Agricultural and Forest Meteorology 206 (2015) 151–162

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

What drives growth of Scots pine in continental Mediterranean climates: Drought, low temperatures or both?

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ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form 9 March 2015
Accepted 11 March 2015

Keywords:
Pinus sylvestris
Drought stress
Elevational gradient
Latitudinal gradient
Minimum temperature
Dendroecology

ABSTRACT

Scots pine forests subjected to continental Mediterranean climates undergo cold winter temperatures and drought stress. Recent climatic trends towards warmer and drier conditions across the Mediterranean Basin might render some of these pine populations more vulnerable to drought-induced growth decline at the Southernmost limit of the species distribution. We investigated how cold winters and dry growing seasons drive the radial growth of Scots pine subject to continental Mediterranean climates by relating growth to climate variables at local (elevational gradient) and regional (latitudinal gradient) scales. Local climate-growth relationships were quantified on different time scales (5-, 10- and 15-days) to evaluate the relative role of elevation and specific site characteristics. A negative water balance driven by high maximum temperatures in June (low-elevation sites) and July (high-elevation sites) was the major constraint on growth, particularly on a 5- to 10-day time scale. Warm nocturnal conditions in January were associated with wider rings at the high-elevation sites. At the regional scale, Scots pine growth mainly responded positively to July precipitation, with a stronger association at lower elevations and higher latitudes. January minimum temperatures showed similar patterns but played a secondary role as a driver of tree growth. The balance between positive and negative effects of summer precipitation and winter temperature on radial growth depends on elevation and latitude, with low-elevation populations being more prone to suffer drought and heat stress; whereas, high-elevation populations may be favoured by warmer winter conditions. This negative impact of summer heat and drought has increased during the past decades. This interaction between climate and site conditions and local adaptations is therefore decisive for the future performance and persistence of Scots pine populations in continental Mediterranean climates. Forecasting changes in the Scots pine range due to climate change should include this site-related information to obtain more realistic predictions, particularly in Mediterranean rear-edge areas.

1. Introduction

Plant growth seasonality is characterized by favorable and adverse climatic conditions for tree growth, such as those faced

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http://dx.doi.org/10.1016/j.agrformet.2015.03.004
0168-1923/

by forests subjected to continental Mediterranean climates, where trees endure the double climatic stress of cold winters and summer droughts (Mitrakos, 1980). As a result, optimal growth conditions occur during the two milder periods with increased rainfall (i.e., spring and autumn) which usually produce a bimodal pattern of cambial activity (Camarero et al., 2010), so the question arises: which climatic factor limits tree growth to a greater extent, the winter cold constraints or drought during the main growing season (spring to summer)? The roles of the two stressors on growth processes such as wood formation are clearly different. For instance, the winter cold affects prior carbohydrate use by reducing photosynthesis and respiration rates (Gimeno et al., 2012), and may determine how well dry soils are recharged with water before spring cambial resumption takes place in spring (Pasho et al., 2011); whereas, drought directly constrains growth rates during the growing season (Camarero et al., 2014; Gutiérrez et al., 2011).

Understanding the effects of climate on tree growth is particularly relevant in continental areas of the Mediterranean Basin, which are considered major climate-change hot-spots where both warming and aridification trends have been observed (Giorgi, 2006). The Mediterranean region is exposed to transitional climatic conditions between the temperate and continental climate in the North and the subtropical climates further South (Köppen, 1936). Recent trends toward a warmer and drier climate have had negative effects on tree growth (Sánchez-Salguero et al., 2012) and forest productivity (Madrigal-González and Zavala, 2014). Thus, it would be of interest to assess how cold and droughts are related to tree growth in such area, particularly over the Western Mediterranean Basin (Xoplaki et al., 2012).

In connection to recent climate trends, in cold-limited Circum-Mediterranean areas such as the high-elevation ranges (e.g., Pyrenees, Iberian mountains, Balkans, Apennines, etc.) or plateaus (e.g., Iberian and Anatolian peninsulas) warmer winter temperatures could facilitate subsequent tree growth by extending the length of the growing season (Vaganov et al., 2006). In contrast, more frequent summer heat waves (Pichler and Oberhuber, 2007) and/or related droughts could limit tree growth by shortening the growing season (Eilmann et al., 2011; Galván et al., 2014). Lastly, the responsiveness of trees to climate is; however, highly dependent on topographical features such as elevation or aspect (Büntgen et al., 2012; Rigling et al., 2002), which moderate the water availability in Mediterranean mountain sites (Camarero et al., 2013; Candel-Pérez et al., 2012).

A comparison of long-term climate and tree growth data usually reveals that the climatic conditions prior to the growing season play a prominent role in wood formation (Fritts, 2001), and Circum-Mediterranean forests are no exception (e.g., Büntgen et al., 2010; Camarero et al., 2013). The dendrochronological approach allows a treeís growth responses to climate to be inferred on a monthly scale, albeit such inferences should be complemented with short-term data (e.g., by using climate data compiled on a weekly or biweekly basis) and would be validated through xylogenesis studies (Camarero et al., 2010; Vaganov et al., 2006).

We used this multi-scalar approach to investigate how low winter temperatures and drought during the growing season in a continental Mediterranean climate drive the seasonal radial growth of Scots pine (*Pinus sylvestris* L.). This is the most widespread conifer species in the world, but it reaches its Southern and dry limit in the Iberian Peninsula (Mirov, 1967). First, we relate growth to changing climate conditions since 1900 at local scales by sampling three sites in the Spanish Central System at different elevations, and therefore varying climatic conditions. We expected lower winter temperatures would be the main climatic constraint on tree growth at high-elevation sites and spring-to-summer water deficits at low-elevation sites. Second, we extrapolated this local analysis to a regional scale along a latitudinal gradient using existing Scots pine tree-ring growth series form continental Mediterranean sites in Spain. We hypothesize that at the global limit to Scots pine distribution, the lowest sites and Southernmost sites will be responsive to drought; whereas, the highest and Northernmost sites will be most sensitive to winter temperature conditions.

2. Material and methods

2.1. Local study area

The local study area is located in the Valsaín forests in "Sierra de Guadarrama" National park, a mountainous area situated on the North-facing slopes of the Spanish Central System near Madrid (40°49′N, 4°1′W, elevation range 1100–2125 m a.s.l.). The forests studied are dominated by managed Scots pine stands and mixed with other less abundant tree species such as *Quercus pyrenaica* Willd. The geological substrates are granite and gneiss. Soils are usually acid, with humic cambisols or leptosols on the high-elevation sites.

The study area has a Mediterranean climate with a continental influence, characterized by dry summers and cool winter conditions. The total annual rainfall is 1266 mm and the mean annual temperature 6.5 °C, at 1890 m a.s.l., where the mean December–January temperature is −0.4 °C and that of July–August 16.5 °C (the coldest and warmest periods, respectively) for the period 1943–2011. We used local daily and monthly climatic data (mean maximum and minimum temperatures and total precipitation) to characterize the climatic conditions along the elevation gradient. For that purpose we obtained climatic data for the above-mentioned period from three meteorological stations located in the study area at different elevations (Puerto de Navacerrada, 40°47′N, 4°00′W, 1894 m a.s.l.; Granja de San Ildefonso, 40°46′N, 4°00′W, 1191 m a.s.l. and Observatorio de Segovia, 40°56′N, 4°10′W, 1005 m a.s.l.; see Appendix A). The temperature at the study site were estimated using data from these three stations and additional forest climatic data provided by Martínez-Alonso et al. (2007). To define a biologically realistic surrogate for the water availability for tree growth, we also estimated the monthly water balance (abbreviated as P-PET) as the difference between precipitation (P) and potential evapotranspiration (PET), according to Hargreaves and Samani (1982). Temporal trends in the monthly temperature and seasonal precipitation were calculated to characterize the climate of each site taking into consideration the reconstructed meteorological data for each elevation (Appendix A).

2.2. Field sampling and dendrochronological methods

We sampled three Scots pine stands located at different elevations in Valsaín forest (see Table 1; additional information on the study area is also available in Touchan et al., 2013). At each site, at least 25 dominant trees with diameters at 1.3 m (dbh) greater than 20 cm were sampled and their size (dbh, tree height) measured (Table 1). All the trees measured were cored at 1.3 m with a Pressler increment borer and two cores were taken per tree perpendicular to the maximum slope.

The cores were air dried, sanded with sand paper of progressively finer grain until tree-rings became clearly visible and then visually cross-dated. Individual tree-ring width series were measured to the nearest 0.01 mm using a LINTAB semi-automatic measuring device (Rinntech, Heidelberg, Germany). Cross-dating quality was checked using the program COFECHA (Holmes, 1983). To assess the quality of tree-ring width series several dendrochronological statistics (Fritts, 2001) were calculated considering the period 1950–2011 (Table 1): first-order autocorrelation of raw width data (AC), mean sensitivity (MS) of indexed growth values, mean correlation between trees (*rbt*), signal to noise