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Health and vitality assessment of two common pine species in the context of climate change in southern Europe

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ABSTRACT

The Mediterranean Basin is expected to be more strongly affected by ongoing climate change than most other regions of the earth. The South-eastern France can be considered as case study for assessing global change impacts on forests. Based on non-parametric statistical tests, the climatic parameters (temperature, relative humidity, rainfall, global radiation) and forest-response indicators (crown defoliation, discoloration and visible foliar ozone injury) of two pine species (*Pinus halepensis* and *Pinus cembra*) were analyzed. In the last 20 years, the trend analyses reveal a clear hotter and drier climate along the coastline and slightly rainier inland. In the current climate change context, a reduction in ground-level ozone (O_3) was found at remote sites and the visible foliar O_3 injury decreased while deterioration of the crown conditions was observed likely due to a drier and warmer climate. Clearly, if such climatic and ecological changes are now being detected when the climate, in South-eastern France, has warmed in the last 20 years (+0.46–1.08 °C), it can be expected that many more impacts on tree species will occur in response to predicted temperature changes by 2100 (+1.95–4.59 °C). Climate change is projected to reduce the benefits of O_3 precursor emissions controls leading to a higher O_3 uptake. However, the drier and warmer climate should induce a soil drought leading to a lower O_3 uptake. These two effects, acting together in an opposite way, could mitigate the harmful impacts of O_3 on forests. The development of coordinated emission abatement strategies is useful to reduce both climate change and O_3 pollution. Climate change will create additional challenges for forest management with substantial socio-economic and biological diversity impacts. However, the development of future sustainable and adaptive forest management strategies has the potential to reduce the vulnerability of forest species to climate change.

1. Introduction

The sensitivity of Europe to climate change has a distinct north–south gradient, with many studies indicating that southern Europe will be the more severely affected (EEA, 2004; Bates et al., 2008). Climate change is expected to be more pronounced in the Mediterranean Basin than in most other regions of the world (Bates et al., 2008). Indeed, in a scenario of increased temperatures worldwide (on average 1.4–5.8 °C) by 2100, the variation should be at least 3 °C in the Mediterranean Basin. Furthermore Mediterranean basin will be one of the areas subject to the most drastic reductions in precipitation (IPCC, 2007) with considerable effects on the environment (EEA, 2004).

Ozone (O_3) and climate change are interlinked (Bytnerowicz et al., 2007). Ground-level O_3 is an important atmospheric pollutant and climate forcer (Ramaswamy et al., 2001). Surface O_3 concentrations in the South-western European Mediterranean Basin are relatively high relative to human well-being and vegetation impacts (Sicard et al., 2013). Indeed, high annual mean O_3 concentrations, exceeding 40 ppb, were recorded in some regions, particularly along the coasts, because of shipping tracks, industrial development, road traffic increment, high temperature, high solar radiation and sea/land breeze recirculation (Vestreng et al., 2009; Sicard et al., 2013). Ground-level O_3 affects trees through visible leaf injury, accelerating leaf senescence, decreasing foliar chlorophyll content, photosynthesis, growth, productivity and carbon sequestration, predisposing to pests attack and a variety of other physiological effects in plants (e.g. Dalstein et al., 2002; Karnosky et al., 2007; Paoletti et al., 2009; Sicard et al., 2011). Ozone is the phytotoxic air pollutant and greenhouse gas of most concern to forests (Paoletti, 2006). The forests have important functions for economic activities, for development of rural areas and for recreational purposes, in terms of nature conservation and

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environmental protection, e.g. as carbon sinks, important in the climate change context (Kohut, 2005; Fischer and Lorenz, 2011). Climate change will alter forest ecology and will change phenology, by advancing time in flowering or rising level of pollinators, and geographical distribution of plants (Giannakopoulos et al., 2009). Disturbances created from the interaction of drought, pests, diseases, and fires are projected to have increasing impacts on forests and their future distributions (IPCC, 2007). An overview of the consequences of climate changes for trees in the Mediterranean basin is provided by Petit et al. (2005). When analyzing the future ranges of some 1400 plant species in Europe, the strongest reshuffling would take place in southern Europe, where 60–80% of the flora present in 1990 would go extinct by 2050 compared to 20–40% further north (Bakkenes et al., 2002).

Climate change, creating additional challenges for European forest, is expected to be more pronounced in the South-eastern France, particularly at the rural alpine Mediterranean area, at highest risk of O_3 injury (Dalstein et al., 2005; Sicard et al., 2011).

The main aim of this study was to establish a state-of-the-art of the health and vitality of two common pine species in South-eastern France, in a context of climate change and high ground-level O_3. For that, the study focused on two valuable bio-indicator species for O_3 stress (i.e. *Pinus halepensis* and *Pinus cembra*) at 20 experimental plots over the time period 2000–2012. Secondary aims were: (i) to detect and estimate trends for surface O_3 concentrations, climatic parameters (temperature, relative humidity, rainfall, global radiation) and visible injury, i.e., crown defoliation, crown discoloration and visible O_3 injury; and (ii) to assess the most important environmental variables that affect crown defoliation, discoloration and visible foliar O_3 injury of adult trees under field conditions.

2. Methodology

2.1. Study area and sampling sites

Experimental sites are located in South-eastern France (Fig. 1 and Table 1) into the Mercantour National Park at relatively high elevations (1700–2400 m a.s.l.) and along the coastline (French Riviera). The Mediterranean weather which rules the coastal area rapidly turns into an Alpine climate when altitude overcomes 800 m. The plots, 13 in the Mercantour National Park and 7 along the Mediterranean coastline, were selected to represent different conditions (north/south-facing side, valley and ridges) in order to consider the impact of local meteorology, topography, soil conditions, water availability on the visible injury occurrence. The study focused on two O_3-sensitive conifer tree species (UNECE, 2004; Q3 Ashmore, 2005): Arolla pine (*P. cembra L.*) from the inland Alps, mostly distributed in high-lying sites (1700–2400 m), and Aleppo pine (*P. halepensis Mill.*), a typical *circum*-Mediterranean conifer, mostly distributed along the coastlines and generally found at low altitudes, from sea level to 600 m. Aleppo pine is very drought-resistant and thermophilic and has an important role in maintenance and reforestation due to its good regenerative potential (Scarascia-Mugnozza, 1986; Voltas et al., 2008). Ozone produces very characteristic injury on the needles of *P. halepensis* and *P. cembra* (Sanz et al., 2000; Kivimäenpää et al., 2010), therefore, are valuable bio-indicator species for O_3 stress.

2.2. Meteorological and ozone data

First, for the trend analysis of *in-situ* climatic parameters, the meteorological data (daily maximum and minimum temperatures, mean temperature, relative humidity, rainfall, global radiation) were supplied by the French national meteorological service (Météo-France) from 3 sites located in the South-eastern France: Nice [43.65°N; 7.20°E; 4 m a.s.l.] and Saint-Auban [44.06°N; 5.99°E; 461 m a.s.l.] over the time period 1973–2012 and Cannes [43.54°N; 6.95°E; 2 m a.s.l.] over the 1993–2012 period.

Secondly, for the statistical analyses, to assess the most important environmental variables that affect crown defoliation, discoloration and visible foliar O_3 injury, the hourly O_3 concentrations and meteorological data (daily temperatures, global radiation, rainfall, relative humidity, soil water content) were obtained from the MM5–CHIMERE modeling system (Bessagnet

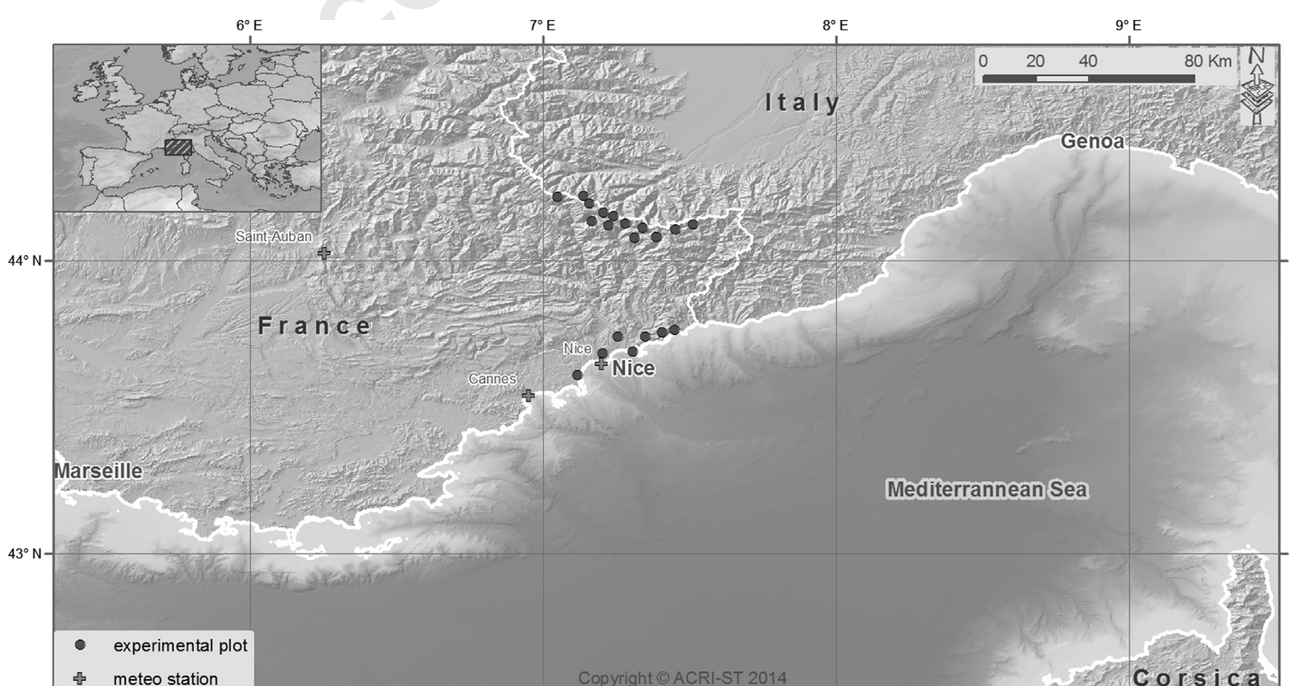

Fig. 1. Location of experimental plots in South-eastern France.

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Table 1
Characteristics of forest plots where symptoms were recorded along the coastline (1–7) and into the Mercantour National Park (8–20).

Q4

Name	N°	Latitude (decimal degree)	Longitude (decimal degree)	Altitude (m)	Main tree species
Gairaut	1	43.7414	7.2547	160	*Pinus halepensis*
Vinaigrier	2	43.7131	7.3008	370	*Pinus halepensis*
Mont Boron Village	3	43.6903	7.3042	160	*Pinus halepensis*
Mont Boron Nice	4	43.6914	7.2994	160	*Pinus halepensis*
Revère	5	43.7394	7.3494	500	*Pinus halepensis*
Col Eze	6	43.7369	7.3539	510	*Pinus halepensis*
Col de Guerre	7	43.7542	7.4044	480	*Pinus halepensis*
Lausetta	8	44.1986	7.1253	1820	*Pinus cembra*
Col Lombarde	9	44.2011	7.1489	2350	*Pinus cembra*
Route Lombarde	10	44.1958	7.1556	2250	*Pinus cembra*
Vacherie du Collet	11	44.1408	7.2128	1880	*Pinus cembra*
Germas	12	44.1414	7.2236	1950	*Pinus cembra*
Pont Ingolf 3	13	44.0786	7.2208	2020	*Pinus cembra*
Pont Ingolf 2	14	44.1447	7.2283	1990	*Pinus cembra*
Pont Ingolf 1	15	44.1433	7.2294	1980	*Pinus cembra*
Col Salèse	16	44.1383	7.2364	2050	*Pinus cembra*
Parking Salèse	17	44.1361	7.2339	1975	*Pinus cembra*
Entrée PNM	18	44.1283	7.2539	1790	*Pinus cembra*
Cabanes Julie	19	44.1061	7.4522	2100	*Pinus cembra*
Valmasque	20	44.1161	7.4886	1820	*Pinus cembra*

et al., 2004) at each experimental plot where survey campaigns were carried out (Fig. 1) over the time period 2000–2012. The regional chemical and transport model CHIMERE is coupled with the MM5 meso-scale meteorological model.

2.3. Sampling and scoring of visible symptoms

At 20 plots, 400 trees were investigated over the time period 2000–2012, following the European protocol defined by the ICP-Forests (International Co-operative Programme on Assessment and Monitoring of Air Pollution on Forests; Fischer and Lorenz, 2011; Michel et al., 2014) to determinate and quantify the visible symptoms per plot i.e.: (i) percentage of crown defoliation, (ii) proportion of discolored needles per tree (crown discoloration) and (iii) percentage of needles surface affected by O_3-induced symptoms (visible O_3 injury). Any survey campaign was done by two trained experts. GIEFS is involved in the validation activities of the Expert panel on Ambient Air Quality of ICP-Forests and have performed intercalibration exercises. Symptoms were evaluated at the end of August when the seasonal exposure to O_3 and the probability of injury expression were highest, and before environmental conditions fostered the development of foliar senescence, at the end of the growing season that can mask O_3 injury (Tagliaferro et al., 2005; Schaub et al., 2010).

2.3.1. Crown defoliation and discoloration

In Europe, crown condition is the most widely applied indicator for forest-health and vitality (Rossini et al., 2006; Fischer and Lorenz, 2011; De Marco et al., 2014) and has been used by the Ministerial Conference on the Protection of Forests in Europe (MCPFE). Both transparency and discoloration rely on the difference of the observed crown characteristic (needle density or color) from a conceptual “reference tree”, defined as the best tree with full foliage that could grow at a particular site, taking into account factors such as altitude, latitude, tree age, site conditions and social status (Rossini et al., 2006). Trees that are fully foliated and green are regarded as healthy. Crown defoliation and discoloration, were assessed on 20 randomly-selected trees per plot where trees were marked and scored. Crown defoliation was assessed in 5% steps. A defoliation of 10–25% was considered a warning stage and a defoliation $>25\%$ was taken as a threshold for damage (Fischer and Lorenz, 2011; Michel et al., 2014). This classification is a practical convention, as real physiological thresholds have not been defined yet (Fischer and Lorenz, 2011). The proportions of leaves/needles discolored (yellowed) were categorized in five classes: class 0 = discoloration $<10\%$ (green tree), class 1 = 11–25%, class 2 = 26–65%, class 3 = 66–99% and class 4 = 100% (yellow tree), as recommended by the ICP-Forests protocol (Schaub et al., 2010). For each plot, a mean needle crown defoliation and discoloration score was calculated, as an average of the 20 trees. If signs of biotic factors (e.g. pest diseases, insect attacks, fungi) are observed, the observed damage symptoms are reported. Crown defoliation and crown discoloration react to different biotic and abiotic factors, including climatic conditions, insect and fungal infestations, site characteristics, deposition of other air pollutants. They are thus aspecific parameters, while visible foliar O_3 injury is specific of O_3 (Günthardt-Goerg and Vollenweider, 2007).

2.3.2. Assessment of visible foliar ozone injury

Assessment was based on the ICP-Forests Manual on Assessment of Ozone Injury (Innes et al., 2001; Schaub et al., 2010). At each plot, 5 sun-exposed trees were randomly selected. For each tree, 5 branches with at least 30 needles per each needle age class (current year foliage (C), one-year-old (C+1) and two-year-old needles (C+2)), were removed from the upper third of the crown by using telescopic secateurs. For each branch, the percentage of total needle surface affected by visible foliar O_3 injury was scored for C, C+1 and C+2. Finally, a mean percentage of needles surface affected by visible foliar O_3 injury was calculated per every plot. When injury was unclear, needles samples were collected for microscopic analyses according to ICP-Forests protocol (Fischer and Lorenz, 2011), to confirm symptom recognition and to eliminate dubious cases (Günthardt-Goerg and Vollenweider, 2007; Eichhorn et al., 2010; Sicard et al., 2011). If injury was due to another factor, different from O_3, the needle was excluded from scoring.

2.4. Statistics and estimation of annual and seasonal trends

Data were tested for normal distribution by the Kolmogorov–Smirnov one-sample *D* test. As D was significant for most of variables, the Spearman rank correlation test was applied to

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measure statistical dependence pairs of variables. Spearman test was carried out to understand the contribution of O_3 concentrations and meteorological and soil conditions to crown defoliation, crown discoloration and visible O_3 injury.

To compare the data distribution, the non-parametric Mann–Whitney *U* test was used to compare the medians from two populations to determine if two sets of data are significantly different from each other. The test was used with *p-values* indicating the statistical significance of correlations. Results were considered significant at $p < 0.05$.

The advantage of the non-parametric tests over the parametric tests is that they are robust and more suitable for non-normally distributed data with missing and extreme values, frequently encountered in environmental time-series, and can be applied to a small number of observations (Sicard et al., 2013). The Mann–Kendall test is a non-parametric statistical test to detect the presence of a monotonic increasing or decreasing trend within a time-series. Seasonality and missing values present no theoretical or computational obstacles to its application (Sicard et al., 2009). To estimate the trend, a consistent nonparametric estimator for the coefficients of a linear regression was suggested and modified by Sen (1968) to include the possibility of ties in the time-series. This method is robust because insensitive to the "extreme" and missing values (Sicard et al., 2009). The seasonal Kendall test is an extension of the Mann–Kendall test for trend (Sicard et al., 2009). The seasonal Kendall test may be applied to data presenting some seasonality. The test is used with four significance levels *p*: 0.1, 0.05, 0.01 and 0.001, this for an observation period of more than 10 years.

Random forests Analysis (RFA) is a non-parametric tree-based ensemble approach that merges the ideas of adaptive nearest neighbors with bagging for effective data adaptive inference (Breiman, 2001; De Marco et al., 2013; Vitale et al., 2014). The procedure is robust, adapts to sparsity, deals with missing data well. RFA is able to account for correlation as well as interactions among features. During the building of each tree, for each split, predictor statistics (i.e., sums of squares regression) are computed for each predictor variable; the best predictor variable will then be chosen for the actual split. The predictor importance values are computed by normalizing those averages so that the highest average is assigned the value of 1, and the importance of all other predictors is expressed in terms of the relative magnitudes of the average values of the predictor statistics, relative to the most important predictor (Svetnik et al., 2003). RFA can be successfully applied to derive information about meteorological conditions impacts on plants vitality and health under real-world conditions.

3. Results

3.1. Climate change

Along the coastline, in Nice, we observed a significant ($p < 0.05$) decrease for annual rainfall and for the relative humidity in the past 20 years (Table 2). From 1993 to 2012, the number of days with rainfall decreased by 2.5 days per decade, and the number of days with daily rainfall greater than 10 mm, by 1.4 days. In Nice, the drier climate in 1993–2012 translates into 5 additional dry days. A significant upward trend ($p < 0.05$) was observed for the daily maximum, minimum and mean temperatures, i.e. +0.16, +0.61 and +0.54 °C per decade, respectively, and the daily global radiation increased. Every 10 years, we observed two additional days with a daily maximum temperature, exceeding 30 °C. Regarding the annual mean temperature, seven of the 10 warmest years (higher than 16.0 °C) on record occurred since 2003. In Nice, the average annual temperature for the decade 2003–2012 was estimated to be 16.1 °C or 0.30 °C above the 1993–2012 global average and +0.60 °C above the 1973–2012 global average. The decadal rate of increase in the global temperature accelerated between 1993 and 2002. Based on the last 20 years, an increase of 4.59 °C of the annual mean temperature is expected between 2015 and 2100.

By using the Seasonal Kendall test (Table 3), annual decreasing trends were found over the last 20 years during the warm and cold periods for the rainfall and relative humidity. The rainfall decreased more during the cold period relative to the warm period (Table 3). The number of days with daily rainfall decreased during the both seasons. For the temperatures and the global radiation, the study related significant upward trends ($p < 0.001$) with the most important increase during the warmer period. The warm season is likely to be warmer by 1.58 °C and the cold season by 0.92 °C between 1993 and 2012. In Nice, in the last 20 years, the trends for the annual temperatures (+1.08 °C), radiation (+7.4%), humidity (−5.8%) and rainfall (−19.8%) reveal a clear hotter and drier climate during the warm and cold seasons.

In the last 20 years, we observed a decrease for the daily minimum temperatures, annual rainfall and for the relative humidity in Cannes (Table 4). Due to the observed decrease of the daily minimum temperature, we obtained an increase of the number of days with temperature below 0 °C. For the other meteorological parameters, we obtained significant upward trends ($p < 0.05$): daily maximum temperatures and daily mean. In Cannes, the drier climate in 1993–2012 translates into 1.8 additional dry days, but the number of days with daily rainfall greater than 10 mm increased. Every year we recorded 0.16 additional days with a maximum temperature exceeding 30 °C. From 2015,

Table 2
Average (± standard deviation) and associated annual trends for the main meteorological parameters in Nice, over the both time periods 1973–2012 and 1993–2012, obtained by the Mann–Kendall test (n.a, non-applicable, p=0.001***, 0.01**, 0.05*, 0.1^{+}, >0.1).

NICE	1993–2012		1973–2012	
	Average	Trend (unit year^{-1})	Average	Trend (unit year^{-1})
Daily maximum temperature Tx (°C)	19.8 ± 0.5	+0.016*	19.4 ± 0.6	+0.040***
Daily minimum temperature Tn (°C)	12.6 ± 0.4	+0.061**	12.3 ± 0.5	+0.037***
Daily mean temperature (°C)	15.8 ± 0.5	+0.054***	15.5 ± 0.6	+0.042***
Annual rainfall (mm)	769 ± 227	−7.60*	782 ± 291	−4.32*
Global radiation (J cm^{-2})	1531 ± 50	+5.71*	n.a	n.a
Relative humidity (%)	68.8 ± 2.5	−0.29**	n.a	n.a
Nb of days Tx > 30 °C	7.5 ± 6.3	+0.20	6.0 ± 5.1	+0.11*
Nb of days Tx > 20 °C	172.3 ± 10.4	+1.00*	165.4 ± 13.4	+0.62***
Nb of days Tn < 0 °C	1.4 ± 2.4	0	1.5 ± 2.3	0
Nb of days with rainfall > 0 mm	91.4 ± 16.2	−0.25	92.9 ± 14.1	−0.18
Nb of days with rainfall > 10 mm	23.5 ± 7.2	−0.14*	24.9 ± 8.1	−0.10*

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Table 3
Average ($\pm$ standard deviation) and associated seasonal trends for the main meteorological parameters in Nice during the warm and cold seasons obtained by the Mann–Kendall test over the time period 1993–2012 (n.a, non-applicable, p-value=0.001***, 0.01**, 0.05*, 0.1^{+}, >0.1).

Meteorological parameters (1993–2012)		NICE	
		Cold period (22/09–20/03)	Warm period (21/03–21/09)
Daily maximum temperature Tx (°C)	Average	15.7 ± 0.8	23.8 ± 0.6
	Trend (°C year^{-1})	+0.027	+0.050**
Daily minimum temperature Tn (°C)	Average	8.3 ± 0.7	16.9 ± 0.7
	Trend (°C year^{-1})	+0.021	+0.095 ***
Daily mean temperature (°C)	Average	11.4 ± 0.7	20.3 ± 0.7
	Trend (°C year^{-1})	+ 0.046**	+ 0.079***
Annual rainfall (mm)	Average	499 ± 209	265 ± 93
	Trend (mm year^{-1})	−9.12*	−5.92*
Global radiation (J/cm²)	Average	886 ± 52	2161 ± 65
	Trend (J cm^{-2} year^{-1})	+1.0	+8.39***
Relative humidity (%)	Average	68.2 ± 3.2	69.6 ± 2.7
	Trend (% year^{-1})	−0.26*	−0.39**
Nb of days Tx > 30 °C	Average	0.1 ± 0.2	7.7 ± 6.4
	Trend (day year^{-1})	0	+0.30*
Nb of days Tx > 20 °C	Average	26.7 ± 7.4	145.6 ± 7.8
	Trend (day year^{-1})	+0.50	+0.60*
Nb of days Tn < 0 °C	Average	1.8 ± 2.9	0
	Trend (day year^{-1})	−0.28*	n.a
Nb of days with rainfall > 0 mm	Average	49.0 ± 12.9	40.6 ± 7.8
	Trend (day year^{-1})	−0.21*	−0.27*
Nb of days with rainfall > 10 mm	Average	14.6 ± 6.8	7.9 ± 2.8
	Trend (day year^{-1})	−0.16	−0.24*

an increase of 1.95 °C of the annual mean temperature is expected by 2100. In the last 20 years, increasing trends were obtained at the inland Saint-Auban station (Table 4) for the daily temperatures, rainfall and for the number of days with a maximum temperature higher than 30 °C.

In the last 40 years (1973–2012), significant trends ($p < 0.001$) were obtained in Nice for the daily maximum, minimum and mean temperatures and a downward trend for rainfall (Table 2). Based on the last 40 years, an increase of 3.57 °C of the annual mean temperature is expected between 2015 and 2100. In Saint-Auban, significant upward trends ($p < 0.001$) were obtained (Table 4) for all meteorological parameters. From 2015, an increase of 3.91 °C of the annual mean temperature is expected by 2100.

3.2. Ozone concentrations

At rural stations, the O_3 mean concentrations, registered during the growing season, ranged from 39.0 to 52.0 ppb along the coastline, and from 32.6 to 53.2 ppb in the Mercantour National Park (Table 5). Largely due to the high altitude of the sites, relatively high concentrations were found in the Mercantour National Park, and the lowest mean concentrations were observed at low altitude sites. Over the period 2000–2012, mean O_3 concentrations decreased over the growing season by 0.07–0.89 ppb per year. We observed an upward trend of the O_3 levels at two sites, i.e. no.1, nearby the city of Nice and no.20 (Table 5).

3.3. Needle loss and discoloration

A 13-year observational study was conducted and allowed obtaining a time-series with 91 data for 7 assessed plots with *P. halepensis* and 169 data for 13 assessed plots with *P. cembra*. Considering all sites, mean crown defoliation was higher (Mann–Whitney test, $p < 0.05$) for *P. halepensis* (34.4 ± 4.7%) than *P. cembra* (27.1 ± 4.1%). Over the time period 2000–2012, the plots with *P. halepensis* presented a range of annual percentage of defoliation of 19–55% and 14% of assessed sites showed a mean defoliation higher than 25%. From 2004, 100% of sites showed a mean

Table 4
Average ($\pm$ standard deviation) and associated annual trends for the main meteorological parameters in Saint-Auban and Cannes, over the both time periods 1973–2012 and 1993–2012, obtained by the Mann–Kendall test (n.a, non-applicable, p-value=0.001***, 0.01**, 0.05*, 0.1^{+}, >0.1).

Meteorological parameters	Saint-Auban				Cannes	
	1993–2012		1973–2012		1993–2012	
	Average	Trend (unit year^{-1})	Average	Trend (unit year^{-1})	Average	Trend (unit year^{-1})
Daily maximum temperature Tx (°C)	19.2 ± 0.8	+0.046*	18.7 ± 1.1	+0.065***	20.0 ± 0.7	+0.090**
Daily minimum temperature Tn (°C)	7.4 ± 0.6	+0.031	7.2 ± 0.8	+0.027***	11.0 ± 0.6	−0.045**
Daily mean temperature (°C)	13.3 ± 0.7	+0.04**	12.9 ± 0.9	+0.046***	15.5 ± 0.5	+0.023*
Annual rainfall (mm)	638 ± 134	+3.88	615 ± 146	+2.42*	734 ± 232	−1.10*
Relative humidity (%)	63.5 ± 4.1	−0.12	n.a	n.a	65.1 ± 2.1	−0.15*
Nb of days Tx > 30 °C	41.7 ± 13.8	+0.82*	33.4 ± 16.3	+1.00***	11.6 ± 8.8	+0.16***
Nb of days Tx > 20 °C	165.2 ± 11.0	+1.02**	152.2 ± 22.7	+1.29***	161.8 ± 25.3	+0.88***
Nb of days Tn < 0 °C	54.2 ± 16.2	0	50.3 ± 17.1	+0.46*	10.3 ± 8.2	+0.62*
Nb of days with rainfall > 0 mm	104.8 ± 15.9	+0.42	107.1 ± 16.3	−0.21	94.3 ± 35.5	−0.09
Nb of days with rainfall > 10 mm	24.0 ± 6.5	−0.07	29.9 ± 17.0	−0.44**	13.6 ± 12.5	+0.67***

Table 5
Averages per site (± standard deviation) of ozone concentrations (ppb) during the growing season (April–September), crown defoliation (mean percentage of needle surface affected per site), discoloration scoring, ozone-induced symptoms (mean percentage of surface affected per site, one year old needles C+1; two year old needles C+2, no injury on current year needles C) and associated annual trends obtained by the Mann-Kendall test over the time period 2000–2012 (n.a, non-applicable, p-value=0.001***, 0.01**, 0.05*, 0.1⁺, >0.1).

Plots no.	Ozone concentrations (April–September)		Crown defoliation		Crown discoloration		Ozone-induced injury			
							C+1 needles		C+2 needles	
	Average (ppb)	Trend (ppb year^{-1})	Average (%)	Trend (% year^{-1})	Average scoring	Trend (unit year^{-1})	Average (%)	Trend (% year^{-1})	Average (%)	Trend (% year^{-1})
1	39.0 ± 4.0	+0.46	26.4 ± 3.1	+ 0.88*	1.3 ± 0.4	+0.01	18.9 ± 11.7	−1.84*	28.3 ± 9.1	−2.70*
2	40.9 ± 2.4	−0.21	32.3 ± 3.7	+0.60**	1.2 ± 0.3	+0.06*	16.8 ± 10.5	−1.91*	21.8 ± 7.5	−3.64*
3	39.0 ± 3.3	−0.72	50.8 ± 6.0	+0.96***	1.3 ± 0.3	+0.02*	21.8 ± 10.6	−2.67**	28.6 ± 8.7	−1.40*
4	40.0 ± 5.3	−0.70	37.5 ± 4.8	+1.45*	1.4 ± 0.3	+0.07*	20.1 ± 9.1	−0.40	26.1 ± 9.9	−0.21
5	51.9 ± 4.2	−0.64	34.7 ± 4.2	−0.77	1.5 ± 0.4	+0.02*	12.4 ± 6.8	−0.85*	23.6 ± 6.9	−0.88*
6	52.0 ± 3.8	−0.40	31.6 ± 2.4	+0.48***	1.2 ± 0.4	+0.10**	14.5 ± 4.5	−0.87*	22.8 ± 7.1	−0.68*
7	42.8 ± 4.2	−0.67	26.9 ± 4.1	+1.11**	1.2 ± 0.4	+0.08**	16.0 ± 6.6	−1.48**	28.2 ± 8.9	−1.68**
8	45.9 ± 3.6	−0.30	33.8 ± 6.7	+1.88***	1.5 ± 0.4	+0.08*	13.5 ± 2.8	−0.43*	25.3 ± 4.8	−1.04**
9	53.2 ± 4.0	−0.17	33.3 ± 4.9	+0.74*	1.7 ± 0.4	+0.05	22.1 ± 4.4	−0.76*	37.5 ± 5.4	−0.94*
10	n.a		26.9 ± 3.6	+0.56*	1.7 ± 0.5	+0.07*	22.4 ± 5.1	−1.33**	35.8 ± 5.9	−1.48**
11	36.5 ± 3.9	−0.07	27.6 ± 7.6	+1.52**	1.1 ± 0.7	+0.11⁺	10.7 ± 2.5	−0.46	20.3 ± 4.8	−0.60*
12	n.a		29.1 ± 5.5	+0.54	1.2 ± 0.5	+0.06	11.4 ± 2.8	−0.28**	23.3 ± 4.0	−1.03**
13	39.1 ± 4.1	−0.34	25.5 ± 5.1	+1.19***	1.3 ± 0.5	+0.09*	13.9 ± 4.0	−0.98*	25.0 ± 5.4	−1.44**
14	41.5 ± 2.5	−0.45	23.7 ± 7.0	+1.65***	1.2 ± 0.7	+0.13**	16.0 ± 3.5	−0.47*	28.5 ± 3.7	−0.69*
15	42.1 ± 3.1	−0.37	31.6 ± 3.0	+0.60**	1.6 ± 0.4	+0.05⁺	14.9 ± 3.1	−0.75**	26.1 ± 4.1	−0.72*
16	48.1 ± 4.2	−0.89	28.7 ± 3.1	+0.25⁺	1.4 ± 0.7	+0.13**	19.9 ± 2.3	−0.40*	33.1 ± 2.9	−0.20
17	n.a		25.3 ± 4.2	+0.95 **	1.4 ± 0.6	+0.11**	19.8 ± 5.5	−1.20*	33.2 ± 5.9	−1.37**
18	32.6 ± 3.8	−0.74	25.6 ± 5.9	+0.88*	1.1 ± 0.6	+0.10*	11.8 ± 3.2	−0.52**	22.8 ± 5.6	−1.00*
19	n.a		34.7 ± 5.5	+0.23⁺	1.9 ± 0.2	+ 0.02 ⁺	21.2 ± 3.4	−0.53**	35.6 ± 5.9	−1.65**
20	49.5 ± 4.0	+0.15	25.5 ± 3.0	+0.70**	1.5 ± 0.4	+0.06**	14.2 ± 1.8	+0.28	26.2 ± 3.2	−0.20

Table 6
Spearman coefficients and p-value (ns=non-significant, p=0.001***, 0.01**, 0.05*) for correlations between crown discoloration, crown defoliation, visible foliar O_3 injury for *Pinus cembra* and *Pinus halepensis* (one year old needles C+1; two year old needles C+2) and annual ozone concentrations (O_3), temperature (T), soil water content (SWC), rainfall, global radiation (G. rad.) and relative humidity (RH).

	O_3	T	SWC	Rainfall	G. rad.	RH
Pinus halepensis						
Crown defoliation	0.31**	0.50***	0.47**	ns	0.31*	−0.31*
Discoloration	0.34**	0.42**	ns	0.30*	0.82***	ns
O_3 visible injury C+1	ns	0.20*	0.38*	ns	ns	0.32*
O_3 visible injury C+2	ns	ns	0.44***	0.35**	ns	0.34**
Pinus cembra						
Crown defoliation	ns	0.30*	0.43*	−0.39*	ns	ns
Discoloration	0.33*	0.45**	ns	ns	0.63 **	ns
O_3 visible injury C+1	ns	ns	0.35**	0.31*	ns	0.38**
O_3 visible injury C+2	ns	ns	0.39**	ns	ns	ns

defoliation exceeding 25%. The mean defoliation per plot, calculated over the 13 years, ranged from 23.7% to 34.7% (Table 5). For *P. cembra*, we observed an annual percentage of defoliation of 8–45% and 25% of sites showed a mean defoliation higher than 25%. From 2007, the mean defoliation is higher than 25% at 100% of sites. Over the study period, the mean defoliation per plot ranged from 26.4% to 50.8% nearby the city of Nice (Table 5).

Between 2000 and 2012, except at the site no. 5 (−0.77% per year), all experimental plots showed a continuously rise in mean crown defoliation of pine trees (Table 6). The crown condition of *P. halepensis* and *P. cembra* showed a significant deterioration ($p < 0.05$), i.e. of 0.67% per year, in average, for plots with *P. halepensis* and of 0.90% per year for plots with *P. cembra* over the time period 2000–2012.

For both pine species, crown discoloration always started with whitish spots that turned progressively yellow and then the older needles dropped off, causing a defoliated canopy. The majority of *P. cembra* and *P. halepensis*, located at high altitudes and along the coastline, were graded Class 1 and 2. Inversely to crown defoliation, considering all sites, mean crown discoloration was slightly higher ($p < 0.05$) for *P. cembra* (1.5 ± 0.2) as compared to *P. halepensis* (1.2 ± 0.1). All sites showed a sharp rise in mean crown discoloration (Table 5). Indeed, we obtained meaningful upward, ranged from +0.01 to +0.13 unit year^{-1}, with in average, +0.05 unit year^{-1} for plots with *P. halepensis* and +0.08 unit year^{-1} for plots with *P. cembra* (Table 5).

3.4. Visible foliar ozone injury

No injury is observed on current year needles (C). Visible O_3 injury was more pronounced on the older needles generation (Table 5). Considering all sites, the mean percentage of injured C+1 needles surface was slightly higher (U test, $p < 0.05$) for *P. cembra* (16.5 ± 2.6%) as compared to *P. halepensis* (16.1 ± 7.6%) and, the same observation was done for the injured C+2 needles surface on *P. cembra* (28.7 ± 3.6%) and *P. halepensis* (26.6 ± 7.3%). For *P. halepensis*, the mean percentage per plot of injured C+1 needles surface ranged from 12.4% to 21.8% and from 10.7% to 22.4% for *P. cembra*. The mean percentage of injured C+2 needles surface ranged from 21.8% to 28.6% (nearby Nice) for plots with *P. halepensis* and from 20.3% to 37.5% (highest altitude site) for plots with *P. cembra*. Between 2000 and 2012 the C+1 needles surface affected by O_3-induced symptoms decreased for both pine species, except at the site no.20 where an increase of the mean O_3 concentrations was observed during the growing season. Regarding the C+2 needles conditions, all sites showed an improvement, with downward trends ranged from −0.21% to −3.64% per year for plots with *P. halepensis* and ranged from −0.20% to −1.65% per year for plots with *P. cembra*.

3.5. Statistical analysis of the meteorological parameters

Based on modeled data and in-field observations at each

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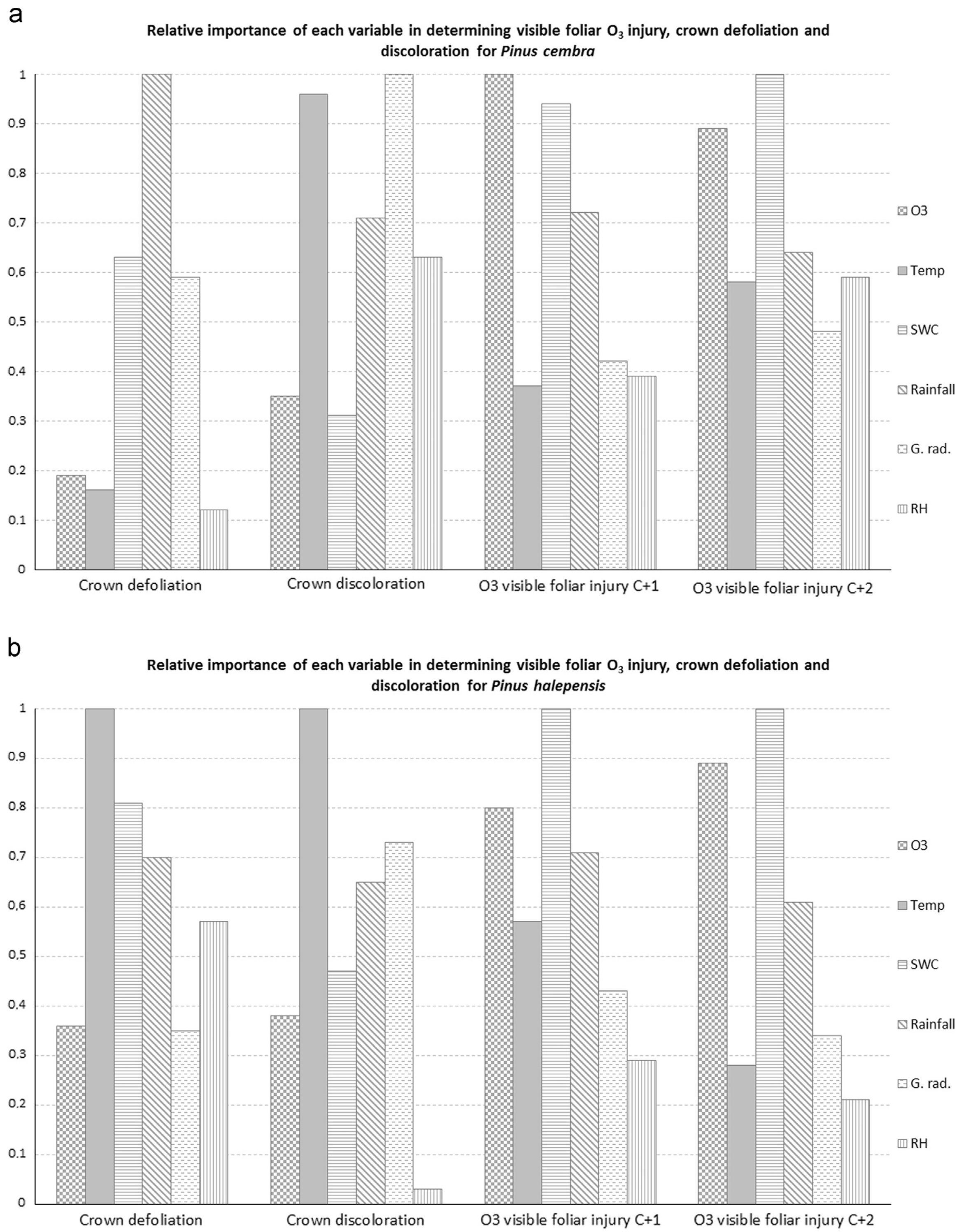

Fig. 2. Relative importance results of each variable (annual O_3 concentrations, temperature (T), global radiation (G. rad.), rainfall, relative humidity (RH), soil water content (SWC)) in determining visible foliar O_3 injury, crown defoliation and discoloration for *Pinus halepensis* (up) and *Pinus cembra* (down).

experimental sites, Random Forest Analysis (RFA) and the Spearman test were performed, over the time period 2000–2012, in order to understand and determine the importance of each variable (annual O_3 concentrations, temperature, global radiation, rainfall, relative humidity, soil water content) in determining visible foliar O_3 injury, crown defoliation and discoloration (Fig. 2).

RFA highlighted that the most important factors affecting crow defoliation were temperature and Soil Water Content (SWC) in *P. halepensis* (Fig. 2a) and rainfall in *P. cembra* (Fig. 2b). For crown discoloration, temperature and global radiation are important in both pine species. From the database 2000–2012, the most important factors affecting the O_3-induced symptoms were SWC and surface O_3 concentrations. In *P. cembra*, the occurrence and severity of O_3-induced symptoms on C+1 needles is affected mostly by O_3 concentrations, while the most important factors affecting the symptoms on C+2 needles were SWC. Thus, the weight of the predictors' O_3 in the severity of visible foliar O_3 injury on C+2 needles is less important, relative to C+1 needles.

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In *P. halepensis*, we obtained the highest correlation (Table 6) between global radiation and crown discoloration (r=0.82) and between temperature and SWC with crown defoliation (*r*=0.50, *r*=0.47, respectively). In *P. cembra*, the highest correlation is obtained between global radiation and crown discoloration (*r*=0.63) and between SWC and crown defoliation (*r*=0.43). A spearman coefficient, ranged from 0.31 to 0.34, is observed between the O_3 concentrations and crown defoliation and discoloration in both species. The most important correlation is found between SWC and O_3-induced symptoms in *P. cembra* (*r*=0.44) and *P. halepensis* (*r*=0.39) for C+2 needles (Table 8) whereas non-significant correlation is obtained with surface O_3 concentrations in both pine species.

4. Discussions

Observed annual mean surface air temperatures in France have been stable in the 20th century until the 1980s (Terray and Boé, 2013). In contrast, the last 20 years are characterized by a strong warming trend, which is clearly outside of the range of low-frequency variability of the previous period. Indeed, the daily mean temperatures have increased on average by 1.08 °C in Nice, 0.46 °C in Cannes and by 0.80 °C in Saint-Auban. Based on the last 20 years, the daily mean temperatures should increase on average by 1.95 °C in Cannes, 3.40 °C in Saint-Auban and 4.59 °C in Nice by 2100. The results are in agreement with the range projected temperature increase at global scale, 1.40–5.80 °C by the end of the century, based on six emission scenarios (IPCC, 2007). The amplitude and seasonal changes in temperature, more pronounced during the warm season, confirm the observations made at the French national scale (Moisselin et al., 2002) and in the Mediterranean area (Giannakopoulos et al., 2009). Between 1993 and 2012, increases in the number of hot days, with a daily maximum temperature exceeding 30 °C, ranged from 3 to 4 days along the coastline to 16 days inland. In last 40 years, the daily mean temperatures have increased on average by 1.68 °C in Nice and by 1.84 °C in Saint-Auban. The amplitude in trends in annual temperatures from 1973 to 2012 is consistent with the study carried out by Lespinas (2008) observing an increase of 1.40 °C from 1965 to 2004 in South of France (Languedoc-Roussillon region) using ground measurements.

In the Mediterranean region, where rainfall is a major limiting factor for organisms, climate models indicate that the Mediterranean Basin will be one of the regions in the world subject to the most drastic reductions in precipitation (IPCC, 2001). During the last 20 years, annual rainfall has decreased along the coastline (19.8% in Nice, 3.0% in Cannes) and increased by 12.2% at the inland station (Saint-Auban). Our results confirm the absence of a general trend for the annual rainfall, in agreement with the previous conclusions of Lespinas (2008) and Pal and Al-Tabbaa (2009) who did not observe significant trend in annual rainfall in South of France and for the whole Mediterranean region, respectively, in the last years.

In short, in the last 20 years, the trends for the annual temperatures, radiation, humidity and rainfall reveal a clear hotter and drier climate along the coastline (Nice, Cannes) and slightly rainier inland (Saint-Auban).

During the warm season, the main O_3 production mechanism is made by photochemistry; this suggests that the reduction in the mean O_3 concentrations in rural stations, representative of background pollution (Sicard et al., 2013), might largely be attributed to the substantial decreases in the O_3 precursor's emissions (NOx, CO and Non-Methane Volatile Organic Compounds) within the European Union which started in the early 1990 (Vestreng et al., 2008; Sicard et al., 2013). Following the reductions in the emissions of O_3 precursors there is a marked downward trend for calculated summer O_3 in central Europe (Jonson et al., 2005). The increase in mean O_3 concentrations, observed nearby the urban area of Nice, can be attributed to a reduced titration of O_3 by reaction with NO in response to a reduction in NOx emissions of road traffic (Sicard et al., 2013). At rural sites, in South-eastern France, significant decreases were found while an increase was recorded in urban and suburban stations (Sicard et al., 2013). An increase in the production of O_3 is influenced by increased temperature, increased solar radiation, decreased relative humidity and rainfall (all components of climate change), and the increase in intercontinental transport of pollutants, e.g. from Asia where the O_3 precursors emissions increase (Paoletti et al., 2009; Sicard et al., 2009). One of the most important feedbacks between O_3 and climate is through temperature-increased emissions of O_3 precursors, including biogenic Volatile Organic Compounds as well as NO from soils and CH_4 from wetlands (The Royal Society, 2008). The above results and climate models predict that conditions, that favor high O_3 levels, will be likely more frequent in the future, e.g. summers will be increasingly characterized by warm, dry weather with calm winds (IPCC, 2001). In short, climate change is projected to reduce the benefits of O_3 precursor emissions controls. Increases in ground-level O_3 levels may lower growth and tree productivity (Karnosky et al., 2007; Mills et al., 2011) and enhance susceptibility to pathogens (Karnosky et al., 2002).

If climate change and O_3 pollution can be considered as problems occurring at global scale, impacts on vegetation vary strongly at regional scale. In the current environmental and climatic context, between 2000 and 2012, the visible foliar O_3 injury on needles slightly decreased while the crown defoliation and discoloration increased. The O_3 impacts were less severe in 2012 than in 2000, but the cumulative stress is still significant.

Due to multi-colinearity and non-linear effects of the co-occurring environmental factors (De Marco et al., 2013), the causes of the visible injury on plants (crown defoliation, discoloration and O_3 injury) can be multiple and are difficult to be untangled (e.g. soil water availability, air temperature, irradiation, O_3 concentration). RFA has proven to be a useful tool to discern the most important predictors affecting tree crown defoliation (Vitale et al., 2014). RFA showed that the most important factors affecting the severity of visible foliar O_3 injury are SWC and surface O_3 levels, but no significant relationship is observed between the O_3 concentrations and the severity of O_3-induced injury on *P. cembra* and *P. halepensis*. The paradox which shows an increase in surface O_3 concentrations associated with a reduction of visible foliar O_3 injury is highlighted at Site no.1 (Table 5). Ground-level O_3 indirectly impacts the occurrence and severity of O_3-induced symptoms. Indeed, the responses of vegetation to O_3 depend not only on atmospheric O_3 concentrations but also on the absorbed O_3 uptake through stomata (stomatal flux), detoxification and repair processes into the needles (Musselman et al., 2006; Matyssek et al., 2007; Paoletti and Manning 2007; Tausz et al., 2007; González-Fernández et al., 2013). As injury occurrence depends on various parameters, the stomatal flux-based model considers the species-specific effects of multiple climatic factors (e.g. soil water availability, air temperature, irradiation), vegetation, soil and site characteristics, plant phenology and O_3 concentration on stomatal functioning (Emberson et al., 2000). The Phytotoxic Ozone Dose can be modeled using the Deposition of Ozone and Stomatal Exchange model (UNECE, 2010) or measured by micrometeorological methods (Cieslik, 2009).

Climate change parameters that trigger stomata opening (e.g., solar radiation) increase the exposure of plants to air pollutants like O_3 whereas parameters that lead to stomata closure (e.g., water stress) reduce the exposure and help to protect the plant from O_3 (Paoletti and Grulke 2010). In addition to the reduction in ground-level O_3 during the growing season at remote sites, the current environmental conditions in South-eastern France (excess light, high temperature, drought, i.e. a decrease of the SWC) reduce stomatal conductance, and thus the stomatal O_3 uptake (e.g. Nunn et al., 2005), at the time of the highest O_3 concentrations (e.g. Solberg et al., 2008), likely explaining the decrease in visible foliar O_3 injury on needles.

By comparison between the both study areas, with *P. halepensis* along the Mediterranean coastline and the mountainous species *P. cembra* from the inland Alps, we observed that the needles surface affected by visible foliar O_3 injury is higher in *P. cembra* than *P. halepensis*. The environmental conditions lead to heavier injuries in *P. cembra* in a colder and wetter climate (favoring stomata opening and thus the O_3 uptake) than *P. halepensis* in a drier and hotter climate (favoring stomata closure).

Furthermore, the Mediterranean tree species appears to be adapted to oxidative stress factors, such as high O_3 levels, drought and high radiation (Paoletti, 2006). The epicuticular wax layer is one of the xeromorphic features which permit conifers to survive under unfavorable conditions, such as temporary drought, high radiation, heat, snow and frost (Bird and Gray 2003). In *P. halepensis*, stomata are sealed with a wax layer (Abido, 1986). *P. halepensis*, which behaves as a drought-avoiding species, have xeromorphic adaptations, thicker cuticle, deeply sunken stomata, fewer stomata per unit area, low gas exchange rates in the dry season (Inclán et al. (2005)) and their constitutional and induced ability to tolerate oxidative stress by an active antioxidant pool (Alonso et al., 2003) thus preventing O_3 products reaches the plasma membrane (Chameides, 1989; Paoletti and Manning, 2007). The mountainous species *P. cembra* have a low cuticular conductance and epicuticular wax on needles in order to be efficient in reducing needle water losses (Andofillo et al., 2002). The near-surface O_3 levels (Sicard et al., 2011), the cuticular conductance and the gas exchange rates increase with altitude (Andofillo et al., 2002) whereas the cuticle thickness decreases with altitude (Wieser and Tausz, 2007). These observations are consistent with the positive correlation between the percentage of needles surface affected by O_3-induced symptoms and site altitude.

The both applied statistical analyses confirmed that the crown defoliation and discoloration are aspecific indicators of O_3, reacting mainly to abiotic factors (temperature, global radiation and rainfall) in both pine species (Ferretti et al., 2003). The mean crown defoliation was higher for *P. halepensis* as compared to *P. cembra*, inversely to crown discoloration. In both pine species, crown discoloration increase in agreement with the observed upward trend for the global radiation and mean temperatures, which are the main impacting factor. The crown defoliation of mountainous *P. cembra* species is mainly affected by rainfall and SWC. The increase in crown defoliation of *P. halepensis* and *P. cembra* is mainly due to the observed strong warming trend and to the reduction in SWC, rainfall and air humidity (drier climate and soils). The crown conditions are also impacted by other biotic and abiotic factors (e.g., pest diseases, insect attacks, fungi). Indeed, between 2000 and 2012, the number of pine trees affected by fungi has increased (e.g. *Crumenulopsis sororia, Mycosphaerella pini*) and pests (e.g. processionary moths) leading to higher crown defoliation.

The study highlighted that the most important factor affecting the crown defoliation and the occurrence and the severity of O_3-induced symptoms was the SWC. Soil water content in forests will be strongly influenced by changes in both temperature and precipitation. Drought is one of the most important climate-related events through which rapid ecosystem changes can occur as it affects the very survival of existing tree populations (Moore and Allard, 2008). Longer and warmer growing seasons lead to increased water losses from evaporation and evapotranspiration, resulting in severe moisture stress, drought and in reduced water use efficiency of plants (Mortsch, 2006). Moisture stress and drought can lead to reductions in the growth and health of trees as well as a higher susceptibility to disturbances such as insect pests and pathogens and forest fires.

De Marco et al. (2014) estimated crown defoliation of 12 tree species over Europe by 2030, under different environmental conditions, and showed that the defoliation is clearly increasing in Mediterranean environment with an increase in drought and temperature. It is very likely that South-eastern France may have to face the effects of climate change in the near future. The predicted changes in environmental conditions in South-eastern France, i.e., increases in air temperature and solar radiation, and decreases in relative humidity and rainfall, deteriorate the crown conditions. The increase in crown defoliation and discoloration must be considered important threats to the vitality of *P. halepensis* and *P. cembra* forests, and are worthy of detailed consideration to predict the future of Mediterranean vegetation under changing climate conditions.

In addition to the challenges of climate change, the predicted climatic conditions favor high O_3 levels, more frequent in the future, and may increase the uptake of air pollutants, such as O_3, with an associated increase in visible foliar O_3 injury on needles, at both remote and urban sites. In addition, an increase in O_3 concentrations in the air can cause stomatal "sluggishness" leading to incomplete closure of stomata (Paoletti and Grulke, 2010) and then an increase in water loss and O_3 uptake. Even if O_3 induces the stomata sluggishness, and by consequence a higher O_3 uptake, the drier and warmer climate should induce a lower SWC, leading to a lower O_3 uptake because the O_3 injuries are mainly linked to the SWC than the air O_3 concentrations. These two effects will act together, in an opposite way, and could mitigate the harmful impacts of O_3 on forests.

5. Conclusions

The Mediterranean area can be considered a test area for studying global change (e.g. Scarascia-Mugnozza et al., 2000; Palahi et al., 2008; Sicard et al., 2013). It is very likely that South-eastern France may have to face the effects of climate change in the near future. One way to evaluate its consequences is to look for lessons from the past. Clearly, if such climatic and ecological changes are now being detected when the climate, in South-eastern France, has warmed by an estimated average range of 0.46–1.08 °C in the last 20 years, it can be expected that many more impacts on tree species and ecosystems will occur in response to changes in temperature predicted by IPCC (1.40–5.80 °C) and by this study (1.95–4.59 °C) by 2100. Our results showed a reduction in ground-level O_3 at remote sites, but the benefits of O_3 precursor emissions controls can be reduced by the climate change (e.g. increase in temperature, reduction in air humidity). The development of coordinated emission abatement strategies, considering both environmental and climate considerations is useful to reduce both climate change and O_3 pollution.

In the current climate change context, between 2000 and 2012, assessed pine species are less affected by visible foliar O_3 injury than crown defoliation and discoloration. Even if the Mediterranean forest vegetation appears to be adapted to stress factors, we observed a deterioration of the crown conditions likely due to a drier and warmer climate (e.g. drought, high solar radiation). Thus, forest health protection, management and planning is becoming more challenging in the perspective of climate change, needing a deeper understanding of the complex relationships between a changing climate and forests. Indeed, while a fair amount of

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information is available concerning the climatic factors impacts on forest, we need to acquire knowledge on the interaction between the different climate change factors and how climate change impacts disturbances *and vice versa*. In agreement with the Green Paper (COM (2010)66) on "Forest Protection and Information in the European Union: preparing forests for climate change", further studies are needed for the development of future sustainable forest management strategies and assist forest managers and policy-makers for a more coherent policy on forest protection in Europe, in response to the challenges of climate change. For climate change adaptation, additional studies are needed to: (i) assess the climate change impacts on tree species composition and distribution; (ii) assess the interaction between the climate change factors and disturbances; (iii) evaluate whether forests able to address magnitude of the climate change; (iv) elaborate adaptive and sustainable management strategies and (v) develop innovative adaptation technology.

In conclusion, climate change creates additional challenges for forest management with substantial socio-economic and biological diversity impacts. To protect forest health from the climate change impacts, and understand how and where tree species are vulnerable, in addition to a continuous follow-up system at forest sites, the information technologies such as simulation models, geographic information systems (GIS) and remote sensing can be used for a comprehensive and effective risk assessments (Moore and Allard, 2008). A GIS-based monitoring system of climatic and forest variables (e.g. phenology, genetic diversity) can be useful to elaborate strategies of adaptive management.

Q2 Uncited reference

ICP Mapping Manual (2004).

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