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How do mixing tree species and stand density affect seasonal radial growth during drought events?

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ABSTRACT

Forecasted climate change impacts on temperate forest ecosystems include increased summer drought. Forest managers can increase the resistance of forest stands against summer drought by reducing stand density and favoring tree species mixtures. These strategies have been studied separately, but their combined effect on increasing forest stand resistance to summer drought is unknown.

The main objective of our study was to quantify tree species interaction effects on radial growth during a water stress period and to determine whether these effects changed with different levels of competition reflected by stand density.

The study was based in the Orleans state forest (Central France) at a long-term triplet experimental site (OPTMix) with pure and mixed stands of mature *Quercus petraea* and *Pinus sylvestris*. The experimental design comprised three repetitions of two densities (low and medium) in each composition (pure oak, mixed stands, pure pine). We monitored tree radial growth with 216 manual dendrometers placed throughout 18 plots, on small, medium and large trees. We analyzed three consecutive years with contrasted water stress: no water stress, a summer stress period, and a late summer stress period.

We found that mixture did not improve tree growth of the either species during the summer water stress period. On the other hand, there was a mixture effect during the late summer water stress period but only in medium-density stands inversely for the two species studied. More growth occurred for oaks in mixtures while, inversely, more growth occurred for pines in monocultures. A density effect occurred only for oaks, which grew more in lower-density stands than in medium-density stands. Finally, tree size did not influence seasonal resistance to drought.

1. Introduction

The IPCC expert group has forecasted an increase in summer drought events in temperate regions with climate change (IPCC, 2014), and water is one of the most important resources for tree growth. When water resources become too scarce, the tree greatly reduces its growth to maintain vital processes at a basic minimum (Aussenac, 2000). Therefore, radial growth is a good proxy for water stress (Locosselli et al., 2013) and can be used to assess silvicultural management options designed to cope with climate change.

Reducing stand density and mixing tree species are two options that may help forest stands cope with the future climate (Loreau and Hector, 2001; Tilman et al., 2001; Puettmann, 2011). The former limits water loss in the ecosystem by reducing stand leaf area index (LAI), and thus evapotranspiration. As a consequence, the decrease in soil water content is slower and sufficient soil water availability is maintained for the trees during water stress events (Bréda et al., 1995). Though dominant trees have the highest growth, it is also necessary to follow the growth of co-dominant and dominated trees to study the overall effect of lower stand density (Pape, 1999; Merlin et al., 2015). Moreover, researchers do not agree on how tree social status affects sensitivity to drought. Some studies have found large trees to be more sensitive (Castagneri et al., 2012; Zang et al., 2012) while in other studies, they appear to be less affected than small trees (Piutti and Cescatti, 1997; Zang et al.,

Abbreviations: CI, circumference increment; SP, summer period; LSP, late summer period; REW, relative extractable water

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Table 1
Dendrometrical characteristics of the 18 plots in 2015. For the mixtures, the quadratic mean diameter, the basal area, number of stems and RDI columns provide values by species. The total value for the stand is the sum of these values. Standard deviations are given in parentheses.

Density	Composition	Species	Dg (cm)	Basal area (m^2/ha)	Number of stems (/ha)	RDI
Low	Pure oak	Oak	23.5 (2.5)	14.8 (0.4)	347 (60)	0.41 (0.01)
	Mixture	Oak	23.5 (2.1)	8.9 (0.9)	209 (38)	0.24 (0.03)
		Pine	35.9 (3.6)	10.7 (1.5)	106 (19)	0.24 (0.03)
	Pure pine	Pine	33.8 (1.2)	21.7 (3.2)	242 (45)	0.48 (0.07)
Medium	Pure oak	Oak	22.5 (2.4)	20.8 (1.6)	530 (75)	0.57 (0.05)
	Mixture	Oak	23.6 (1.9)	10.4 (1.1)	245 (60)	0.29 (0.03)
		Pine	36.0 (3.3)	15.7 (2.8)	154 (19)	0.35 (0.06)
	Pure pine	Pine	33.6 (1.7)	30.7 (1.7)	348 (23)	0.68 (0.04)

2012). Finally, some studies found no influence of tree size on drought response (Lebourgeois et al., 2014).

The second silvicultural strategy – mixing tree species – can have several benefits, one of which is better tree growth (Richards et al., 2010) likely due to the complementarity effect, i.e. resource partitioning or positive interactions lead to increased resource use and thus greater growth (Loreau and Hector, 2001). Complementarity is widely found in herbaceous communities and in agriculture, and its growth response effect is now being transposed to forestry (Richards et al., 2010; Forrester and Bauhus, 2016). Many studies show higher productivity for tree mixtures compared to monocultures (Liang et al., 2016). However, contrasted results are observed and can depend on certain conditions. Some authors have shown that the greater growth in mixtures (i.e. over-yielding) is site-dependent (Toïgo et al., 2015a; Lu et al., 2016) and occurs mainly when site quality is poor (Condés et al., 2013; Toïgo et al., 2015a) or in drought-prone environments (Grossiord, 2014). Over-yielding has also been observed in associations of shade-tolerant and shade-sensitive species (Toïgo et al., 2017) and in evergreen-deciduous mixtures, though not in deciduous-deciduous mixed stands (Lu et al., 2016). The stand composition effect can even result in under-yielding during long water stress periods (Richards et al., 2010; Ge et al., 2011).

Studies on tree growth are most often carried out through comparisons of inter-annual radial increment (Pretzsch et al., 2008; Michelot et al., 2012a; Mina et al., 2016); ring width is correlated to different stand or climatic variables to assess their potential effects on radial growth (Lebourgeois et al., 2014; Toïgo et al., 2015b). In temperate forests, annual growth data is readily available and this makes studying a wide variety of situations relatively easy. However, the inter-annual scale only makes it possible to study the long-term effect of drought (i.e. retrospective studies); to study the short term effects of drought on tree growth the seasonal scale is more appropriate (Lloret et al., 2012). Other studies have focused on seasonal growth by monitoring tree ring formation dynamics linked to variations in environmental conditions (Mäkinen, 2000; Michelot et al., 2012b; Sohn et al., 2016). This approach can improve tree growth models for dryer and warmer conditions (Zweifel et al., 2005; McMahon and Parker, 2015) and provide more accurate predictions in a changing climatic context.

In this study, we tested whether stand density and stand composition affected the radial growth of trees during seasonal drought events for two tree species: sessile oak (*Quercus petraea (Matt.) Liebl.*) and Scots pine (*Pinus sylvestris* L.). We were particularly interested in determining whether stand density changed the intensity or type of interaction between the two species during a drought event. We also tested whether the results differed according to tree size.

We hypothesized that (1) growth would be greater in low-density stands compared to medium-density stands for both species, (2) mixing tree species would improve tree growth during a drought event, (3) the mixture effect on growth would be greater in the highest density, and finally (4) the smallest trees would be the most sensitive to drought events.

2. Materials and methods

2.1. Study site

This study took place in the Orléans state forest (France, 47° 49′N, 2°29′E). It is the biggest forest managed by the National Office of Forest (ONF) in metropolitan France, covering 35,000 ha. Two main species are represented: sessile oak (*Quercus petraea*) and Scots pine (*Pinus sylvestris*), in both pure and mixed stands. The study used the long-term experimental site OPTMix (Oak Pine Tree Mixture, https://optmix.irstea.fr/, (Korboulewsky et al., 2015), installed in even-aged adult stands (aged 60–80 years) over a total of 44 ha. The area has a temperate continental climate with an oceanic influence: the mean annual temperature is 10.6 °C and mean annual rainfall is 716 mm (1959–2017 data from the SAFRAN and ISBA analytical platforms, Météo-France (Durand et al., 1993)).

The soil is qualified as a primary planosol (IUSS Working Group WRB, 2015). This type of soil is poor and acidic ($C < 1\%$, $C/N < 20$, pH = 4.5). The first horizon is loamy sand lying on a more or less impermeable clay horizon about 40 cm deep; this leads to temporarily waterlogged conditions in winter and spring.

2.2. Experimental design

OPTMix consists of three triplets of pure oak (*Quercus petraea*), pure pine (*Pinus sylvestris*) and mixed stands of both species (making nine stands overall) (Korboulewsky et al., 2015). In each stand, there are two 0.5 ha plots with two different tree target densities: low (Relative Density Index, target RDI = 0.4) and medium (target RDI = 0.7) (Reineke, 1933). The distance between two repetitions of the triplet is at least a few kilometers. The dendrometrical characteristics of the stands are given in Table 1. Some stands were thinned during the experiment. The data from the thinned plots were excluded from the analyses for the thinning year (two mixed plots in 2015 and the same two mixed plots plus a pure pine plot in the 2014, out of a total of 18 plots).

In each of the 18 plots, we selected nine individuals per species according to their relative size class (large, medium and small) based on their circumference at breast height. We measured the DBH of all the trees in the plot, then used the cumulated frequencies of the DBH values to divide the trees in the plot into three quantiles corresponding to three within-plot size classes. We rejected any trees whose circumference fell within a 10% margin between any two size classes to clearly differentiate among them. Species proportion and local stand density were checked within a 10-meter circle centered on each target tree. In mixed stands, a tree could be selected if the other species represented between 40 and 80% of the basal area of the neighboring trees. These thresholds were chosen to mark the contrast in composition between mixed and pure stands. Lastly, for low and medium density respectively, RDI ranged from 0.25 to 0.4 and from 0.5 to 0.75 within the 10-meter circle. We obtained a final stratified sampling of 216 trees as follows: