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RESEARCH PAPER

Volcanic explosive eruptions of the Vesuvio decrease tree-ring growth but not photosynthetic rates in the surrounding forests

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Abstract

Volcanic eruptions impact the global and the hemispheric climate, but it is still unknown how and to what degree they force the climate system and in particular the global carbon cycle. In this paper, the relationships between individual eruptions (reconstructed for the past using written records), tree primary productivity (estimated using ring widths), photosynthetic rate and stomatal conductance (assessed by carbon and oxygen isotope data) are investigated, to understand the impact of volcanic eruptions on net primary production. Data from a mixed stand of *Fagus sylvatica* L. and *Acer pseudoplatanus* L. located in the area of the Vesuvio volcanic complex (Southern Italy) showed a significant decrease in ring width following each eruption. Isotope analyses indicate a change in climatic conditions after such events. Specifically, the lower oxygen isotope ratio in the tree-ring cellulose strongly suggests an increase in relative humidity and a decrease in temperature, with the latter resulting in a strong limitation to tree-ring growth. The carbon isotope ratio was only moderately but not significantly reduced in the years of volcanic eruption, suggesting no major changes in C fixation rates. This work is a case study on the effects of volcanic eruptions resulting in strong climatic changes on the local scale. This is an opportunity to explore the process and causal relationships between climatic changes and the response of the vegetation. Thus, we propose here a realistic model scenario, from which we can extrapolate to global scales and improve our interpretations of results of global studies.

Keywords: climate change, dendroecology, δ^{13}C and δ^{18}O, multivariate analysis, photosynthesis, relative humidity, tree rings, volcanic eruptions, Vesuvio

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Introduction

Volcanic explosive eruptions are an important natural climatic driver, ejecting large amounts of insoluble silicate matter and gases, mainly ash and sulfur aerosols, into the stratosphere and troposphere (Stothers, 1984; Hofmann, 1987; McCormick *et al*., 1995). Volcanic eruptions decrease air temperatures up to 0.2–0.3 °C for several years after large eruptions on hemispheric and global scales, primarily as a result of released sulfate aerosols, rather than of ejected silicate dust (Self *et al*., 1981; Rampino & Self, 1984; Stothers, 1984; Sigurdsson, 1990; Briffa *et al*., 1998b; D'Arrigo & Jacoby, 1999). As possible consequences of large volcanic eruptions, a sequence of cool and rainy summers (Stommel & Stommel, 1979), an increase in sea ice off America (Catchpole & Hanuta, 1989), narrow and frost rings in tree-ring patterns at various sites around the world (LaMarche &

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Hirshboeck, 1984; Scuderi, 1992) and neoglaciations (Porter, 1981, 1986; Nesje & Johannessen, 1992) were observed. Because of the potential effects on the climate system, volcanic eruptions should, therefore, be considered in global climate models as an important external forcing, explaining global temperature variations (Bradley & Jones, 1993; Mann *et al*., 1998; D'Arrigo *et al*., 1999). However, recent modeling efforts of the Mt. Pinatubo eruption in 1991 indicated that the relationships between volatile emissions and climate fluctuations are not simple (Bekki & Pyle, 1994) and represent a multifactorial problem. Although understanding the response of climate to volcanic eruptions would help to quantify natural climatic fluctuations, and to separate them from anthropogenic impacts on the climate system (D'Arrigo *et al*., 1999), the question is still open whether the relationships established are fortuitous rather than dependent, and to which degree the impact of volcanic eruptions on the global climate is significant. Long records of observations are, therefore, needed. Because of the scarcity of direct observations (Bradley & Jones, 1993), proxy records, mainly provided by ice cores, are needed to reconstruct past volcanic activity (Hammer *et al*., 1980; Herron, 1982; Mosley-Thompson & Thompson, 1982; D'Arrigo *et al*., 1999). Another valuable proxy of climatically effective eruptions over the past centuries and millennia with annual resolution are tree rings (LaMarche & Hirshboeck, 1984; Baillie, 1989, 1995; Briffa *et al*., 1998a, b; D'Arrigo & Jacoby, 1999; D'Arrigo *et al*., 2001).

The decrease in temperature caused by volcanic eruptions may have dramatic consequences on terrestrial vegetation. Several tree-ring growth studies have shown that narrow rings (e.g. D'Arrigo *et al*., 2001), rings with lower lignin content in the latewood (Briffa *et al*., 1998a, b, i.e. light rings *sensu* Filion *et al*., 1986), and even injuries at the wood cell structure (i.e. frost rings *sensu* Glerum & Farrar, 1966), (LaMarche & Hirshboeck, 1984; D'Arrigo *et al*., 2001) usually occur after major volcanic explosive eruptions worldwide.

Tree growth is limited by different factors, depending on the species and on the site where trees grow. A decrease in air temperature may cause a reduction in tree growth at sites where temperature is limiting, typically at high elevations and latitudes (Fritts, 1976; Briffa *et al*., 1990; Briffa & Jones, 1994; Mann *et al*., 1998; Hughes, 2002). At such sites, lower tree-ring growth, and potentially also lower photosynthetic rates, should be expected after volcanic eruptions. However, photosynthetic rates of terrestrial vegetation are predominantly influenced by light availability, and recent studies show that the vegetation is directly sensitive to changes in the diffusive fraction of photosynthetically active radiation (PAR) induced by volcanic activity with important implications on both the productivity and structure of terrestrial vegetation and ultimately on the global carbon cycle (Gu *et al*., 2003). It was demonstrated that canopy scale photosynthesis increases more or less linearly with the diffuse fraction (Norman & Arkebauer, 1991; Choudhury, 2001a, b) and that a large increase in the diffuse fraction occurs because the aerosols resulting from volcanic eruptions predominantly enhance the scattering of the incoming solar radiance (Garrison, 1995). Thus, a slight decline in atmospheric CO_2 concentration may result from an increase in CO_2 uptake by the vegetation cover, following the eruptions. These findings are critical for the assessment of the global carbon cycle (Beerling & Berner, 2005).

This increase in photosynthetic rates following eruptions, however, would not be expected when considering the formation of narrow rings by trees after volcanic eruptions, as commonly reported by dendrochronologists. To resolve this controversial issue, we established two different hypotheses (Fig. 1): (1) According to the first hypothesis, the change in radiation balance cools the atmosphere, leading to an increase in relative humidity and a reduction of tree growth. Visible signs on the trees would be a decrease in tree-ring width (Briffa *et al*., 1988a, b, 1998a, b; Scuderi, 1990; Jones & Bradley, 1992). The increase in relative humidity, leading to high stomatal conductance results, also leads to a reduction of δ^{18}O values in the organic matter. In this scenario, δ^{13}C is also expected to decrease, due to high stomatal conductance and a possible decrease in photosynthetic rate. (2) According to the second hypothesis, the increase in diffusive radiation, caused by volcanic ashes and aerosols in the atmosphere, enhances the photosynthetic rate (Gu *et al*., 2003), resulting in an increased plant growth. In this case, we expect wider tree rings with increased δ^{13}C values, and no changes or lower δ^{18}O values, as a result of higher relative humidity and stomatal conductance.

To evaluate these hypotheses, we analyzed the Somma-Vesuvio volcanic complex, one of the most-studied volcanoes in the world, because of the long intervals between its eruptions and the long record of observations available. The detailed analysis of the effects of Vesuvio's eruptions enables a better understanding of the process and causal relationships between climatic changes and the potential response of the vegetation and can serve as a model for global approaches. The regional-scale scenarios require regional interpretations of global-scale storylines. Several studies recommend to embed the scenario analysis at the global scale by performing regional-scale quantifications of the global qualitative driving forces scenario (Döll & Vassolo, 2004). This in turn helps to interpret results from other studies on a global scale even for different site conditions.

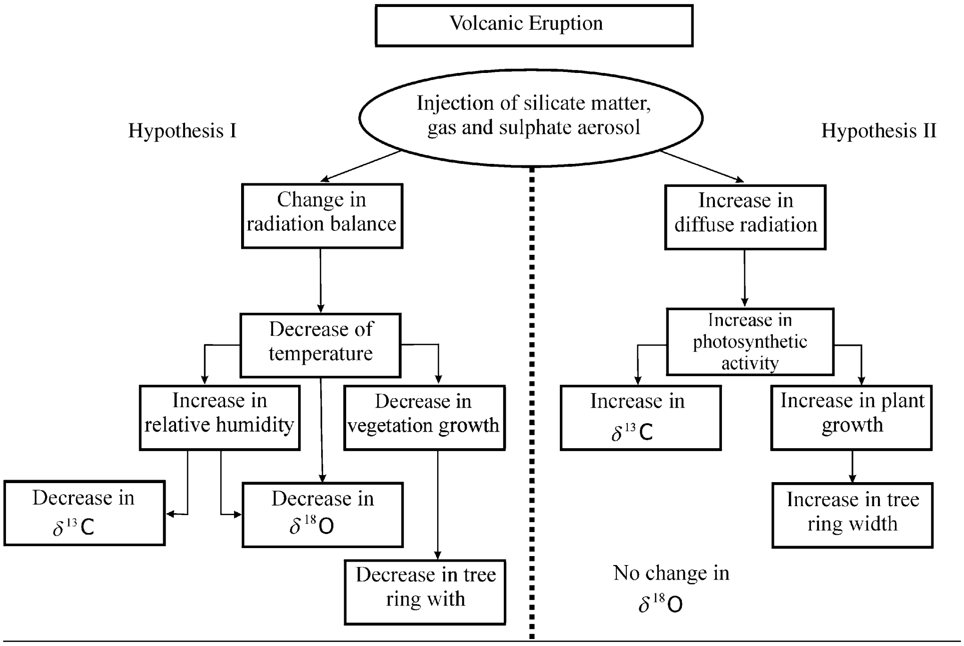

Fig. 1 Theoretical development of the work hypotheses, with two different scenarios following volcanic eruption. One hypothesis illustrates the cooling effect caused by aerosol, which decreases plant growth and enhances relative humidity, leading to a reduction of δ^{18}O and δ^{13}C in tree rings (Hypothesis 1). The second hypothesis proposes the increase in photosynthesis and plant growth, as a consequence of a better canopy light use efficiency under diffuse light, with an increase in δ^{13}C (Hypothesis 2).

To reconstruct the impact of past volcanic eruptions on tree physiology, we used tree-ring stable isotopes. The δ^{13}C and δ^{18}O values correlate well with environmental factors (Leavitt & Long, 1991; Saurer *et al.*, 1997) and record the physiological responses of vegetation to climatic changes (Scheidegger *et al.*, 2000). The δ^{13}C provides insights into past stomatal activities and water use efficiency (Farquhar *et al.*, 1989). The δ^{18}O values in organic matter are a strong signal for temperature, precipitation water and relative humidity (Dansgaard, 1964; Epstein & Krishnamurthy, 1990; Roden & Ehleringer, 1999; Jäggi *et al.*, 2003). The aim of this study is to understand the effects of volcanic activity on plant productivity and tree physiology, as a consequence of a change in the irradiation, temperature and air humidity regime.

Materials and methods

Site description

The Somma-Vesuvio volcanic complex is located at about 15 km SE of Napoli (Southern Italy, 40°49′N, 14°26′E). It is a composite stratovulcano composed by an older and a younger structure (Mt. Somma and Mt. Vesuvio, respectively) characterized by many subterminal and lateral fissures. This volcanic complex is structurally located close to two principal fault systems, along the NE–SW, evidenced by geophysical surveys (Finetti & Morelli, 1974). Studies on its eruptive history over the past 2000–3000 years suggest the presence of a shallow magma chamber (Scandone *et al.*, 1993). The most active structures are the NE–SW and the N–S magma chambers, as suggested by the location of relevant eruptions and the opening of eccentric craters (Alfano & Friedlander, 1929; Delibrias *et al.*, 1979).

After the 1631 large eruptive event, Vesuvio had been in persistent activity until 1944. Its activity was characterized by cycles, beginning with a quiescence period of <7 years and ending with an explosive eruption. Moreover, the proximity to the seismogenic Apennines chain and the fact that the prolongation of the SW–NE fractures crosses two main seismogenic areas of the Southern Apennines play an important role for eruption dynamics (Scarpa *et al.*, 1983). The systematic acquisition of leveling data at Somma Vesuvio began in 1974. Since then, leveling measurements have been performed yearly and they are linked to the North zones of Sannio and Irpinia, where the influence of eruptions is quite strong.

Mount Vesuvio has a mild Mediterranean-type climate with a dry summer period. At the meteorological station of the 'Osservatorio Vesuviano' at 612 m a.s.l., the average temperature varies from 22 °C in July to 5–7 °C in January. The mean yearly rainfall is 1000 mm with a mean monthly minimum in July (19 mm) and a maximum in November–December (137 mm). Snowfall is frequent at the top of the

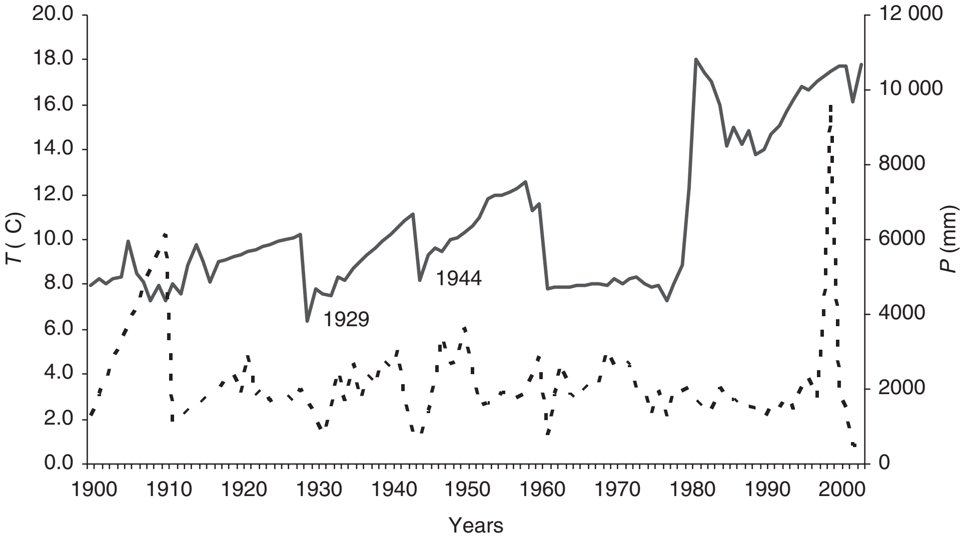

Fig. 2 Mean annual temperature (solid line) and total annual precipitation (broken line) recorded at Montella meteo station from 1900 to 2003. The decrease in Temperature during eruption events is evident.

crater (around 1280 m). The surface water run-off is negligible because of the permeability of the volcanic soils and water-bearing strata occur close to the ground surface only where compact under layers of lava are present (Mazzoleni & Ricciardi, 1993).

There is a long history of botanical survey on Vesuvio. Its southern slopes and the valleys have been largely afforested with *Pinus pinea* L. mixed with *Robinia pseudacacia* L. and *Cytisus scoparius* L. Link. The northern slopes of Monte Somma have extensive *Castanea sativa* Miller plantations below 900 m a.s.l., whereas above this level there is a mixed forest of *Ostrya carpinifolia* Scop., *Acer neapolitanum* (Ten.) with few individuals of *Betula pendula* Roth.

The volcanic substrates of recent origin and the frequent eruptions of the last years support pioneer plant communities and in any case the vegetation is very young. For this study, tree-ring chronologies containing the signal of the largest possible number of eruptions were selected from forest old stands in the surrounding area. The sampling site was on the Picentini Mountains (45°21′N, 33°50′E) about 40 km away from the volcano, but an area influenced by the Vesuvio activity and characterized by forest stands formed by *Fagus sylvatica* L. and *Acer pseudoplatanus* L. The site, around 800 m a.s.l., is characterized by mesic conditions where both temperature and precipitation influence tree growth. *F.sylvatica* and *A.pseudoplatanus* are species both characterized by a great intraspecific variability and with a large area of distribution (Sierra *et al*., 2001). These species developed different ecological adaptations linked to their specific location. Although *F. sylvatica* and *A. pseudoplatanus* can live at high elevations in the Alps (1300–1500 m a.s.l.) and the Apennines (1600 m a.s.l. if the precipitation levels are high, 1000 m a.s.l. when aridity is remarkable), in the Mediterranean area their distribution is strongly influenced by frost during the growing period (Bernetti, 1995). Temperature changes are known to alter their growth especially during spring and fall (Pignatti, 1982).

Meteorological data and historical record of past eruption

Daily mean temperature, precipitation and relative humidity data for the Picentini study site, from the beginning of 20th century, were obtained from the meteorological stations of the Osservatorio Vesuviano, at 612 m, and of Montella at 670 m a.s.l., 4 km from the sampling site. Missing values were calculated as the mean of the daily values before and after the data gap. From daily values, monthly and annual values were calculated and organized in a complete matrix; best correlations between monthly climate data and corresponding isotope values were selected and used for further analysis. Figure 2 shows a diagram with total annual precipitation and mean annual temperatures for the period 1900–2003. To identify the years of eruption, we used the historical records of eruptions of the Vesuvio along with a description of their main geophysical characteristics collected by the Osservatorio Vesuviano station (see Table 1).

Fieldwork and sampling

Twelve *F. sylvatica* and 10 *A. pseudoplatanus* trees were sampled in January 2004 at the study site. We sampled

Table 1 Main characteristic of all eruption events registered for the Vesuvio since 1838

Start date (d/m/y)	End date (d-m-y)	Duration (days)	Volcanological notes	*D* δ^{18}O (%)	*D* tree width (%)
01/01/1839	03/01/1839	2	Effusive-explosive; lava fountains up to 400 m; lava volume erupted:$10 \times 10^6\,m^3$	−8	−69
05/02/1850	16/02/1850	11	Effusive-explosive; two strong explosions; the cone collapses into two craters lava volume erupted: $20 \times 10^6\,m^3$	−1.4	−51
01/05/1855	27/05/1855	26	Effusive with lava emission and mild strombolian activity; lava volume erupted: $17 \times 10^6\,m^3$	−3.3	−63
13/04/1861	31/12/1861	261	Effusive mildly explosive lateral with strong earthquakes; lava volume erupted: $120 \times 10^6\,m^3$	−5.8	−32
01/06/1868	26/11/1868	177	Effusive-explosive with strong eruptive column; lava volume erupted: $6 \times 10^6\,m^3$	−4.1	−42
24/4/1872	30/4/1872	6	Effusive-explosive; ash emission with ejection up to 130 m; lava volume erupted: $20 \times 10^6\,m^3$	−5.7	−40
1/2/1884	01/05/1855	455	Effusive with consistent lava flow; lava volume erupted: $7 \times 10^6\,m^3$	−4.7	−51
27/08/1903	30/09/1904	400	Effusive-explosive with intracrateric lava, large amount of ash; lava volume erupted: $0.05 \times 10^6\,m^3$	−2.1	−38
03/02/1906	22/04/1906	77	Effusive-explosive: intense activity with strong explosions and lava emission; increase of seismicity; lava volume erupted: $22 \times 10^6\,m^3$	−1.5	−46
03/06/1929	08/06/1929	5	Effusive-explosive with injection of scoriae and lava fountain 400 m high; lava volume erupted: $12 \times 10^6\,m^3$	−1	−36
06/01/1944	04/04/1944	87	Effusive-explosive: lava fountains turn ashy with a column 6–7 km a.s.l. high, small glowing avalanches and several seismic activities; lava volume erupted: $10 \times 10^6\,m^3$	−2.7	−46

The start and end date of the volcanic activity (day–month–year); the duration of the eruptive event and the volcanological notes, describing the main features observed in the period and the volumes of lava erupted, are reported, together with the relative percent variation (*D*%) recorded in δ^{18}O and tree-width. *D* indicates the % variation between individual tree-ring value of δ^{18}O and the mean curves calculated from all the tree-width measurements and the δ^{18}O data. The negative % values indicate the negative %change.

mature, dominant, old trees of approximately the same diameter. To avoid the effect of any wood alteration (particularly for analyzing tree-ring stable isotope ratio) and of exogenous disturbances on ring growth, only trees without abrasion scars or other visible evidence of injury were selected. Two increment cores at breast height (1.3 m) were collected from each tree, following standard methods (Schweingruber, 1998). The location and topographic microsite conditions of each tree were recorded. Cores were stored in paper straws and transported to the laboratory.

Laboratory analyses

The tree cores were mounted on supports, and sanded according to the standard dendrochronological procedures (Douglass, 1941; Swetnam *et al.*, 1985). Ring-width measurements were made with a resolution of 0.01 mm on each of the cores, using LINTAB measurement equipment (Frank Rinn, Heidelberg, Germany) fitted with a Leica MS5 stereoscope (Leica Microsystems, Germany) and analyzed with the TSAP software package. The ring-width series were plotted and visually synchronized for identification of errors during the measurements and for potential missing or double rings (Fritts, 1976; Schweingruber, 1996). Cross dating of all the tree-ring data was verified using the Program COFECHA, which assesses the quality of cross dating and measurement accuracy of tree-ring series using the segmented time-series correlation technique (Holmes, 1983). This program is primarily used to pick up inconsistencies in the data and to identify possible human error by letting the users know how far off a particular sample is from the master sequence. When cross-dating errors were indicated for the collected data, we went back to the original cores and determined the possible source of error. Individual cores that did not cross date were first compared with the paired core from the same tree and then with the mean ring-width chronology for the site. When they were not coincident and corrections could not be made, usually because of the extreme narrowness of the rings, the problematic core was deleted from the database. Thus, for this study we only used the successfully cross-dated cores, having

Table 2 Correlation Coefficient (r) between tree width and monthly maximum ($T_{\max}$) and minimum ($T_{\min}$) temperatures for the two tree species investigated

Species	Months ($T_{\max}$)	r	Months ($T_{\min}$)	r
Fagus sylvatica	March + April + May + June	0.35**	August + September + October + November	0.36**
			September + October + November + December	0.60***
Acer pseudoplatanus	April	0.35**		
	June + July + August + September	0.56***		

*$P \leq 0.05$; **$P \leq 0.01$; ***$P \leq 0.001$.

a significant ($P \leq 0.05$) '*Gleichläufigkeit*.' This is a statistical measure of the year-to-year agreement between the interval trends of the chronologies, based on the sign of agreement (Kaennel & Schweingruber, 1995) and Student's t-test, which determines the degree of correlation between curves. As a result of this analysis, we discarded 42% of the cores for *F.sylvatica* and 40% for *A. pseudoplatanus*. For each problematic tree whose annual growth rate was more likely influenced by competition than by climatic factors, both replicate cores were discarded. By excluding those cores, the correlation coefficient between the curves increased and the confounding competition effects were reduced.

Isotope analysis

All the rings of all the cores, after ring-width measurements, were split into earlywood and latewood. Several studies (Lipp *et al.*, 1991; Hill *et al.*, 1995; Robertson *et al.*, 1996; Switsur *et al.*, 1996; Jäggi *et al.*, 2003) suggested that significantly different isotope ratios exist between earlywood and latewood, because earlywood bears the isotopic signature of stored carbohydrate synthesized in the previous years. Therefore, only latewood was used in this study. The latewood of the different cores and trees was pooled year by year, in order to reduce the number of samples. Each tree-ring value, therefore, represent pooled material from different cores (Leavitt & Long, 1991; Leavitt, 1993; Saurer *et al.*, 1997; Borella *et al.*, 1998). The samples were ground with a centrifugal mill (ZM 1000, Retsch, Retsch Technology, Haan, Germany) using a mesh size of 0.5 mm to assure homogeneity. For measurement of small subsamples, a good homogeneity of the wooden material must be guaranteed because coarsely milled samples could lead to an over-representation of one tree ring (Borella *et al.*, 1998). From every latewood sample the α-cellulose was extracted to avoid isotope variations that are purely based on changes in the relative abundance of individual wood constituents, differing typically in their isotope signatures.

The method for cellulose extraction (Loader *et al.*, 1997) was based on a double-step digestion: the first step consisted in the treatment of wood with a solution of 5% NaOH for 2 h at 60 °C, repeated twice, in order to remove lipids, resins, oil, tannins and hemicelluloses. In the second step, samples were washed with a 7% $NaClO_2$ solution for a minimum of 36 h at 60 °C. Because the solution is only reacting for 10 h, it was changed daily and refilled as necessary. During this stage lignin was eliminated. Finally, samples were washed three to four times with boiling distilled water and dried overnight at 50 °C.

The $\delta^{13}C$ values were measured by combustion and $\delta^{18}O$ by pyrolysis of the cellulose samples in an elemental analyzer (Carlo Erba 1110, Milano, Italy) interfaced via a Conflo II Interface (Thermo Finnigan, Bremen, Germany) to a dual inlet/continuous flow isotope ratio mass spectrometer (Delta S, Thermo Finnigan) operating in the continuous flow mode. The isotope signature is expressed in the δ notation for carbon and oxygen, where $\delta^{13}C$ or $\delta^{18}O = (R_{\text{sample}}/R_{\text{standard}} - 1) \times 1000$ (‰), relative to the international standard, which is VPDB for carbon and VSMOW for oxygen. R_{sample} and R_{standard} are the molar fractions of $^{13}C/^{12}C$ for the sample and the standard, respectively. The standard deviation for the repeated analysis of an internal standard (commercial cellulose) was better than 0.1‰. The calibration vs. PDB was carried out by measurement of IAEA USGS-24 (graphite) and IAEA-CH7 (polyethylene).

Data analysis

As the series of consecutive observations are collected from the same tree (annual rings from an increment corer), data autocorrelation may arise (Monserud, 1986; Monserud & Marshall, 2001).

Thus, to determine and remove long-term trend without altering or modifying the existing data, the first differences (1 year minus the previous one $DY(t) = Y(t) - Y(t-1)$) method was applied to all measurements (Loader & Switsur, 1995; Saurer *et al.*, 1995; Robertson *et al.*, 1997; Anderson *et al.*, 1998). Such a procedure also minimized the problems of changing atmospheric CO_2 and $^{13}CO_2$ values, which is especially

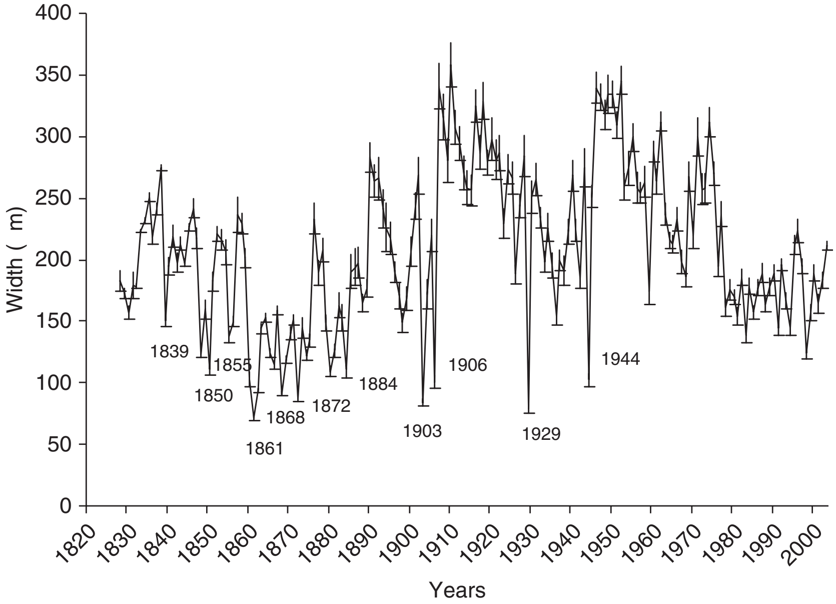

Fig. 3 Mean ring-width chronology calculated from 14 of the 24 measured cores of *Fagus sylvatica* plotted against calendar date. Bars are standard error.

important for long-term records (Schleser *et al.*, 1999). The new dataset was used for all the statistical analysis.

To select the ring-width pointer years, the single standard deviation of a given period is used as a threshold (Cropper, 1979; Hughes *et al.*, 1982; Hüsken, 1994) and the values crossing this threshold are defined as pointer values, keeping in mind that the pooling methods already average several single trees. The pointer values were compared with meteorological data of the corresponding year, looking for relationships with environmental conditions. Mean ring-width chronologies and mean curves were calculated from 14 of the 24 measured cores for *F. sylvatica* and from 12 cores of *A. pseudoplatanus*. The percent variation between the annual growth and the mean ring-width chronology, as well as the percent variation between the δ^{18}O values of each tree ring and the mean δ^{18}O curve, were expressed as *D*%. Negative values indicated a negative change in %. All statistical analyses were carried out with the program STATVIEW (SAS Institute Inc., Cary, NC, USA) or SIGMASTAT 3.1 (Systat Software, CA, USA) and independent group comparison tests were used as *t*-test and Mann–Whitney test. The latter is an alternative to the independent group *t*-test, when the assumption of normality or equality of variance is not met.

Finally, to show differences between the eruption years from the rest of the data, a principal component analyses (PCAs; Cook & Kairiukstis, 1990) was applied using the package SYN-TAX 5.0. Two data matrices, respectively of 86 years × six variables (δ^{13}C, δ^{18}O and ring width both for *F. sylvatica* and *A. pseudoplatanus*) and of the 175 years × three variables (δ^{13}C, δ^{18}O and tree-ring width for *F. sylvatica* only), were processed as ordination method for indirect gradient analysis (Podani, 2000). The aim of this analysis is to replace the different variables with linear combinations, which are independent. In this way the new linear combinations appear in order of importance, and at the same time the relative importance of these linear combinations can be calculated. This allowed for the reduction of the number of independent variables by eliminating those accounting for only a few percent of the total variance (Podani, 1993).

Results

Ring-width chronologies

During eruption years narrow rings are formed (Table 1). Extremely narrow rings were formed in the years 1861, 1903 and 1944 when, according to the historical records, some of the largest volcanic explosions took place. The occurrence of narrow rings in eruption years is evident from the mean ring-width in *F. sylvatica* chronology, which starts in 1828 and recorded several volcanic events (Fig. 3). The sampled *A. pseudoplatanus* trees were young and their chronologies cover only 90 years, during which only two volcanic eruptions occurred.

The mean ring-width chronology with standard error, obtained from all of the *F. sylvatica* trees, selected after cross dating with COFECHA, are plotted in Fig. 3. Of the

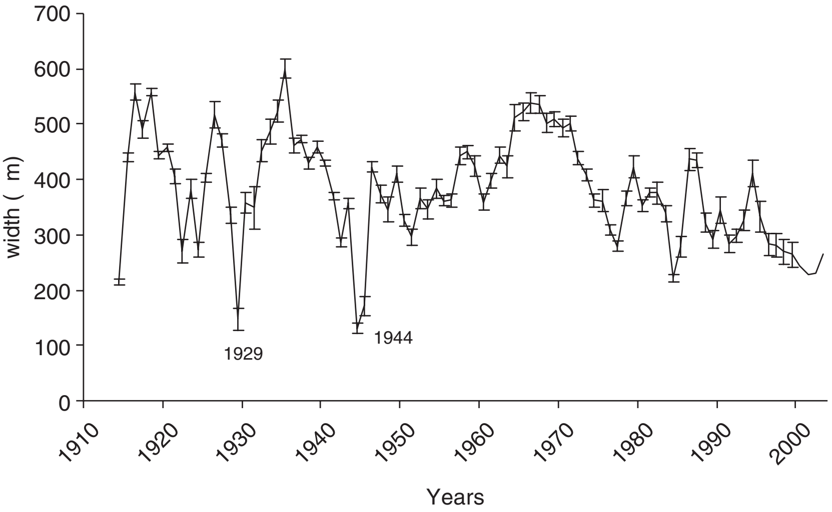

Fig. 4 Mean ring-width chronology from 12 cores of the *Acer pseudoplatanus* trees, plotted against calendar date. Bars are standard error.

24 measured cores, 14 (two cores × seven trees) were selected for further analyses because they were significantly correlated with each other. Comparing the mean chronologies built for each species revealed highly significant ($P \leq 0.05$) *Gleichläufigkeit* values (always higher than 70%), and correlation coefficients (r) that show a good synchronization between the cores (the highest r being 0.77 and the lowest 0.37). For *A. pseudoplatanus* trees the same procedure was performed, and 12 cores from six trees were used for cross dating (Fig. 4). The *Gleichläufigkeit* value was always higher than 65%.

Narrow rings were not only formed during eruption years. Low ring-width values occurred also in 1880, 1898 and 1998 for *F. sylvatica*, and in 1914 and 1984 for *A. pseudoplatanus*. To clarify if these were caused by adverse climatic conditions, we analyzed the relationship between temperature, precipitation and ring widths. The total precipitation amount occurring during the months of April and May influenced the tree-ring growth of both species significantly ($r = 0.44\%$ and 0.61%, respectively). In order to minimize the side effect of other growth factors, only the first differences was correlated, i.e. by comparing the change in precipitation with the change in ring width of the successive years (Schleser *et al*., 1999). Air temperature seemed to be more important than precipitation; Table 2 shows the correlation between tree-ring width for the two species and maximum ($T_{\max}$) and minimum temperatures ($T_{\min}$) recorded at the closest meteorological stations. Unfortunately, the climate dataset is much shorter than the *F. sylvatica* chronologies, whereas for *A. pseudoplatanus* it is possible to cover all the sampled period. Nevertheless, significant correlations between temperature and ring width were found. In particular, spring and early summer (April + May + June + July) $T_{\max}$ was highly correlated with growth of both species, while fall $T_{\min}$ influenced ring width of *F. sylvatica* only.

The meteorological data (Fig. 2) reveal that there is a significant decrease in the mean annual temperature (2–3 °C) in the years when volcanic eruptions occurred. This supports our first hypothesis that after an eruption, the release of silicate matter, aerosols and gases in the atmosphere has a cooling effect. The decrease in the mean annual temperature is still evident at least 1 year after the event, and is much bigger if the main portion of the eruption occurs during the months of the growing season (Table 1).

Carbon and oxygen-stable isotopes

A dramatic decrease in the δ^{18}O of tree rings formed during the eruption events of Vesuvio was found, whereas the reduction in tree-ring δ^{13}C was not as strongly expressed, as a result of the eruption activity (Fig. 5). Indeed, there is a slight decrease in δ^{13}C recorded in most eruption years but it is not significant according to Mann–Whitney test, (Sigma Stat 3.1). Although a clear temporal trend is indicated in Fig. 5a, no significant difference was found either ($P \leq 0.01$) according to Student's t-test between the average δ^{13}C value for all volcanic years and the average for all nonvolcanic years. Yet, the tree-ring δ^{13}C values of cellulose for the two species, however, show a good agreement between species suggesting a common climatic signal.

The decrease in δ^{18}O values was significant according to Student's t-test, and consistently observed in all the eruption years ranging between a variation (D) of

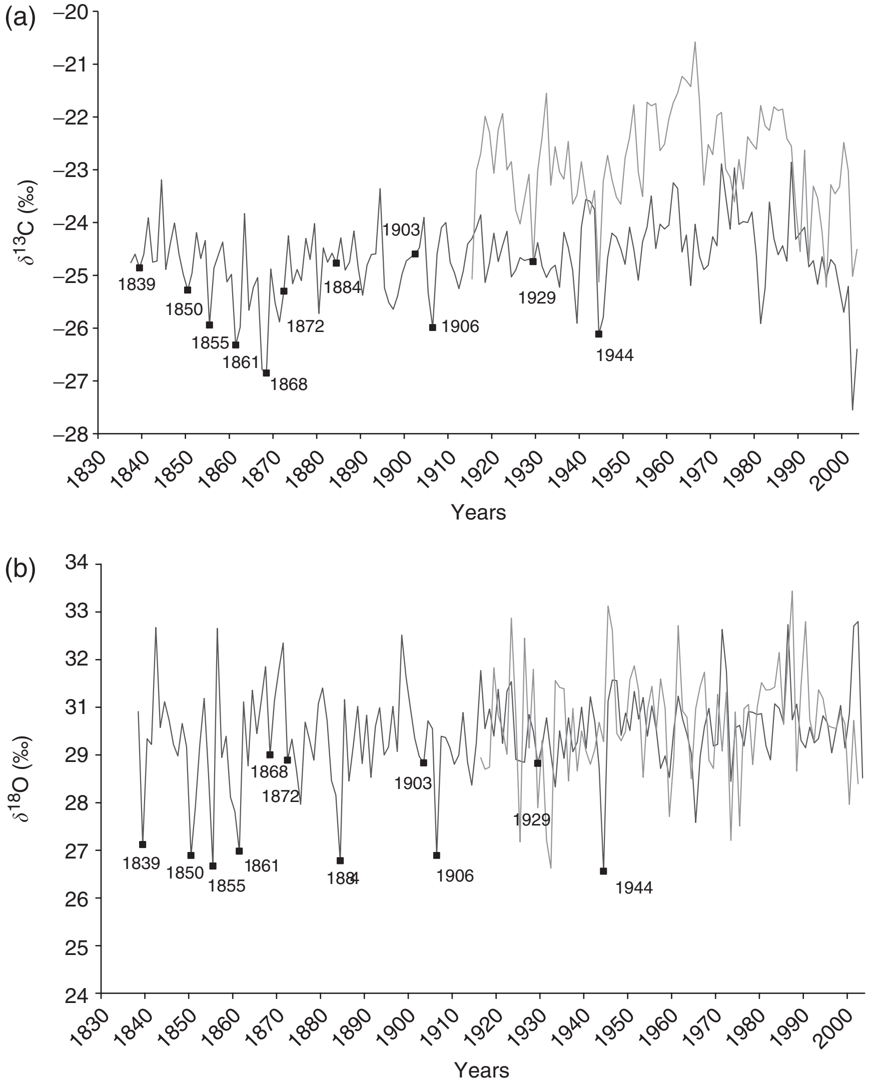

Fig. 5 (a) δ^{13}C time series of *Fagus sylvatica* and *Acer pseudoplatanus* trees. Each annual isotopic value is the result of pooled material of the same year, from different cores selected per each species. In this way a mean mass-weighted δ^{13}C value is produced. (b) Annual courses of δ^{18}O of tree-ring cellulose of *F. sylvatica* and *A. pseudoplatanus*. Each curve is obtained as described for (a).

−1% recorded in 1929 and −8% in 1839 (see Table 1). A high Pearson's correlation coefficient (r) was found between the δ^{13}C and δ^{18}O values and precipitation of April and May (0.40 and 0.45, respectively) while the δ^{13}C of both species is strongly related to $T_{\min}$ of the autumn period (September–October with a 0.40 and 0.47, for *F. sylvatica* and *A. pseudoplatanus*, respectively).

Because relative humidity at these sites is believed to be the major climatic factor controlling the variation in oxygen isotope composition of tree organic matter (Roden & Ehleringer, 1999), the mean δ^{18}O values for *F. sylvatica* and *A. pseudoplatanus* are shown as a function of the mean annual minimum relative humidity (Fig. 6). We decided to use the minimum values of relative humidity because of their relationship to the highest diurnal photosynthetic activity of the plants. While daily data were available, mean annual values were used for a dataset that could be correlated with yearly tree-ring isotopic data. As the oxygen isotope signal of the leaf water is transferred to the organic matter, it should be mostly influenced by environmental conditions at the time of the highest carbohydrate production.

Both the δ^{13}C and the δ^{18}O are related to air humidity [the δ^{13}C via stomatal regulation of the plants, the δ^{18}O via changes of the ratio between the atmospheric and intercellular vapor pressure (e_a/e_i)] and, therefore, we expected that the C and O isotope ratios would be

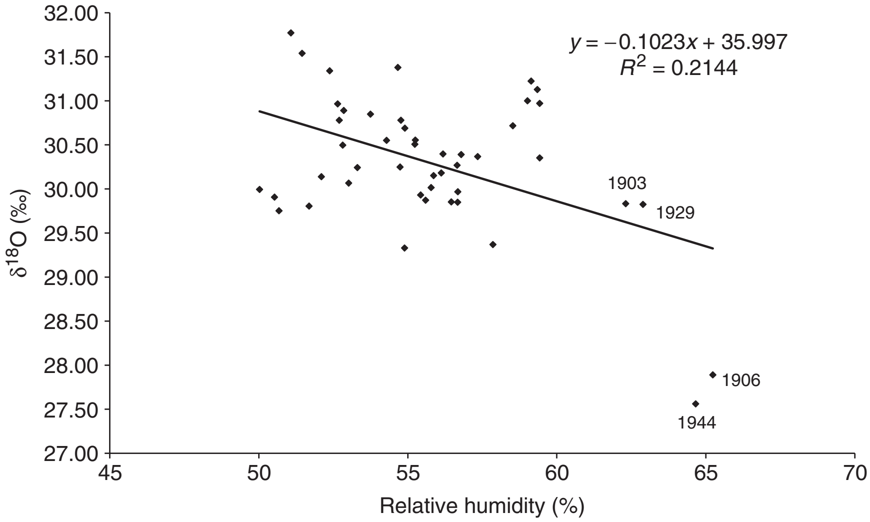

Fig. 6 The measured δ^{18}O of the cellulose extracted from *Fagus sylvatica* tree-rings plotted against mean minimum annual relative humidity recorded at the Montella meteo-station (41°01′16"N; 14°52′09"E, 670 m a.s.l.).

related to each other. However, we found no significant correlation between the two variables.

PCA

Figure 7 shows the first two components resulting from PCA applied to δ^{13}C, δ^{18}O and tree-ring width values for both species, for the period 1916–2003 where complete information for *F. sylvatica* and for *A. pseudoplatanus* was available. First and second component are used for the biplot so both objects (years) and variables are represented in the same *best* plane explaining the maximum of variance present in the data. The first and second principal components accounted for 32% and 20% of the total amount of variation, respectively. The first component reflects variations of δ^{13}C for both species and of ring width for *F. sylvatica*, and to a smaller extent for *A. pseudoplatanus*. Two clear ring-width and δ^{13}C gradients from negative toward positive quadrants are evident, with years with lower values of both variables showing negative scores on the first component and years with higher, positive values. This gives the possibility to evaluate the weight that each single variable has on the years of distribution (the closer a vector is to a year, the larger is its influence on it). The eruption years (1929 and 1944) were clearly separated and this separation appears to be mainly due to lower ring-width values corresponding with volcanic events. In the diagram, the same variables for both species appear to be coupled with their vectors pointing in the same directions, suggesting that both seem to be correlated with each other, indicating that the two species are related in the same way to the volcanic events. Moreover, the fact that δ^{18}O variable vectors of both species are perpendicular to the other vectors shows that they do not correlate with the other variables.

In Fig. 8 the diagram with the first two components resulting from PCA applied only to the *F. sylvatica* data, for the 1838–2003 period, is reported. The first and second components accounted for 49% and 30% of the total amount of variation, respectively. The diagram confirms and better highlights the relationship between the variables and volcanic events. The first axis mainly reflects the slight variations of δ^{13}C and ring width with increasing values from the negative to the positive quadrants. Eruption years (white squares) are clearly separated in the negative–positive quadrants of the diagram and an indirect gradient can be observed with the years of interest when eruptions occurred for a couple of years (gray squares) located between eruption years and years without eruptions, indicating a different impact on *F. sylvatica* individuals. Contrasting with the previous PCA diagram, δ^{18}O appears to be negatively correlated with the 'eruption gradient' with lower values corresponding with eruption events. On the other hand, the lack of correlation between δ^{18}O and the other two variables is confirmed by the opposite direction (perpendicular to the gradient) of its vector with respect to the other variable vectors.

Discussion

Severe explosive volcanic eruptions cause strong changes in the local climate as a result of the ejection of dust particles and aerosols, altering the radiation balance. This leads to a reduction in the air temperature,

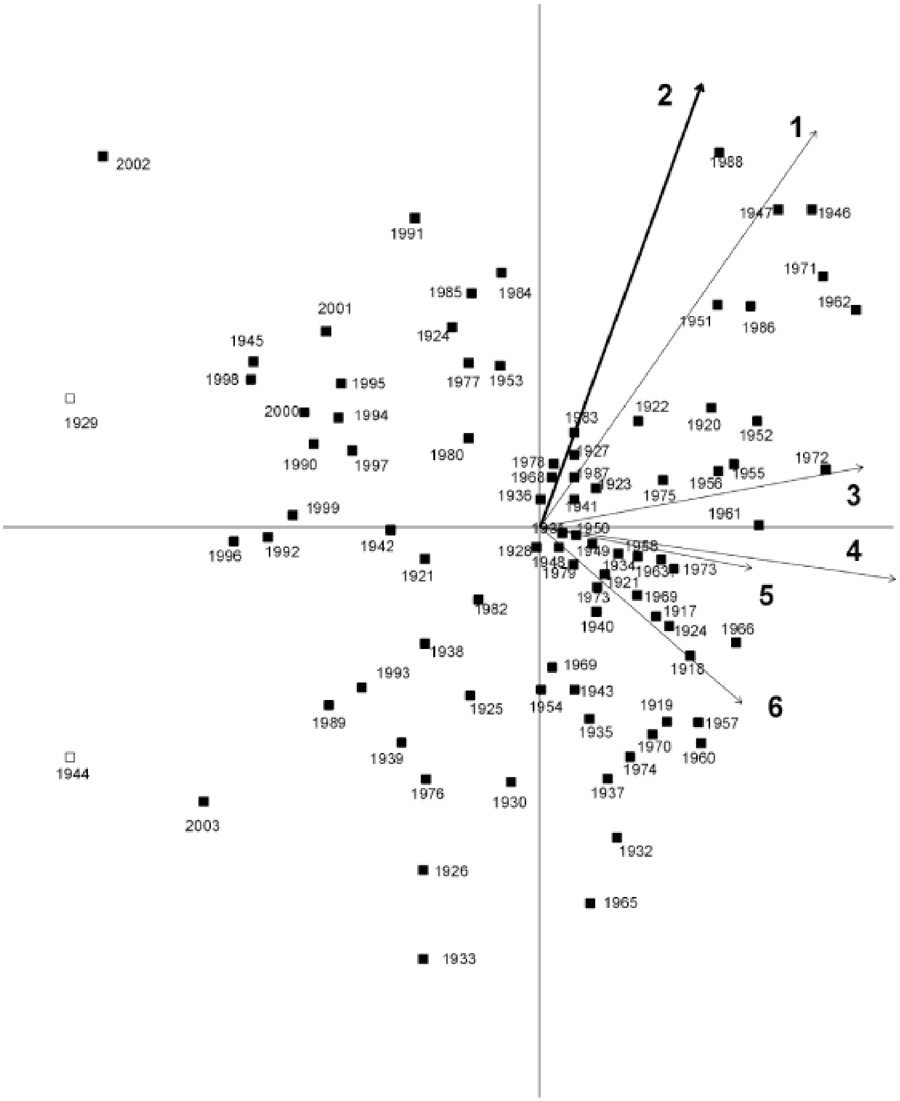

Fig. 7 Ordination by Principal Component Analysis of a sample plot in *Fagus sylvatica* and *Acer pseudoplatanus* communities. The biplot in the first and second component plane, resulting from principal component analysis applied to the period 1916–2003, is reported with either the years (squares) or the parameters (vectors) in which they have been measured. The first and second principal component accounted for 32% and 20% of the total amount of variation, respectively. 1, δ^{18}O *F. sylvatica*; 2, δ^{18}O *A. pseudoplatanus*; 3, δ^{13}C *F. sylvatica*; 4, δ^{13}C *A. pseudoplatanus*; 5, ring-width *F. sylvatica*; 6, ring-width *A. pseudoplatanus*; ■, years without eruption; □, years with eruption.

an increase in the relative humidity and a possible decrease in the photosynthetic active radiation, with its consequences on the local vegetation. At a global scale, volcanic eruptions have long been considered the cause of reduced photosynthetic rates, decreased tree growth and the formation of narrow tree rings, and so called light rings (rings with very low latewood density; Filion *et al.*, 1986; Hughes *et al.*, 1982; Cherubini *et al.*, 1996) or frost rings (D'Arrigo *et al.*, 2001). For example, the impact of the Katmai eruption has been detected in tree rings of the Alps. Recent volcanic eruptions have been described as a driving force for an increase in plant photosynthetic rates (Gu *et al.*, 2003). The ejection of dust particles and aerosols reduce the direct irradiation, while the diffusive light component increases, causing a higher light distribution in the lower part of the plant canopy layer. As a result, whole-tree photosynthetic rates are increased. On the other hand, a decrease in temperature is commonly reported after volcanic eruptions due to an altered irradiation regime (Briffa *et al.*, 1998a). At a regional scale, relative air humidity data from the meteorological station close to the study site (data not shown) demonstrated increasing relative humidity during the years with an eruption event. This

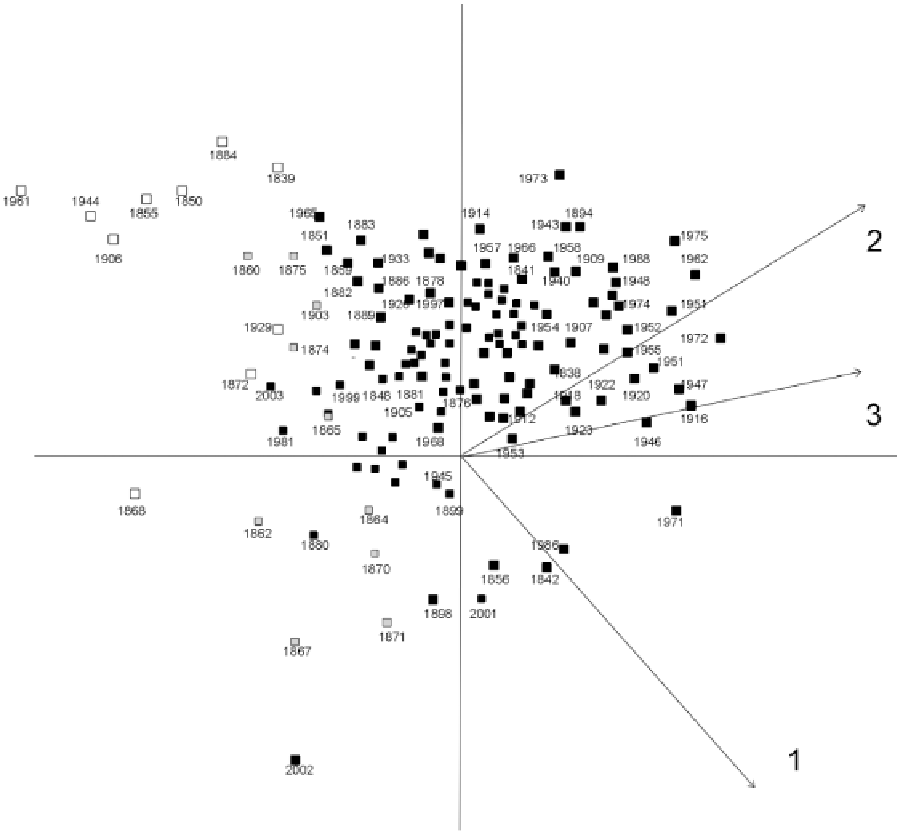

Fig. 8 Biplot of the first two principal components, which accounted for the total variance of 49% and 30%, respectively. Biplot in the first and second component plane resulting from the principal component analysis applied only to *Fagus sylvatica* data for the 1838–2003 period. Years (squares) and variables (vectors) are both reported. 1, δ^{18}O; 2, δ^{13}C; 3, ring width; ■, years without eruption; □, eruption years; ▨, years with partial volcanic activity.

results from the decrease in air temperature, resulting in reduced saturation vapor pressure and thus in an increase in the mean relative humidity.

An increase in air humidity, along with a higher diffusive radiation, represents good conditions for high photosynthetic carbon fixation and potentially higher growth rates. Although a reduction in the direct irradiation component potentially reduces the photosynthetic rate of the leaves in the top canopy layer, this is usually well compensated by an increase in the C-assimilation rate by the shaded leaves in the lower canopy part, as they experience a higher light exposure from the diffusive light component than under direct light conditions. An increase in stomatal conductance due to a high air-humidity regime has a synergetic effect and would allow a higher C-assimilation rate and increase net primary production reflected in tree-ring width if temperature decreases do not become limiting for growth.

These conditions of high diffusive irradiation should be reflected in both an increase in tree-ring width and less negative δ^{13}C values, along with no change or reduced δ^{18}O values, due to increased stomatal conductance and high relative humidity (Fig. 1, Hypothesis 2), but the data do not support this hypothesis.

Stomatal conductance is mostly high during high ambient air humidity as the water loss is very small due to a small water vapor pressure difference between the leaf intercellular spaces and the ambient air. Under these conditions, a high retro-diffusion of $H_2{}^{18}O$-depleted water vapor from the ambient air into the leaf takes place, reducing the δ^{18}O values of the leaf water, which is reflected in the organic matter. This explains the low δ^{18}O values observed in our tree rings during the year of eruptions. Under these conditions, the water vapor would even be more depleted because of the reduced temperature. Cooling alone could not explain the strong reduction in δ^{18}O values measured in our samples. In fact, based on the temperature –δ^{18}O relationship of Dansgaard (1964) or Rozanski *et al.* (1993), the temperature drop would have to be two to four times as much as it was measured, even more so as this reduction in δ^{18}O was found in organic matter. We can, therefore, conclude that the observed reduction in δ^{18}O was caused by both higher stomatal conductance and higher ambient, δ^{18}O-depleted, air humidity, during the years when eruptions occurred.

These results demonstrate a strong significant decrease in tree-ring width and δ^{18}O values during the years of eruptions. This suggests that the intensive volcanic eruptions led to a strong reduction of direct sun radiation, with extremely high dust and aerosol loads in the atmosphere and frequent dense fog events, due to a large increase of condensation nuclei in the atmosphere and a persistent cooling of the air. The reduced temperature after the volcanic eruptions may have contributed to low tree-ring width, as carbohydrates are not as rapidly transformed into cellulose and wood biomass at a persisting low-temperature regime (Hoch & Körner, 2003). We did not, however, observe a strong significant decrease in δ^{13}C, for the years with strong volcanic eruptions, nor did the slight decrease in δ^{13}C correlate with the decrease in δ^{18}O (Figs 7 and 8). Higher stomatal conductance should have resulted in lower δ^{13}C values, which in turn would have correlated well with δ^{18}O. Had lower photosynthetic activity occurred due to decreased temperature/irradiation, further reduction in the δ^{13}C should have been measured (Farquhar *et al.*, 1989). Why was this not observed? Our best interpretation is that in this study, slightly decreased δ^{13}C values resulted from the enhanced stomatal conductance; however, the photosynthetic activity appeared not to have changed significantly (see Fig. 1). The decrease in δ^{18}O was more marked due to the coexistence of two parallel forcing: increase of stomatal conductance and decrease in temperature.

At our study site, we observed a mean decrease in tree-ring width of up to −47% during the years of eruptions as a direct consequence of the cooling effect. The temperature data correlate well with tree-ring width. Monthly temperatures were significantly lower not only during some single-eruption years but also for a few years after the event. Additionally, reduced tree-ring widths corresponded with more negative δ^{13}C values. Furthermore, reduced δ^{18}O values as we found along with a reduced tree-ring width suggests high stomatal conductance, which is mostly the case under a high-humidity regime.

Other factors might explain reduced tree growth for trees close to volcanic eruptions (i.e. within a range of 100 km for explosive eruptions) such as volcanic dust and aerosols (Eggler, 1967; Seymour *et al.*, 1983; Yamaguchi, 1985). Other than climatic influences, there are numerous mechanical damages to foliage or wood from ash accumulation or lapillus fallout that reduce the amount of photosynthetic tissue and reduce wood growth. Dust layers shading the leaf surface and covering the stomata reduce the gas exchange rates, and a dense ash cover of the soil could decrease the oxygen supply to the roots and change the soil chemistry and water and nutrient absorption. These combined phenomenon, observed after the most significant eruptions, support Hypothesis 1 (Fig. 1) as the best explanation for tree growth and physiology at our site.

Conclusion

Isotopic analyses coupled with dendrochronological records give us the opportunity not only to reconstruct the past influence of eruptions on tree growth but also to analyze the tree physiological responses to environmental changes, which are important to understand tree response in future climate and global-change-induced scenarios. For the retrospective evaluation of the response of the vegetation to such events with climatic consequences, the combined use of tree-ring width and C- and O isotope analysis provides specific information for such local events, impacting the local climate. This information represents a model scenario from which we can derive potential future responses of the vegetation to similar global alterations of climate.

Severe volcanic explosive eruptions with the ejection of large amounts of dust particles and the subsequent aerosol formation cause a strong change in the light regime and in air temperature. As a consequence, mean annual temperatures decrease to the extent that tree growth (ring-width increment) is significantly reduced and air humidity is increased, leading to reductions in tissue δ^{18}O. As *F. sylvatica* and *A. pseudoplatanus* show the same responses in tree-ring widths and the C- and O- isotope signals, the changes of the local climate were large enough to trigger the same reaction across different tree species. Our study provides no evidence for any significant change in photosynthetic rates due to changes in irradiation. Conclusions in other studies proposing an increase in growth or photosynthetic rates after a volcanic eruption, however, cannot be fully ruled out nor can it be confirmed. This is strongly dependent on the magnitude of the climatic changes resulting from individual volcanic eruption events.

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