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Reduction of stand density increases drought resistance in xeric Scots pine forests

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ABSTRACT

In Valais, a dry Inner-Alpine valley in Switzerland, increasing tree mortality has been related to drought and reduced forest management, which have led to increased competition between trees. Since increasing drought and reduced forest management were co-occurring during the last decades, it is not clear if forest management alone could increase tree resistance to drought. To test whether thinning of Scots pine (*Pinus sylvestris* L.) stands could be used to mitigate the effects of drought, we analyzed a long-term thinning trial set up in xeric Pfynwald forest in 1965. The trial featured one control (unmanaged plots; basal area 40 m^2 ha^{-1}) and three thinning intensities; light (33 m^2 ha^{-1}), medium (22 m^2 ha^{-1}) and heavy (11 m^2 ha^{-1}). Thinning was repeated in 1971, 1978 and 2010. Individual tree radial growth responses and tree leaf area to sapwood area ratio were assessed and compared among treatment. Additionally, stand-level growth, tree mortality and the relationship between stand density and tree diameter (allometric slope *r*) were analyzed and compared between two periods (1978–1990; 1991–2009) where the last period was drier. Individual tree basal area increment increased significantly for up to three decades after heavy thinning and mortality rates decreased with decreasing basal area while stand-level growth did not significantly differ. The higher mortality rate and the more negative allometric slope *r* in the second period suggests that site conditions have become hotter and drier and can partially explain a decrease in the basal area in the control plots and in the light thinning treatment. Leaf area to sapwood area ratio increased with lower basal area and suggests that competition for water was reduced. Taken together, our results suggest that a reduction in basal area of 40–60% to ca. 15–25 m^2 ha^{-1} could mitigate drought effects on Scots pine on xeric sites for the coming decades prolonging the provision of important ecosystem services. After this time, sustainability of Scots pine forests at xeric sites will depend on the intensity of anticipated climate change, so that in the worst case, thinning might be applied to convert Scots pine forests to mixed forests with more drought-resistant species.

1. Introduction

Drought and warming induced tree mortality has been observed worldwide among many tree species and has increased in recent years (van Mantgem et al., 2009; Allen et al., 2010). In particular, Scots pine (*Pinus sylvestris* L.), widely distributed across Europe, is declining on xeric sites in areas ranging from the Central Alps (Oberhuber, 2001) to the southern edge of its distribution (Martínez-Vilalta and Piñol, 2002; Galiano et al., 2010).

In Valais, a dry Inner-Alpine valley in Switzerland, Scots pine forests provide various ecological services, including protection (against avalanches, landslides, rockfall and erosion), biodiversity and recreation (Huber et al., 2013). In the past decades, drought resulted in growth decline (Bigler et al., 2006; Eilmann and Rigling, 2012), and increased tree mortality, particularly in Scots pine since the 1990s (Rigling and Cherubini, 1999; Rebetez and Dobbertin, 2004; Rigling et al., 2013). There is evidence that drought and warming promotes outbreaks of phytopathogens and insects (Mattson and Haack, 1987; Dobbertin et al., 2007; Wermelinger et al., 2008) and aggravates the negative impact of the semi-parasite pine mistletoe (*Viscum album* ssp. *austriacum*) (Dobbertin and Rigling, 2006; Rigling et al., 2010; Zweifel et al., 2012).

In Switzerland, temperature has increased by 1.6 °C during the 20th century (Begert et al., 2005) and most of this increase has occurred since 1975 (Rebetez and Reinhard, 2008). While precipitation did not show a clear trend, increasing temperature led to increasing evaporative demand and thus aggravated drought

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intensity (Rebetez and Dobbertin, 2004). Warming is predicted to increase in intensity (IPCC, 2007) and extreme events like warm and/or dry summers (e.g. heat wave in 2003) may become more frequent (Schär et al., 2004). Consequently, the impacts of drought could be particularly pronounced in dry areas (Rebetez and Dobbertin, 2004), so that important ecosystem services (e.g. protection) provided by xeric forests are threatened (Huber et al., 2013).

Besides recent warming, also various land-use practices have altered many European forests. In Valais, forests were utilized intensively for firewood and railway construction (Meyer, 1950; Kempf and Scherrer, 1982). Clear-cutting, goat grazing and litter collecting facilitated the establishment of light-demanding species such as Scots pine. Low prices for timber in recent decades have reduced management intensity, and the more shade-tolerant downy oak (*Quercus pubescens* Willd.) is spreading (Gimmi et al., 2010; Rigling et al., 2013). Reduced management has resulted in increased stand density and increased inter- and intra-specific competition for Scots pine (Weber et al., 2008), thus increasing the vulnerability of Scots pine to further stressors. Reduced forest management and increasing drought stress have both contributed to the recent increase in Scots pine mortality. However, the relative importance of the two factors in the current decline remains unclear and the potential for drought mitigation via forest management is yet to be explored.

Thinning, as one of the main forest management tools, reduces tree density and fosters individual tree growth by increasing the resources available to the remaining trees (Aussenac, 2000). Since Scots pine is economically important, many thinning studies have been conducted mainly in the central and boreal forests of Europe to optimize their growth and yield (Valinger et al., 2000; Pukkala et al., 2002; Mäkinen and Isomäki, 2004). While boreal forests are expected to benefit from increasing temperatures and are not prone to severe water limitations (Briceño-Elizondo et al., 2006), increasing temperatures will aggravate the evaporative demand and thus increase drought in the southern part of Europe, where few studies have occurred (Montero et al., 2001; del Río et al., 2008). These have mainly focussed on non-xeric sites, as indicated by site index, with trees being 17–29 m tall at an age of 100 years. In contrast to mesic forests, long-term thinning trials in xeric forests are rare, probably because their low quality implies low economic value. One study at a xeric site showed that the thinning effects on growth in ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws.) can last for more than 15 years (McDowell et al., 2003). This suggests that thinning in dry areas could reduce water and light competition for many years after thinning.

If water is limiting tree growth and thinning increases water availability through reducing stand transpiration and reducing rain interception, then the greater water supply enables higher transpiration of the remaining trees (Aussenac, 2000). Increasing water availability after thinning would then foster carbon allocation towards the transpiring surface, i.e. leaf area (A_l) at the expense of the rooting area. Consequently, an increase of the leaf area (transpiring surface) to the sapwood area (water supply) (A_l:A_s) is expected after thinning. Such increases of A_l:A_s were observed when soil moisture increased at a given site (Larcher, 2003) or stand density was reduced by thinning (McDowell et al., 2006). Likewise, decreasing A_l:A_s where observed for Scots pine across Europe, with increasing drier conditions (Mencuccini and Bonosi, 2001). To the best of our knowledge, there is no investigation of A_l:A_s in thinning experiments in Scots pine.

Tree mortality provides further information to assess the long-term effectiveness of thinning. Tree mortality can be divided into three categories: background mortality (e.g. trees that die due a range of often unknown causes), which is usually low (Franklin et al., 1987); catastrophic mortality (e.g. bark beetle outbreaks) (Dobbertin and Biging, 1998), which depends on the frequency and intensity of the stress factors and the vigor of the trees, which may be increased by thinning; and competition-related mortality, which depends greatly on stand density and available resources and can thus be altered by thinning (Dobbertin and Biging, 1998). Competition-related mortality is not only a function of stand density, but also of the growth rates of the trees. Therefore, to foster comparisons with other studies, mortality rates can be used along with the allometric relationship between stand density and corresponding mean tree diameter (Reineke, 1933) which as been shown to have a logarithmic slope being close to −1.605. A slope more negative than −2.0 indicates a decline in basal area, and could be an indicator of changing site conditions in the absence of catastrophic mortality or old stands where gaps are created (Pretzsch and Biber, 2005). Therefore, if increasing drought or additional biotic stressors reduce the maximum basal area at a given site, this should be reflected in slopes below −2.0.

In this paper, we analyzed a long-term thinning trial established in 1965 in a Scots pine forest in Valais. Our general objective was to test whether reductions in stand density in a xeric environment increase tree resistance to drought. Specifically, we postulated that: (i) thinning increases individual tree growth not only for a few years but for decades following the thinning; (ii) thinning reduces long-term tree mortality as a function of stand density; (iii) the relationship between stand density and mean tree diameter (the allometric slope) becomes more negative with increasing drought, and (iv) thinning increases A_l:A_s for individual trees as an indicator of increasing water availability.

2. Materials and methods

2.1. Study sites

The thinning experiment was conducted on North-exposed sites on the valley floor in the central part of Valais, Switzerland (46°18′ N and 7°36′ E, 620 m a.s.l.). The forest stand is dominated by 95 year old Scots pines (10–12 m in height) with sparse downy oak mixed in. The forest type is an *Erico-Pinetum caricetosum albae* (Ellenberg, 1988). It is situated on an alluvial fan and debris cone of the Ill river ('Illgraben'), with stony soils and low water-holding capacity (Brunner et al., 2009). The mean annual temperature for the reference period 1961–1990 was 9.2 °C (MeteoSwiss, station Sion, distance 20 km). The mean annual precipitation is typically around 600 mm, evenly distributed across the year, with individual years (e.g. 1986, 2003) receiving as little as 300–400 mm (MeteoSwiss, station Sierre, 8 km).

2.2. Experimental design

The initial thinning trial was set up in early 1965 by Prof. Leibungut of ETH Zürich to determine the growth reaction of Scots pine to a reduction in stand density, and also to improve stemwood quality. The forest was thinned for the first time in February 1965 and the trial included three treatments with three replicated plots each. The "light" treatment decreased basal area by 14% from 40 m^2 ha^{-1} to 33, the "medium" by 40% to 22 m^2 ha^{-1} and the "heavy" by 68% to 11 m^2 ha^{-1} (Appendices A, Fig. 1). All plots were rethinned in autumn 1971 and 1978. In 1974, three control (unthinned) plots nearby with similar tree characteristics (i.e. tree age and tree height) were added. 35% of the area of one control plots experienced bark beetle attacks in the 1980s. In the "light" thinning plots, thinning from below was applied while in the "medium" and "heavy" thinning plots, trees were removed in all diameter classes (data not shown). All plots are 30 m × 30 m in size, but only the control plots have a buffer zone with a width