

1 **Title**

2 Douglas-fir climate sensitivity at two contrasting sites along the southern limit of the European
3 planting range

4

5 **Author**

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12

13 **Abstract**

14 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) is an interesting exotic tree species planted
15 across a large part of Europe during the last century. In both experimental trials and conventional
16 forest plantations, the species has demonstrated high growth rate and valuable timber quality, with
17 high phenotypic plasticity. This study aimed to investigate climate-growth relationships of Douglas-
18 fir ~~in~~ at two Italian sites with a contrasting climate regime. A Mediterranean area in Southern Italy
19 (Mercurella site) and a cooler and moister one in the Northern Apennines without summer aridity
20 (Acquerino) were selected as study sites. The relationship between tree-ring chronologies and
21 monthly climatic variables was investigated by mean and moving correlation analysis. [The](#)
22 [minimum](#)~~Late winter~~ temperatures [of](#) (February and March) play a key role for Douglas fir at both
23 sites, with a positive effect on growth. At the northern site, Douglas fir experiences also a high
24 sensitivity to late summer temperatures (negative correlation) and spring-summer precipitation
25 (positive correlation). On the whole, the species demonstrates high growth rates at southern
26 latitudes even in Europe and in– Mediterranean environment, with low sensitivity to climatic

27 fluctuation. However, further common garden experiments should be planned in order to test
28 adaptation [and the interaction between genetic and environment](#) of the second or third generation
29 seeds from old stands across the whole Europe.

30

31 **Keywords**

32 *Pseudotsuga menziesii*; tree ring analysis; dendroclimatology; forest plantations; exotic forest
33 species

34 **Introduction**

35 Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) is one of the most promising exotic tree species
36 in Europe, first introduced from North America more than 150 years ago (Isaac-Renton et al., 2014;
37 Schmid et al., 2014) and currently distributed in almost all European countries for high-quality
38 timber production (Hermann and Lavender, 1999). During the first years of its experimentation,
39 every European country was used to work separately by collecting seed from the native range
40 independently, mainly according to local climate and experts knowledge. Afterwards, during the
41 second half of XX century, the adaptive traits of 180 provenances of Douglas fir were tested within
42 the IUFRO (International Union of Forest Research Organizations) 1969-70 experimental network
43 (Eilmann et al., 2013), which still represents one of the more extensive and standardized
44 experimental trials in Europe for Douglas fir. The “pure seed” collected from almost the whole
45 native range was there also compared with some “second-generation provenances” (i.e., from
46 plantations in the European introduction range that had already reached reproductive age) were
47 tested, showing high productivity, sometimes even higher than the American seeds (Ducci and
48 Tocci, 1987). However, direct comparisons of the growth response of such introduced provenances
49 to contrasting climates have not been carried out so far. Nevertheless, provenance trials
50 demonstrated that, under favourable climatic conditions, Douglas-fir grows faster than native
51 conifers, e.g. Scots pine (*Pinus sylvestris* L.) or European larch (*Larix decidua* Miller) in forest
52 stands (Eilmann and Rigling, 2012). The high degree of genetic variability and plasticity that
53 Douglas fir exhibits and due to its huge natural range, has allowed European countries to
54 successfully test its use, from Mediterranean to continental Europe (Brus et al., 2012; Eilmann et
55 al., 2013; Howe et al., 2010). Very recently, Hintsteiner et al. (2018) also showed that the detection
56 of the correct provenance of old Douglas fir stands in Europe could be very difficult. In this sense, a
57 connection between performances in native and introduced zones is generally hard.

58 A variety of empirical and experimental approaches has been exploited to assess plant response to
59 climate variability and climate change over large geographic areas (Bréda et al., 2006; Chen et al.,

60 2010). Examples are provenance trials or common gardens (Lipow et al., 2003; Rehfeldt et al.,
61 2014), empirical analyses of growth and mortality by permanent forest inventory plots (Marchi,
62 2019; Poschenrieder et al., 2018; Stephenson et al., 2014), remote sensing and detection of net
63 primary productivity (Fassnacht et al., 2014; Smith et al., 2008) as well as dendrochronological
64 analysis of growth-climate correlations from tree ring time series (Avanzi et al., 2019; Eilmann and
65 Rigling, 2012; Mazza et al., 2018). The latter type of data might improve knowledge on species
66 requirements to adjust predictions of growth simulators even on Douglas fir trees outside its native
67 range (Castaldi et al., 2017) and [evaluate/predict](#) the trees' response to long-term climate variations.
68 In particular, dendrochronological climate-growth response models may help to evaluate the trees'
69 response to past climate variations and to forecast future ecosystem responses to climate change,
70 especially when analysing the same species under different climatic conditions (Corona, 2016;
71 Härdtle et al., 2014). If a species shows local growth acclimation, i.e. it responds differently when
72 grown under different climates (Case and Peterson, 2005), provenances with a higher tolerance of
73 warm and dry conditions may play an important role in climate change adaptation, as they would
74 probably acclimate well when translocated to northern latitudes or higher elevations that are about
75 to experience a warming climate trend (Hampe and Petit, 2005). [Actually knowledge of available
76 genotypes as well as information on the genetic structure of forest tree systems and populations is
77 fundamental to cope with a changing climate, understanding long-term adaptation processes and
78 balancing statistical models properly](#) (Benito Garzón et al., 2019; Piotti et al., 2017).
79 In its native range, Douglas fir's growth is positively affected by precipitation, [especially between
80 May and September, often referred as its-in-the-“growing season”](#) (Case and Peterson, 2005) and
81 negatively by winter cold spells and snowpack depth (Littell et al., 2008). Sensitivity to growing
82 season temperatures generally shifts from negative to positive with increasing elevation. However,
83 even at the northernmost/highest sites, precipitation limits Douglas-fir radial growth more than
84 temperatures (Griesbauer and Green, 2010), ~~and~~ [Then](#) summer drought is the main limiting factor
85 for both coastal (i.e. *viridis*) and interior (i.e. *glauca*) varieties also in Europe (Vejpustková and

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86 Čihák, 2019) ~~but highly vulnerable to~~ exceptional and recurrent drought [often stress the species](#)
87 [more than native ones species](#) (Thurm et al., 2016), especially on less fertile soils (Sergent et al.,
88 2014). ~~However, particularly when in association with beech and Norway spruce, growth of~~
89 ~~Douglas fir in~~ Europe, may be also promoted by warm winters, ~~due to the fact that~~ [thanks to active](#)
90 photosynthesis ~~may be active~~ even in winter months (Chen et al., 2010), possibly combined with
91 the benefit of additional water supply after snowmelt. [This issue has been detected in association](#)
92 [with beech and Norway spruce](#) (Schmid et al., 2014). As a consequence, when compared to native
93 European tree species, Douglas fir has high potential to cope with warmer climates, and can
94 outcome them in virtue of a higher resistance and faster recovery from drought.

95 The aim of this paper is to analyse the strength and spatio-temporal stability of the relationship
96 between radial growth of Douglas fir and main climatic drivers under Mediterranean environment.
97 The growth-climate response of Douglas fir at two plantations sites in Italy with contrasting climate
98 regimes is here analysed and discussed.

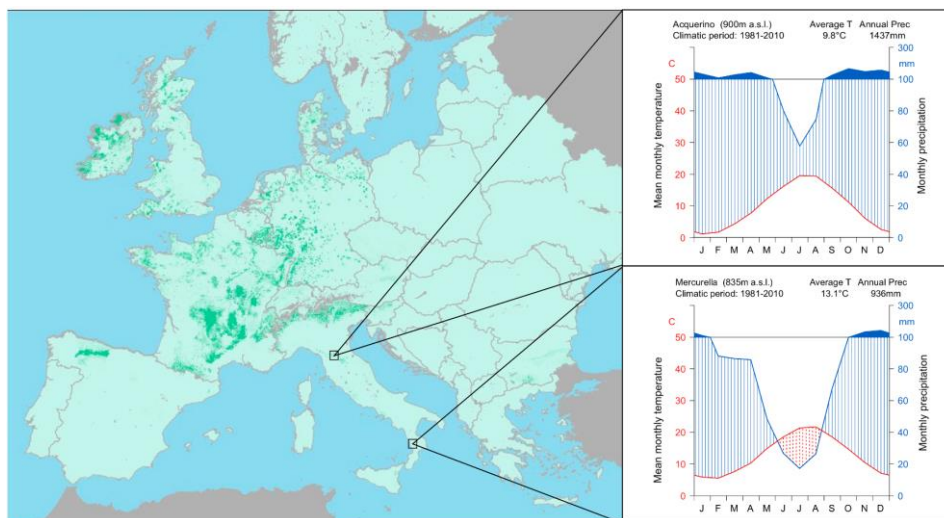
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100 **Materials and methods**

101 *Study sites*

102 Italy is one of the countries where Douglas fir was extensively tested by both IUFRO programs and
103 national experimentation since 1922 (Castaldi et al., 2017). The two study sites here selected
104 (Figure 1) were Acquerino in the northern Apennines (44°0'38.97" N, 11°0'25.47" E) and
105 Mercurella in the southern Apennines (39°20'11.55" N, 16°4'49.42" E). Both sites are characterized
106 by pure artificial plantations of Douglas fir established around 1940s, with similar elevation (900
107 and 835 m a.s.l., respectively). [Just few information were available on the genotype of planting](#)
108 [materials. According to literature and information available in the archives, both stands were](#)
109 [established by 3-year-old seedlings from the nursery of Vallombrosa with "Italian" seeds collected](#)
110 [from mature trees with unknown origin \(probably from Washington, Oregon or California\) around](#)
111 [1930](#) (Avolio and Bernardini, 2000).

112 The two sites are characterized by mild climate with average mean summer–temperatures in
113 Summer (June-July-August) around 20°C which is close to the temperature known to be the
114 ecological optimum for Douglas fir growth (Wang et al., 2012). On the other hand, the two sites
115 display different climatic regimes, mainly due to a different latitude and distance from the
116 Mediterranean sea. The southernmost site (Mercurella) has a warmer and drier climate (warm-
117 temperate, Cs zone according to Köppen-Geiger classification), with a mean annual temperature of
118 13.1°C and annual precipitation of 936 mm. The northern site (Acquerino) is cooler (mean annual
119 temperature = 9.8 °C) and wetter (mean annual precipitation = 1437 mm). According to Metzger et
120 al. (2013) Acquerino and Mercurella sites fall within the J (cool temperate and moist) and K (warm
121 temperate and mesic) bioclimatic belts, respectively. These two sites do not represent the full range
122 of climatic conditions throughout the native range of Douglas-fir in the Pacific Northwest of the
123 United States. However, the northern site has a substantially longer humid period during winter and
124 spring, while the southern site is subject to a three-month summer aridity. In our hypothesis, such
125 differences should be sufficient to highlight differences in local acclimation (Aitken et al., 2008).
126



127 **Figure 1.** Location and mean monthly climate in the study sites, drawn over the geographic
128

129 *distribution of Douglas fir in Europe (Brus et al. 2012). The red line is mean temperature and blue*
130 *line is precipitation. Blue area: wet period; red dotted area: dry period.*

131

132 According to the soil database of Italy (Costantini et al., 2014), the area of Acquerino is mainly
133 characterized by Cambisols (Dystric and Calcaric) while Mercurella by Haplic Umbrisols. No
134 significant disturbance has been documented to affect either the sites since planting (e.g.,
135 windthrow or pests). The two analysed sites have also similar tree density (Table 1); this suggested
136 also a similar silvicultural history i.e. no thinning was recorded in the last decades in either the sites.
137 However, the effect of diverging site fertility was evident, with a top height of 43.5 m at Acquerino
138 and 36.9 m at Mercurella. [Top height was also used as a proxy of soil nutrient condition given the](#)
139 [unavailability of soil samples.](#)

140

141 **Table 1.** *Stand characteristics at the two investigated sites.*

	Acquerino	Mercurella
Elevation (m)	900	835
Distance from the sea (km)	63.8	3.4
Trees (ha⁻¹)	247	294
Basal area (m² ha⁻¹)	111.8	90.4
Mean DBH (cm)	75.9	62.5
Stand top height (m)	43.5	36.9

142

143 *Sampling method and tree-ring series preparation*

144 In order to derive comparable data, the sampling size was differently designed according to sites'
145 characteristics. Indeed, while Mercurella is a pure experimental forest plot approximately 1 hectare
146 wide, the Acquerino plantation covers about 30 hectares. For this reason the same number of
147 dominant trees (20) was sampled within each site. Firstly 20 points were randomly thrown across
148 each site. Then the dominant Douglas-fir tree nearest to each point was cored twice on the cross-
149 slope sides at 130 cm stem height with an angle of 90° between samples. Cores were fixed on a
150 wooden support to be transported in the lab, prepared and measured with 0.01 mm precision using

151 LINTAB6®. Tree ring series were cross-dated using TSAP-WIN software and an average single
152 ring-width series was obtained for each sampled tree. Finally a site mean chronology was obtained
153 averaging all the single-tree series. Each cored tree was also measured for diameter at breast height
154 (DBH) and total height.

155 Each cross-dated series was standardized separately by a double detrending procedure to isolate the
156 climatic signal: a negative exponential curve was first applied to remove age trends, then a spline
157 function (50% cut-off and 10 years) was fitted to emphasize higher frequency inter-annual climatic
158 variance (Biondi and Qeadan, 2008; Mazza et al., 2018; Yamaguchi et al., 1991). Autoregressive
159 modelling was performed on each detrended ring-width series to check for the existence of
160 significant ($p < 0.05$) first-order temporal autocorrelation. Residual series were finally averaged
161 using a bi-weight robust mean to obtain residual site chronologies, upon which all subsequent
162 analyses were based. The quality of the sampling procedure was checked by analysing the
163 expressed population signal (EPS), a measure of how well the mean chronology represents the
164 sampled population.

165

166 *Climate-growth relationships analysis*

167 As meteorological stations nearest to the study sites did not provide continuous and consistent data,
168 monthly precipitation and temperatures (maximum and minimum) from 1901 to current time were
169 obtained from the Climate Explorer (<http://climexp.knmi.nl>) portal (Trouet and Van Oldenborgh,
170 2013) for the $1 \times 1^\circ$ cell where each site was located. The three-month Standardized Precipitation and
171 Evaporation Index (SPEI) was also calculated for each site, using the SPEI package (Maca and
172 Pech, 2016) for the R statistical language. As minimum and maximum monthly temperatures were
173 highly correlated in both sites (Pearson's $r = 0.982$ and 0.993 , respectively in Acquerino and
174 Mercurella), only the latter was used in subsequent analyses.

175 The influence of climate on tree-ring growth was investigated using mean correlation functions
176 (CF) and moving correlation functions (MCF). While the first method is used to evaluate the most

177 influential climatic drivers during the whole life-span of the trees, the second is computed on a
 178 moving window with a smaller width to assess the change in growth response through time (Biondi
 179 and Waikul, 2004; Marchi et al., 2015) (Biondi and Waikul, 2004; Marchi et al., 2015). We used a
 180 30-year moving window, which satisfied the conditions whereby sample size is less than 80% of all
 181 available years and more than twice the number of predictors (Biondi and Waikul, 2004). Maximum
 182 temperature, total precipitation and SPEI were computed at a monthly resolution from May of the
 183 previous year (t-1) to September of the year of growth (t), so as to include the autumn and winter
 184 before ring formation. Significant Pearson's correlations between residual site chronologies and
 185 climate variables were detected using the 95th percentile range method without bootstrap
 186 resampling. The R packages dplR (Bunn et al., 2017) and treeclim (Zang and Biondi, 2015) were
 187 used for tree ring series management and analysis.

188

189 **Results**

190 The individuals selected at the two sites were on average 68 and 70 years old, with 78 and 76 years
 191 which were counted for the two oldest individuals respectively. The average diameter of cored trees
 192 was 69 and 73 cm, respectively. Mean sensitivity was 0.125 at both sites with a mean ring width
 193 between 4 and 5 mm.yr⁻¹ (Table 2). Of all individual raw tree-ring series (Figure 2), 60% at
 194 Acquerino and 85% at Mercurella could be fitted by a negative exponential curve; for the others, a
 195 linear decreasing or horizontal fit was used in the first detrending.

196

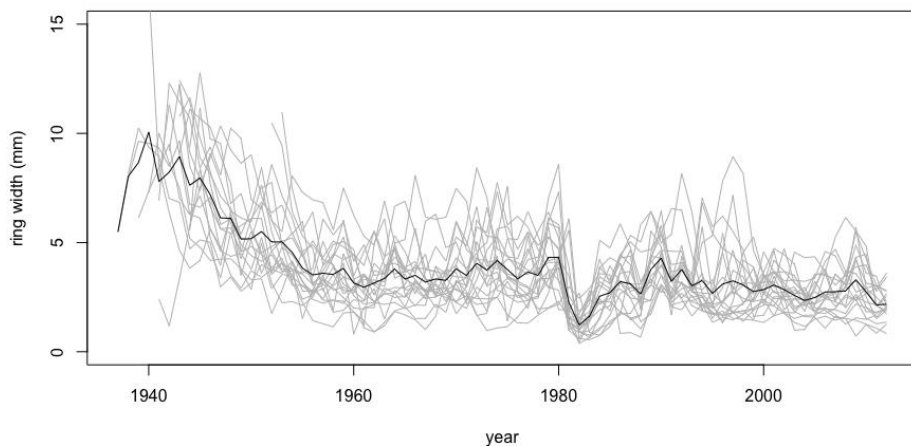
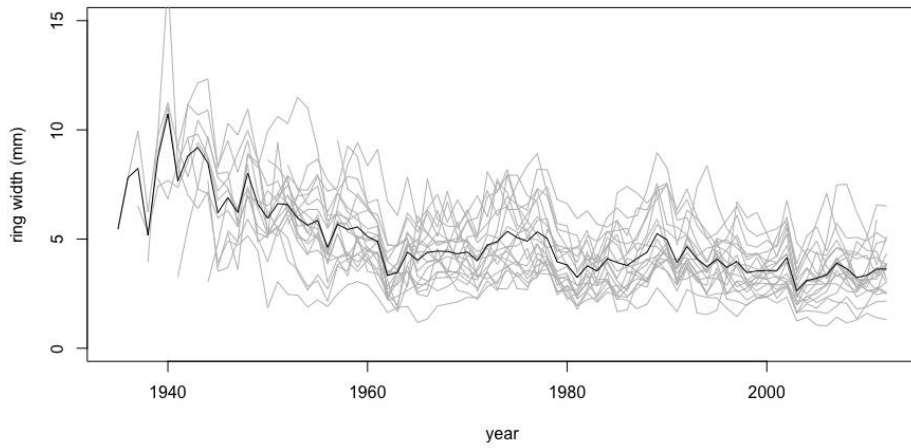
197 **Table 2.** Statistical parameters of mean tree-ring width chronologies for the two investigated sites.

	Acquerino	Mercurella
Mean DBH, cored trees (cm)	69.4 ±5.1	73.1 ±4.7
Length of site chronology (years)	78	76
Mean sampling depth (number of cores)	14.9 ±4.5	16.3 ±2.2
Mean sensitivity	0.121 ±0.03	0.127 ±0.04
Mean ring width (mm)	4.969 ±1.66	4.031 ±1.83
Expressed population signal (EPS)	0.926	0.918
Mean interseries correlation (RBAR)	0.418 ±0.11	0.365±0.12

Signal-to-noise ratio	12.452	10.544
First-order autocorrelation after indexing (chrono)	-0.144	0.179

198

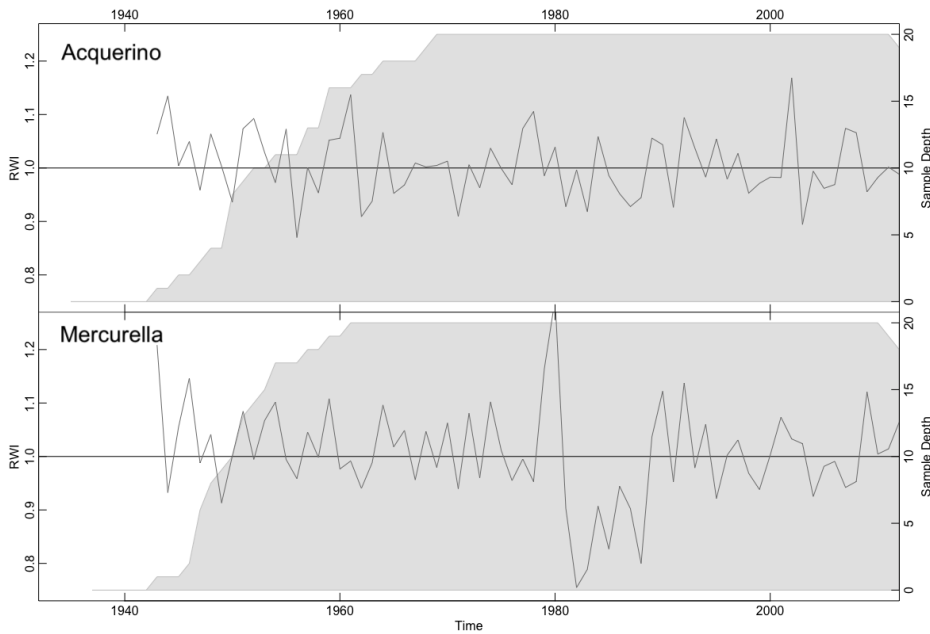
199 As evidenced by **Figure 2**, a negative pointer year was clearly evident for the Mercurella site in
200 1981-1982. A negative pointer year is defined as an extremely narrow [tree ring width \(TRW\)](#) with
201 growth reduction exceeding 40% compared with the average TRW in the previous four years.
202 Moreover, we have a very big ring in 1980 followed by two very small ring width in 1981 and
203 1982. This was connected to exceptional long growing season in 1980 and a heavy frost event in
204 autumn. This event seriously damaged trees' needles and two years occurred for the species to
205 regenerate the crown.



206
 207 **Figure 2.** Raw individual chronologies at Acquerino (above) and Mercurella (below).

208
 209 Over the analysed time period the residual ring-width site chronologies (Figure 3) had a mean inter-
 210 series correlation (RBAR) of 0.42 and 0.36, negligible first-order autocorrelation, and an EPS
 211 much higher than 0.85, value generally accepted as minimum threshold to detect valid climatic
 212 correlations and indicating a common macro-environmental influence on growth (Wigley et al.,
 213 1984).

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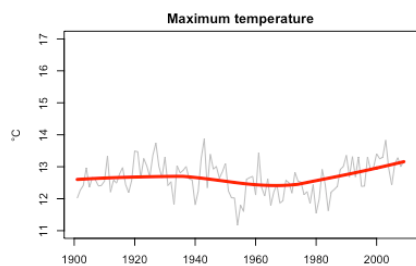
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 216 **Figure 3.** Residual site chronologies at Acquerino (above) and Mercurella (below) – biweighted
 217 mean of individual series after detrending individual series with a negative exponential (or linear)
 218 and a 10-year spline smoother.

219
 220 Both sites exhibited a significant climatic trend during the second half of the last century (p of the
 221 regression slope <0.05) as a drying trend at the northern site of Acquerino, and a warming trend at
 222 Mercurella (Figure 4). Many significant correlations [between growth and climate variables](#) were
 223 found by CF (Figure 5). At Acquerino, maximum temperature was significant in July of the year
 224 prior to growth, February (positive correlation) and during the mid- and late summer of the growth
 225 year (July, August, September - negative correlation). Precipitation showed a negative correlation
 226 with growth in October and November of the previous year (t-1), and positive in May and July of

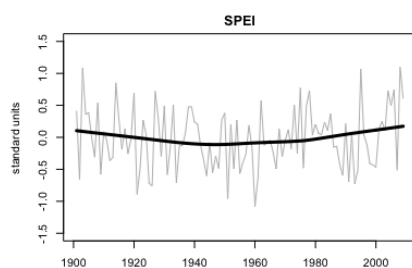
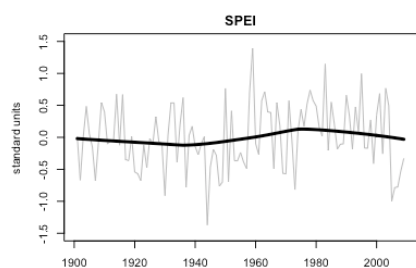
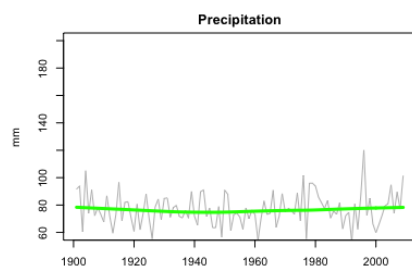
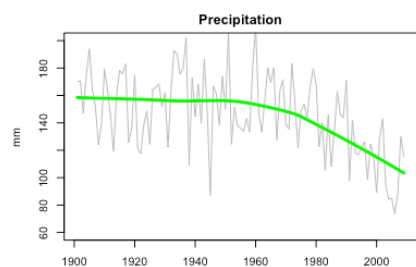
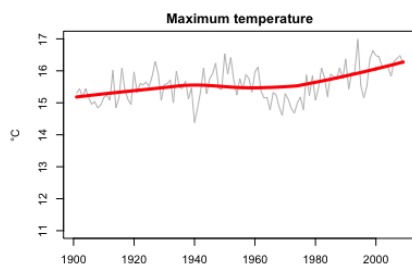
227 the current year. Summer SPEI (July-October) had a positive effect on growth with a lag of one
228 year, and a negative effect (July) of growth of the current year. Less months were detected as
229 significant at Mercurella. Ring width showed a significantly negative correlation with maximum
230 temperatures in October (t-1) and July. Positive correlation arose only with temperatures in the
231 winter of the year of growth t (February and March). Precipitation showed only significantly
232 negative correlation with growth in December (t-1), while a negative effect on growth was detected
233 for SPEI on June (t-1).

234

Acquerino



Mercurella

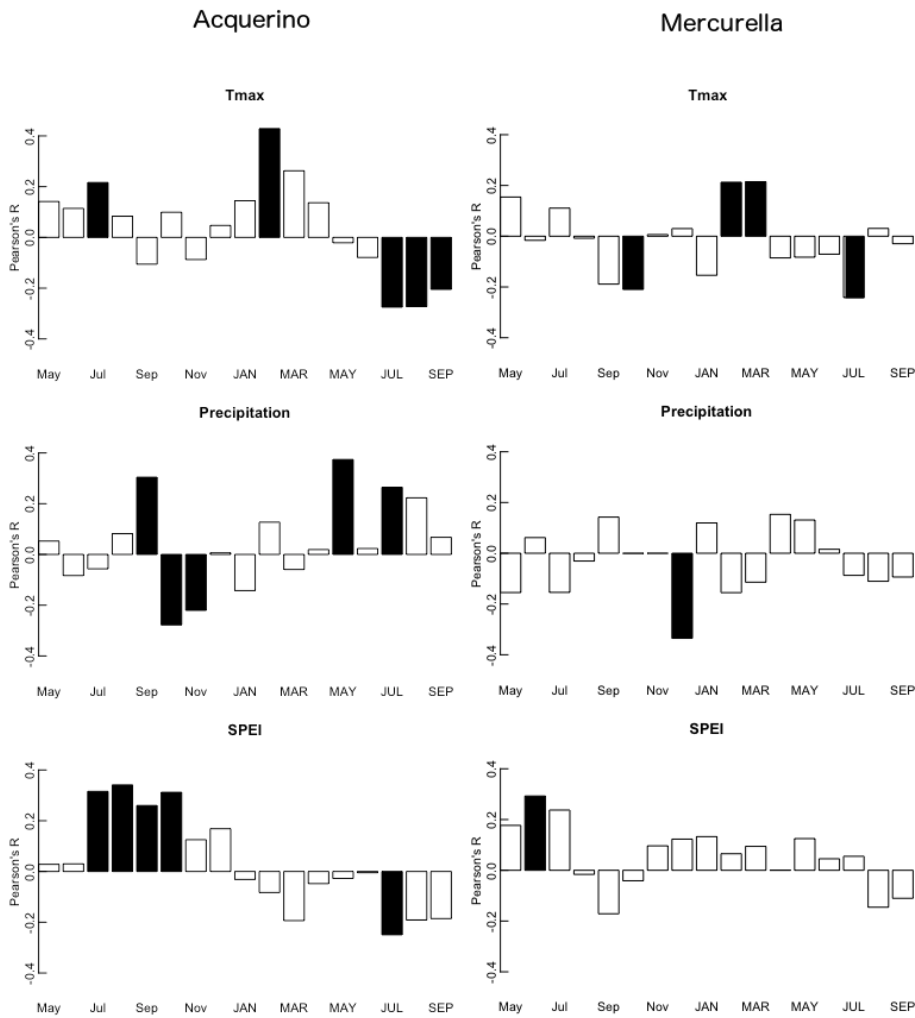


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236 **Figure 4.** Climate time series at Acquerino and Mercurella from 1901 to 2010 (thin line: annual

237 data, thick coloured line: cubic-spline trend)

238



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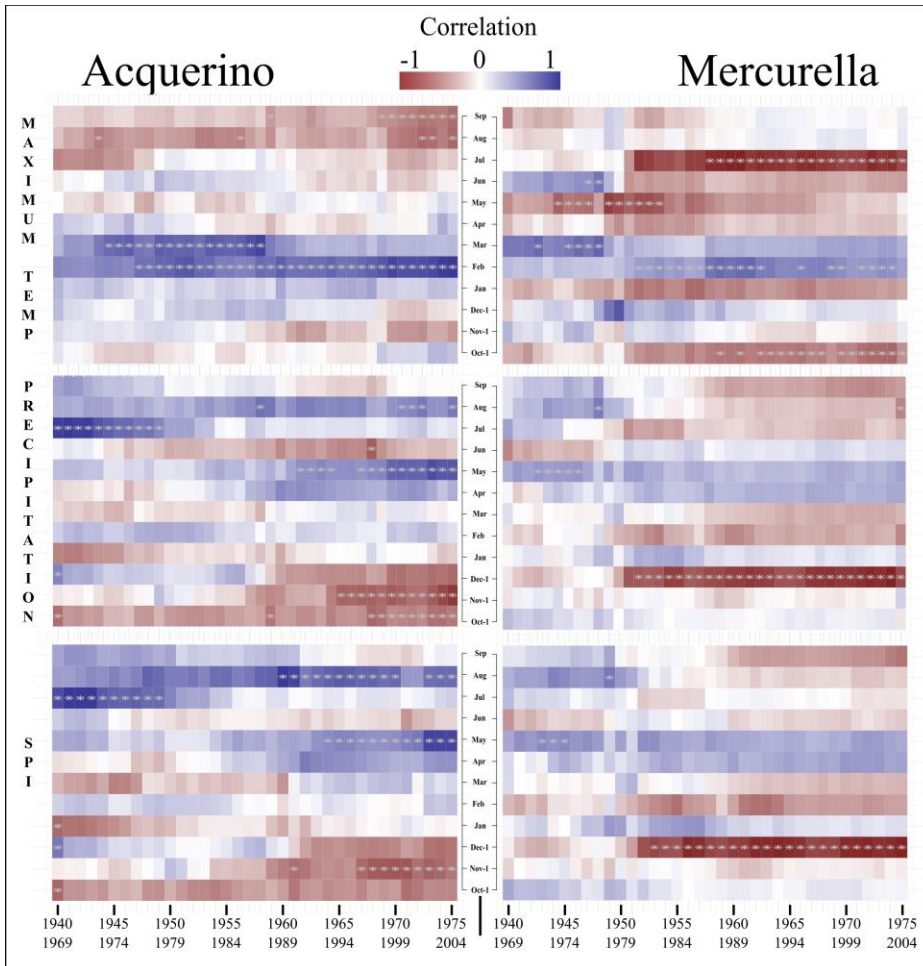
240 **Figure 5.** Correlation functions (CF) between ring width and climatic variables (significant
 241 correlations, $p < 0.05$, are marked by black bars)

242

243 The MCF analysis highlighted several periods with significant correlation between ring width and
 244 climate, but not all the correlations were stable over time. At Acquerino, spring and summer

245 temperatures were rarely significant, but February and also March as long as the period 1958-1988
246 were highlighted as stable positive correlation. [The average maximum September](#) temperatures [of](#)
247 [September](#) became relevant in the last decades for growth of the current year, and in the period
248 1955-1991 for growth of the following year. This could be seen as a possible a prolonging of
249 vegetative season. In the first part of study period, maximum temperature of the previous May also
250 had a positive influence on tree ring width (Figure 6). Correlations with water availability were also
251 unstable, with a positive influence of previous year precipitation shifting from September to June,
252 and of current year from July to May. Summer drought (measured by SPEI) had generally a
253 negative effect on growth, but this was significant only in recent years. On the contrary, a
254 significantly positive effect of water availability in previous summer was detected for the first part
255 of the study period. At Mercurella, MCF evidenced similar relationships with growth, i.e., a stable
256 positive influence of February/March maximum temperature, a negative influence of December (t-
257 1) precipitation and positive influence of September (t-1) precipitations, and a generally positive
258 effect of water availability (positive SPEI) in the year before growth. An additional relevant effect
259 was the negative influence of July maximum temperature on current year growth, which has been
260 significant since 1960. Possible impacts on growth trends might also be addressed to water supply
261 as reserve in soil; the two stands are growing on different soil types: While Cambisols characterize
262 Acquerino, Haplich Umbrisols (more humid) characterise Mercurella.

263



264

265 **Figure 6.** Moving correlation functions (MCF) between ring width and climatic variables

266 (significant correlations, $p < 0.05$, are marked by stars)

267

268 **Discussion**

269 The Mediterranean basin represents the southern edge of Douglas fir's introduction range in Europe

270 and here, under both a Mediterranean (Mercurella) and ~~a more a less dry~~ continental-like climate

271 (Acquerino), late winter (February and March) is recognised as a key season for Douglas fir growth.

272 On the basis of the obtained empirical evidence our findings may ~~confirm~~explain the successful
273 introduction of such valuable exotic forest tree species even at the southern limits of Europe. As
274 overall, the ~~low~~ sensitivity of the species we calculated with our sampling was almost the half of the
275 value generally found for *Abies alba* Mill. or *Fagus sylvatica* L. in Italy (Mazza et al., 2014; Rita et
276 al., 2014),which represents the Italian native tree species generally growing in similar climatic
277 conditions to those our stands were located. This aspect might suggest a low interaction between
278 climate and tree species, i.e. growth trends are often uncorrelated with the climate. The positive
279 correlation between growth and February-March temperatures, which has been detected also by
280 other studies in Europe (e.g. Thurm et al., 2016), highlights that some cambial activity is possible
281 even in winter, an important adaptive trait of many conifer species (Gričar et al., 2015). The absence
282 of frost events during winter might favour growth of the species in the growing season. For instance
283 the negative pointer year we found around 1980s was mainly addressed to an intense foliar damage
284 trees experienced during the winter, which probably limited photosynthesis in the first part of the
285 following growing season. Then, summer temperature in the year of growth is found to be a limiting
286 factor under both climate regimes here considered; the fact that summer temperature in the previous
287 year have instead positive influence might be related to faster organic matter turnover and higher
288 resource availability for growth in the following year.

289 Summer precipitation was recognized as a ~~limiting~~influencing factor only at the northern location
290 (Acquerino), suggesting local acclimation, and a different temporal regulation of photosynthesis
291 and physiological activity for the southernmost provenance. On the other hand, high precipitation in
292 autumn preceding growth has a negative effect on productivity at both sites. This might seem
293 counter intuitive, but can be explained by a complementary effect of rain versus snow. Rain gauges
294 are generally not able to measure both snow and rain; measurements of low rainfall in late autumn
295 and early winter months might “hide” snowfall (relatively frequent at both sites), which is
296 beneficial to next year’s growth via increased water availability in the soil after snowmelt (Littell et
297 al., 2008).

298 The current-year growing conditions are mainly able to influence latewood growth whereas
299 earlywood growth is influenced by antecedent and current-year conditions (Eilmann and Rigling,
300 2012; Watson and Luckman, 2002). In this case and regarding water balance, previous year drought
301 was found to strongly limit growth (probably via an influence on earlywood formation) only at
302 Acquerino, where usually no aridity occurs during the summer, and the soil is more fertile (top see
303 height at age 70, [Table 1](#)). Only one month of significant correlation ~~between TRW and~~ with SPEI
304 has been detected at Mercurella. Recent studies have found Douglas fir to be vulnerable to
305 exceptional and recurrent drought episodes only on low fertility sites (Sergent et al., 2014), which is
306 the opposite to what we have found. However, Mercurella is both dryer and hotter than Acquerino
307 and closer to the seaside. In this particular environment trees might have deal with low water
308 availability and moisture deficit by local acclimation. Such effect may be stronger than what
309 implied by soil characteristics. Another possibility might consider this skill as already included in
310 the genotype of the trees and not expressed in other zones (Mathys et al., 2014). This represents a
311 potential research question which should be addressed with adequate molecular techniques. Indeed,
312 the genetic provenance of old Douglas fir stands in Europe is rarely known and only recently
313 addressed by means of dedicate sampling procedures and nuclear markers (Hintsteiner et al., 2018).
314 ~~In our study the only information available is that both stands were established by 3 year old~~
315 ~~seedlings form the nursery of Vallombrosa with “Italian” seeds collected form mature trees with~~
316 ~~unknown origin (probably form Washington, Oregon or California) around 1930~~ (Avolio and
317 Bernardini, 2000) In this framework, it remains unknown whether instead the smaller top height at
318 the southern site is a result of some resistance (i.e. productivity trade-off of the southern
319 provenance). To solve this, common garden experiments with such provenance might be pursued to
320 evaluate the productive performance of this seed source under different climate regimes. Actually
321 the growth response to climatic conditions in the previous year and winter based on tree-ring width
322 time series measured at an annual time step is supposed to be maintained. This aspect might open

323 new research scenarios for other studies where second-stage seed sources from such old Douglas fir
324 stands might represent a valuable potential for forest management in Italy.

325 Testing provenance materials and monitoring the growth response of rear-edge populations in warm
326 and dry climates is fundamental for adaptive forest management in Europe (Provan and Maggs,
327 2012). Under such perspective, this study could represent an opportunity to derive useful insight on
328 this exotic species in Europe. Actually, climate is challenging for plant growth across the whole
329 Europe, both in the warm-temperate zone due to summer aridity periods with increasing
330 temperatures, and in wetter areas that are undergoing significant drying trends. Under this scenario,
331 acclimated old populations of Douglas fir showing high growth plasticity and tolerance to drought
332 (Boiffin et al., 2017; Isaac-Renton et al., 2014) may be seen as to have a good potential for timber
333 supply in Europe (Rais et al., 2014; Sergent et al., 2014). The role of active forest management may
334 be relevant in this end, since the stand structure can have a deep influence on the mitigation of
335 water stress, also in the case of Douglas fir (Mazza et al., 2018; Rebetez et al., 2006).

336 The MCF analysis showed a quite complicated framework where just few correlations were stable
337 and dominant. Indeed this aspect was not surprising given the nature of the relationship: an exotic
338 species introduced in a new environment. The analysis detected that the strength and significance of
339 most correlations with Douglas fir growth against temperature, precipitation, and SPEI shifted from
340 months in the year prior to growth to those in the year when growth occurs. At Acquerino, late
341 summer temperature became significantly limiting only after the year 1970 (and after 1960 at
342 Mercurella). Anyway this aspect should not be addressed to a possible adaptation of the species.
343 The negative correlations of growth with summer temperature in the recent decades suggest that
344 temperatures have increased and are now at or above the temperature optimum for growth i.e.
345 around 20°C (Briffa et al., 2001). No consistent sign could be found for any divergence-like
346 weakening of tree responses to temperature in recent decades (Briffa et al., 1998; Wigley et al.,
347 1984). The most important month for winter temperature shifted from March to February also at
348 Acquerino, and for summer precipitation from July to May as a possible consequence of the

349 anticipation of growing season onset and precipitation reduction induced by climate change. Also,
350 at Mercurella, the previous years' drought has maintained its importance throughout the study
351 period, which may again reflect the interaction between climate and soil in determining tree growth
352 (i.e., a higher water availability may compensate for the limitation of a poor soil by increasing the
353 resources available to the tree in the following year).

354

355 **Conclusions**

356 After almost 100 years of experimentation, Douglas fir has demonstrated a relevant potential for
357 timber production across Europe. ~~The species is probably there to stay, and many countries are~~
358 ~~currently implementing silviculture aiming to regenerate the species naturally.~~ Known as a drought-
359 tolerant species, Douglas fir has in fact demonstrated a high acclimation capacity when grown in
360 warm and dry climates (southern provenances). It is relevant to highlight that the Mercurella stand
361 here examined represents the southernmost plantation at the southern limit of European planting
362 range of Douglas fir. ~~Late winter temperatures play here a key role for Douglas fir growth, while~~
363 ~~precipitation has a lower effect.~~ However, the differences in potential maximum productivity
364 between southern and northern Mediterranean provenances have to be further assessed. ~~Given the~~
365 ~~adaptive capacity of this species to European climate, current plantations may be considered as a~~
366 ~~climate smart seed sources to establish new populations with high adaptive capacity under future~~
367 ~~climate change.~~ However, further common garden experiments should be planned in order to
368 properly test adaptation of the second or third generation seed generated by old Douglas fir stands
369 across Europe. An interesting study could compare adaptation of this species in both zones, the
370 Pacific North West and Europe, collecting seeds from both and to test them with a novel field trial
371 network to be established in both areas. In our opinion, further experimental should be welcomed
372 such as the IUFRO 1960s experimentation as well as the EUDIREC (Grant agreement ID:
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374

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381

382 **Conflict of Interest:** the authors declare that no conflict of interest exists

383

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