

# Response of *Pinus sylvestris* L. to recent climatic events in the French Mediterranean region

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**Abstract** Exceptional climatic events from 2003 to 2005 (scorching heat and drought) affected the whole of the vegetation in the French Mediterranean region and in particular the Scots pine (*Pinus sylvestris* L.), one of the most important forest tree species in this area. To understand its response to these extreme conditions, we investigated its radial growth, branch length growth, architectural development and reproduction for the period 1995–2005, and linked these variables to climatic parameters. We used four plots situated in southeastern France and presenting different levels of site quality and potential forest productivity. The results show that: (1) the climatic episode 2003–2005 was highly detrimental to the growth (bole and branches), crown development, and cone production but favored the production of male flowers; (2) these variables depend on climatic factors of both the

current and previous years; (3) the 2003 scorching heat impact was strong but was mainly apparent from 2004; it was part of a 6-year-long unfavorable cycle beginning in 2000, characterized by high minimum and maximum temperatures and very dry springs; (4) in spite of a significant effect of site quality, the Scots pine's response to extreme climatic conditions was homogeneous in the French Mediterranean area; and (5) the stress induced by poor site conditions generally resulted in the same consequences for tree growth, architecture, and reproduction as in unfavorable climatic conditions.

**Keywords** *Pinus sylvestris* L · Scorching heat · Drought · Growth · Reproduction

## Introduction

The Mediterranean climate is characterized by strong summer water stress, linked to high temperatures combined with low rainfall (Le Houérou 2005). In the French Mediterranean region, the 2003 summer scorching heat (Rebetez et al. 2006) is, however, considered as exceptional over the last five centuries, as in most of Europe (Luterbacher et al. 2004). The monthly maximum and minimum temperatures of May, June, and August exceeded the normal values (1961–2002) by 4–6°C, those of July by 2°C, with very little rainfall during 4 months. The drought continued in 2004 and 2005, with a rainfall deficit reaching, respectively, 50 and 40% for the first 6 months (Vennetier et al. 2009).

Because of the rapid climate warming and the decreasing rainfall in spring and summer forecast for the 21st century in the Mediterranean basin (Hesselbjerg-Christiansen and Hewitson 2007) and the related increase in climate variability (Schar et al. 2004), such extreme events and successions of

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dry years would become more frequent in the coming decades (Beniston and Diaz 2004). These periods of low water availability and high temperatures that limit physiological processes will be of major importance, limiting trees' photosynthetic activity and growth. As most Mediterranean soils are eroded (Butzer 2005), their water holding capacity is often low which can extend periods of water limitation and increase the impact of drought events. Tree survival may be at stake in the case of extreme soil water depletion (Landmann et al. 2003; Breda et al. 2006). To observe and measure the consequences of the 2003–2005 climate episode on the Mediterranean forest are thus useful to provide input for the debate regarding its future.

In the French Mediterranean hinterland, the Scots pine (*Pinus sylvestris* L.), favored by agricultural land abandonment since the end of the 19th century, is the most common conifer. But in this region, at the very limit of its distribution area (Price et al. 1998), summer water stress and high temperatures are the main factors limiting its geographic extension. These constraints exceeded vital thresholds in 2003, leading to the degradation of its health status: loss of a high proportion of needles, twig withering and partial crown dieback. Since 2005, extensive dieback of whole stands over several thousand hectares has been reported in the French southern Alps (Pauly and Belrose 2005), confirming the observations of Rebetez and Dobbertin (2004) in the Swiss Alps. But the impact of such climatic events may also depend on site conditions. High water availability in the soil can partly compensate for climate worsening. This is why it is necessary to take into account plot quality in such studies.

With climate change, the Scots pine may be at risk in the Mediterranean area. It is therefore urgent to assess its response to recent extreme climatic events.

Tree ring indices are known to be good indicators of tree health in the long term (Fritts and Swetnam 1989; Dobbertin 2005). In a previous study on Scots pine located at Sainte-Baume mountain, Vila et al. (2008) evidenced strong long-term trends regarding radial growth over the period 1900–2000. To better understand the growth pattern and potential response of this species to climate change, it was necessary to complete the previous study with several new, complementary parameters, and to analyze the impact of recent extreme climatic events.

Our goal in this study was to assess the impact of the 2003 heat wave and subsequent repeated droughts (2004–2005) on Scots pine in the French Mediterranean region according to various site conditions. We analyzed not only branch architectural development and length growth, size and number of needles, and reproduction (flowering, fruiting) as indicators of tree health and stress status in the short-term, but also radial growth to relate findings to the previous study, linking all these variables to climatic factors.

## Materials and methods

### Study sites

The study area includes two sites in Provence (southeastern France). They are characterized by a Mediterranean climate tempered by the altitude, with on average one to two dry months in summer, but up to five dry months once every 5–10 years. Four plots of Scots pine were sampled. Three are situated at an altitude of 850 m on the north slope of the Sainte-Baume massif (Bouches-du-Rhône) close to the Mediterranean Sea, and the last at 1,360 m in the hinterland near the village of Courchons (Table 1). In the Sainte-Baume massif and Courchons area, the annual rainfall is, respectively, 826 mm and 936 mm and the mean annual temperature 10.3 and 9.7°C (data 1961–2005). The three Sainte-Baume plots are situated on a limestone substrate. They were chosen as representative of three levels of site quality according to the site index developed for the French Mediterranean area by Vennetier et al. (2008), which proved to be closely related to forest productivity and water availability for plants. This index is computed from six variables describing soil (depth, % of coarse fragments and rock, water holding capacity of fine earth), topography (at local and landscape scale), and geology (mother rock outcrops). According to this topographic site index (SI) the values of which span the –80 to +80 interval (Ripert and Vennetier 2002), we sampled plots characterized (Table 1) by highly contrasted site quality (plot graded A, SI = 24; plot graded B, SI = –11; and plot graded C, SI = –40). The soil at Courchons, graded B (SI = 10), derives from a hard clayey limestone bedrock covered by colluvium.

### Measurements

To study radial growth, three cores per tree were collected from 15 dominant trees at each site at 1.3 m height. After sanding and cross-dating, ring width was precisely measured by means of an Eklund device (1/1,000 mm) supplying core elementary series. The three elementary series of each tree were averaged to obtain individual chronologies. These were standardized (PPPhalos software, <http://www.imep-cnrs.com/>, window of 15 years) to keep only the inter-annual variations (Guiot and Goeury 1996). A standardized average chronology was computed by site from the 15 trees. For every year, the radial growth index was noted *Rw*.

To study all crown variables (architecture, growth, needles, reproduction), six branches at least 11 years old were harvested per tree between April and June 2006 from five trees per plot. These branches were chosen according to their position in the crown (two at the top, two in the

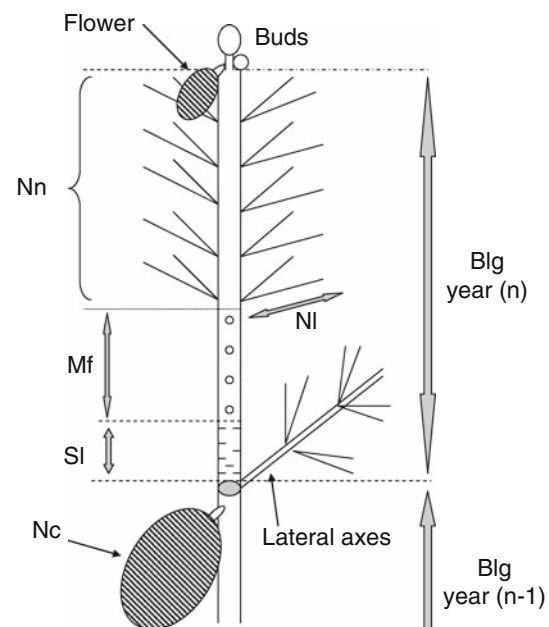
**Table 1** Description of the plots

Site	3A	3B	3C	COU1
Diameter (cm)	39.94 ± 9.44	36.17 ± 5.09	30.64 ± 7.12	21.99 ± 4.21
Height (m)	14.585 ± 1.88	10.8 ± 2.08	9.75 ± 1.79	10.73 ± 0.84
Density (tree/ha)	210	190	220	250
Age (mean ± std error)	114 ± 14	104 ± 10	83 ± 29	43 ± 5
Lon (°W)	43°20'42".97	43°20'40".13	43°20'22".15	43°55'17".62
Lat (°N)	5°49'76".65	5°49'80".14	5°50'21".84	6°29'55".70
Altitude (m)	860	875	850	1,360
Slope (°)	10	20	10	18
Aspect (Gr)	400	400	400	400
Soil depth (cm)	>100	50	15	75
Soil superficial layer	Colluvium	Alterite	Lapiaz	Colluvium
Texture	Clayey silt	Silty clay	Silt	Silty clay
Coarse fragments (%)	40	75	95	70
Topography	Concave	Plane	Convex	Plane
Soil water reserve (mm/cm)	1.95	1.8	1.5	1.95
Site index	24	−11	−40	10

middle, two at the base) and orientation (sunny or shaded). The measurements were performed on four axes per branch: the main axis (A1), one secondary axis of the branch whorl from the base of the annual shoot of 1995 (A2) and two tertiary axes (A3) from the branch whorls at the base of the annual shoot of 2000, respectively, on the main and the secondary axis. We measured for every year from 1995 to 2005 and every axis (Fig. 1): the total length of the annual shoot [branch length growth (Blg)], the length of the zone of the initial sterile scales at the base of the shoot [Scale length (Sl)], the length of the zone carrying male flowers (Mf), the number of yearly secondary axes with cones (Nbc) and without cones (Nbx), and the total number of cones on yearly shoots, main and secondary axes (Nc). From these variables, we computed the total number of annual secondary axes (Nby = Nbc + Nbx), giving the branching rate of the main axis for a given year, and the percentage of secondary axes with cones (%bc = Nbc/Nby). On plots 3A and 3C, the total number of needles (Nn), including live needles and the scars of fallen needles, was counted for the last 6 years (2000–2005) on all measured shoots. On all plots, the needle length (Nl) was measured on each of the annual shoots where needles remained, taking at random ten needles per annual shoot when available, or else all the existing or remaining needles.

#### Statistical analysis

A principal components analysis (PCA) was first performed to provide an overall assessment of the role of time (year of measurement) and the correlations between

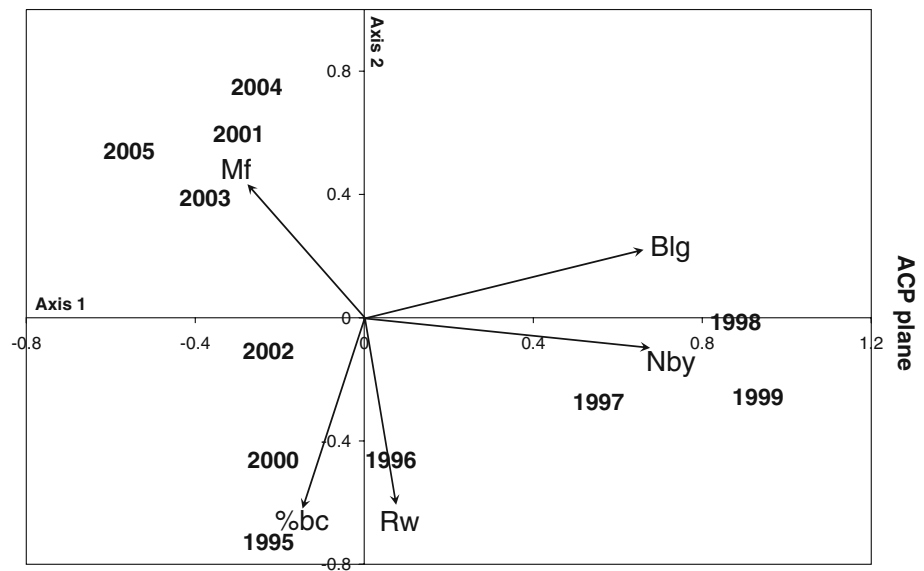


**Fig. 1** Variables measured on branches of Scots pine: (1) *Blg* total length of the annual shoot; (2) *Sl* length of the basal sterile scales; (3) *Nc* number of cones, (4) *Mf* length of the area with male flowers; (5) *Nn* annual number of needles; (6) *Nl* needle length. The number of secondary axes in the branch whorl at the base of the annual shoot with cones (Nbc) and without cones (Nbx). Note that the last studied parameter, ring width (Rw), was measured at 1.3 m height, on the bole

measured variables. It was computed for all the trees for which eight variables (*Blg*, *Sl*, *Mf*, *Nbc*, *Nby*, *Nc*, *Rw*, %bc) were available for the period 1995–2005.

Then, the difference between years and between plots for all measured variables was tested with a two-factor variance

**Fig. 2** PCA main plane (axes 1 and 2), 1995–2005 period, for every tree and all plots, using five non-redundant variables (Rw, Blg, Nby, Mf, and %bc). The first two axes explained, respectively, 31 and 22% of the total inertia



analysis and a Tukey test, with a confidence interval of 95%. Finally, the relation between these variables and the climate was investigated with a partial least square (PLS) regression. PLS regression was chosen because it makes handling many variables with relatively few observations possible (Cramer et al. 1988) and copes with correlated variables (Wold 1995). The number of components was chosen by a permutation test (Good 1994) with a 5% threshold for the explained variance. Variables were tested with a 1,000-step cross-validation test (Amato and Vinzi 2003): variables were accepted only when the confidence interval ( $P < 5\%$ ) for their partial correlation coefficient did not include 0. The development of tree organs during one year ( $n$ ) depends on climatic conditions of the current year and on those of the previous year ( $n - 1$ ): the climatic parameters tested for the regression were the rainfall ( $P$ ), the maximum temperature ( $T_{\max}$ ), and the minimum temperatures ( $T_{\min}$ ) from January of year ( $n - 1$ ) to June of year ( $n$ ) over the period 1994–2005, according to the phenology of this species in Southeastern France (Orshan 1989). A synthetic drought index ( $S = P - 2T_{\max}$ ) was also used when rain and temperature variables were not significant separately. Statistical analyses were computed with R software (R\_Development\_Core\_Team 2004).

## Results

### Discrimination of the years with tree development parameters

We finally used for the PCA a group of five non-redundant variables describing radial growth, crown development, male bloom, and fruiting. Nbc, NC, and SI, redundant,

respectively, with Nby, %bc and Blg, were eliminated after a first test with all variables.

The PCA first axis (Fig. 2), strongly correlated with Nby and Blg, corresponded clearly to the crown development (branch growth, branching rate). Axis 2 contrasted the male bloom (Mf) with abundant fruiting (%bc) associated with wide rings (Rw). The male bloom was generally contrasted with all variables related to a good growth (crown and rings).

In the PCA plane, years were represented as the bary-center of the observations concerned (one observation = one measurement of all the parameters on one tree for a given year).

Three groups of years appeared:

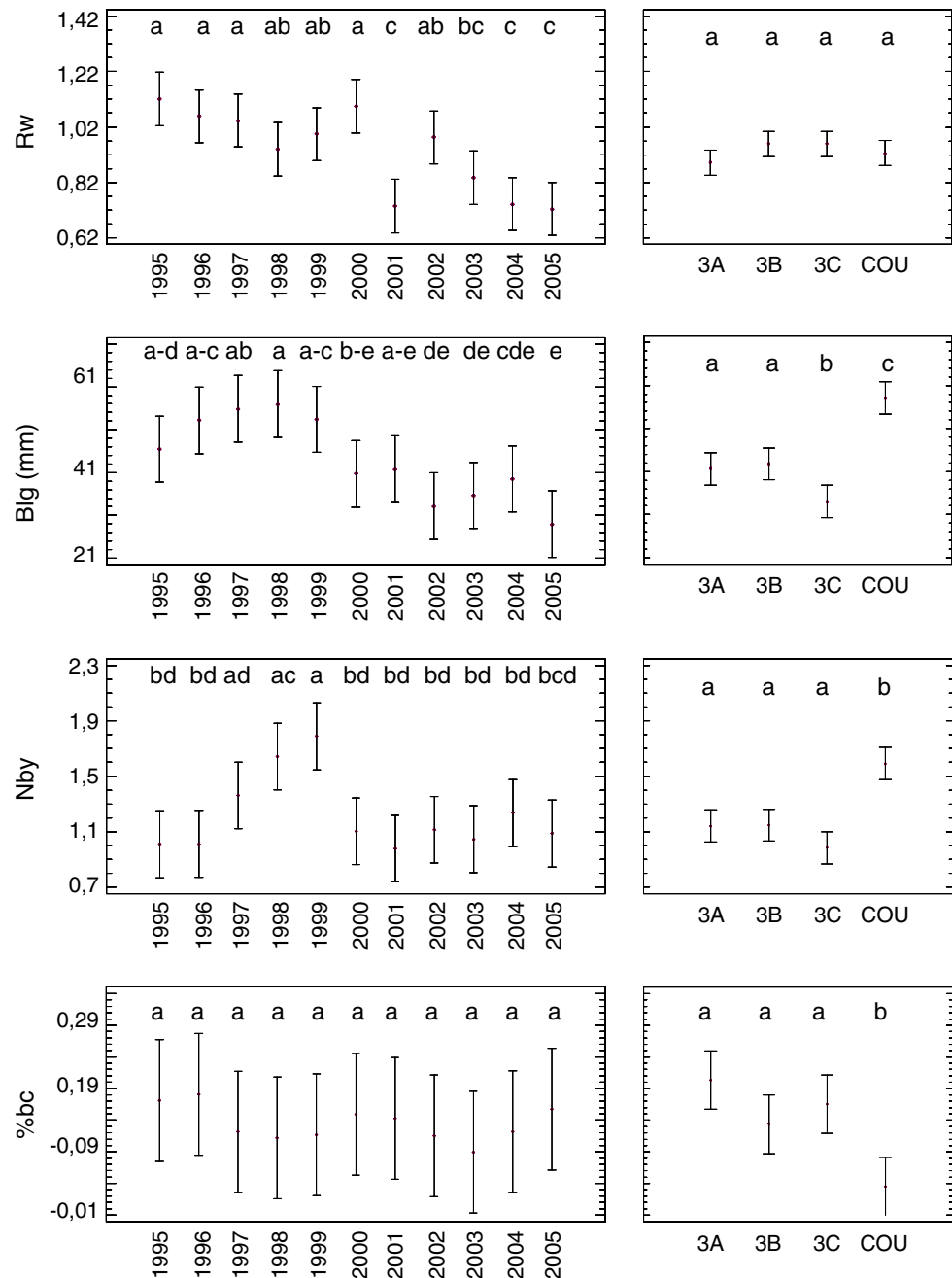
- 1995–1996 + 2000, characterized by good fruiting associated with wide rings but with weak development of the crown and few or no male flowers.
- 1997–1998–1999 characterized by good development of the crown, intermediate radial growth and fruiting, and no male flowers.
- 2001–2003–2004–2005 characterized by a strong male bloom, no fruiting, and very slow growth (rings and crown).

2002 was intermediate for most of the parameters, crown development being rather weak.

### Differences between plots and between years

The variance analysis and Tukey test (Fig. 3) showed wide and often significant differences between plots for a majority of variables, due either to the Courchons plot (Blg, Nc, Nby), or to differences between the plots at Sainte-Baume (Blg, Mf, Nn, NI). Within the Sainte-Baume massif, plot 3C differed from the two others for Blg and

**Fig. 3** Two ANOVA factors for all measured variables, average and confidence interval (95%) for years and plots



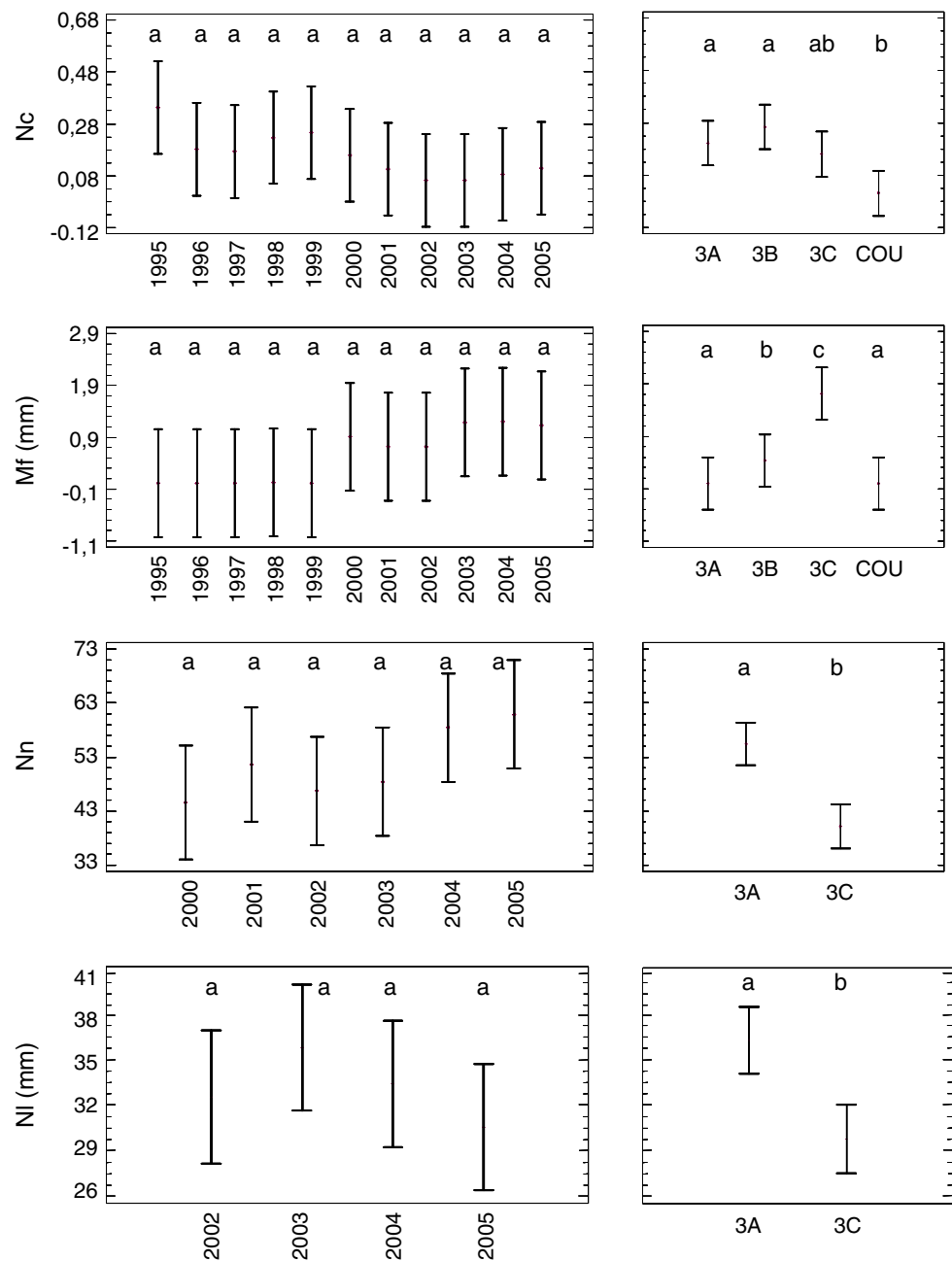
Mf, whereas the transition was progressive for Nl. Site quality was overall a discriminant factor.

With ANOVA tests, years differed mainly for  $R_w$ ,  $Blg$ , and  $N_{by}$ . Even if fruiting ( $N_c$ ) seemed to be stronger from 1995 to 1999 and decreased to very low in the last years, and no male flowers (Mf) could be found before 2000, differences were not significant for these two parameters. This is probably due on the one hand to a few outliers in data increasing the variance and on the other a large number of null values. The trends observed for these variables in Fig. 3 confirm and explain clearly the groups of years differentiated by the PCA.

#### Relations between tree parameters and climate

In the PLS regression, the low number of observations (16) and the high annual variability of the climate made grouping monthly climatic parameters necessary to obtain significant variables. We grouped the months having the same sign for their individual correlation coefficients. Figure 4 shows the relations between tree variables and climate parameters. Overall, the climatic conditions of year ( $n - 1$ ), rainfall as well as temperature, seemed to play an important role in the growth, crown development, and reproduction of Scots pine.

Fig. 3 continued



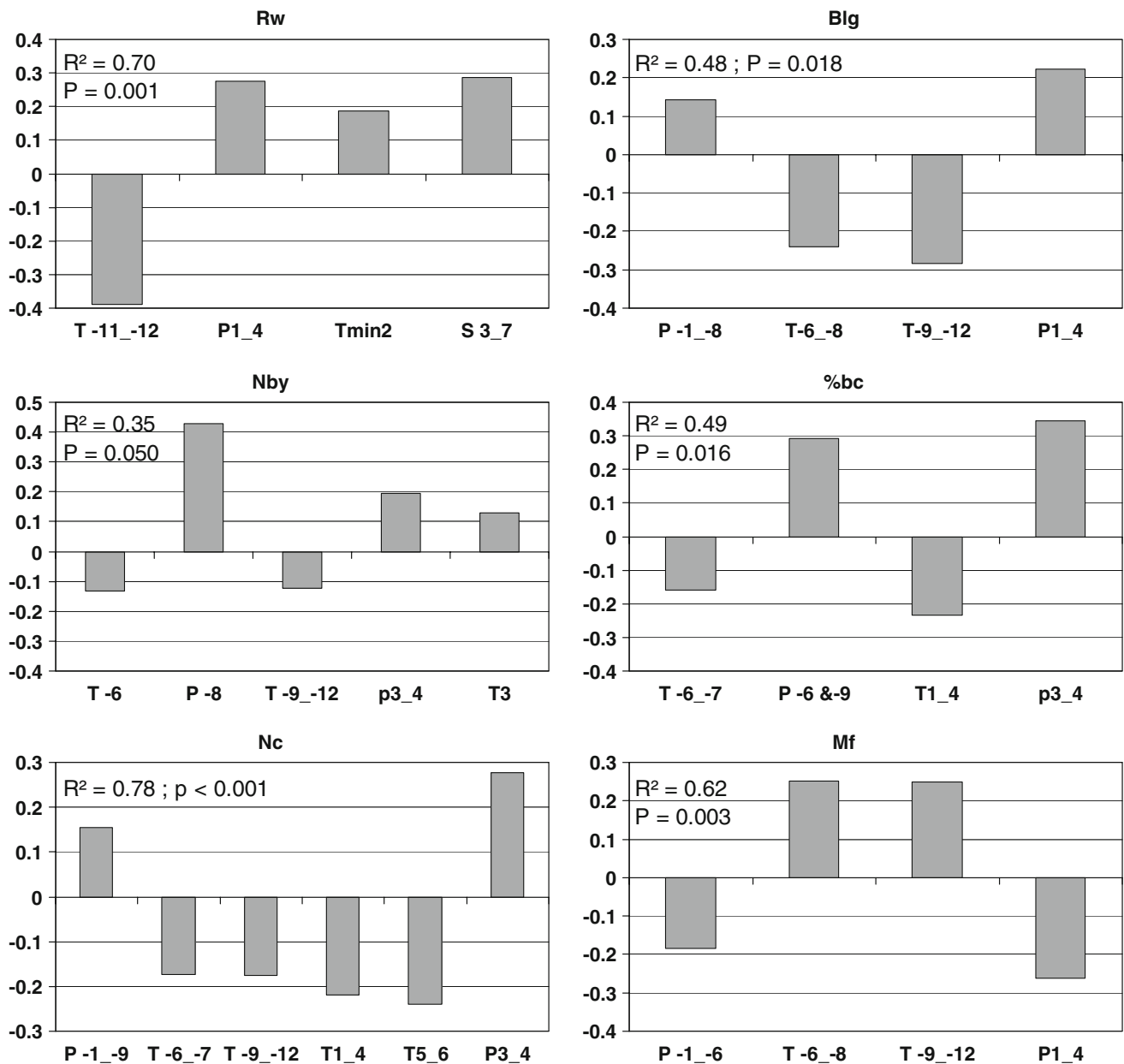
## Discussion

### Impact of climate and time on tree development and reproduction

In the PCA main plane, the crown development (Blg and Nby) seems to be independent of the radial growth (Rw). This independence is also clear in the relative weight of the explanatory variables highlighted by the PLS: radial growth is more sensitive to the climatic parameters of the current year ( $n$ ), while crown development depends more on the climate of the previous year ( $n - 1$ ). Male blooming

is in opposition to fruiting, and overall to good growth of the trees. These oppositions explain the distribution of the years in three groups in the PCA plane.

Fruiting potential (%bc) and branching (Nby) are assumed to be predetermined in the terminal buds formed in the previous year ( $n - 1$ ), and therefore linked to the climate of the months preceding and accompanying bud formation. Practically, each cone takes the place of one secondary axis in the branch whorl on the main axis. This is why good fruiting years showed a low or intermediate branching rate. Therefore, fruiting and branching are independent in the PCA plane and partially explained by different climate



**Fig. 4** Significant climate parameters  $R^2$  and  $P$  values in PLS regression (one significant component) for the main measured variables.  $P$  rainfall,  $T$  monthly mean maximum temperature,  $T_{min}$  monthly mean minimum temperature,  $S = (P - 2T)$ . 4 and -4 means, respectively, April of the current year ( $n$ ) and of the previous

year ( $n - 1$ ).  $T-9_-12$  and  $P1_4$  means, respectively, the average (for the temperatures) or the sum (for rainfall) of monthly climatic parameters between September and December of year ( $n - 1$ ) and from January to April of year ( $n$ ).  $P-6$  and  $-9$  means the sum of the rains of June and September of year ( $n - 1$ )

parameters in the PLS regression. Climate conditions determining potential female flowers in the buds may be partly different from those inducing only potential secondary axis. Fruiting potential (%bc) is to some extent opposed to branch length growth (Blg), although PLS regression showed that they partly depend on the same climate parameters. When cones develop, they use a large amount of the resources of the axis. The competition between fruit and shoots seems to increase with increasing stress, as several

main axes finally aborted on measured branches when cones developed at their base in the last 5 years.

Ring width index collapsed from 2003 to 2005, significantly below the levels of 1995–2000, confirming the response of Scots pine to the 2003 scorching heat in Austria (Pichler and Oberhuber 2007). Earlier in our study area, Tessier (1984, 1989) observed ring width reduction for previous severe droughts equivalent to that of 2003 or 2001, but trees recovered after 1 or 2 years. Confirming

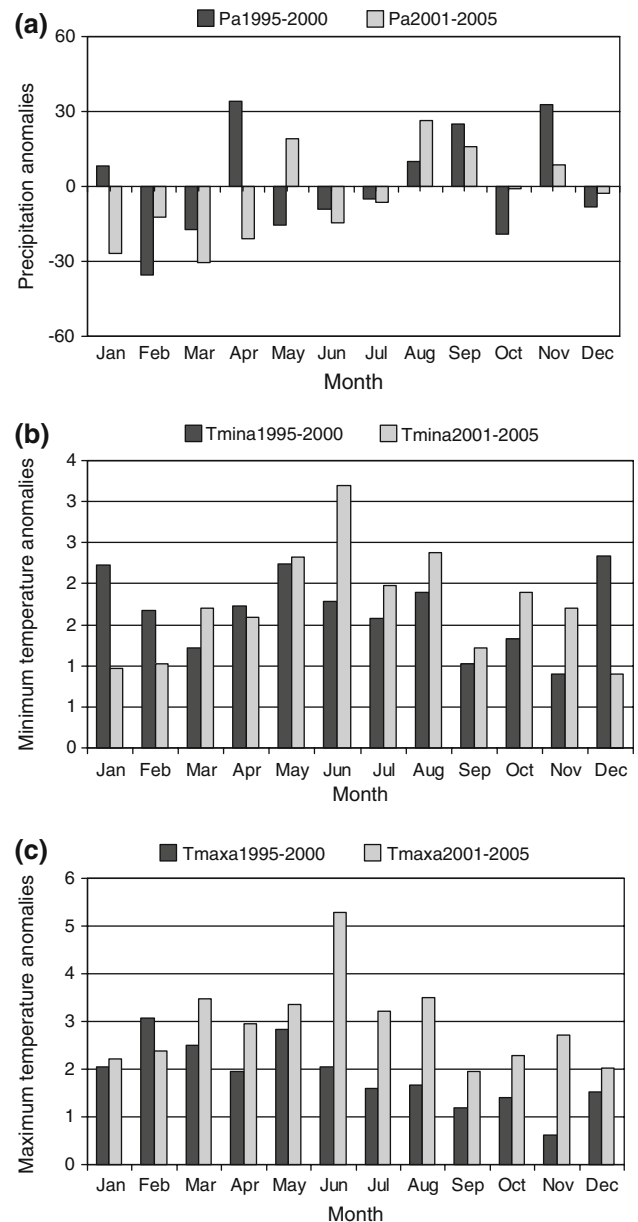


these results, after a very bad year in 2001, 2002 was favorable and allowed trees to recover. The impact of the 2003 scorching heat is clear but was less than that in 2001. The small 2003 ring is mainly due to the very narrow latewood, tree radial growth having been halted suddenly by continuous extreme temperatures and water stress since the end of May, when most of the earlywood was already formed. At the end of summer 2003, only the needles of the current year remained on most of the trees. Repeated drought in 2004 and 2005 meant they were unable to restore their leaf area. The cumulative impact of years 2001–2005 explains the continuous decrease of  $R_w$  since 2003, as well as the same trend and very low values of  $B_lg$  and  $N_{by}$  in the last 5 years. As a result of the small number of observations (11 years), the sometimes wide seasonal grouping of monthly climatic parameters in the PLS regression varies from one studied variable to another, even when these variables are strongly correlated. The months of May had been rainy twice in the middle of the period of generally very dry springs and summers from 2000 to 2005. These two outliers, in opposition to the seasonal overall water-balance (Fig. 5), rule out using this parameter individually or including it in a small group with the previous or following months. In previous studies at the same sites, May rainfall and temperature were considered as key parameters for Scots pine radial growth (Vila et al. 2008).

Nevertheless, groups of climate parameters selected by PLS regression can be considered as representative of five ecologically critical periods:

1. *January to July, August or September of year ( $n - 1$ ):* high total rainfall preceding or accompanying bud formation is favorable for all variables except  $M_f$ . This group is the most variable due to the high variation of rainfall data in May (see above).
2. *June to August of year ( $n - 1$ ):* high temperatures just before or during bud formation are unfavorable to crown development ( $N_{by}$ ,  $B_lg$ ) and fruiting ( $N_c$ ,  $\%bc$ ).
3. *September to December of year ( $n - 1$ ):* high temperatures in this period are unfavorable for all variables except  $M_f$ .
4. *January to April of year ( $n$ ):* during this period, high rainfall improves growth and fruiting, whereas high temperatures are unfavorable to crown development and fruiting.
5. *April to June of year ( $n$ ):* in this last critical period, water stress (high temperatures or low rainfall) limits the radial growth and the number of surviving cones.

The first two periods determine tree vigor and the amount of available reserves at the time of bud formation, when all growth units and architecture for the next year are predetermined (Debazac 1966; Junttila 1986; Philippe et al.



**Fig. 5** Shift of monthly mean rainfall and temperatures of 1995–2000 and 2001–2005 periods compared with that of 1961–2005 at the Sainte-Baume massif. **a**  $P_a$  precipitation (rainfall); **b**  $T_{min}$  minimum temperature **c**  $T_{max}$  maximum temperatures

2006). This is why their coefficients are high in PLS regression for crown development, fruiting, and male bloom. Adverse conditions in the first half of year ( $n - 1$ ) limit the potential growth, branching, and number of cones even in the case of good conditions during the current growing year. Unlike polycyclic pines, Scots pine being monocyclic have no possible way to compensate this limitation with a second or third annual growth cycle (Serre 1976). The trend to produce fewer cones and more male flowers is natural with branch aging, at the base of the canopy and on shaded branches, that is to say as soon as the



branches lose dominance or lack resources (Caraglio et al. 2007). Inside the complex bud of the main shoot, male flower meristems appear at the beginning of summer while female flower meristems form at the end of summer or the beginning of autumn, according to a set of complex interacting processes (Philippe et al. 2006). With high temperature in the second period (summer  $n - 1$ ), or when their health status is poor overall, trees favor the production of male flowers in most of the crown, less resource-demanding than cones and ensuring long distance dissemination for their genes.

The third critical period is the end of year ( $n - 1$ ), mainly for temperature. Cruziat et al. (2002) showed that a lack of cold in winter (successions of warm and cold periods) leads to reversible cavitation in the vessels, decreasing their conductivity at budbreak. This is likely to happen in the Sainte-Baume where deep frosts alternating with hot periods are common in winter. Falusi and Calamassi (1990) and Calamassi (1996) also showed that the lack of cold in winter delays budbreak. This delay is particularly detrimental to Scots pine in the Mediterranean region where its growth season is already very short. Finally, hot temperatures maintain significant physiological activity after the growth season, which wastes a lot of energy (Damesin 2003). Holst et al. (2008) have shown for Scots pine that  $\text{CO}_2$  net uptake could occur in winter during mild weather conditions. Whereas this process can partially compensate for the carbon loss in summer drought periods, the reserves used in this period are no longer available for spring growth and organ development. This could explain the decrease of Nc (abortion) without a decrease of %bc.

Abundant rainfall in the fourth period (first months of the year  $n$ ) fills soil water reserves, limiting the stress at the beginning of the growth period and improving naturally all growth variables as well as helping cones to develop and survive. High temperatures during this period are detrimental to fruiting but, probably indirectly through limited competition with cones, improve branching rate (Nby).

In the last critical period (spring of year  $n$ ), combined abundant rainfall and moderate temperature (good  $S$  index) are necessary for good radial growth.  $S$  index is significant up to July. High temperatures in May and June (like in previous months) reduce fruiting success, leading probably to partial cone abortion.

If the number of cones which appear at the base of the main axis is predetermined in the summer of year ( $n - 1$ ), their successful development seems to depend broadly on the climate conditions at the beginning of their growth. Although floral initiation is not controlled by a single stimulus but a range of processes which interfere mutually, climatic conditions of the year ( $n - 1$ ) and of the year ( $n$ ), respectively, appear to have considerable weight in

governing the differentiation of the bud, and so has the factor determining the growth. However, growth and flowering/fructification also depend largely on other factors which influence the initiation and the development of meristems, support their orientation in sexual buds or not and in some cases their male or female orientation (Philippe et al. 2006).

#### Differences between plots

We observed a significant plot effect for several parameters.

Crown development (Blg and Nby) was better at Courchons than at Sainte-Baume. The difference seems to be explained by the younger age of Courchons plot (Table 1), as branch length growth and branching rate decrease gradually with age (Makela and Vanninen 1998) and perhaps by a more favorable climate at Courchons. However, the collapse of Blg and Nby since 2000 cannot be explained by these natural and slow age trends. It is clearly related to the climate shift since 2000, with increasing minimum and maximum temperatures between 1995–2000 and 2001–2005, and to extreme climate conditions since 2003 (Fig. 5). Within the Sainte-Baume massif, lower Blg values in 3C plot are explained by unfavorable site conditions, water stress occurring early in spring (Fig. 5) limiting female flowers and secondary axis induction in the bud in year ( $n - 1$ ), and favoring cone and axis abortions in year ( $n$ ). The same constraints gradient explains why Nn and Nl are higher in plots 3A compared with that is 3C in Sainte-Baume, as observed by Niinemets and Lukjanova (2003) on contrasted sites. No significant difference was found between years for Nn and Nl due to a high variability between trees and between plots.

Within the Sainte-Baume massif, male bloom is all the more intense as the site conditions are unfavorable, confirming the key role played by stress in this bloom (Philippe et al. 2006), as already shown by PLS analysis with climate parameters. The trend to produce more male flowers with increasing age (Peter et al. 1997, Caraglio et al. 2007) could explain the generally low production of male flowers at Courchons, where this production however increased in the last years as at Sainte-Baume.

Soil water reserve becomes smaller when grading from plot A to plot C (Table 1) with conditions progressively more adverse to growth and to survival. Water limitations probably occur earlier in the growth season and are higher during drought episodes in plot C. In plots A and B, soil water reserve probably becomes a limiting factor to physiological processes later in the growth season inducing longer growth seasons and higher growth rates. In 2003–2005, water limitations occurred earlier in the growth

season. This considerably limited the growth season, especially for the trees of plots A and B. At their limit of growth capacity, trees of plots C were no more affected than usual. Consequently, effects appeared weaker at the poor sites.

Results for short-term ring width trends complete those obtained by Vila et al. (2008) for the long term. They highlight the relation between crown development and radial growth through the delayed impact of previous years' climatic parameters on tree health status and vigor in year  $n$ . They confirm the role of drought and scorching heat and their repetition in the negative radial growth trend observed over the 1900–2000 period.

## Conclusion and prospects

The immediate impact of the 2003 scorching heat and drought was not exceptional, but contributed to a series of unfavorable years beginning in 2000. Because of the delayed effects of water or thermic stress on crown development, the impact of 2003 was especially significant in 2004. Repeated drought in 2004 and 2005 increased and extended the impact of 2003, leading to a collapse of Scots pine radial growth and crown development, and extensive dieback in Southeastern France. It is difficult to assess the respective weight of 2003 direct impact and that of repeated droughts in forest die-back or poor growth. In other countries, occasional severe droughts caused middle term decline in productivity and delayed die-back up to 10 years later (Bigler et al. 2006) without repeated or exceptional stress in following years.

Our study enhances our knowledge on Scots pine. We have clarified the relative weight of climate parameters of the current and previous year in tree growth, morphological development, and reproduction, and shown that the stress induced by poor site conditions leads generally to the same consequences for trees as unfavorable climate conditions. The significant interaction between years and plots demonstrated the importance of the interaction between site conditions and climate in the response of trees to climate change.

Series of unfavorable years including extreme events such as 2003 are likely to become common in the next decades and should be considered at least as important as the mean climate shift for the future of Scots pine in the Mediterranean region. With the forecast climate change, the Scots pine appears to be at risk in these regions. The reduction of leaf area and crown density after such repeated stress should be taken into account in tree growth models and in all models using tree canopy or leaf area characteristics as input to calculate gas, energy, and water flows between vegetation and the atmosphere.

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