an apparent unimodal effect of thinning intensity on $T_{50,BW}$, with the lowest duration of the effect at 30% removal of basal area. However, the variability of $T_{50,BW}$ was higher at low thinning intensities, since the lower absolute effect of thinning made the duration of this effect more susceptible to extreme climatic years.

Similarly, high thinning intensities also resulted in higher values of $T_{50,Stress}$, i.e. a higher number of year for which the effect of thinning on $SI_{year}$ is superior to 50% (Fig. 4B). There was often a high variability between the simulation replicates, which tended to decrease with thinning intensity. For a given thinning intensity, there was no systematic direction in the differences between the climatic scenarios NoCC and B2 and differences tended to be overridden by simulations dispersion when it was noticeable. On the contrary the climate scenario A2 had a large, negative impact on the duration of the effect of thinning on $SI_{year}$ (Appendix D in Supplementary material). Furthermore, the extent of the differences between the climate scenarios was largest at the humid site and lowest at the xeric site, indicating that the duration of the thinning effect on alleviating drought stress is more negatively impacted by climate change at the humid than at the xeric site.

### 3.3. Trade-offs between stand productivity and water balance

Average blue water (*BW*) and final stand basal area increased simultaneously with thinning intensity for light thinnings (Fig. 5A). In all cases, there was an optimum thinning intensity at which *BW* increased without inducing a decrease in final basal area. This optimum yielded a lower *BW* value and final basal area for drier climatic scenarios/sites. From this point, higher thinning intensities resulted in decreases in basal area, while *BW* kept increasing. This negative relationship was close to linear and represented the trade-off between productivity and the amount of available water, the slope of which was similar amongst sites and scenarios.

There was an analogous relationship between average stress index (*SI*) and the final basal area (Fig. 5B): *SI* decreased consistently with thinning intensity, while the final basal area reached an optimum and then decreased. However, there was a strong combined effect of site and climatic scenario on this relationship. At the humid site, *SI* was reasonably low (i.e. <0.5) even when no thinning treatment was applied, while low to moderate thinning intensities (<30% removal of BA) led to the greatest productivity in terms of final basal area. The same pattern was observed at the mesic site under the NoCC or B2 scenarios. However, for the A2 scenario, *SI* under low intensity thinning remained high at both the mesic and the xeric site, and drought stress could only be reduced to values <0.5 through intense thinning, with the consequence of substantially decreasing the final basal area of the stand (Fig. 5B).

## 4. Discussion

Our results highlight the existence of a trade-off between the gain in stand productivity and the improvement in tree water status obtained by thinning for moderate or heavy thinnings. Although this trade-off has not received much attention yet, it has important implications in the context of forest management for multiple objectives and under climate uncertainty. More interestingly, the trade-off was site- and climate-dependent, and strongly argue against general recipes across sites.

### 4.1. Effect of thinning intensity on stand structure and production

The stand structure resulting from the simulations after thinning matched previous observational studies with Scots pine: final mean tree diameter in heavily thinned stands was on average 1.6 fold higher than control stands after 40 years and double at the end of the simulations, values very close to those previously reported for Scots pine in Spain (Montero et al., 2001; del Rio et al., 2008). BAI was initially doubled by moderate or heavy thinning (>30%), also in accordance with previous studies (del Rio et al., 2008; Sohn et al., 2016), and final basal area after 90 years under no climatic scenario matched values commonly observed in managed stands in Catalonia (Piqué et al., 2011a). Previous experimental studies have shown that the maximum stand production is reached at intermediate thinning intensities, since the strong growth increase of individual trees in the heavy thinning treatments is usually not enough to compensate the sharp reduction in stand density (Montero et al., 2001; del Río et al., 2008; Giuggiola et al., 2013). Our simulation study led to patterns in accordance with observations, and it showed maximum stand production to occur at lower thinning intensities the more xeric the initial site conditions and the more severe the climatic scenario.

### 4.2. Effect of thinning intensity on tree drought stress and blue water

Previous studies have highlighted a direct relationship between thinning intensity, the amelioration of tree water status, and the increase of available blue water. Thinning increases throughfall precipitation due to the decrease of the canopy density (Limousin et al., 2008). It also has the potential to substantially decrease the stand-level transpiration despite increasing the tree-level water use (del Campo et al., 2014; Gebhardt et al., 2014). Hence, it increases soil water availability (Bréda et al., 1995; Jiménez et al., 2008), reduces tree drought stress (Aussenac and Granier 1988; Rodríguez-Calcerrada et al., 2011) and increases the amount of water exported via deep drainage (del Campo et al., 2014). Our water balance model allowed us to simulate all these effects with a reasonable degree of realism. For instance, del Campo et al. (2014) showed that removing 75% of the stand basal area in an Aleppo pine forest increased blue water percentage by almost 30% in the two following years and by 20% a decade later, which is similar to the 20–40% average increase obtained in this simulation experiment.

More generally, thinning had the effect of consistently increasing the amount of blue water along with the treatment intensity, as it was reported by del Campo et al. (2014). However, this effect was very little dependent on the site and climatic scenario. This is partially due to the fact that we defined $BW_{year}$ as a ratio between exported water and precipitation. Thinning as a means to improve the blue water provision therefore seems to be a suitable management option in the Mediterranean area (Callegari et al., 2003), regardless of the local climate conditions.

Previous works report a direct reduction of drought-induced mortality of Scots pine for high thinning intensities (Giuggiola et al., 2013). However, there are more ambiguous results on whether thinning favours the resistance of trees (i.e. it reduces the growth decline caused by drought; Misson et al., 2003; Martín-Benito et al., 2010; Giuggiola et al., 2013), the recovery of growth following drought events (Sohn et al., 2013, 2016), or both (D'Amato et al., 2013). The water potential inducing 50% of loss of conductivity has been associated to a threshold provoking irreversible drought damage for conifer species (Brodribb and Cochard, 2009; Brodribb et al., 2010). One can therefore assume that the combination of climate, site and treatment with a *SI* value superior to 0.5 is likely to induce die-off events. At the xeric site, the control treatment induced values of $SI > 0.5$ even under current climatic conditions,

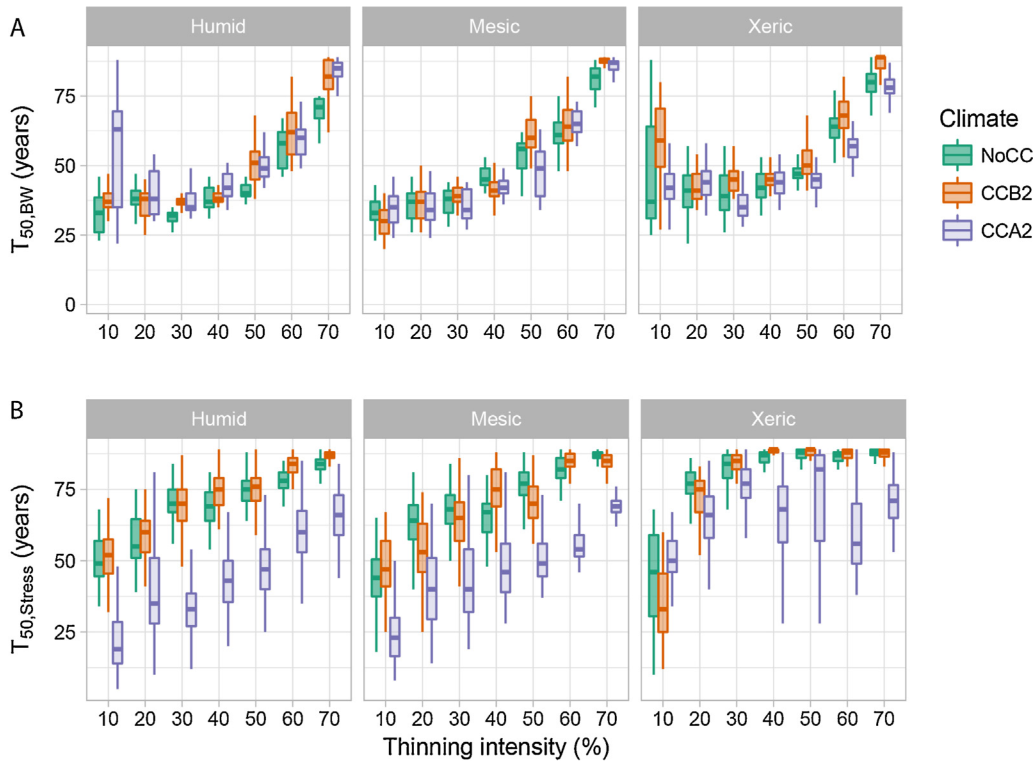


**Fig. 4.** Effects of thinning intensity (in percentage of removed BA) on (a) $T_{50,BW}$ and (b) $T_{50,stress}$ for three plots of Scots pine (*Pinus sylvestris*) across a range of climatic conditions. For all boxplots, the central solid line indicates the median, whereas lower and upper hinges indicate the first and third quartile (i.e. the Inter Quantile Range, IQR). The upper (lower) whisker extends from the hinge to the largest (smallest) value under (above) 1.5 × IQR from the hinge. Outliers are not represented.

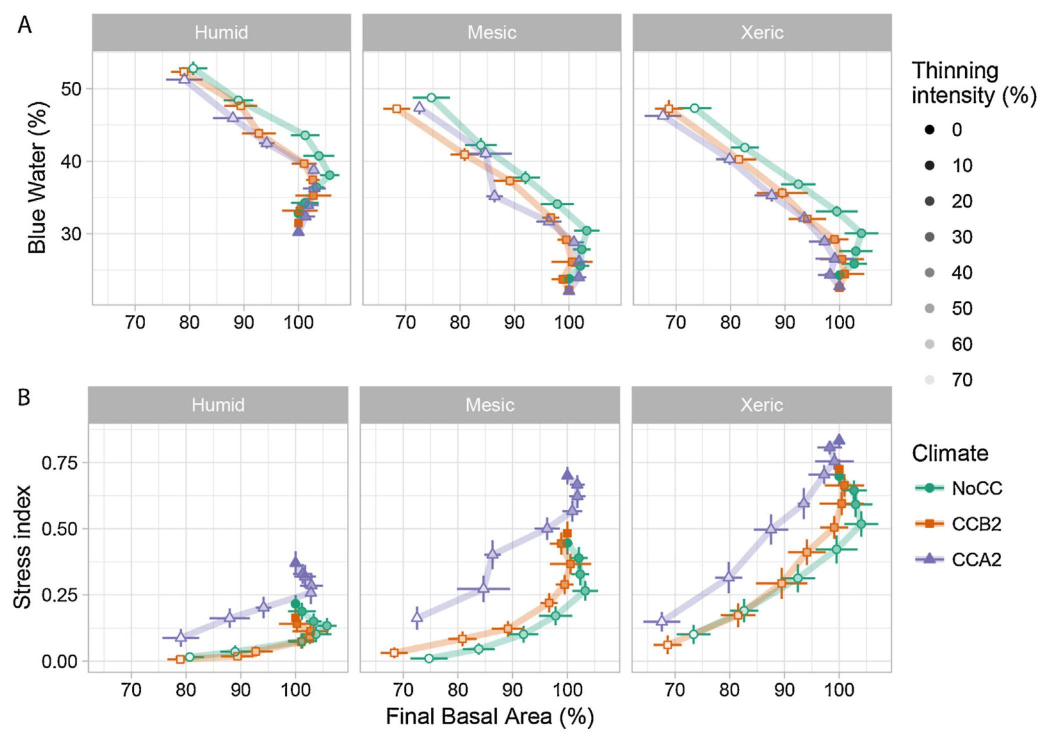


**Fig. 5.** Effects of thinning intensity on the interaction between final basal area and (a) blue water (BW), expressed in percentage of annual precipitation; and (b) stress index (SI) for three plots of Scots pine (*Pinus sylvestris*) across a range of climatic conditions. Final basal area is the basal area of the standing trees at the end of the simulation relative to the final basal area of the unthinned plots. Points and error bars represent the mean ± 1 SD of the simulation replicates (x-axis: n = 5, y-axis: n = 75).

which can be linked to the drought related die-off and defoliation events that have been observed since the 1990s in a *P. sylvestris* stand of NE Spain with similar site conditions (Martínez-Vilalta and Piñol, 2002; Hereş et al., 2012). Here, we observed that the drought stress index was lower and decreased almost linearly with thinning intensity for the mildest conditions (humid site, or mesic site without climate change), whereas the initial stress was higher and its decrease was steeper for heavier thinning intensities under the most xeric conditions. These results suggest that decreasing drought stress would be necessary in drought-exposed areas in order to avoid important die-off events under future climatic conditions, and that intense thinning in these areas could be an efficient way to reduce drought stress and hence mortality (Sohn et al., 2016). Although the alleviation of drought stress was more important at xeric sites, the effect lasted similarly across the three studied sites. For a given thinning intensity, the effect of thinning lasted similarly between NoCC and A2 but was generally much shorter for A2. Previous studies with Scots pine found that the effects of thinning on tree growth were still noticeable for up to three decades in xeric stands (Giuggiola et al., 2013), but anticipated lower effectiveness under severe climatic change (Sohn et al., 2016). In agreement with these results, our model simulated the effects of thinning on basal area increment to last for 30–40 years and the return time of drought stress to be much lower for climate scenario A2, which could potentially lower the long term effect of thinning in this case. Frequent thinning regime may therefore be required under severe climate change scenarios in order to maintain the positive effects on the remaining stand (Sohn et al., 2016).

### 4.3. Potential shortcomings of the modelling approach

The results showed that our approach could correctly predict the dynamics of Scots pine forest stands after thinning. We validated the model of forest dynamics (SORTIE-ND) against an independent dataset, and it produced unbiased estimations of tree growth and stand basal area increment across a wide range of initial tree densities (see Appendix C in Supplementary material). On the other hand, the water balance model had been previously validated against measurements of soil moisture dynamics and plant transpiration in several forest plots, providing satisfactory results (De Cáceres et al., 2015). However, some processes could not be included in our approach and are worth mentioning, since they represent further development goals.

First, tree mortality in our simulations was not drought-stress dependent, but density-dependent. Previous observational studies have shown that thinning can reduce the slope of the allometric relationship between stand density and corresponding mean tree diameter (Giuggiola et al., 2013), so this could lead to underestimations of tree mortality, particularly at the most xeric sites and the most severe scenarios (Condés et al., 2016). However, it is difficult to model drought-related mortality either using process-based models or empirical models (but see Gustafson and Sturtevant, 2013), and accounting for drought-dependent mortality would require the parameterization of this process across a range of water conditions, which is yet to be done in the study area and was beyond the scope of this work. Moreover, we could not include the shrubby layer in our simulations due to the lack of available data to model their growth, mortality and water balance under contrasting environmental conditions. Shrub abundance in Scots pine stands is closely related to tree canopy cover (Coll et al., 2011), so heavy thinnings can promote its development and increase the understory to overstory transpiration ratio (Simonin et al., 2007; Gebhardt et al., 2014). Last, the allometries used to derive LAI based on forest structure are also likely to be affected by thinning. While drought-induced tree mortality could potentially induce an overestimation of the stand LAI, especially for the unthinned treatments, the effect of using static allometries and not accounting for understory growth could lead to an underestimation of the LAI recovery rate after thinning. Put together, those inaccuracies have the potential to exaggerate the actual differences between the control and the thinned treatments, which in turn potentially leads to an overestimation of the effect of thinning on blue water and water status improvement. However, we believe that these potential shortcomings are not affecting the main results obtained in this simulation study, although they constitute future research topics that could help further refine our predictions.

### 4.4. Thinning to enhance the adaptability of Scots pine to climate change: implications for management

Low or medium intensity thinning could simultaneously improve stand productivity and water yield at all sites, but only in a scenario without climate change. Under climate change scenarios, a simultaneous positive effect of thinning on the two main objectives was only possible – in a lesser extent – at the humid site, when tree water stress was relatively low regardless the thinning treatment. Conversely, thinning could barely improve stand productivity when the drought stress of the control treatment was strong. However, it should be taken into account that the present work did not evaluate the effects of complex thinning regimes including simultaneous variation in thinning intensity and rotation. Its is thus possible that less intense but more frequent thinning treatments could lead to different outputs.

Our results agreed with del Campo et al. (2014) in that hydrology-oriented silviculture can be an interesting option to increase the resistance of forests to drought in xeric sites. In these areas, our simulations found effective reductions of tree water stress following thinning treatments, although under severe climate warming scenarios very heavy or repeated thinning would be needed. Our modelling approach may provide interesting insights here, since the duration of the thinning effect on water stress ($T_{50,Stress}$) could be used as a guideline to design thinning regimes (in particular, thinning schedules) that maintain tree water stress below critical values. However, in some particular sites (i.e. at the xeric edge of the species distribution), even heavy, repeated thinnings may not be enough to alleviate drought stress, and the persistence of the species could be compromised no matter the thinning regime (see also Elkin et al., 2015). In this context, treatments may be conceived to promote the transition of these Scots pine forests to mixed forests with more drought-resistant tree species (Giuggiola et al., 2013).

In the mesic and humid areas, where most productive Scots pine stands locate, a compromise between the maintenance of stand production and the improvement of blue water provisioning and/or drought stress relief could be achieved by the application of intermediate to heavy thinning (as also reported by Magruder et al., 2013). However, in the mesic areas, particular caution needs to be taken when defining the treatments, since for a giving thinning intensity the effects on productivity and tree water stress can substantially vary depending on the climatic scenario considered. In summary, our results strongly argue against general management recommendations that do not take into account the specificity of site conditions and thinning intensities to be applied. Instead, a case-by-case approach would be needed in order to elaborate guidelines adapted to the particularities of each situation. In this context, modelling approaches such as the one presented here could be interesting to provide the flexibility needed to produce case-specific recommendations.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolmodel.2017.04.006.

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