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Insensitivity of tree-ring growth to temperature and precipitation sharpens the puzzle of enhanced pre-eruption NDVI on Mt. Etna (Italy)

Seiler, Ruedi; Kirchner, James W; Krusic, Paul J; Tognetti, Roberto; Houlié, Nicolas; Andronico, Daniele; Cullotta, Sebastiano; Egli, Markus; D'Arrigo, Rosanne; Cherubini, Paolo

Abstract: On Mt. Etna (Italy), an enhanced Normalized Difference in Vegetation Index (NDVI) signature was detected in the summers of 2001 and 2002 along a distinct line where, in November 2002, a flank eruption subsequently occurred. These observations suggest that pre-eruptive volcanic activity may have enhanced photosynthesis along the future eruptive fissure. If a direct relation between NDVI and future volcanic eruptions could be established, it would provide a straightforward and low-cost method for early detection of upcoming eruptions. However, it is unclear if, or to what extent, the observed enhancement of NDVI can be attributed to volcanic activity prior to the subsequent eruption. We consequently aimed at determining whether an increase in ambient temperature or additional water availability owing to the rise of magma and degassing of water vapour prior to the eruption could have increased photosynthesis of Mt. Etna's trees. Using dendro-climatic analyses we quantified the sensitivity of tree ring widths to temperature and precipitation at high elevation stands on Mt. Etna. Our findings suggest that tree growth at high elevation on Mt. Etna is weakly influenced by climate, and that neither an increase in water availability nor an increase in temperature induced by pre-eruptive activity is a plausible mechanism for enhanced photosynthesis before the 2002/2003 flank eruption. Our findings thus imply that other, yet unknown, factors must be sought as causes of the pre-eruption enhancement of NDVI on Mt. Etna.

DOI: <https://doi.org/10.1371/journal.pone.0169297>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-146034>

Journal Article

Accepted Version

Originally published at:

Seiler, Ruedi; Kirchner, James W; Krusic, Paul J; Tognetti, Roberto; Houlié, Nicolas; Andronico, Daniele; Cullotta, Sebastiano; Egli, Markus; D'Arrigo, Rosanne; Cherubini, Paolo (2017). Insensitivity of tree-ring growth to temperature and precipitation sharpens the puzzle of enhanced pre-eruption NDVI on Mt. Etna (Italy). *PLoS ONE*, 12(1):0169297.

DOI: <https://doi.org/10.1371/journal.pone.0169297>

1 **Insensitivity of tree-ring growth to temperature and precipitation sharpens the puzzle of**
2 **enhanced pre-eruption NDVI on Mt. Etna (Italy)**

3

4 short title: Climatic response of trees on Mt. Etna

5

6 Ruedi Seiler^{1,2}, James W. Kirchner^{1,3}, Paul J. Krusic^{4,5}, Roberto Tognetti⁶, Nicolas Houlié⁷, Daniele
7 Andronico⁸, Sebastiano Cullotta⁹, Markus Egli², Rosanne D'Arrigo¹⁰ and Paolo Cherubini^{1,2,10}

8

9 ¹Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Zürcherstrasse 111, CH-8903 Birmensdorf,
10 Switzerland

11 ²Department of Geography, University of Zurich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

12 ³Department of Environmental Systems Science, ETH Zurich, CH-8093 Zürich, Switzerland

13 ⁴Navarino Environmental Observatory, Messinia, Greece

14 ⁵Institutionen för Naturgeografi, Stockholm University, Sweden

15 ⁶Dipartimento di Bioscienze e territorio, Università del Molise, Contrada Fonte Lappone, 86090 Pesche, Italy

16 ⁷Department of Earth Sciences, ETH Zurich, CH-8093 Zürich, Switzerland

17 ⁸Osservatorio Etneo, INGV, Sezione di Catania, Italy

18 ⁹Università di Palermo, Palermo, Italy

19 ¹⁰Lamont-Doherty Earth Observatory, Palisades, New York, USA

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23

24 **Abstract**

25 On Mt. Etna (Italy), an enhanced Normalized Difference in Vegetation Index (NDVI) signature was
26 detected in the summers of 2001 and 2002 along a distinct line where, in November 2002, a flank
27 eruption subsequently occurred. These observations suggest that pre-eruptive volcanic activity may

28 have enhanced photosynthesis along the future eruptive fissure. If a direct relation between NDVI
29 and future volcanic eruptions could be established, it would provide a straightforward and low-cost
30 method for early detection of upcoming eruptions. However, it is unclear if, or to what extent, the
31 observed enhancement of NDVI can be attributed to volcanic activity prior to the subsequent
32 eruption. We consequently aimed at determining whether an increase in ambient temperature or
33 additional water availability owing to the rise of magma and degassing of water vapour prior to the
34 eruption could have increased photosynthesis of Mt. Etna's trees. Using dendro-climatic analyses
35 we quantified the sensitivity of tree ring widths to temperature and precipitation at high elevation
36 stands on Mt. Etna. Our findings suggest that tree growth at high elevation on Mt. Etna is weakly
37 influenced by climate, and that neither an increase in water availability nor an increase in
38 temperature induced by pre-eruptive activity is a plausible mechanism for enhanced photosynthesis
39 before the 2002/2003 flank eruption. Our findings thus imply that other, yet unknown, factors must
40 be sought as causes of the pre-eruption enhancement of NDVI on Mt. Etna.

41

42

43 **Introduction**

44 Early detection of precursors to volcanic eruptions is important in preventing major damage and
45 loss of life. To date, these precursors have mainly included seismic, geochemical, petrographic,
46 ground deformation and gravimetric changes that are used to assess volcanic activity shortly before
47 eruptions (e.g., McNutt, 1996; Battaglia et al., 1999; Williams-Jones & Rymer, 2002; Sherburn et
48 al., 2007; Hooper et al., 2012; Sicali et al., 2015). Surface deformation, small earthquakes, and
49 release of volcanic gases are typically triggered by the ascent of magma in volcanoes (Sparks et al.,
50 2012). Volcanic monitoring by remote sensing includes the acquisition of different geochemical and
51 geophysical parameters which record volcanic processes, such as gas emissions and hydrological

52 variations, over time (e.g., Jong, 1998; McNutt et al., 2000; Andronico et al., 2009). Using remote
53 sensing data, Houlié et al. (2006) observed an increased Normalized Difference Vegetation Index
54 (NDVI) along subsequent eruptive fissures on Mt. Nyiragongo (Congo) and Mt. Etna (Italy), as
55 early as two years prior to eruptions of both volcanoes. NDVI is closely associated with the amount
56 of photosynthetically active radiation intercepted by vegetation, and thus with both the spatial
57 coverage of green biomass and the chlorophyll content in leaves (Gamon et al., 1995; Goetz et al.,
58 2005). On Mt. Etna, the enhanced NDVI signal (Houlié et al., 2006) was detected along a narrow
59 line on the northeastern flank; this line later developed into an eruptive fissure during the 2002/2003
60 flank eruption, suggesting that enhanced photosynthesis may be related to a coming volcanic
61 eruption.

62 The observed NDVI signal raises the question of whether, and how, eruptive precursor activity
63 could influence photosynthetic rates. A comparison of tree growth with environmental parameters is
64 necessary to estimate their influence on tree growth and to assess the potential contribution from
65 volcanic activity. Increased photosynthesis may be induced by a number of environmental factors
66 that are affected by pre-eruptive volcanic processes, but the most probable are an increase in heat or
67 water availability associated with volcanic degassing (e.g., Andronico et al., 2005; Aiuppa et al.,
68 2007; Shinohara, 2008).

69 Trees in temperate climates form annual growth rings, and variations in their tree-ring
70 characteristics (width and density) reflect changes in the environmental conditions in which they
71 grow. At high elevations and high latitudes, where the limiting factor is summer air temperature,
72 tree growth is typically enhanced during warm summers (e.g., Buntgen et al., 2006; Briffa et al.,
73 2013). Conversely, in semi-arid ecosystems, such as in Mediterranean lowlands, growth is primarily
74 regulated by precipitation and is enhanced during wet years (Cherubini et al., 2003; Gea-Izquierdo

75 et al., 2011). Consequently, tree rings, often used as indicators of photosynthetic rates (Dobbertin,
76 2005), also serve as useful proxies for climate (Fritts, 1976; Begum et al., 2013).

77 The Mediterranean region is characterized by hot and dry summers and mild, humid winters
78 (Köppen, 1923; Walter & Lieth, 1960). Maximum rainfall occurs predominantly in autumn and
79 sometimes during winter (Bolle et al., 2006). Precipitation minima and temperature maxima
80 coincide with the period of most intense solar radiation, limiting water availability during the
81 summer season (e.g., Ma et al., 2007). High rainfall variability over the year greatly affects drought
82 severity and hampers growth (Cotrufo et al., 2011). Rainfall during spring is the most important
83 factor influencing tree growth and vegetation activity of Mediterranean forests, particularly at more
84 xeric, low-elevation sites, as also shown by remote-sensing-based model simulations and tree-ring-
85 based growth analyses (Maselli et al., 2014). In more temperate high-elevation conditions, drought
86 often has a minor impact on tree growth because precipitation is less limiting. In the high-elevation
87 forests on Mt. Etna where Houlié et al. (2006) detected the increase in NDVI prior to eruption, tree
88 growth might be enhanced by increased air temperature during the vegetation period or, given the
89 southern latitude, by increased water availability.

90 Here we analyse the relationships between ring width indices of *Pinus nigra* J.F. Arnold and
91 monthly precipitation and air temperature, and compare our ring-width series from Mt. Etna with
92 series from trees growing at similar elevations in Calabria, a region located at a similar latitude on
93 the Italian peninsula without the direct influence of volcanic activity. Our hypotheses are that i)
94 ascending magma led to an increase in local ambient air and soil temperature which positively
95 influenced photosynthesis rates and tree growth, and that ii) water vapour from volcanic degassing
96 locally provided additional humidity/moisture/water which became available to trees influencing
97 photosynthesis rates and tree growth. To address these issues we assess to what extent tree-ring
98 growth at the highest elevations on Mt. Etna is influenced by climate, i.e. air temperature and

99 precipitation, to indirectly determine i) whether an increase in temperature caused by an incipient
100 volcanic eruption (e.g., Bonneville & Gouze, 1992; Andronico et al., 2005) would likely induce
101 higher photosynthetic productivity, and ii) whether, at specific locations close to rift zones,
102 additional water availability induced by degassing of water vapour associated with the rise of
103 magma prior to an eruption (water is the most abundant component in volcanic gas, Shinohara,
104 2008) would likely increase the photosynthetic capacity of Mt. Etna's trees (see Houlié et al., 2006).

105

106

107 **Materials and Methods**

108 *Study area*

109 Mt. Etna is a stratovolcano situated in the northeastern part of Sicily. With an area of approximately
110 1600 km² and a summit elevation of roughly 3330 m a.s.l., Mt. Etna is an isolated high mountain
111 exposed to air masses from the Mediterranean Sea. The climate on Mt. Etna is strongly maritime on
112 the eastern flank (Poli Marchese & Grillo, 2004; Branca et al., 2008), with drier conditions on its
113 western flank (Burga & Klötzli, 2004). The slopes are characterized by lava flows of different ages
114 (Doglioni et al., 2002). Most of the lower elevations, being especially fertile, have been settled and
115 used for agriculture for thousands of years. The higher elevations, from 1000-1600 m a.s.l., are
116 dominated by European beech (*Fagus sylvatica* L.), and from 1600 m to treeline (~2000 m a.s.l.) by
117 Corsican black pine (*P. nigra*). Though the treeline climatically determined at such latitudes would
118 otherwise be higher (Hermes, 1955; Körner, 1998), eruption-induced wildfires and the lack of soils
119 on lava flows hinder its uphill development (Certini et al., 2001; Dazzi, 2007; Egli et al., 2012).

120 Besides volcanic eruptions and lava flows on Mt. Etna, other volcanic processes, such as degassing
121 through small vents, are also present but difficult to quantify (Allard, 1997). The soils of Mt. Etna
122 are primarily classified as Regosols, Eutric or Dystric Cambisols and (Mollic) Andosols. The

123 characteristics of these soils predominantly depend on the surface age of the lava flow and volcanic
124 deposits from which they have developed (Dazzi, 2007; Lulli, 2007; Egli et al., 2008). In general,
125 soils at intermediate to high elevation on Mt. Etna (i.e. above 800 m a.s.l.) are mostly described as
126 Andisols with a sandy loam texture, vitric characteristics, an udic moisture regime (Egli et al.,
127 2012) and good water holding capacity (Maeda et al., 1977). However, less mature, young soils on
128 fresh lava flows may be less developed resulting in lower water holding capacity.

129 The forests around the flanks of Mt. Etna are greatly affected by both natural and anthropogenic
130 disturbances, such as wildfires, lava flows, avalanches and logging. At the lowest elevations, from
131 the plains up to 900 m a.s.l., agricultural crops and orchards, e.g., orange, lemon, almond, pistachio,
132 and chestnut, are found. Only a few forest stands, mainly at the highest elevations on the northern
133 or northeastern side of the mountain, are undisturbed (Poli Marchese & Grillo, 2004).
134 Meteorological station data from Linguaglossa (530 m a.s.l., 15°08'42" E, 37°50'27" N, timespan:
135 1893-2004) based on daily temperatures and precipitation measurements give an average annual
136 temperature of 18°C and a total annual precipitation of 1400 mm. Additionally, monthly
137 temperature averages in winter are above zero at all stations.

138

139 *Sampling*

140 In total, we sampled 143 trees (*P. nigra*), with permission issued by the local forest authorities
141 (Corpo Forestale della Regione Siciliana, Distaccamento di Bronte, Piazza Cadorna 11, I-95034
142 Bronte, Catania, Italy), at four high-elevation (1500 to 1900 m a.s.l.) forest sites on the northeastern
143 and western slopes of Mt. Etna (Fig 1): 52 trees growing close to the 2002/2003 eruptive fissure
144 (Group 1), 27 trees growing close to the 1928 eruptive fissure (Group 2), 38 trees growing in the
145 same elevation band but far from any obvious fissures (Group 3), and 26 trees growing close to the
146 1974 eruptive fissure (Group 4). All sites are located at a comparable elevation and slope with NNE

147 aspect except for group 4, which is located on the western flank on a western-aspect slope. Apart
148 from that, there were no evident differences between the four sites in terms of forest-stand density,
149 composition of tree species, topography and slope (about 14%). From each tree, two 0.5 cm
150 diameter cores were taken orthogonally with respect to each other using a corer with a three-
151 threaded auger by Haglof (Haglof Inc., Sweden), wrapped in paper and transported to the
152 laboratory. All samples were mounted on wooden supports and cut following the technique
153 suggested by Gärtner et al. (2015), using a microtome at an angle of roughly 30° to the radial axis
154 of the tree to prevent core breakage. For later comparisons, three ring-width chronologies, located
155 close to Mt. Etna, derived from coniferous trees uninfluenced by Mt. Etna growing at similarly high
156 elevations in Calabria (Gambarie, Monte Pollino and Sierra da Crispo) were retrieved from the
157 International Tree-Ring Databank (ITRDB, NOAA, U.S.A.)

158

159 **Fig 1. Map of sample locations.**

160 Mt. Etna sample sites (Group 1-4) on the northeastern and western slopes at an elevation range from
161 1600 to 1850 m a.s.l. indicating the location where samples were taken and the location of the
162 meteorological stations.

163

164 *Ring-width measurements*

165 All ring widths were measured to the nearest 0.01 mm using a Leica Wild M32 binocular
166 microscope (Leica, Germany) with 25-50x magnification, coupled to a LINTAB measuring table
167 and computer with TSAPwin (Time Series Analysis Program) software (RinnTech, Heidelberg,
168 Germany). Core measurements were visually crossdated against each other and any inconsistencies,
169 if found, were eliminated. Subsequent crossdating of the single-tree chronologies with their
170 respective mean site chronology by visual and statistical measures was performed using TSAPwin

171 and COFECHA (50-year segments with a 25-year overlap) (Holmes, 1983; Grissino-Mayer et al.,
172 2001). Since the sampling dates of all trees were known, crossdating was primarily used to ensure
173 that prominent tree-ring patterns were not shifted between trees and no rings were missing.

174

175 *Meteorological data*

176 We used monthly precipitation and air temperature data recorded at three meteorological stations on
177 Mt. Etna: Floresta (1275 m a.s.l., 14°54'31" E, 37°59'15" N, Timespan: 1924-2004), Linguaglossa
178 (530 m a.s.l., 15°08'42" E, 37°50'27" N, Timespan: 1893-2004) and Taormina (248 m a.s.l.,
179 15°17'34" E, 37°17'34" N, Timespan: 1906-2004). Although longer records are available for
180 Linguaglossa and Taormina, we only used data from 1924-2004 at all three sites so that they could
181 be compared over a common period. In addition, interpolated monthly temperature, precipitation,
182 cloud cover and Palmer Drought Severity Index (PDSI) data for the Mt. Etna region and Calabria
183 from the Climatic Research Unit, University of East Anglia, Norwich, U.K. (CRU; Mitchell et al.,
184 2004) were compared to the above-mentioned station data and the tree-ring data (Griggs et al.,
185 2007; Carrer et al., 2010). Opposed to temperature and precipitation data, the PDSI incorporates
186 both temperature and precipitation, representing long-term drought taking prior months' condition
187 into account. On the other hand, delayed water runoff from snow during spring is not accounted for
188 in the index (e.g., Lüdeke et al., 1996). Correlations between the data recorded at the meteorological
189 stations and the interpolated datasets were calculated, to assess whether the interpolated data could
190 be used to further analyse relationships between climate and tree growth.

191

192 *Data analysis*

193 All raw measurement series were standardized using the program ARSTAN
194 (<http://www.ldeo.columbia.edu/tree-ring-laboratory>) by applying 30-year spline detrending

195 combined with a variance stabilization, to remove the age trend and produce detrended ring-width
196 indices (Holmes, 1983; Cook, 1985; Büntgen et al., 2005). All chronologies were used individually
197 to analyse the relationships between climate and growth at different sampling sites.

198

199 We performed correlation analysis and response function modelling to quantify the influence of
200 climate on tree growth (Cook et al., 1990). We tested the statistical significance of temperature,
201 precipitation, cloud cover and Palmer Drought Severity Index (PDSI) (e.g., García-Suárez et al.,
202 2009; Cai et al., 2014) in different months and seasonal combinations of monthly values, including
203 prior-year values, using Spearman rank correlation. Linear regression, as described by Tomé &
204 Miranda (2004), was used to remove long-term trends in the meteorological data and avoid
205 artificially inflating correlation values. Based on results from simple Spearman rank correlations
206 between all the Mt. Etna chronologies and monthly meteorological data, we built "Visual
207 Regression Models" (VRM) which were defined as standard multiple linear regression models
208 including statistically significant ($p < 0.05$) monthly variables or monthly groupings.

209 In addition to VRM, Stepwise Linear Regression Modelling (SLRM), based on the Akaike
210 Information Criterion (AIC) and using a forward-backward approach (Cook & Pederson, 2011),
211 was used to identify those climate variables that explained the greatest variance in each chronology
212 on Mt. Etna. The SLRMs were based on monthly variables and groupings that defined the spring
213 and summer seasons. For all models we only used variables that did not overlap in time (e.g.,
214 precipitation in May and precipitation in spring would not be used together because both contain
215 May precipitation values).

216 The models (SLRM) were tested for collinearity among explanatory variables using variance
217 inflation factor (VIF) analysis (Kutner et al., 2005). VIF values were all lower than 4, implying a
218 lack of strong collinearity among explanatory variables (O'Brian, 2007). This led to selecting the

219 final climate models based on the AIC.

220 We compared how well the two model types (VRM and SLRM) explained the climate – ring width
221 relationship:

222 1) Qualitative differences between the two model types included differences in monthly parameters
223 used in the models.

224 2) Quantitative differences, comparing adjusted- R^2 , show the increase/decrease of explanatory
225 power from one model type to another.

226 To test the reliability of the models, as well as the degree of overfitting due to including too many
227 variables during the stepwise model selection process, we divided the timespan covered by both
228 meteorological and ring-width measurements at Mt. Etna (1924-2004) and Calabria (1924-1980)
229 into two segments (Todaro et al., 2007; Griggs et al., 2014). The models were run on both segments
230 to compare differences over time. In addition, the two segments were used for both forward- and
231 backward validation to quantify model robustness over time (Cook & Kariukstis, 1990).

232 On Mt. Etna, forward validation used a model based on the time segment 1925-1964 to predict tree
233 growth during 1965-2004, and backward validation used a model based on the latter time segment
234 to reconstruct 1925-1964 tree growth. For the Calabria chronologies we used the same validation
235 procedure based on the two time segments from 1925-1951 and 1952-1980. AIC was used to test
236 for overfitting.

237 We calculated how the explanatory power (R^2) varied through time by applying our SLRMs to a 15-
238 year moving window with 14 years overlap to identify periods of higher and lower correlations
239 between ring-width and our climate models (Carrer et al., 2010).

240

241

242 **Results**

243 The Mt. Etna chronologies show higher variability in their ring-width patterns than the chronologies
 244 from Calabria (Fig 2). The four raw ring-width chronologies (Group1-4) from Mt. Etna display
 245 growth patterns that are strongly influenced by the establishment of new generations of trees.
 246 Young trees, most germinating after 1950, greatly increase the mean ring-width, producing a clear
 247 age trend (Fig 2). Tree age ranges from 55 to 122 years on Mt. Etna, and from 128 to 299 years in
 248 Calabria. Descriptive chronology statistics are given in Table 1.

249

250 Fig 2. **Chronologies and sample replication.**

251 Average chronologies (black lines) and sample replication of all samples (grey area) of Mt. Etna
 252 (Group 1-4) and Calabria (Gambarie, Monte Pollino and Sierra da Crispo).

253

		no. of series	total length	ser.interc.	mean length	elevation	species
Mt. Etna	Group 1	104	229	0.498	97	1850	<i>Pinus nigra</i>
	Group 2	54	121	0.577	67.1	1700	<i>Pinus nigra</i>
	Group 3	76	195	0.529	82.7	1600	<i>Pinus nigra</i>
	Group 4	52	130	0.597	95	1670	<i>Pinus nigra</i>
Calabria	Gambarie	26	191	0.344	130.7	1850	<i>Abies alba</i>
	Monte Pollino	24	181	0.403	128.2	1720	<i>Abies alba</i>
	Sierra da Crispo	22	540	0.421	299.1	2000	<i>Pinus leucodermis</i>

254

255 Table 1. **Sample overview information.**

256 Descriptive statistics of sample chronologies (Group 1-4) from Mt. Etna, and the chronologies from
 257 Calabria (Gambarie, Monte Pollino and Sierra da Crispo) displaying number of series (core-series),

258 total length (years) of group chronologies, series intercorrelation (measure of common growth
 259 signal in the chronology), mean sample length (years), elevation (m a.s.l.) and species.

260

261 The monthly meteorological data show stronger inter-station correlations for air temperature
 262 (Spearman correlation coefficients up to $r = 0.86$; $p < 0.01$) than for precipitation (up to $r = 0.83$; p
 263 < 0.01), as usually reported in the literature (e.g., Graumlich, 1987; Griggs et al., 2007). In addition,
 264 we find that instrumental station data also correlates significantly with the interpolated CRU data
 265 (highest Spearman $r = 0.67$ to 0.87 for temperature; $r = 0.67$ to 0.78 for precipitation; $p < 0.01$).
 266 Given these correlations, comparable to those found in previous studies (Griggs et al., 2007), we
 267 used the interpolated data to assess the climate influence on tree growth.

268 In general, total summer precipitation produces similarly high correlation values with tree growth as
 269 single monthly variables in the same season. Average spring and summer temperature and total
 270 spring precipitation produce generally lower correlations than single months during the same season
 271 (Table 2). Prior-year precipitation and temperature were also considered but results are not reported
 272 because the current year's correlations are higher. Cloud coverage is not significantly correlated
 273 with tree growth. In contrast to all other sites, tree growth at Group 3 exhibits a significant negative
 274 correlation with PDSI from April to December (results not shown).

275

	Mt. Etna				Calabria		
SPEARMAN rank correlations	Group 1	Group 2	Group 3	Group 4	Gambarie	Monte Pollino	Sierra da Crispo
T February	0.176	0.189	0.217	0.055	0.209	0.184	0.114
T March	** 0.427	* 0.265	** 0.327	0.197	0.152	0.163	0.018
T April	0.144	-0.109	0.064	0.169	0.148	** 0.490	0.203
T May	-0.106	-0.213	-0.15	-0.033	-0.018	* 0.271	0.061
T avg. spring	** 0.337	0.197	* 0.284	0.14	0.21	** 0.348	0.11
T June	0.035	-0.094	-0.004	0.172	* -0.283	-0.019	-0.068
T July	-0.158	* -0.223	-0.136	0.06	* -0.296	-0.068	0.026
T August	** -0.326	-0.182	** -0.397	-0.032	** -0.408	-0.05	-0.131

T September	-0.117	-0.147	-0.198	-0.01	-0.178	0.026	0.117
T avg. summer	-0.172	-0.206	-0.203	0.088	** -0.375	-0.07	-0.084
prior P December	-0.16	* -0.261	** -0.304	-0.028	0.087	0.181	0.111
P January	0.131	-0.095	0.091	0.021	-0.137	-0.018	0.059
prior P winter	0.027	* -0.251	-0.078	0.043	0.03	0.184	0.182
P February	-0.048	-0.113	-0.159	-0.125	-0.057	-0.128	0.029
P March	* -0.279	-0.151	-0.12	-0.079	-0.007	-0.001	0.044
P April	0.009	0.121	0.15	0.103	-0.22	* -0.279	-0.031
P May	0.185	0.088	* 0.227	0.025	0.209	-0.026	-0.179
P tot. spring	* -0.228	-0.104	-0.107	-0.095	-0.19	* -0.308	-0.015
P June	0.114	0.03	* 0.236	-0.117	* 0.279	0.138	0.076
P July	* 0.279	0.092	* 0.222	* 0.225	* 0.303	** 0.416	0.186
P August	0.165	-0.043	0.209	0.09	0.083	0.083	0.136
P tot. summer	* 0.271	0.09	** 0.346	0.118	* 0.325	* 0.314	0.24

276

277 Table 2. **Climate-ring width correlation statistics.**

278 Spearman rank correlations between climate variables and detrended ring width from Mt. Etna
279 chronologies (Group 1-4) and from Calabria chronologies (Gambarie, Monte Pollino and Sierra da
280 Crispo), where P = precipitation, T = temperature, tot. = total amount of precipitation, avg. =
281 average temperature, and prior = prior year. Values printed in bold are statistically significant with
282 (* = $p < 0.05$, ** = $p < 0.01$, two-tailed). The significance threshold at Mt. Etna is lower than in
283 Calabria ($r = 0.222$ vs. $r = 0.271$, respectively) because the climate and tree ring records overlap for
284 longer on Mt. Etna than in Calabria (81 vs. 57 years, respectively).

285

286 In Calabria the Gambarie chronology is primarily sensitive to summer temperature and summer
287 precipitation (Table 2). The Monte Pollino chronology responds more to spring temperatures as
288 well as spring and summer precipitation, and the chronology from Sierra da Crispo is not
289 significantly correlated with any climate variables. The Mt. Etna chronologies correlate with spring
290 and summer temperatures (Groups 1-3), as well as spring and summer precipitation (Groups 1 and
291 3). Group 4 has no significant correlations with climate. Over all months and seasons the Mt. Etna

292 (Groups 1-4) chronologies are, on average, less strongly correlated with temperature and
293 precipitation than the Calabria chronologies are. The difference in the (absolute value) strength of
294 the correlations between Mt. Etna and Calabria was not, however, statistically significant (Student
295 *t*-test).

296 Overall we observe similar responses in the chronologies from Mt. Etna and in those from Calabria
297 (Table 2 and Fig 3). The raw numbers of significant correlations between temperature or
298 precipitation and ring width are broadly similar (20 out of 88, or 23% at Mt. Etna, and 14 out of 66,
299 or 21%, in Calabria).

300

301 **Fig 3. Climate - ring-width correlations.**

302 Spearman rank correlation data points of single months and seasonal groupings (red dots) of
303 chronologies from Mt. Etna (top panel) and Calabria (bottom panel) showing the correlation range
304 of each monthly- or seasonal variable with the different group-chronologies; where T =
305 temperature, P = precipitation and p = prior year. Boxplots show the median and lower and upper
306 quartiles, and the whiskers display the minimum and maximum values.

307

308 We used the sign test to evaluate whether the correlations between climate and ring width were
309 positive or negative more often than expected by chance. If we pool both the Mt. Etna and Calabria
310 correlations (Table 2), we see that ring widths are positively correlated with spring temperature (22
311 of 28 month and site combinations; $p < 0.01$ by the two-tailed sign test), negatively correlated with
312 summer temperature (22 of 28 correlations; $p < 0.01$ by the two-tailed sign test), and positively
313 correlated with summer precipitation (18 of 21 correlations; $p < 0.05$ by the two-tailed sign test),
314 but not significantly correlated with spring precipitation (17 negative correlations out of 28 month
315 and site combinations; $p > 0.05$ by the two-tailed sign test). Thus tree growth in these mountain

316 environments tends to be favoured by warm springs (suggesting that water is not limiting in the
 317 springtime) and cool and relatively wet summers.

318 Comparing the VRM and SLRM modelling results (Table 3), we distinguished between models
 319 explaining ring width on Mt. Etna and models explaining ring width in Calabria. SLRM's yielded
 320 average R^2 values of 20% (8% to 33%) on Mt. Etna and 26% (13% to 39%) in Calabria,
 321 demonstrating that precipitation and temperature are not strongly correlated with tree growth
 322 compared to other climatic regions. The regression models include both precipitation and
 323 temperature variables from spring and summer. There are, however slight differences between the
 324 models (Table 4).

325

	Visual Regression Models			Stepwise Linear Regression Models			Model improvement (%)	
	R^2	adj. R^2	<i>p-value</i>	R^2	adj. R^2	<i>p-value</i>	R^2	adj. R^2
Group 1	0.23	0.19	<0.01	0.29	0.24	<0.01	6	5
Group 2	0.09	0.04	0.13	0.09	0.06	0.03	n/a	n/a
Group 3	0.27	0.22	<0.01	0.33	0.27	<0.01	6	5
Group 4	0	-0.01	0.96	0.08	0.06	0.03	n/a	n/a
average Mt. Etna	0.15	0.11	0.27	0.2	0.16	0.02	6	5
Gambarie	0.2	0.17	<0.01	0.26	0.23	<0.01	6	6
Monte Pollino	0.3	0.24	<0.01	0.39	0.34	<0.01	9	10
Sierra da Crispo	-	-	-	0.13	0.1	0.02	n/a	n/a
average Calabria	0.25	0.2	<0.01	0.26	0.22	0.01	7.5	8

326

327 Table 3. **Statistics of climate models.**

328 Overview of model R^2 and adjusted R^2 statistics of the Mt. Etna and Calabria chronology models.

329 Visual Regression Models (VRM) are shown in the left panel, Stepwise Linear Regression Models

330 (SLRM) in the middle panel and the percentage of "model-improvement" from VRM to SLRM is
 331 shown in the right panel.
 332

		temperature										precipitation										
		February	March	April	avg. spring	May	June	July	August	avg. summer	December	January	tot. winter	February	March	April	tot. spring	May	June	July	August	tot. summer
Mt. Etna	Group1	VRM		X					X						X					X		
		SLRM		X					X			X				X						X
	Group 2	VRM		X				X			X	e										
		SLRM					X				X											
	Group 3	VRM		X					X		X							X				X
		SLRM				X	X		X	e	X											X
	Group 4	VRM																	X			
		SLRM						X						X								
Calabria	Gambarie	VRM								X											X	
		SLRM			X					X												
	Monte Pollino	VRM			X		X								X				X			
		SLRM			X	e					X				X							X
	Sierra da Crispo	VRM																				
		SLRM			X																	X

333
 334 Table 4. **Model variables used by climate models.**
 335 Climate variables (single months and seasonal groupings) used in VRM and SLRM models.
 336 Monthly variables included in the models are designated as X. Due to time overlaps between single
 337 months and seasons, variables that were excluded from the models are designated as e.
 338
 339 We calculated an average improvement in adjusted R² from VRM to SLRM of 5% on Mt. Etna and
 340 8% in Calabria (Table 3; Fig 4).

341 When comparing VRM and SLRM which were statistically significant ($p < 0.05$), a significant
342 model-improvement ($p < 0.05$) was only obtained with Mt. Etna's Group 1 models. These results
343 show that on Mt. Etna even complex models such as our SLRM are not able to explain tree-growth
344 variability much better, demonstrating that tree growth is further influenced by parameters other
345 than climate which induce additional noise to our ring-width data.

346

347 **Fig 4. Climate model comparison.**

348 Comparisons between individual VRMs (visual regression models) and SLRMs (stepwise linear
349 regression models) revealed only one case (Group 1) where the VRM and the SLRM were both
350 significant ($p < 0.05$) and where a statistically significant model improvement ($p < 0.05$) was
351 calculated. On Mt. Etna, the Group 1 model significantly improved from adjusted $R^2 = 0.19$ (VRM)
352 to adjusted $R^2 = 0.24$ (SLRM). Details are summarized in Table 3.

353

354 When comparing differences over time by running the SLRMs on both time segments separately,
355 on Mt. Etna only two out of eight model-runs on the two time segments led to significant R^2 values
356 ($p < 0.05$), whereas in Calabria the R^2 in four out of six runs was significant (results not shown).

357

358 Mt. Etna model validations demonstrate that the only forward verification resulting in a significant
359 R^2 value ($p < 0.01$) was obtained with the Group 3 model. Forward validation of the Group 1,
360 Group 2 and Group 4 models resulted in statistically non-significant R^2 values. Further, backward
361 validations show that all models calibrated on the second segment show a decrease to non-
362 significant R^2 values when run on the first segment. Out of eight validation runs (forward and
363 backward) on Mt. Etna only one retained significant R^2 values ($p < 0.01$). Including all validation
364 runs (statistically significant and non-significant), forward validation lost 4% (from an average R^2

365 of 0.18 in the first period to 0.14 in the second period) and backward validation lost 37% (from an
366 average R^2 of 0.48 in the second period to 0.11 in the first period) of explained ring-width variance
367 on Mt. Etna.

368 The same calculations for Calabria showed that forward validation (earlier to later time-segment)
369 lost 32% of the explained variance (average R^2 changed from 0.53 to 0.21), while backward
370 validation lost 11% (average R^2 changed from 0.55 to 0.44). We calculated that of all six validation
371 runs (forward and backward) in Calabria, only two backward validations retained significant R^2
372 values ($p < 0.05$).

373 These results show that our models (SLRMs) of tree-ring data on Mt. Etna and in Calabria do not
374 withstand the cross-validation test and demonstrate the importance of validating tree-ring based
375 climate models, especially in regions such as the Mediterranean, where climatic factors are not
376 strongly limiting tree growth.

377 The explanatory power of all models is generally low. The changes in the explanatory power of all
378 models over time are shown in Fig 5. The Mt. Etna models (Groups 1-4) display a wider range of
379 performance with some visual suggestion of a trend of increasing explanatory power over time,
380 while the Calabria models showed less temporal variability.

381

382 Fig 5. **Model strength over time.**

383 Change of SLRM model goodness-of-fit statistics for 15-year moving windows over time, showing
384 a visual suggestion of higher temporal consistency among the Calabria models.

385

386

387 **Discussion**

388 In the Mediterranean region, seasonal drought conditions can persist at low elevations for up to five
389 months and have a strong negative impact on tree growth (Scarascia-Mugnozza et al., 2000;
390 Cherubini et al., 2003), whereas at higher elevations precipitation is usually not a limiting factor
391 (e.g., Maselli et al., 2014). At the treeline in temperate regions, air temperature is generally the
392 major driver of tree growth, being positively correlated with ring width (e.g., Eckstein & Aniol,
393 1981; Schweingruber, 1987; Briffa et al., 1996; Hughes, 2002; Leonelli et al., 2009). Similar
394 correlations have been observed in the Mediterranean mountains as well (Serre-Bachet & Guiot,
395 1987; Büntgen et al., 2012). At lower elevations, higher temperatures reduce tree growth by
396 increasing evaporative demand and drought stress (Campelo et al., 2006; Olivar et al., 2012). Our
397 study showed that tree growth at high elevation on Mt. Etna is not much limited by climatic
398 conditions: the correlations between tree-ring width and meteorological data (monthly precipitation,
399 air temperature, PDSI and cloud coverage) were rather weak, suggesting that an increase in local
400 moisture or temperature caused by pre-eruptive volcanic activity was unlikely to have affected tree
401 growth. On Mt. Etna, the correlations between ring width and meteorological data were weaker
402 than in Calabria, suggesting that the tree-ring/climate relationship on Mt. Etna might be affected by
403 other factors. Stepwise linear regression models (SLRM) explained an average adjusted R^2 of 16%
404 of tree growth on Mt. Etna and 22% in Calabria. By comparison, linear regression models using
405 spring to summer temperature at similar elevations in south-western Anatolia explained up to 51%
406 of ring-width variance (Touchan et al., 2007). Furthermore, climate correlation values on Mt. Etna
407 and in Calabria are lower than those found using response function analyses in the Aegean (Hughes,
408 2001). Tree-growth response to temperature across the Mediterranean region is complex and
409 strongly affected by longitude, elevation (Seim et al., 2012) and the age of the trees studied
410 (Navarro-Cerrillo et al., 2014). The dependence of tree growth on spring temperature may be
411 reduced at sites that, like Mt. Etna and Calabria, are very close to the sea.

412 In general, the ring-width chronologies on Mt. Etna showed higher inter-annual variability than
413 those from Calabria, even though the Mt. Etna chronologies were based on greater numbers of trees
414 with a correspondingly greater averaging of random inter-tree variations. Our analyses suggest that
415 non-climatic factors may give rise to a greater variability in tree-ring growth on Mt. Etna than in
416 Calabria. This argument is supported by the larger differences on Mt. Etna between the regression
417 models fitted to the two time periods.

418 On Mt. Etna, the correlation with summer precipitation ($r = 0.27$ to 0.35) is lower than in previous
419 studies that found that water is the limiting factor in the Mediterranean region (Hughes et al., 2001;
420 Maselli et al., 2004; Touchan et al., 2007; Akkemik et al., 2008; Allard et al., 2008; Griggs et al.,
421 2014). Near treeline on Mt. Etna, which is lower than at other sites at similar latitudes, because not
422 determined by climatic conditions but rather by volcanic activities, other factors, such as higher air
423 humidity with increasing elevation, seem to reduce the influence of summer precipitation on tree
424 growth.

425 The low correlation values between PDSI and ring width on Mt. Etna (maximum $r = 0.29$) confirm
426 that moisture availability is not strongly limiting tree growth. Similar results have been reported by
427 Aloui (1982) for *Pinus halepensis* Mill. in Tunisia and by Tessier (1984) for *Pinus sylvestris* L. in
428 south-eastern France. It is notable that *P. nigra* exhibits a drought-avoidance strategy characterized
429 by efficient stomatal control of transpirational water loss (Lebourgeois et al., 1998). At the same
430 latitudes in Spain, the drought response of *P. nigra* varied along an aridity gradient with the
431 strongest response at the most xeric sites (Camarero et al., 2013). At comparable latitudes and
432 elevations in Calabria, studies on *F. sylvatica* found no correlations between either water use
433 efficiency or basal area increment and an estimated drought index, suggesting a minimal effect of
434 climate on tree growth during the last century (Tognetti et al., 2014), especially when considering
435 the rather udic soil moisture regime at intermediate to high elevations on Mt. Etna (Egli et al.,

436 2012). No significant differences in soil properties from soils adjacent to eruptive fissures and soils
437 away from such fissures (Reisser, 2014) revealed homogeneity of soils on Mt. Etna.

438 Due to their high elevation and the subsequent cold, snowy, foggy and humid environmental
439 conditions, the Mt. Etna trees do not appear to be strongly affected by Mediterranean summer
440 drought. The combination of proximity to the sea and high elevation favours persistent seasonal fog
441 and shading by clouds, thus limiting the vapour pressure deficit and raising water use efficiency
442 (Limm et al., 2009). To survive summer droughts, vegetation uses water coming from spring
443 precipitation or, at higher elevation, melting snow, which in some regions can be half of the annual
444 precipitation amount (Renault et al., 2010). At the highest elevations on Mt. Etna, winter
445 precipitation is mainly snowfall and, based on our analyses, is not strongly correlated with tree
446 growth (Table 2). The high porosity of the volcanic soils allows rapid infiltration, making a large
447 fraction of the annual precipitation unavailable to the trees, and making it unlikely that winter or
448 spring precipitation could be stored long enough to significantly alleviate summer drought stress.

449 Significant positive correlations between ring width and spring temperatures were found, except for
450 Group 4. These results confirm those of previous studies on silver fir in southern Italy (Carrer et al.,
451 2010), and in southwestern Anatolia (Touchan et al., 2014). Based on the positive correlations
452 between March temperatures and ring width on Mt. Etna, high spring temperatures appear to
453 promote an early start of the growing season. Based on the above zero average temperatures during
454 winter measured at all meteorological stations, possible heat discharge from the volcanic fissure in
455 the years before the eruption (e.g., Aubert, 1999) could not have caused such an early start of the
456 growing season. In contrast, pines are able to photosynthesize during winter; thus mild temperatures
457 in late winter may enhance the availability of reserves (non-structural carbohydrates) for allocation
458 to cambial growth in spring. Mild conditions in spring may stimulate cambial dynamics or induce
459 early cambial reactivation, increasing production of early-wood.

460 We found negative correlations between ring width and summer temperature, as previously
461 described by Hughes (2001), Griggs et al. (2007) and Köse et al. (2011; 2013) in Turkey, as well as
462 in north-eastern Greece and the Spanish Pyrenees (Tardif et al., 2003). These correlations may be
463 related to heat waves and the negative effect of drought stress on tree growth. An increase in
464 frequency in hot and dry summers under climate change during the recent past (Christensen et al.,
465 2013) may also increase drought stress indirectly in autumn and further constrain tree growth.

466

467

468 **Conclusions**

469 We conclude that tree growth at the highest elevations on Mt. Etna is not significantly limited by
470 climate. Our samples were taken near Mt Etna's upper treeline, but this treeline is not climatically
471 determined; instead it is defined by volcanic activity and related disturbances such as wildfires.
472 Consequently, climatic influences on tree growth are weaker than would be expected in trees
473 growing at a climatically induced treeline where temperature is the limiting factor (Maselli et al.,
474 2014). At the same time, the Mt. Etna trees are growing at an elevation that is too high to be
475 strongly affected by summer drought as in Mediterranean lowlands (Cherubini et al., 2003). The
476 intermediate elevation between the two extremes (high elevation where temperature is limiting and
477 low elevation where summer drought is limiting) makes it difficult to explain the tree-growth
478 variability using meteorological data. The low sensitivity of tree growth to climate suggests that
479 neither i) an increase of surrounding air temperature caused by heating from magma at shallow
480 depths, nor ii) an increase in water availability induced by pre-eruptive subsurface pressures and
481 water vapour, is likely to have enhanced photosynthesis before the 2002/2003 flank eruption. Thus
482 to explain the NDVI signal previously observed by Houlié et al. (2006), one must search for factors
483 (volcanic or not) other than additional water or heat induced by volcanic activity.

484

485

486 **Acknowledgements**

487 We thank our colleagues from the WSL, Dr. Ulf Büntgen, Dr. David Frank and Richard L. Peters,
488 for their help with ring-width and climate analyses, Dr. Alexander Bast for helping with
489 programming in R, and Anne Verstege for her continuous support in the dendro laboratory. Also we
490 wish to thank Vincenzo Crimi (Corpo Forestale, Bronte) for his logistical support during our
491 fieldwork on Mt. Etna, as well as the Corpo Forestale della Regione Siciliana (Distaccamento di
492 Bronte, Catania, Italy) for their permission to take samples.

493 We celebrate the memory of our colleague and friend, Sebastiano Cullotta, who tragically passed
494 away while this paper was in preparation. This work was supported by the Swiss National
495 Foundation (205321_143479).

496

497

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