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

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

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

Study area

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

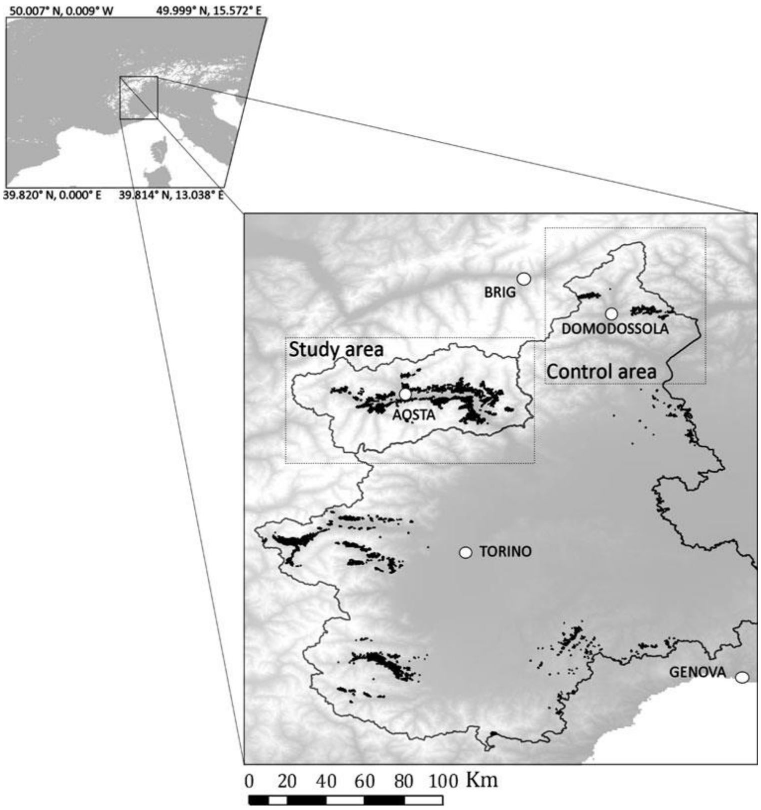

Fig. 1 MODIS image tile and study and control sites (geographical datum: UTM WGS 1984). Scots pine coverage in black. Data source for shaded relief: Jarvis et al. (2008).

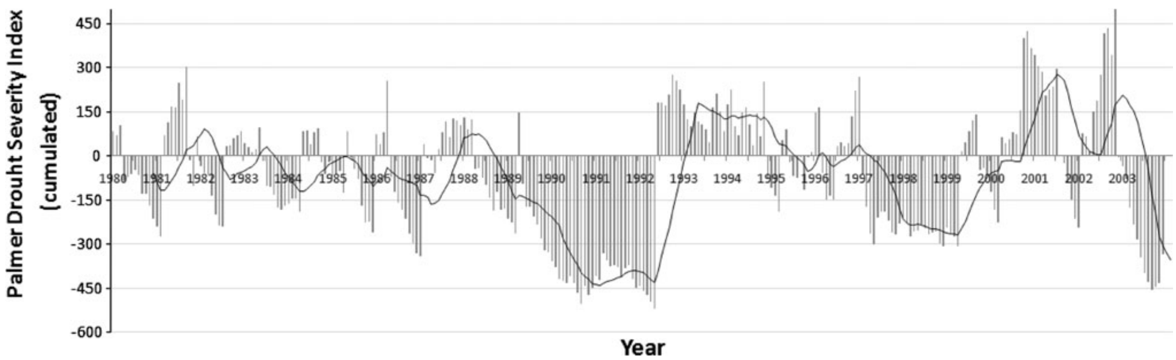

Fig. 2 Cumulated Palmer Drought Severity Index between 1980 and 2003 for the city of Aosta (source: van der Schrier et al. 2007) and smoothed 10-year mean (solid line).

The study area exhibits both crystalline (granites) and metamorphic bedrocks, but most landscape is covered by quaternary deposits of glacial, gravitative, or colluvial origin. Soils belong to the series of western and central Alpine soil on igneous and metamorphic rocks (Costantini et al. 2004) and are mostly represented by shallow soils (Lithic, Umbric and Dystric Leptosols), eroded soils (Eutric and Calcaric Regosols), acid soils with organic matter, iron oxides and aluminum accumulation (Dystric Cambisols, Haplic Podzols, Humic Umbrisols), or alluvial soils (Eutric Fluvisols).

Pine stands in the study area occur on 5,372 ha (6% of total forest cover), on both acidic and basic substrates of well-exposed, bottom to mid-elevation slopes. Pure stands cover southerly exposed slopes and shallow soils (Ozenda 1985). A greater broadleaved component, represented predominantly by downy oak (Quercus pubescens Willd.) and chestnut (Castanea sativa Mill.), exists on sites with a more favorable water balance (Camerano et al. 2007). A Regional Forest Inventory (RFI) was carried out in the years 1992–1994. Base grid size was 500 m; sample plots were circular with a variable radius (8–15 m according to overstory density). For each plot, the following site-and stand-level variables were recorded: geographic coordi-nates, elevation, slope, forest cover type, percent canopy cover, seedling count, number of mortality trees, occur-rence of grazing by domestic or wild ungulates, and severity and cause of crown damage. Species and diameter at breast height (dbh) of all living individuals bigger than
7.5 cm in dbh were recorded to the nearest cm. A total of 130 plots were sampled in the Scots pine cover types. Mean structural descriptors of pine stands from RFI are sum-marized in Table 1.

To test the drought-related decline hypothesis, we con-trasted Scots pine against Norway spruce (Picea abies (L.) Karst.) cover as a control species in the same study area, and to Scots pine on a control site. This was represented by the Northern Piedmont region (Fig. 1), where the amount and seasonal distribution of rainfall are typical of a mesic climate (1,479 mm year -1 in Domodossola, 46° 07’N, 8 17’E, for years 1961–1990).

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

	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%

Methods

Satellite imagery

Stress in trees may result in the reduction in chlorophyll content, leaf necrosis, defoliation, or tree death, which in turn affect the radiation characteristics of tree and stand canopies (Jackson 1986; Carter 1993; Pen˜uelas and Filella 1998; Carter and Knapp 2001). Forest vegetation change can be remotely detected by means of spectral vegetation indices, which are linear combinations of satellite-sensor, multispectral re.ectance data (Tucker 1979; Bannari et al. 1995). Decline in vegetation greenness and presumably, crown vitality can be detected by the difference of the index images (Collins and Woodcock 1996) through time.

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

$$EVI = G(NIR - red)(NIR + a_1 red - a_{2blue} + L)^{-1}$$

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

We used data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Earth Observing System-Terra platform, which outputs maps on a global basis every 1–2 days (Justice et al. 1998), beginning from year 2000. MODIS standard products include preprocessed EVI and quality analysis (QA) of the product. Input reflectance data are corrected for nadir and standard sun angles, molecular scattering, ozone absorption, and aerosols (Vermote et al. 2002). In order to filter out residual atmospheric errors, daily EVI data are combined into 16-day maximum-value compositing (MVC) intervals (Holben 1986; van Leeuwen et al. 1999) at a base resolution (grain) of 250 m (MODIS product code MOD13Q1.004).[2] For production purposes, MODIS maps are output in 1,200 9 1,200 km georeferenced tile units in the integerized sinusoidal (ISIN) geographical projection.

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

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

Change detection

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

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

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

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

u.d. Unpublished data

[a] The assessment was carried out by visual assessment of crown conditions (average defoliation and extremes)

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

	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

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

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

Effect of predisposing factors

We employed path analysis (Shipley 2000) to assess the effect size of predisposing factors on pine decline. Path analysis is a specialized version of Structural Equation Models, testing the relationships between the putative causal variables (climate, site, and stand characteristics) and the hypothesized effect. Path analysis allows modeling of both observed (manifest) and unmeasured (latent) variables. A graphical conceptual model is presented (Fig. 3) for all pixels including a RFI plot (n = 105 after exclusion of outliers and plots with less than 5 tallied tree). Arrows symbolize cause-and-effect relationships between variables that are represented by rectangles (manifest) and ellipses (latent). The response variable was Pine decline, i.e., the EVI difference between 2000 and 2007. Independent variables included:

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

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

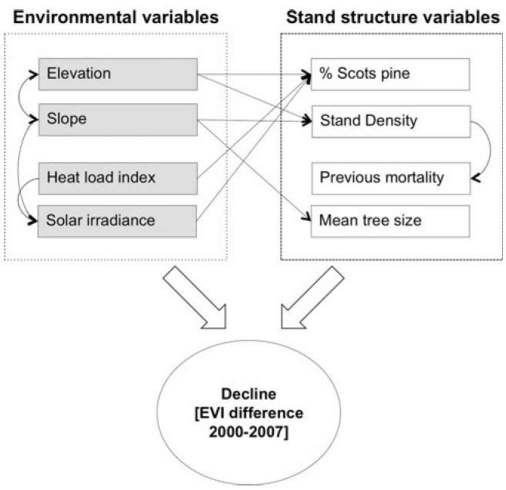

Fig. 3 - Conceptual model of decline predisposing factors.

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

Variable effects were quantified by standardized regression coefficients (β). Quantitative model compari-sons used a combination of Akaike's Information Criterion (AIC) statistic and the Root Mean Square Error of Approximation (RMSEA) that is relatively independent of sample size. The models with the smallest AIC statistic were selected as the most parsimonious ones (Hu and Bentler 1999). A model with RMSEA<0.06 was consid-ered a good .t (Hu and Bentler 1999). Path analyses were conducted using Mx software that works with covariance matrices as input data and a maximum likelihood (ML) .t function (Neale 1994).

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

Year of assessment	Model	Producer's accuracy (decline pixels)	KHAT
0 ($n = 41$)	EVI, intercept	0.14	0.04
	EVI	n.s.	n.s.
0, +1 ($n = 57$)	EVI, intercept	0.30	0.18
	EVI	0.80	0.22[a]

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

n.s. model not significant

[a] Significant at alpha = 0.05

Results

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

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

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

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

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

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

Conversely, two alternative models (Fig. 6), one each for lower elevation and higher elevation pine forests, emerged as having significant sup-port. At higher elevation, environmental factors alone appeared to have a significant influence on decline (Fig. 6b). These included a direct effect of elevation (β = 0.38), slope (β = 0.17), and aspect (β = 0.32), with sun-exposed sites more subject to decline.

The model for low-elevation stands had less explanatory power, i.e., lower goodness of fit (Table 8), but additionally included an explicit influence of stand structural variables (Fig. 6a), i.e., percent Scots pine and SDI. In particular, mixed forests with low SDI resulted more prone to decline. Significant environmental variables for model (a) included slope (β =0.31) and aspect, with sun-exposed sites less sensitive to decline (β =-0.12).

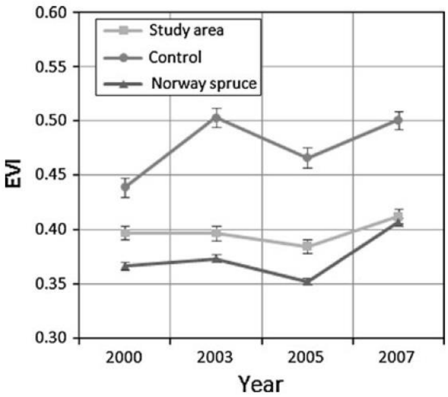

Fig. 4 - Temporal trend of mean EVI in the study (2 species) and control sites. Bars represent standard error of estimate for each year and site

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

Discussion

MODIS has the potential for identifying large, homogeneous damaged areas; omission errors may occur for small patches (less than 1.5 ha according to Lunetta et al. 2006) or low defoliation severities. Past studies using reflectance indices as a diagnostic element have provided mixed results, likely due to the confounding factors that affect EVI at different sites, i.e., stand structure (Carter et al.1989; Guyot et al. 1989; Asner 1998), topography (Burgess et al. 1995; Matsushita et al. 2007), or radiometric errors (Myneni and Asrar 1994). However, the classification of ‘‘decline’’ pixels was fairly accurate when tested against crown transparency of the current and subsequent year (consistent with findings by Heikkila¨ et al. 2002). It is noteworthy that EVI provided some predictive power, being able to spot changes associated with decline some-what earlier than ground-based estimates.

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

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

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

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

Table 6. Summary of EVI anomalies (2007–2000) and incidence of signi.cant decline (EVI anomalies \ [mean -1 SD]) for 250 m 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

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]

[a] Correlation significant at alpha = 0.05

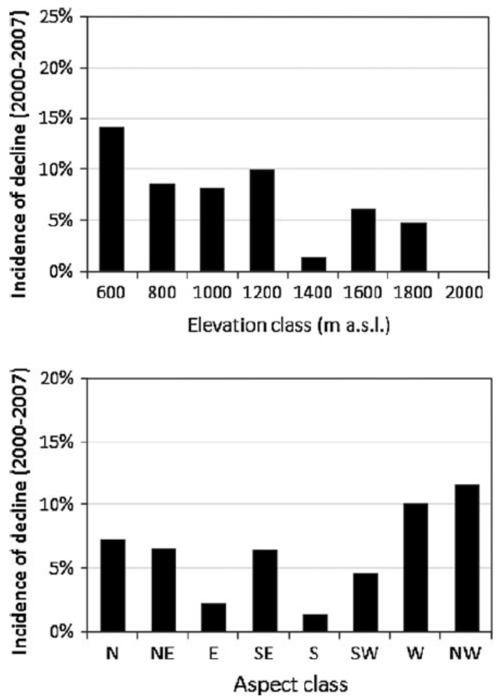

Fig. 5- Incidence of decline (i.e., relative frequency of decline pixels) in Scots pine stands as a function of elevation and aspect for the study area.

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; Yuhas 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.

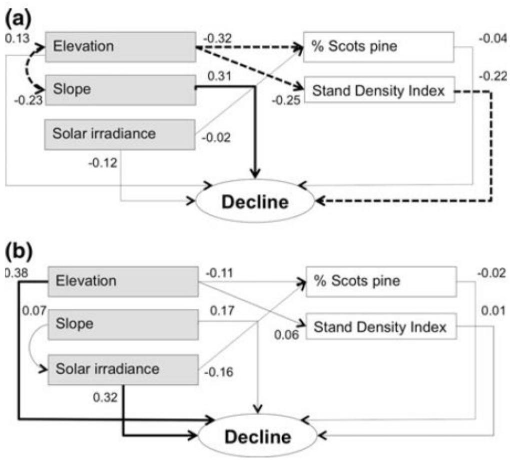

Fig. 6 *- Path diagrams for Scots pine forests at **a** low (<1,250 m a.s.l.) and **b** high (> 1,250 m a.s.l.) elevations, showing the effect of environmental (gray) and stand structural variables (white)on DEVI response. Continuous arrows positive paths; dashed arrows negative paths. Thickness of path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

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

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

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

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

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

Conclusion

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

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

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

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

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