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Evidences of drought stress as a predisposing factor to Scots pine decline in Valle d'Aosta (Italy)

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Abstract

Scots pine (*Pinus sylvestris* L.) forests of many inner Alpine valleys have recently displayed a quick loss of vitality. A decline disease has been suggested as the cause, with drought as the main predisposing factor and the additional contribution of biotic agents inciting tree die-back. This study is focused on Valle d'Aosta, a dry, inner-Alpine region in NW Italy. We inferred vitality changes between years 2000 and 2007 by computing reductions in enhanced vegetation index (EVI). Image differencing was carried out on pre-processed Moderate Resolution Imaging Spectroradiometer (MODIS) imagery taken in late spring-time and validated against ancillary ground truth. We: (1) tested whether EVI reductions in Scots pine forests were significantly higher than those of a control species and of a wetter region for the same species, (2) analyzed decline incidence as a function of site and topographic variables, and (3) assessed the relative influence of site and stand structure on decline probability by means of path analysis. Mean EVI in the study area increased due to an early onset of the 2007 growing season. Nevertheless, the incidence of decline was 6.3% and significantly greater for Scots pine than the control species and site. Low-elevation, northerly exposed sites exhibited the highest incidence of decline.

Path analysis suggested that the most important determinants of decline probability were slope, solar radiation, and stand sparseness.

Keywords: *Pinus sylvestris* - Decline disease – Drought - Enhanced vegetation index - MODIS

Introduction

Unusually high mortality of Scots pines (*Pinus sylvestris* L.) has recently been observed in many inner-alpine valleys of Italy (Minerbi et al. 2006; Vacchiano et al. 2008), Switzerland (Dobbertin et al. 2005), Austria (Cech and Perny 2000), and southern France (Thabeet et al. 2009). When analyzed one at a time, such mortality episodes have been explained by a number of different agents, including water shortage (Bigler et al. 2006), tree and herbaceous competition (Weber et al. 2008; Giuggiola et al. 2010), and

39 mistletoe (*Viscum album* ssp. *Austriacum*) (Dobbertin and Rigling 2006). Wood-boring insects, nematodes,
40 and fungi have been found on dying trees, but they did not appear to be the main cause of mortality
41 (Polomski et al. 2006; Gonthier et al. 2007, 2010; Wermelinger et al. 2008; Giordano et al. 2009).

42 Even if Scots pine is considered a drought-tolerant species, pine growth and survival in the inner Alps are
43 shown to be strongly limited by high temperatures and summer rain shortage (Oberhuber et al. 1998; Rebetez
44 and Dobbertin 2004; Eilmann et al. 2006). Therefore, it is reasonable to consider pine mortality events as
45 different occurrences of a unique, region-wide climatic response. Recent changes in precipitation regimes,
46 coupled with elevated temperatures and the occurrence of repeated dry years (Schar et al. 2004;
47 Intergovernmental Panel on Climate Change 2007), have proven damaging to normally drought-tolerant tree
48 species in other temperate mountain forests (e.g., Hasenauer et al. 1999; Breshears et al. 2005; Guari'n and
49 Taylor 2005; Shaw 2006; van Mantgem et al. 2009; Allen et al. 2010). Climatic anomalies may act as a
50 predisposing factor (*sensu* Manion 1991) to pine decline, increasing physiological stress (Waring 1987;
51 Breda et al. 2006; McDowell et al. 2008) and thus sensitivity to secondary pathogens and insects (Logan et
52 al. 2003; Rouault et al. 2006).

53 We hypothesized that recent dry periods were the strongest determinant of region-wide Scots pine decline. In
54 order to test this assumption, we pursued the following specific aims: (1) assess the extent and intensity of
55 decline in a dry alpine region following recurrent dry years; (2) test whether stands located on drought-
56 sensitive sites, e.g., inner alpine areas, south-facing slopes and lower elevations, i.e., with a more negative
57 water balance due to higher evapotranspiration (Baumgartner et al. 1983) exhibit a higher decline; and (3)
58 assess the importance of interacting agents that may predispose stands to decline in sensitive areas, including
59 site, climate, and forest stand structure.

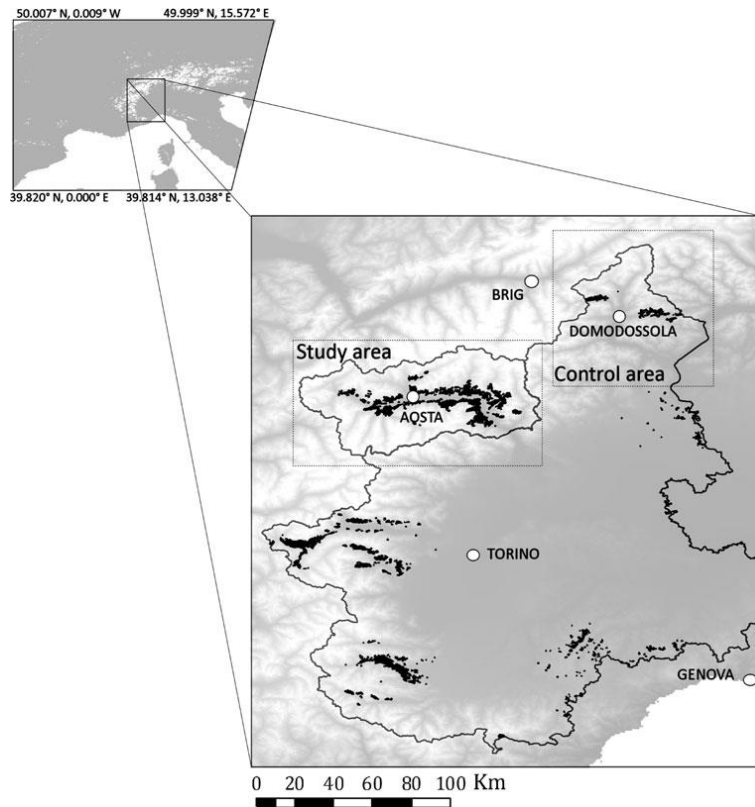
60

61 **Study area**

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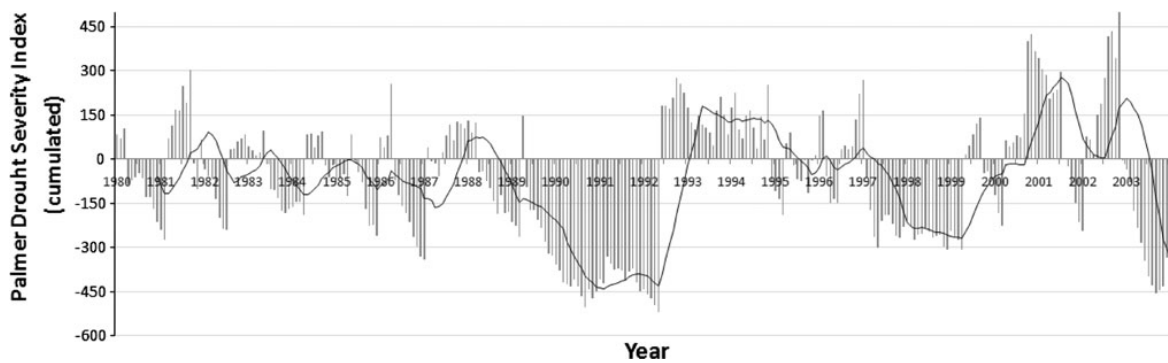
63 The study is focused on the Valle d'Aosta region (Fig. 1) that covers about 3,262 km². Topography is shaped
64 by a main east–west valley with several north–south protrusions, legacies of the last ice-age. Climate is
65 continental with cold winters and hot summers; July and January monthly means may differ by as much as
66 22°C. Mean annual rainfall in Aosta (45° 26'N, 7° 11'E) for the years 1961–1990 was 494 mm, i.e., much
67 lower than average on the Alps (Biancotti et al. 1998), with an aridity period extending from June to
68 September. Winter precipitation usually comes as snow. Like other inner-alpine valleys, Valle d'Aosta is
69 particularly subject to multi-year drought spells, as those in the early 1990s and between 2003 and 2006
70 (Fig. 2; see also Rebetez et al. 2009).

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Fig. 1 MODIS image tile and study and control sites (geographical datum: UTM WGS 1984). Scots pine coverage in black. Data source for shaded relief: Jarvis et al. (2008).



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Fig. 2 Cumulated Palmer Drought Severity Index between 1980 and 2003 for the city of Aosta (source: van der Schrier et al. 2007) and smoothed 10-year mean (solid line).

82

83 The study area exhibits both crystalline (granites) and metamorphic bedrocks, but most landscape is covered
84 by quaternary deposits of glacial, gravitative, or colluvial origin. Soils belong to the series of western and
85 central Alpine soil on igneous and metamorphic rocks (Costantini et al. 2004) and are mostly represented by
86 shallow soils (Lithic, Umbric and Dystric Leptosols), eroded soils (Eutric and Calcaric Regosols), acid soils

87 with organic matter, iron oxides and aluminum accumulation (Dystric Cambisols, Haplic Podzols, Humic
 88 Umbrisols), or alluvial soils (Eutric Fluvisols).
 89 Pine stands in the study area occur on 5,372 ha (6% of total forest cover), on both acidic and basic substrates
 90 of well-exposed, bottom to mid-elevation slopes. Pure stands cover southerly exposed slopes and shallow
 91 soils (Ozenda 1985). A greater broadleaved component, represented predominantly by downy oak (*Quercus*
 92 *pubescens* Willd.) and chestnut (*Castanea sativa* Mill.), exists on sites with a more favorable water balance
 93 (Camerano et al. 2007). A Regional Forest Inventory (RFI) was carried out in the years 1992–1994. Base
 94 grid size was 500 m; sample plots were circular with a variable radius (8–15 m according to overstory
 95 density). For each plot, the following site-and stand-level variables were recorded: geographic coordi-nates,
 96 elevation, slope, forest cover type, percent canopy cover, seedling count, number of mortality trees,
 97 occur-rence of grazing by domestic or wild ungulates, and severity and cause of crown damage. Species and
 98 diameter at breast height (dbh) of all living individuals bigger than
 99 7.5 cm in dbh were recorded to the nearest cm. A total of 130 plots were sampled in the Scots pine cover
 100 types. Mean structural descriptors of pine stands from RFI are sum-marized in Table 1.
 101 To test the drought-related decline hypothesis, we con-trasted Scots pine against Norway spruce (*Picea abies*
 102 (L.) Karst.) cover as a control species in the same study area, and to Scots pine on a control site. This was
 103 represented by the Northern Piedmont region (Fig. 1), where the amount and seasonal distribution of rainfall
 104 are typical of a mesic climate (1,479 mm year⁻¹ in Domodossola, 46° 07'N, 8 17'E, for years 1961–1990).

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106

107 *Table . Summary of structural descriptors of Scots pine stands in Valle d'Aosta for trees larger than 7.5 cm*
 108 *in dbh (n = 130 sampling plots).*

109

	Mean	SD
Trees per hectare	881.8	545.6
Basal area per hectare	25.7 m ²	12.7 m ²
Quadratic mean diameter	20.6 cm	5.1 cm
Percent basal area of Scots pine	93.8%	7.0%
Canopy cover	71.5%	17.7%

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111

112 **Methods**

113

114 *Satellite imagery*

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116 Stress in trees may result in the reduction in chlorophyll content, leaf necrosis, defoliation, or tree death,
 117 which in turn affect the radiation characteristics of tree and stand canopies (Jackson 1986; Carter 1993;
 118 Peñuelas and Filella 1998; Carter and Knapp 2001). Forest vegetation change can be remotely detected by

119 means of spectral vegetation indices, which are linear combinations of satellite-sensor, multispectral
120 reflectance data (Tucker 1979; Bannari et al. 1995). Decline in vegetation greenness and presumably, crown
121 vitality can be detected by the difference of the index images (Collins and Woodcock 1996) through time.

122 The literature dealing with the use of vegetation indices for remote detection of drought stress is vast (e.g.,
123 Peters et al. 1991; Liu and Kogan 1996; Breshears et al. 2005; Deshayes et al. 2006). Recently, an enhanced
124 vegetation index (EVI) has been proposed, which is characterized by reduced influence of atmospheric
125 conditions and canopy background signals as compared to the widely used Normalized Difference
126 Vegetation Index (NDVI). EVI is more sensitive to leaf area index, stand and canopy structure, and plant
127 phenology and stress than NDVI (Huete et al. 2002). EVI is computed on a per-pixel basis as:

$$EVI = G(NIR - red)(NIR + a_1 red - a_2 blue + L)^{-1}$$

129 where NIR, red, and blue are surface reflectance bands in the near-infrared, red, and blue regions, G is a gain
130 factor to limit the EVI value to a fixed range, L is the canopy background adjustment, a_1 and a_2 are the
131 coefficients of the aerosol resistance term, which uses the blue band to correct for atmospheric differences in
132 the red band (Xiao et al. 2004).¹

134 We used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Earth
135 Observing System-Terra platform, which outputs maps on a global basis every 1–2 days (Justice et al. 1998),
136 beginning from year 2000. MODIS standard products include preprocessed EVI and quality analysis (QA) of
137 the product. Input reflectance data are corrected for nadir and standard sun angles, molecular scattering,
138 ozone absorption, and aerosols (Vermote et al. 2002). In order to filter out residual atmospheric errors, daily
139 EVI data are combined into 16-day maximum-value compositing (MVC) intervals (Holben 1986; van
140 Leeuwen et al. 1999) at a base resolution (grain) of 250 m (MODIS product code MOD13Q1.004).² For
141 production purposes, MODIS maps are output in 1,200 × 1,200 km georeferenced tile units in the integerized
142 sinusoidal (ISIN) geographical projection.

143 We selected images taken in late springtime (Julian Days 145–159) from the 2000, 2003, 2005, and 2007
144 datasets. Spring images were preferred so that each year's image was not influenced by that year's summer
145 drought; therefore, two images predated the 2003 drought spell and two images followed. MODIS metadata
146 for the four images reported that cloud cover of the MVC was between 1 and 4%. We re-projected the multi-
147 band images to the Universal Transverse Mercator (UTM 32N) projection (datum: WGS84) and split them in
148 single-band images representing EVI and QA. Pixels with a QA score of 2 and 3 (i.e., targets covered by
149 snow/ice or cloudy pixel) as well as EVI scores lower than 0.15 or null (open water) were filtered out.
150 Co-registration between images (Townshend et al. 1992) was visually checked by inspecting pixels in coastal
151 areas (Toscano 2008).

¹ The coefficients adopted in the MODIS-EVI algorithm are $L = 1$, $a_1 = 6$, $a_2 = 7.5$, and $G = 2.5$. These enclose EVI in a range between -1 and +1.

² Data distributed by the Land Processes Distributed Active Archive Center (LP DAAC), located at the US Geological Survey (USGS) Earth Resources Observation and Science (EROS) Center (<http://lpdaac.usgs.gov>). Accessed 28 February 2009.

152 Validation of EVI data was performed against an ancillary dataset of 114 plots sampled for mean crown
153 transparency, a variable that we considered indicative of stress at the stand scale (Zarnoch et al. 2004). The
154 dataset covered the study area and nearby regions and was assembled from existing sources with variable
155 plot size, year of sampling, and methods for defoliation assessment (Table 2). For validation purposes alone,
156 stands with a mean crown transparency higher than 20% were classified as declining (Wulff 2002); the
157 cutoff was chosen as to allow harmonization of different sampling methods and amplitude of crown
158 transparency classes. EVI was computed for each site from available MODIS MVC tiles with a maximum
159 time lag of ± 1 year since field assessment. We fitted a logistic regression model of crown transparency
160 (ground truth) using EVI as a predictor. We computed validation metrics for the logistic models such as
161 producer's accuracy, i.e., the proportion of decline pixels correctly classified by the remote sensing method,
162 and Kappa (KHAT) statistics (Cohen 1960; Rosenfield and Fitzpatrick-Lins 1986).

163

164 *Change detection*

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166 In order to detect significant reflectance changes, we applied an ordinary image differencing technique
167 (Coppin et al. 2004; Lu et al. 2004) to the most and least recent satellite tiles. The variable of interest was the
168 7-year (2007–2000) EVI difference (Δ EVI). To reduce variance in spectral data due to species composition
169 (including the presence of deciduous species, which have brighter foliage), we filtered out pixels with less
170 than 90% overlap to Scots pine cover polygons (Falkenstrom and Ekstrand 2002). Perimeters of forest .res
171 from 1961 to 2007 (G. Cesti, unpublished data) were digitized and georeferenced, and affected areas were
172 excluded from further analysis (Yuhas and Scuderi 2009), in order to differentiate dieoff from reductions in
173 reflectance caused by stand replacing disturbances. It is noteworthy that clearcutting is not routinely carried
174 out in the study area.

175 The subtraction produced an image dataset where positive or negative values represented areas of change;
176 values close to zero indicated areas relatively unchanged (Muchoney and Haack 1994). We assumed that
177 Δ EVI was normally distributed with a zero mean. In order to distinguish reflectance anomalies from random
178 or systematic error (Morisette and Khorram 2000), we classified as decline pixels those where Δ EVI was
179 lower than (mean -1 SD), as computed from the full scene (Fung and LeDrew 1988). The Δ EVI map was
180 then clipped to the regional distribution of Scots pine in both the study and comparison site and that of
181 Norway spruce in the study area as a control species (see Table 3 for summary site characteristics).

182 We computed summary statistics for EVI at different sites and image years. After failing to detect normality
183 of EVI distributions (Kolmogorov–Smirnov test), we assessed the significance of EVI temporal trend at each
184 site by means of a pairwise Wilcoxon test. We computed decline incidence for each species and site as the
185 ratio between declining and total pixel counts. We also carried out a pairwise comparison of pixel-based
186 Δ EVI between the study and control site, by means of a two-sample t test, or a Welch test where the
187 homoscedasticity assumption was not met.

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Table 2. Plot data used in validation of reflectance-based estimates of pine decline.

Plot network	References	# Plots	Plot area	Country	Crown transparency assessment	Years of assessment
Regional Forest Inventory	Gottero et al. (2007)	87	200–700 m ²	Piemonte (IT)	3 or more dominant trees	1999–2001
Swiss Alps 1	Rigling et al. (2006), Weber et al. (2008)	2	500 m ²	Wallis (CH)	All pine trees	2000, 2001, 2005, 2006
Swiss Alps 2	Bigler et al. (2006), Wermelinger et al. (2008)	2	1 ha	Wallis (CH)	250 (co)dominant pine trees	2000, 2001
Swiss Alps 3	M. Dobbertin, u.d.	1	2,000 m ²	Wallis (CH)	All pine trees	2003–2006
Italian Alps 1	Vacchiano et al. (2008) G. Nicolotti, u.d.	13	4,900 m ²	Valle d'Aosta, Piemonte (IT)	All pine trees	2005–2007
Italian Alps 2	G. Vacchiano, u.d.	9	5,000 m ²	Valle d'Aosta, Piemonte (IT)	Visual, plot-wise ^a	2004–2007

191

u.d. Unpublished data

192

^aThe assessment was carried out by visual assessment of crown conditions (average defoliation and extremes)

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Table 3. Topographic Count Elevation (m a.s.l.) HLI Slope (.) characteristics of sites corresponding to the pixels used in this study (mean ± SD).

196

	Count	Elevation (m a.s.l.)	HLI	Slope (°)
Study area	862	1,368 ± 285	0.51 ± 0.36	21.7 ± 6.7
Control	417	1,131 ± 235	0.42 ± 0.34	19.4 ± 8.2
Norway spruce	2,080	1,652 ± 169	0.70 ± 0.29	19.3 ± 8.1

197

198

199 In order to assess the effect of site variables on decline incidence, we extracted elevation, aspect, slope, and
200 solar irradiance (MWh m⁻² year⁻¹) for each pixel from a region-wide digital elevation model (DEM) with a
201 grain of 50 m, subsequently downscaled to 250 m. Aspect data were transformed to heat load index (HLI)
202 (McCune and Keon 2002). Differences in dieback incidence between classes of topographical variables were
203 assessed by means of multiple Chi-square tests.

204 All analyses were carried out at a significance level of $\alpha = 0.05$ (2-tailed); software used included ENVI 4.3
205 (ITT Visual Information Solutions, Boulder CO) for image processing, ArcGIS Desktop 9.3 (ESRI Inc.,
206 Redlands CA) for geographical data handling, and SPSS 16.0 (SPSS Inc., Chicago IL) for statistical
207 analyses.

208

209 *Effect of predisposing factors*

210

211 We employed path analysis (Shipley 2000) to assess the effect size of predisposing factors on pine decline.
212 Path analysis is a specialized version of Structural Equation Models, testing the relationships between the
213 putative causal variables (climate, site, and stand characteristics) and the hypothesized effect. Path analysis
214 allows modeling of both observed (manifest) and unmeasured (latent) variables. A graphical conceptual
215 model is presented (Fig. 3) for all pixels including a RFI plot (n = 105 after exclusion of outliers and plots
216 with less than 5 tallied tree). Arrows symbolize cause-and-effect relationships between variables that are

217 represented by rectangles (manifest) and ellipses (latent). The response variable was Pine decline, i.e., the
218 EVI difference between 2000 and 2007. Independent variables included:

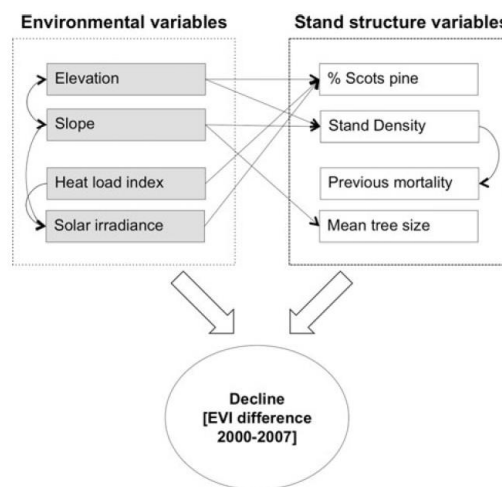
219

220 1. Stand structure variables on a per-hectare basis for each RFI plot, including tree density, basal area (BA),
221 percent abundance of Scots pine on plot BA, quadratic mean diameter (QMD), percent standing mortality,
222 and Reineke's (1933) Stand Density Index (SDI) as an indicator of competition intensity (Shaw 2000).

223

224 2. Environmental variables: HLI, solar irradiance, elevation, and slope - all considered as proxies for water
225 availability, due to the absence of a high-resolution network of weather stations on the ground.

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Fig. 3 - Conceptual model of decline predisposing factors.

231 The conceptual model was tested first on all data, then on two subsamples based on an elevation cutoff of
232 1,250 m a.s.l. This allowed us to take into account potential dissimilarities in the decline process
233 characterizing different ecological sectors of Scots pine distribution.

234 Variable effects were quantified by standardized regression coefficients (β). Quantitative model
235 comparisons used a combination of Akaike's Information Criterion (AIC) statistic and the Root Mean
236 Square Error of Approximation (RMSEA) that is relatively independent of sample size. The models with the
237 smallest AIC statistic were selected as the most parsimonious ones (Hu and Bentler 1999). A model with
238 RMSEA<0.06 was considered a good fit (Hu and Bentler 1999). Path analyses were conducted using Mx
239 software that works with covariance matrices as input data and a maximum likelihood (ML) fit function
240 (Neale 1994).

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246 *Table 4 Validation of EVI against crown transparency measured on the ground as predicted by logistic regression models.*
 247

Year of assessment	Model	Producer's accuracy (decline pixels)	KHAT
0 (<i>n</i> = 41)	EVI, intercept	0.14	0.04
	EVI	n.s.	n.s.
0, +1 (<i>n</i> = 57)	EVI, intercept	0.30	0.18
	EVI	0.80	0.22 ^a

248
 249
 250 Year of assessment: time lag of ground survey to remotely sensed data

251 n.s. model not significant

252 ^aSignificant at alpha = 0.05

253
 254
 255 **Results**

256
 257 EVI was successfully validated against plot-level crown transparency (Table 4). The best validation metrics
 258 were provided by ground truth sampled with a +0 or +1 year lag from the satellite image (*n* = 57).

259 Descriptive statistics and dynamic range of EVI in the control and study area (2 species) are displayed in
 260 Table 5. Control stands constantly exhibited the highest mean EVI; the spectral response of Norway spruce
 261 cover showed a wider range, but lower mean and dispersion than Scots pine across the entire study period.

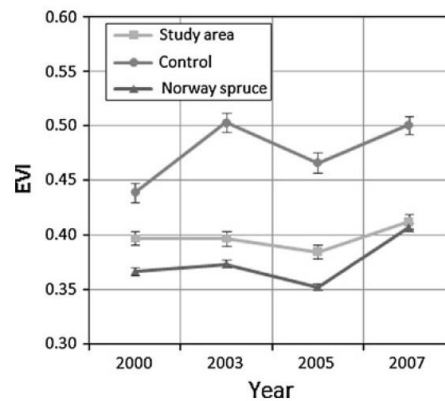
262 While mean EVI at each site significantly increased in time, Scots pine cover in the study area exhibited a
 263 very limited change (+3.9%), as opposed to the larger increase in mean reflectance experienced by the
 264 control species and site (+11.0 and +14.2%, respectively) (Fig. 4). Additionally, Scots pine in the study area
 265 showed increasingly lower extremes, while EVI minima in the control stands experienced an increase
 266 similar to that of average values.

267 All 7-year Δ EVI values were positive, showing a mean increase in greenness at all sites. The variability of
 268 Δ EVI was comparable, but on average, the improvement experienced by Scots pine cover was much more
 269 limited, e.g., 0.016 versus 0.06 in the control stands and 0.04 in Norway spruce sites, respectively. A two-
 270 sample t test significantly segregated pine Δ EVI from both control and Norway spruce sites ($P < 0.001$). The
 271 incidence of 7-year decline was 6.3% in the study area, i.e., almost double than in the control area and
 272 manifold greater than in Norway spruce cover type (Table 6).

273 In declining Scots pine cover, topographical variables significantly correlated to EVI throughout the study
 274 period (Table 7). The spectral index was inversely related to elevation, heat load, and irradiance, with larger
 275 correlation coefficients in the year 2003. When pixels were apportioned to topography classes (Fig. 5), Chi-
 276 square tests evidenced a significantly higher decline incidence at low lying (below vs. above 1,200 m a.s.l., P
 277 = 0.002) and north-facing sites ($P = 0.010$ vs. all southerly octants).

278 In order to describe the influence of predisposing factors on pine decline, more than 60 alternative path
 279 models were tested. When applied to the full dataset, the path models did not yield significant results.

280 Conversely, two alternative models (Fig. 6), one each for lower elevation and higher elevation pine forests,
 281 emerged as having significant sup-port. At higher elevation, environmental factors alone appeared to have a
 282 significant influence on decline (Fig. 6b). These included a direct effect of elevation ($\beta = 0.38$), slope ($\beta =$
 283 0.17), and aspect ($\beta = 0.32$), with sun-exposed sites more subject to decline.
 284 The model for low-elevation stands had less explanatory power, i.e., lower goodness of fit (Table 8), but
 285 additionally included an explicit influence of stand structural variables (Fig. 6a), i.e., percent Scots pine and
 286 SDI. In particular, mixed forests with low SDI resulted more prone to decline. Significant environmental
 287 variables for model (a) included slope ($\beta = 0.31$) and aspect, with sun-exposed sites less sensitive to decline
 288 ($\beta = -0.12$).



289
 290 *Fig. 4 - Temporal trend of mean EVI in the study (2 species) and control sites. Bars represent standard error of estimate for each*
 291 *year and site*

293 *Table 5. Statistical descriptors of EVI for selected monitoring years in the control and study area (2 species).*

		Mean	SD	Min	Max	Range	Count
Year 2000	Study area	0.397	0.094	0.202	0.680	0.478	862
	Control	0.438	0.096	0.249	0.706	0.456	417
	Norway spruce	0.367	0.080	0.187	0.797	0.610	2,080
Year 2003	Study area	0.397	0.094	0.151	0.734	0.582	862
	Control	0.503	0.092	0.231	0.843	0.611	413
	Norway spruce	0.373	0.084	0.152	0.873	0.721	2,080
Year 2005	Study area	0.384	0.093	0.158	0.669	0.512	857
	Control	0.466	0.096	0.268	0.764	0.496	417
	Norway spruce	0.352	0.066	0.197	0.697	0.500	2,068
Year 2007	Study area	0.412	0.095	0.151	0.723	0.572	862
	Control	0.501	0.089	0.317	0.771	0.454	417
	Norway spruce	0.407	0.082	0.153	0.934	0.781	2,080

295
 296
 297 **Discussion**

298
 299 MODIS has the potential for identifying large, homogeneous damaged areas; omission errors may occur for
 300 small patches (less than 1.5 ha according to Lunetta et al. 2006) or low defoliation severities. Past studies
 301 using reflectance indices as a diagnostic element have provided mixed results, likely due to the confounding

302 factors that affect EVI at different sites, i.e., stand structure (Carter et al.1989; Guyot et al. 1989; Asner
 303 1998), topography (Burgess et al. 1995; Matsushita et al. 2007), or radiometric errors (Myneni and Asrar
 304 1994). However, the classification of “decline” pixels was fairly accurate when tested against crown
 305 transparency of the current and subsequent year (consistent with findings by Heikkila et al. 2002). It is
 306 noteworthy that EVI provided some predictive power, being able to spot changes associated with decline
 307 some-what earlier than ground-based estimates.

308 The dynamic range and distribution of EVI in this analysis were consistent with previous findings (Huete et
 309 al. 2002; Li et al. 2007). As our study showed, spruce canopies generally have lower reflectance than pine
 310 (Kleman 1986).

311 Contrary to expectations, we witnessed a mean increase in vegetation greenness throughout the study period.
 312 However, this can be explained by an region-wide advance of the growing season in the year 2007 (Colombo
 313 et al. 2009). Spring 2007 and Spring 2003 exhibited the two highest temperatures on record in the Alps
 314 (Rutishauser et al. 2008), which affected leaf dynamics and hence canopy reflectance, making our
 315 interpretation difficult.

316 Minimum EVI increased in the control and Norway spruce sites, but decreased in Scots pine cover,
 317 suggesting that canopy stress occurred on sensitive sites. Vegetation greenness exhibited meaningful
 318 topographical gradients, i.e., higher at low elevations and moister (cooler) sites. Correlation analysis showed
 319 that reflectance was inversely related to irradiance and heat load, especially in spring 2003 when the drought
 320 spell began.

321 The incidence of decline was moderate in the study area (6%) but significantly higher than in the control site,
 322 which conformed to our hypothesis. We detected pine forests as being more sensitive to decline below 1,200
 323 m a.s.l. Similar studies have detected a prevalence of drought-induced decline events at low-lying sites, due
 324 to the unfavorable temperature and precipitation gradients (e.g., Allen and Breshears 1998; Dobbertin et al.
 325 2005; Jolly et al. 2005; Knutson and Pyke 2008).

326

327 *Table 6. Summary of EVI anomalies (2007–2000) and incidence of signi.cant decline (EVI anomalies \ [mean -1 SD]) for 250 m*
 328 *pixels in the study and control area.*

Site	Pixel count	Mean ΔEVI	SD ΔEVI	Decline pixels	Decline incidence (%)	Total cover (ha)	Decline cover (ha)
Study area	862	0.0155	0.0846	54	6.3	5,387.5	337.5
Control	417	0.0623	0.0555	1	0.2	2,606.2	6.2
Norway spruce	2,080	0.0404	0.0837	80	3.8	13,000.0	500.0

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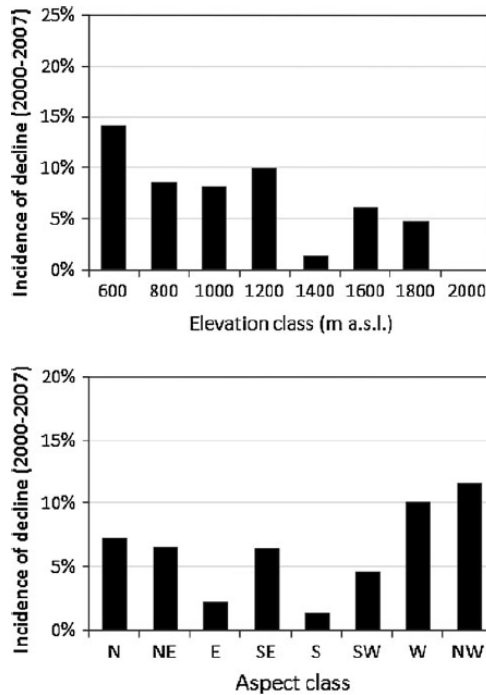
330

331 *Table 7. Correlation between EVI and topographic variables for the study area*

Pearson's R	EVI 2000	EVI 2003	EVI 2005	EVI 2007
HLI	-0.161 ^a	-0.298 ^a	-0.158 ^a	-0.145 ^a
Elevation	-0.322 ^a	-0.320 ^a	-0.216 ^a	-0.333 ^a
Slope	0.024 ^a	0.047	0.062	0.067 ^a
Solar radiation	-0.092 ^a	-0.191 ^a	-0.043	-0.119 ^a

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333 ^a Correlation significant at alpha = 0.05



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Fig. 5- Incidence of decline (i.e., relative frequency of decline pixels) in Scots pine stands as a function of elevation and aspect for the study area.

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The higher incidence of decline on north-facing slopes (low HLI) contradicted both our expectations and the results from previous studies (e.g., Rigling et al. 2006; Yuhás and Scuderi 2009). However, Quaglino et al. (1987) had already detected, in the same study area, more severe dieback in mixed, low-elevation forests of north-facing slopes. We offer two alternative explanations for this: (1) pines on southern slopes may be physiologically adapted to regular drought conditions (Letts et al. 2009); (2) due to different land use in the study area, and not to aspect itself, pine forests occur at low elevations on northern slopes and on southern slopes at high elevations.³ The latter have already been shown as being less sensitive to decline.

346

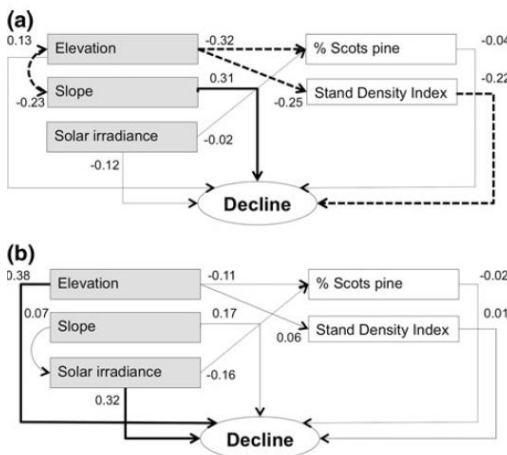


Fig. 6 - Path diagrams for Scots pine forests at **a** low (<1,250 m a.s.l.) and **b** high (> 1,250 m a.s.l.) elevations, showing the effect of environmental (gray) and stand structural variables (white) on DEVI response. Continuous arrows positive paths; dashed arrows negative paths. Thickness of path vectors corresponds to the strength of the effect. Only significant path coefficients are presented next to each path.

³ Pixels with pine coverage > 90% (n = 594) exhibited a significant difference in mean elevation between southern slopes (1,501 m a.s.l.) and northern ones (1,253 m a.s.l., P < 0.001 after Welch t test).

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Table 8. Fit indices for path models of pine decline at (a) low (<1,250 m a.s.l.) and (b) high (>1,250 m) elevations.

Model	ML χ^2	df	P	RMSEA	AIC
(a)	7.941	5	0.160	0.121	-2.059
(b)	6.018	11	0.872	<0.001	-15.982

358

359 AIC Akaike's Information Criterion; RMSEA Root Mean Square Error of Approximation; *df* degrees of freedom; ML χ^2 maximum
360 likelihood χ^2 fit function value and its P probability.

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362 This was a good reason to test predisposing factors in a multivariate way, accounting for both their direct and
363 indirect effects. No significant model could be fit to the totality of plots. Hence, we developed models for
364 two different elevation belts, assuming that the causal chain in the area with high decline incidence (1,250 m
365 a.s.l. and below) would differ from that associated to the low-inci-dence area. In the latter, environmental
366 factors alone drove changes in greenness, with a direct effect of elevation and aspect. Mid-elevation forests
367 could bene.t more than high elevation from the anticipation of the 2007 growing season and showed larger
368 increases in photosynthetic activity. Southerly slopes were more sensitive to decline, suggesting that when
369 precipitation is not limiting, high temperature and radiation directly impact pine tree vitality.

370 Below 1,250 m a.s.l. the process differed. Environ-mental factors had an inverse effect on decline, in that
371 low lying, northerly exposed stands were more sensitive. In continental valleys, precipitation is limiting at
372 low eleva-tions. In this case, the negative impact of repeated pre-cipitation shortage was more important than
373 that of temperature, a fact that produced a negative elevation gradient in pine decline. We have already
374 explained the potential causes for a higher sensitivity of northerly aspects in low-lying forests. Slope also
375 played a significant role: on sites with an unfavorable water balance, steepness may be associated to thinner
376 soils, and hence, more severe water stress after drought events.

377 In these stands, the degree of mixture was slightly associated to decline, confirming that interspecific
378 competition has the potential to expose pines to further stress (Weber et al. 2007). On the other hand, we
379 detected a strong effect of stand density, in that sparser stands were more prone to decline. This
380 counterintuitive result could once again be linked to water balance: sparser stands exhibit a higher cover by
381 the herb and shrub layers, which may exert a strong competition for water due to their extensive root systems
382 (McMurtrie and Wolf 1983). Alternatively, low-density pine stands may have developed on poor sites (e.g.,
383 rocky out-crops), where drought events can severely impact an already limiting water balance. Finally,
384 infection by mistletoe, a shade-intolerant, hemi-parasitic species common in the study area, preferentially
385 occurs on open-grown trees and spreads faster in open stands (Vallauri 1998). Mistletoe negatively affects a
386 plant's water balance, acting as a sup-plementary evapotranspiratory organ for the branches it infects, and
387 has already been found as a contributing factor to pine decline North of the Alps (Dobbertin and Rigling
388 2006; Rigling et al. 2010).

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393 **Conclusion**

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395 The study was designed to evaluate the impact of drought as a potential key factor limiting the vitality in
396 Scots pine stands. The study was carried out in Valle d'Aosta, an inner-alpine valley subject to multi-year
397 drought episodes (average precipitation: 494 mm year⁻¹), as those between 2003 and 2006. To assess the
398 drought decline hypothesis, pine stands with a typical mesic climate (average 1,479 mm year⁻¹) were used as
399 a control.

400 The major achievements of this study were: (1) producing a spatially explicit estimate of the extent and
401 incidence of 7-year decline in Scots pine vitality across the study area. Significant decline of canopy
402 greenness occurred on 337 ha, or 6.8% of overall pine cover, at a 250-m grain; (2) ascertaining the role of
403 drought in Scots pine decline, since reflectance changes of pine cover were significantly higher than both the
404 control species and the control site; (3) evaluating the effect of potential factors predisposing stands to
405 decline, including site, climate, and stand structure. Path analysis suggested that sparser stands, low-
406 elevation and north-facing slopes were more prone to decline. Where precipitation was limiting (i.e., low-
407 elevation stands), environmental and stand structural variables interacted in predisposing water-stressed
408 sites to decline. At higher elevations, environmental drivers alone affected pine decline.

409 The novelty of our approach lied in linking information from remotely sensed data to ground-based forest
410 inventories, in the study versus control design of drought response analysis, and in the multivariate
411 investigation of direct and indirect causal drivers.

412 Scots pine proved to be a sensitive species, showing early signs of vitality decline that may be remotely
413 detected even by coarse-resolution, readily available satellite imagery (MODIS). Furthermore, MODIS-
414 derived EVI provided some predictive power, being able to spot changes associated to decline earlier than
415 ground-based estimates. “Early warning” systems (Verbesselt et al. 2009) and decision support systems
416 aimed at prioritizing the management of drought-sensitive pine forests may be designed based on such
417 approach.

418

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420

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