

## Scots Pine dieback in the Isarco Valley due to severe drought in the summer of 2003

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### Abstract

#### Scots Pine dieback in the Isarco Valley due to severe drought in the summer of 2003

Scots pine forests located on dry and sunny slopes of the Isarco and Adige valleys are dying due to the intensive and extended drought that hit Europe during summer 2003. Interdisciplinary surveys carried out by the Forest Department of Bolzano were aimed at identifying causal elements at different functional levels of the ecosystem and of the tree species, which is particularly sensitive to climatic anomalies. The results of the analysis provided a scientific interpretation of the forest dieback, mainly caused by water stress, and offered useful insights for defining urgent forest protection interventions and future silvicultural management.

**Keywords:** carbon and oxygen stable isotopes, climate change, dendrochronology, forest dieback, Scots Pine, South Tyrol, summer drought.

### 1 Introduction: main features of vegetation and historical outline

In the submontane zone that covers the slopes of the main valleys of South Tyrol (Adige Valley, Isarco Valley) between 500 and 1000 metres above sea level, Scots Pine stands are the most common. In this area, due to the constitutional aridity of the typically continental climate of the Central Alps, the Scots pine (*Pinus sylvestris* L.) replaces the beech (*Fagus sylvatica* L.),

in all sites with extreme edaphic conditions for the most part in pure formation as a lasting association (*Vaccinio-Pinetum sylvestris*). Due to their extent these stands constitute the main feature of today's landscape together with sweet chestnut woods, vineyards, low-lying meadows and pastures and rural population centres.



Fig. 1  
Typical landscape of the hills, characterised by dying Scots pine forests.

Secondarily, the Scots pine is dominant in current upper hill formations in combination with temperate broadleaves, with the downy oak in particular on the south-facing slopes (*Antherico liliaginis-Pinetum arcostaphyletosum uvae-ursi*) or with chestnut in cooler and more shaded places (*Phyteumo betonicifoliae-Quercetum vaccinietosum mirtilli*) (BOLZANO FORESTRY DEPARTMENT: 2006), spreading into the hillside below, typically covered by thermophilic broadleaves with manna ash and hop-hornbeam as the main species (*Orneto-Ostryetum quercetosum*).

The little ice age, which finished in Europe around the first half of the 19<sup>th</sup> century, caused the descent of the vegetation from the upper hillside towards the valley bottom and consequently the spread of the Scots pine to lower levels. Subsequently, in concomitance with the progressive increase in temperatures, the hillside was reconquered by broadleaves (*Quercus pubescens*, *Quercus petraea*, *Castanea sativa*, *Prunus avium*, *Tilia cordata*, *Fraxinus ornus*, *Corylus avellana*), a process still in progress today.

At the beginning of the 20<sup>th</sup> century the land in the environs of Bressanone, where today

the wood is almost purely of Scots pine, was occupied by chestnut woods and vineyards. Subsequently it was intensely exploited throughout the year for grazing, above all for sheep, in the same way as the nearby pastures belonging to the farmsteads. Until the period 1920-1940 they therefore underwent considerable deterioration.

After the Second World War, spontaneous recolonisation of the surface by the Scots pine followed the progressive reduction of grazing, locally assisted by reforestation carried out by the forestry authority, which led to a wood of average density with ericaceous undergrowth. Today the current stands, of first generation with an average age of about 60 (90) years, have undergone progressive deterioration because of hay harvesting and lack of management.

These forests have weakened their structural and ecological stability in the face of various endemic parasites, the established cause of mortality since the beginning of the 1990s: *Viscum album* (European mistletoe), *Cenangium ferruginosum* (Cenangium limb canker), *Sphaeropsis sapinea* (Sphaeropsis shoot blight), *Armillaria* sp. (Armillaria root-rot fungus).

On the basis of the above references regarding vegetation and history, it is also clear how the dynamics of the stands under consideration can be particularly susceptible to exogenous damaging factors such as, in fact, the extreme climatic conditions of 2003, whose consequences, in the form of crown discolouration (*chlorosis*) in September (Figs.1 and 2), followed by the complete dieback of single trees or extensive groups of trees, exclusively affected stands of Scots pine in pure and mixed formation on the sunny slopes of the Isarco Valley between Bolzano and Bressanone at altitudes between 500 and 800m. above sea level (Fig.4).

The phenomenon has affected up to 80% of the stands in a patchy way, with a total of 150 hectares and 8,000 m<sup>3</sup> of timber. The absence of harmful primary biotic agents (insects, fungal infections, etc.) was particularly notable, while decline was not followed by the feared explosion of secondary pathogens, which, however, are always present in this type of cenosis.

On the other hand, no form of permanent damage was observed in spontaneous broadleaf understorey vegetation. (Fig.3)



Fig. 2  
Scots pine stands characterised by extensive crown chlorosis and dieback.

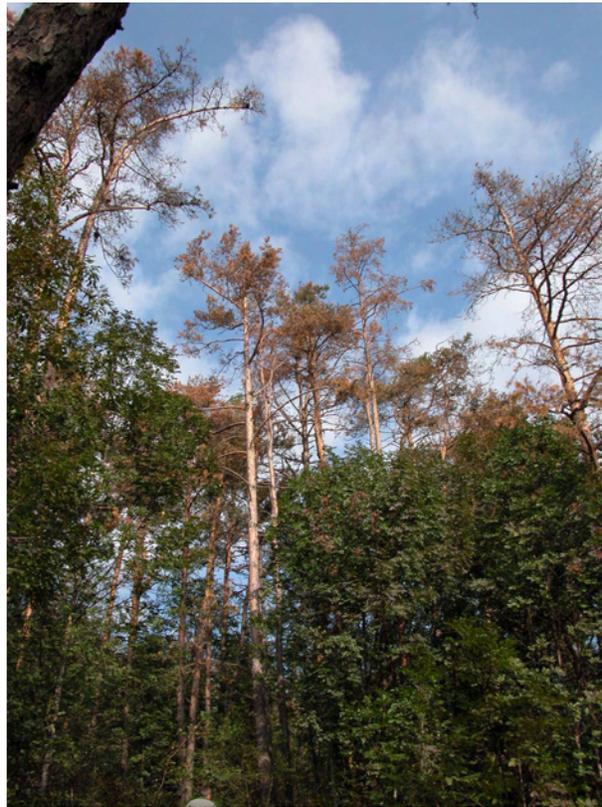


Fig. 3  
Understorey vegetation of temperate broadleaves.

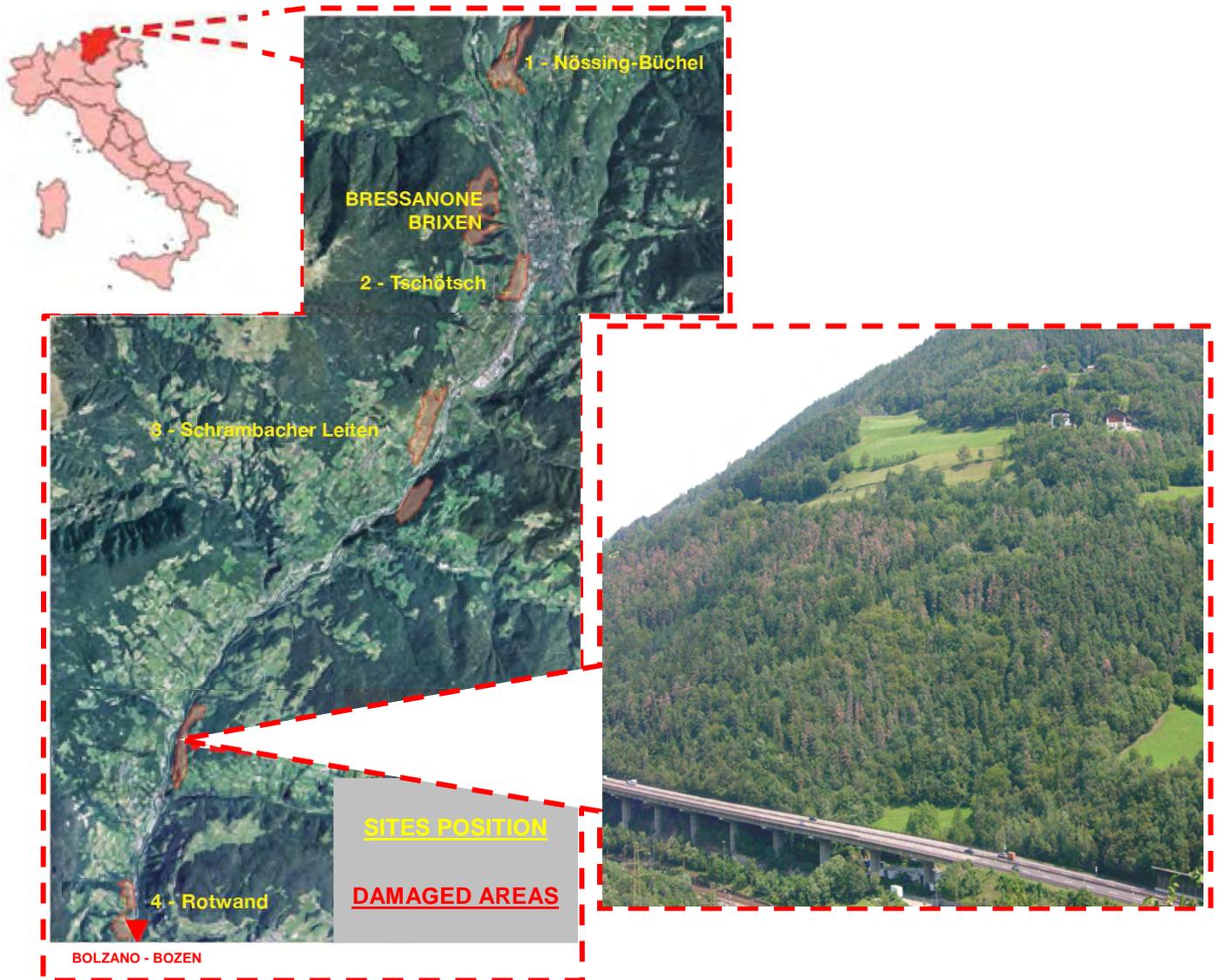


Fig. 4  
 Aerial photograph of sampling plots and of the areas characterized by extensive dieback of Scots pine (*Pinus sylvestris* L.) in the Isarco Valley during summer 2003.

## 2 Methodology

### 2.1 Objective – Investigation approach

In view of the progressive spread of dieback to the whole Scots pine stands, with presumably negative consequences for the hydrogeological stability of the slopes and for the safety of important communication and transport infrastructures along the Isarco Valley (the Brenner motorway, the railway, local roads: Fig.4), the Forestry Department of Bolzano/Bozen considered it advisable to verify the hypothesis according to which the main cause of the phenomenon was the drought of 2003, adopting an interdisciplinary approach (auxometric, climatological, pedological, phytopathological, dendrochronological and vegetable physiological) for which it availed itself of the collaboration of specialised institutes and consultants.

More specifically, the investigations had the aim of investigating the following questions:

- analysis of climatic trends during the 2003 vegetative season and establishing whether it was normal / exceptional in the context of the time series 1926-2003;

- reconstruction of the hydrological balance for the soil of the forest sites affected by dieback in order to verify / assess previous conditions of physiological weakness (degree of water stress) to which the pine forests were subjected;

- examination of the connections between the water balance of affected sites and the stomatal control of transpiration by means of a specific historical investigation of the relationship between stable carbon and oxygen isotopes;

- investigation of the difference in behaviour between dying and healthy plants in relation to the availability / accessibility of water;

- the presence of pathogens and their role in the dynamics of the phenomenon;

- assessment of the future development of the phenomenon based on the ecosystem and dynamics of the population in order to plan forest protection and selvicultural management interventions.

### 2.2 Study sites

The experimental investigation took place at the four sampling sites of Nössing-Büchel, Tschötsch, Schrambach and Rotwand situated along the

Isarco Valley (Tab.1; Fig.4), characterised by clear symptoms of dying and death of the Scots pine.

Tab. 1  
Main characteristics of the experimental site.

	Experimental sites	Elevation m	Slope %	Slope °	Aspect °
1	Nössing-Büchel	670	0	0	0
2	Tschötsch	720	80,0	38.7	125°
3	Schrambacher Leiten	600	45,5	24.5	140°
4	Rotwand	560	50,0	26.6	100°

### 2.3 On-site sampling

At each of the three sites of Nössing-Büchel, Tschötsch and Schrambach Leiten, in the winter of 2003/2004 two groups of adjacent trees (maximum distance 15m) were found that had identical microsite conditions except for the podological substratum. In these groups samples were taken from 3 dead trees on loose soil of average depth and 3 living trees near rocky outcrops.

Suitable sections of wood were taken for dendro-ecological, dendrochronological and wood isotopic composition investigations, in particular:

*dead trees*: a transversal section at the base of the trunk (disk);

*living trees*: 4 cores per tree extracted at the trunk base using a Pressler borer.

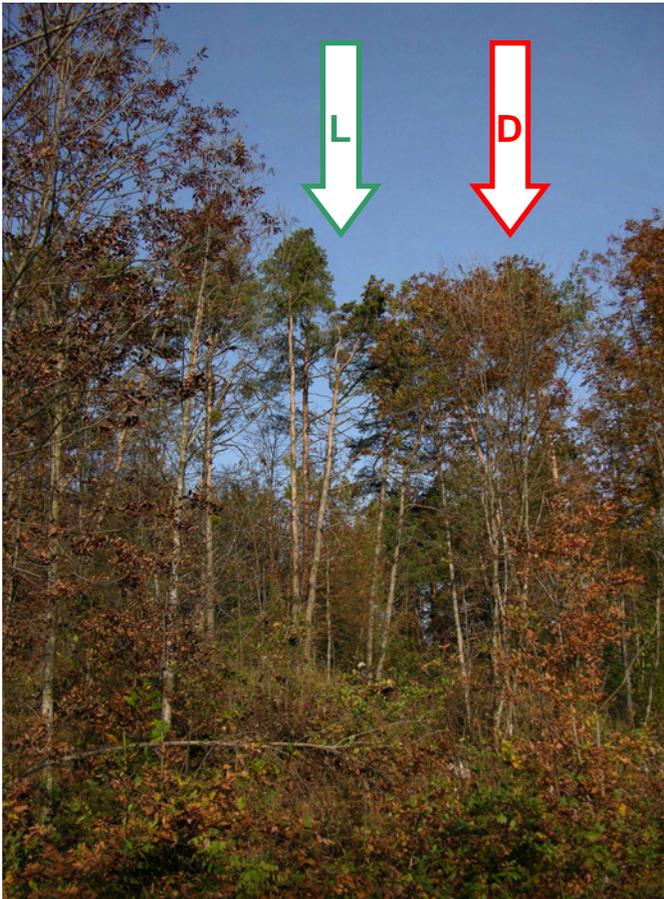


Fig. 5  
Living (L) and dead (D) sampled trees at the Tschötsch experimental plot.

At the Rotwand site 3 cores were extracted from the trunk base of 5 dying, but not yet dead, trees using a Pressler borer. So altogether 9 disks and 51 cores were collected.

The wood samples (disks and cores) were subsequently prepared for analyses (NÖTZLI & STARY 2004) at the laboratories of the Federal Institute for Forest, Snow and Landscape Research in Birmensdorf (WSL), Switzerland:

- glueing to supports and polishing with sandpaper on a belt sanding machine, going over with increasing degrees of fineness (80, 120, 320, 400)
- stereomicroscopic dating and separation of the various rings and of parts of them (spring wood and late wood);
- measurement of ring width with a stereomicroscope fitted with a micrometer with a precision of 1 / 100mm and subsequent processing using TSAP software (Time Series Analysis Program, Rinntech, Heidelberg, Germany);
- grinding, weighing in suitable capsules for isotope analyses using an atomic mass spectrometer;

- microtome-cut sections, coloration of the thin sections with safranine, digital photographs for anatomical analysis.

At the same time, at the two most seriously damaged sites of Tschötsch and Schrambacher Leiten the soil was sampled with two profiles per site and at 6-8 different depths for examination of the necessary physical parameters (Fig.6).

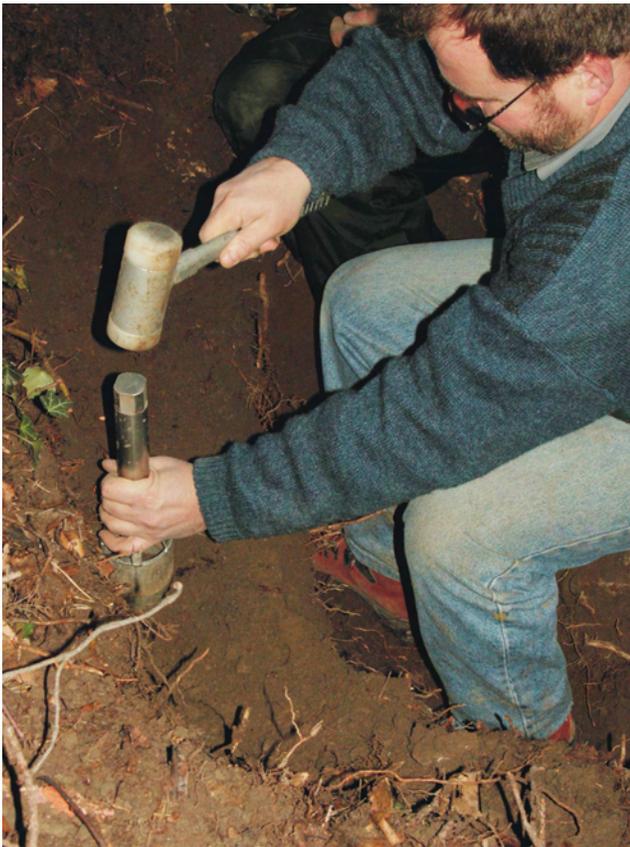


Fig. 6 a  
Soil sampling for analysis of the physical properties of the soil.



Fig. 6 b  
Soil profile at the Tschötsch experimental site.

Below are the details of the investigations:

Tab.2

<p><b>Dr. Alessandro Cescatti</b> CEA- Centre for Alpine Ecology I 38040 Viote del Monte Bondone (TN)</p>	<ul style="list-style-type: none"> <li>- historical analysis of the water balance of the 4 investigation sites based on Newhall's model (Soil Taxonomy) for the classification of the thermal and pluviometric regimes of the soil;</li> <li>- definition of a monthly water stress index starting from the water deficit and thermal stress data, based on the time series of meteorological data and available water capacity of the soil sampled where there were dead trees.</li> </ul>
<p><b>Dr. Paolo Cherubini</b> Forest Ecosystems and Ecological Risks Swiss Federal Institute for Forest, Snow &amp; Landscape Research (WSL) Zuercherstrasse 111 CH-8903 Birmensdorf</p> <p><b>Matthias Saurer, Rolf Siegwolf</b> Paul Scherrer Institut CH - 5232 Villigen PSI</p>	<ul style="list-style-type: none"> <li>- dendrochronological investigations; ring width analysis of the sample trees;</li> <li>- anatomical analysis of the wood using image analysis;</li> <li>- separate isotope composition analysis (<sup>12</sup>C, <sup>13</sup>C and <sup>18</sup>O) for the spring and summer wood of each growth ring as an indicator of stomatal conductance and water use efficiency (WUE) in the past.</li> </ul>
<p><b>Dipl. Ing. Dr. Gerhard Markart</b> Federal Research and Training Centre for Forests, Natural Hazards and Landscape (BFW) Rennweg 1 – Hofburg A-6020 Innsbruck</p>	<ul style="list-style-type: none"> <li>- soil type classification (FAO, Soil Taxonomy);</li> <li>- analysis of the physical properties of the soil on two profiles per site and 6 / 8 levels:</li> <li>- available water capacity: pF 2.7 – 4.2</li> <li>- granulometric / texture analysis.</li> </ul>
<p><b>Dr. Klaus Hellrigl</b> Entomologist and consultant for the forest health sector Wolkensteinstraße 83 I - 39042 Bressanone/Brixen</p>	<ul style="list-style-type: none"> <li>- plant pathology investigation and plant health assessment</li> </ul>
<p><b>p.i. Claudio Mutinelli</b> Autonomous Province of Bolzano/Bozen Hydrography Office Via Mendola 33 I - 39100 BOLZANO</p>	<ul style="list-style-type: none"> <li>- climatological database</li> </ul>
<p><b>Dr. Stefano Minerbi</b> Autonomous Province of Bolzano/Bozen Forest Department Via Brennero 6 I - 39100 Bolzano</p>	<ul style="list-style-type: none"> <li>- main vegetational features;</li> <li>- coordination and synthesis of results.</li> </ul>

## 2.4 Meteorology and climatology

For climatic analysis data for the mean monthly temperature and monthly precipitation of the meteorological stations of Bolzano and Bressa-

none were used (Tab.3). The data were provided by the Hydrographical Office of the Autonomous Province of Bolzano/Bozen.

Tab. 3

Location of the meteorological stations used for climate analysis and periods for which meteorological data are available.

Site	Elevation (m)	Coord Est (m)	Coord. Nord (m)	Temperature	Precipitation
Bolzano/Bozen	254	677493.7764	151961.1372	1926-2003	1921-2003
Bressanone/Brixen	560	703916.9644	177237.3594	1956-2003	1921-2003

The time series used shows the following interruptions:

Bolzano/Brixen 1944-1948

Bressanone/Brixen 1969-1971

The missing data were not replaced with interpolated data to avoid contaminating the time series with unmeasured data.

## 2.5 The hydrological balance (Newhall's model)

The meteorological and pedological data were used to reconstruct the time series of the hydrological balance of the investigation sites.

For this purpose the hydrological model developed by NEWHALL (1972) was used. This model is currently used by *Soil Taxonomy* of the United States to classify soil thermal-pluviometric regimes. The model works with a monthly time step and so it can be used with time series of mean monthly data such as those available for the sites under examination.

The model simulates water distribution in the soil using a humidity profile that extends from the surface down to a depth that guarantees an available water capacity of 200mm. However, the model is able to simulate the water behaviour of soils with an available water capacity lower than 200mm by using only a part of the humidity profile.

The water status of the soil profile is represented by a diagram for humidity consisting of a square matrix of components, each having an available capacity of 0.78mm. Two states are attributed to the individual components of the matrix: a condition of complete hydration and of complete dehydration. The model keeps in consideration the increase in energy (in terms of potential evaporation) necessary to extract humidity from the soil as a result of its progressive drying up, attributing a "potential" to the individual components of the matrix based on their position.

This "potential" represents the number of potential evaporation units necessary to evaporate a unity of humidity and ranges from 1 to 5.

The Newhall model requires the following input data:

- meteorological data (monthly mean temperature and precipitation values);
- topographical data (latitude, elevation, slope, aspect);
- pedological data (maximum available water content of soil, AWC).

In its output the model provides calculations of the following variables:

- potential evapotranspiration
- real evapotranspiration
- water deficit
- water reserves of the soil
- water surplus

The evaporative stress of the atmosphere (potential evaporation) is calculated on the basis of the radiative load (from topographical data) and temperature using THORNWAITE & MATHER'S algorithm (1955). Real evaporation for the site is calculated starting from potential evaporation and the soil water state. A detailed description of the hydrological model used for analysis is given in CESCATTI (1992).

The model was applied using the series of meteorological data of Bolzano and Bressanone and the information gathered with the pedological investigations at the sites in Tschötsch and Schrambacher Leiten.

## 2.6 Dendrochronological investigations

### 2.6.1 Measurement of ring widths

The samples were prepared in the laboratory as described above. For the transversal sections, two opposite radial directions were considered. Some measurements were repeated a number of times.

### 2.6.2 Cross-dating

The cross-dating method presupposes correspondence between the trend of the growth curves (relative periodic datum) of trees grown in analogous site conditions with regard to climate, social position, etc.

So excluding dead trees and considering all the trees that have completed the growth ring for the year 2003 (sampling having been carried out in the winter of 2003/2004), the latter can be taken as a common reference for comparison of the individual growth curves. A further aid is provided by the so-called “characteristic years”, that is, years in which the growth of most of the trees is considerably different from growth for the previous or following years. These sharp variations in the radial growth datum are shown by wider annual rings for positive characteristic years or narrower ones for negative characteristic years (SCHWEINGRUBER 1983).

The correspondence between these sequences of annual rings allows alignment (synchronization) of the growth curves of different trees for the same period.

By superimposing and visually comparing the plots of individual curves selected for quality and significance and placed on a light board (cross-dating), a provisional mean curve is obtained. This is a reference for the synchronization of further curves, which in their turn are integrated into it and consolidate it.

After the correction of any measurement errors due to mistakes or years with conditions extremely unfavourable for growth, (e.g. false rings or missing rings – CHERUBINI *et al.* 2002), the TSAP software plots a standard mean curve and calculates the relative correlated statistical parameters: *coefficient of coincidence*, *t of Student*, *period of superimposition*, *statistical reliability* (SCHWEINGRUBER 1983).

### 2.6.3 Anatomical analysis of the wood using image analysis

For each annual growth ring the effective area of tracheid lumen and of the cell walls is measured. The image of the cross-section, digitalised and enlarged with binocular magnification, suitably calibrated to obtain the surfaces in mm<sup>2</sup>, is first converted on the monitor into the scale of greys and then analysed using the image analysis program *Pro Image Plus*, able to distinguish between the cell walls (dark) and the lumen of tracheids (light).

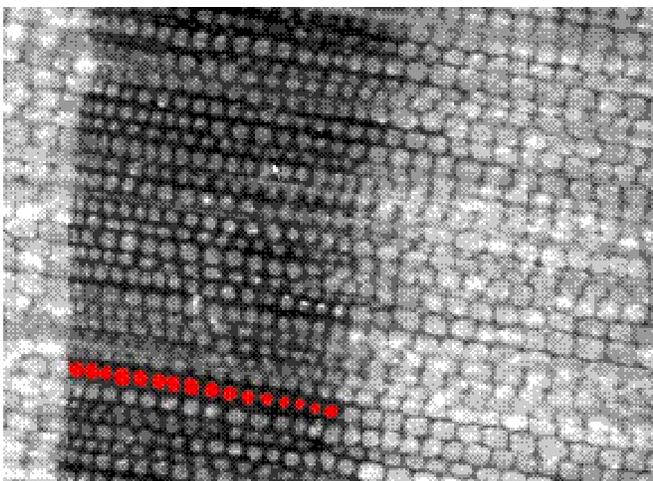


Fig. 7  
Tracheids in late wood (dark) and in early wood (light) of Scots pine (*Pinus sylvestris*).

## 2.7 Ecophysiology: analysis of the stable isotopes of carbon and oxygen

For the first time in South Tyrol use was made of an innovative methodology widely applied in plant ecophysiological studies, which examines the composition of the stable isotopes of carbon and oxygen (without radioactive decay) in the vegetal tissues.

By analyzing specific growth rings, isotopic discrimination makes it possible to ascertain the effects of environmental stress on stomatal conductance, photosynthetic and transpirative processes, carbon intake and the efficiency of water use throughout the plant's existence. This methodology is suitable above all for ascertaining the flows and exchange between the environment and ecosystems, in particular in the study of the biogeochemical cycles of carbon, water and nutrients.

Compared to other methodological processes, isotopic variations in wood growth rings have the advantage of limiting the various coacting factors to a small number.

Moreover information is obtained about site soil and atmospheric conditions (TREYDTE *et al.* 2001) and also about thermal fluctuations and variations in the amount of carbon dioxide in the atmosphere (SAURER *et al.* 2003). Thus for example the content of  $^{13}\text{C}$  in vegetal tissues is affected in first place by the availability of water for the vegetation, that is, by the level of humidity in the air and soil.

The material to be analysed was prepared at WSL (Birmensdorf, Switzerland), in order to

allow comparison of the isotopic relationship of each annual growth ring and the time series of the climatic data, adopting the "pooling technique". This provides a mean annual isotopic value, aggregated by plant groups (dead or living), as if the samples of individual trees had been measured separately and the mean had only been calculated afterwards. This makes it possible to considerably reduce analysis times, but does not allow definition of the standard deviation of each single value.

Before analysis, the rings of each sample tree were therefore separated physically (distinguishing between spring and late wood) with the help of a binocular microscope (Leica, WILD M3Z). In some cases this separation was not possible because of the very low growth rate. In this case the relative years or the whole sample were skipped.

For each sample area the individual samples of spring and late wood of the same year were then put together in a single sample for all the living and dead trees respectively. This was then finely ground with a type ZM 1 (Retsch) ultracentrifuge mill fitted with a sieve with a 0.5mm mesh screen.

The isotopic analyses using mass spectrometry were carried out at the Paul Scherrer Institute (Villigen, Switzerland): small copper cylinders were first filled with 0.6-0.8mg of each sample and then weighed and sealed.

The sections in the appendix briefly illustrate the technique and principles on which the methodology is based.

### 3 Results

#### 3.1 Pedological analysis

Information regarding the physical parameters for the texture and porosity of the forest soil, of fundamental importance for characterising hydric relationships and the definition of the hydrological balance of the sites, and in particular the relationship between water potential and water content, were acquired by the above-described pedological sampling at the Tschötsch and Schrambacher Leiten sites.

Both areas are characterised by soil on partly-terraced slopes of average depth with the presence of slope debris and outcrops of the underlying Bressanone Quarzophyllite geological substratum.

The typology of the soils examined is substantially homogeneous for the two sites: it is

brown soil, generally moder type at Schrambacher Leiten, ascribable to the *Oxisol-group* (US-Soil Taxonomy) or *Cambisol* (FAO classification).

While at Tschötsch there is an amphemull, at Schrambacher Leiten the humus layer is more similar to moor.

With regard to the size distribution of soil fractions, the Schrambacher Leiten site has a greater amount of rock (38% compared with 23% for Tschötsch), which is already abundant in the surface layers. The high rock fraction of the Schrambacher Leiten site reduces its porosity (24% compared with 41% for Tschötsch) and consequently its available water holding capacity.

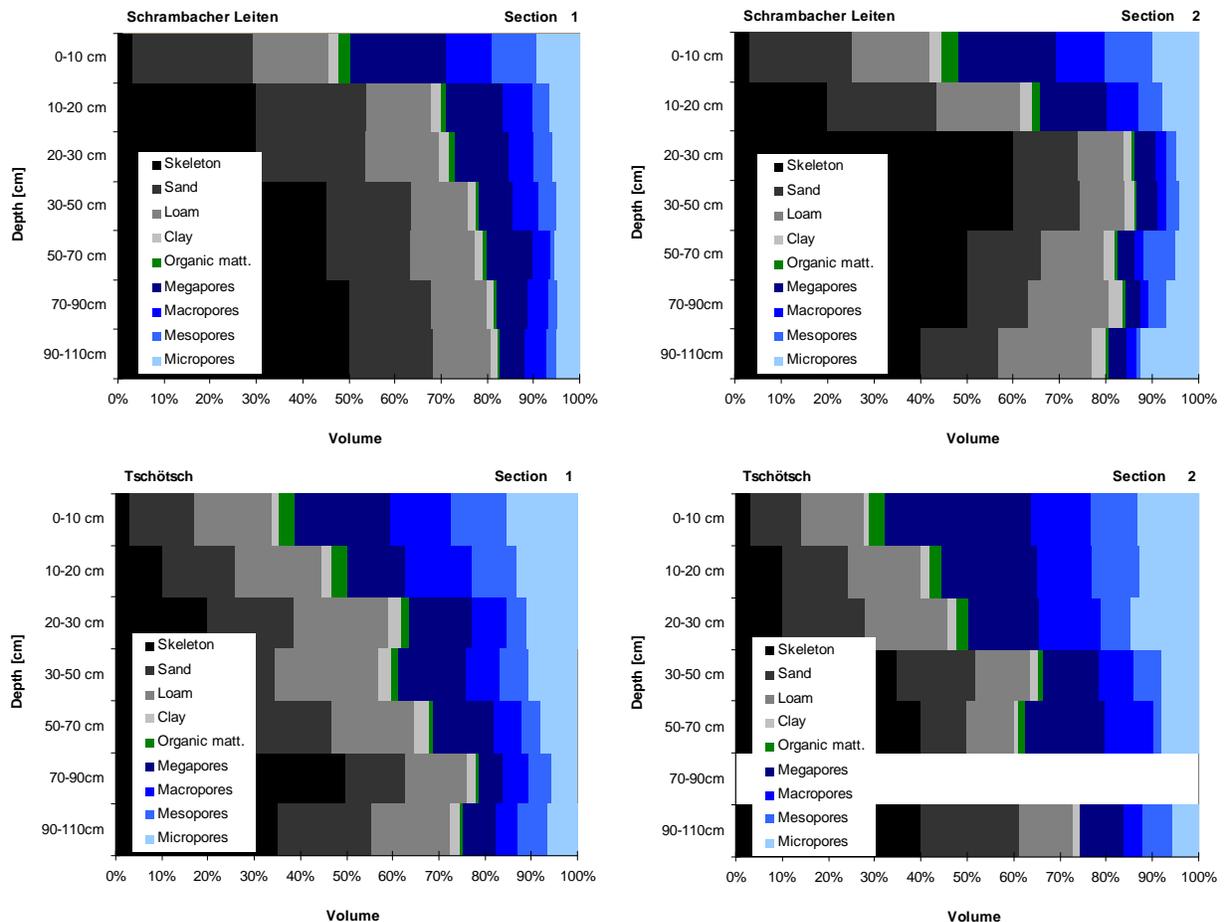


Fig. 8 Distribution in size classes of soil volume fractions in the two experimental areas of Schrambacher Leiten e Tschötsch

Fig. 9  
Frequency distribution of soil texture and porosity in the two experimental plots (averages of two profiles are shown). The richness in silt at Tschötsch justifies the abundance of macro and mesopores in this area.

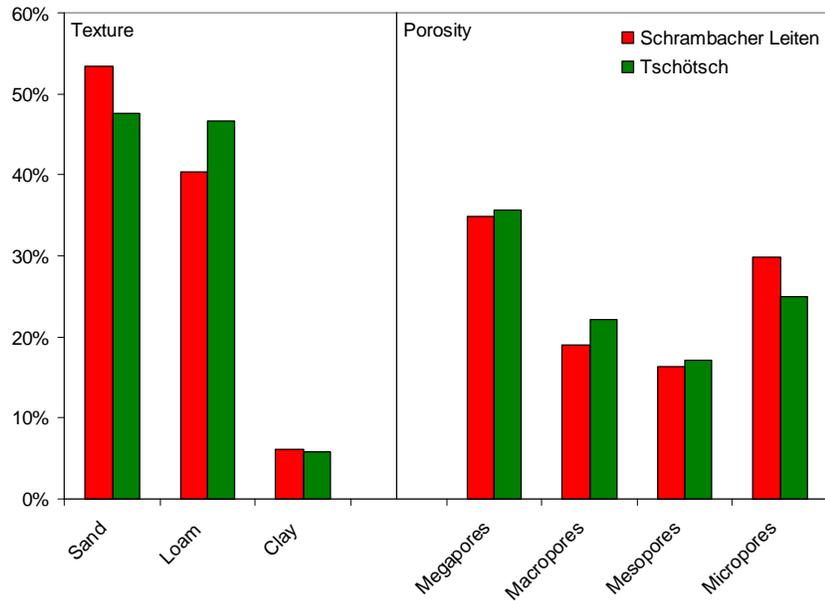
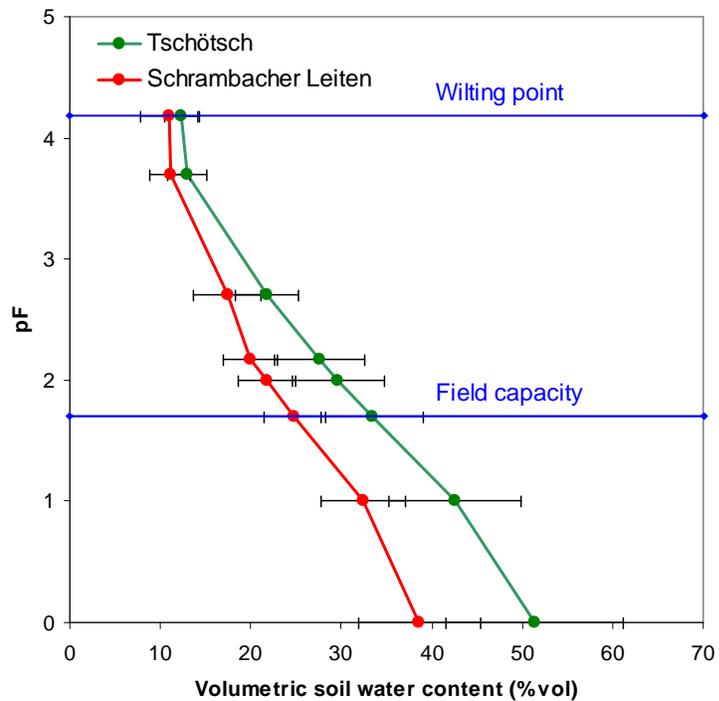


Fig. 10  
Relationship between soil water content and soil water potential (pF, avg  $\pm$  st.dev) in the two experimental plots. Thanks to the lower rock fraction and favourable texture (Fig. 9) the Tschötsch site shows a higher water holding capacity than Schrambacher Leiten.



The water available for vegetation is that held by the soil, with a potential ranging between the field capacity (pF 1.7) and the wilting point (4.2). In terms of volume, this was found to be 21.2% of the soil volume for the Tschötsch site and 13.8% for the Schrambacher Leiten site, that

is, 63% and 55% respectively of the field capacity. The higher percentage of the field capacity available for root absorption in the Tschötsch site is due to its higher silt content, which allows a greater abundance of macro- and micropores (cf. Fig.9).

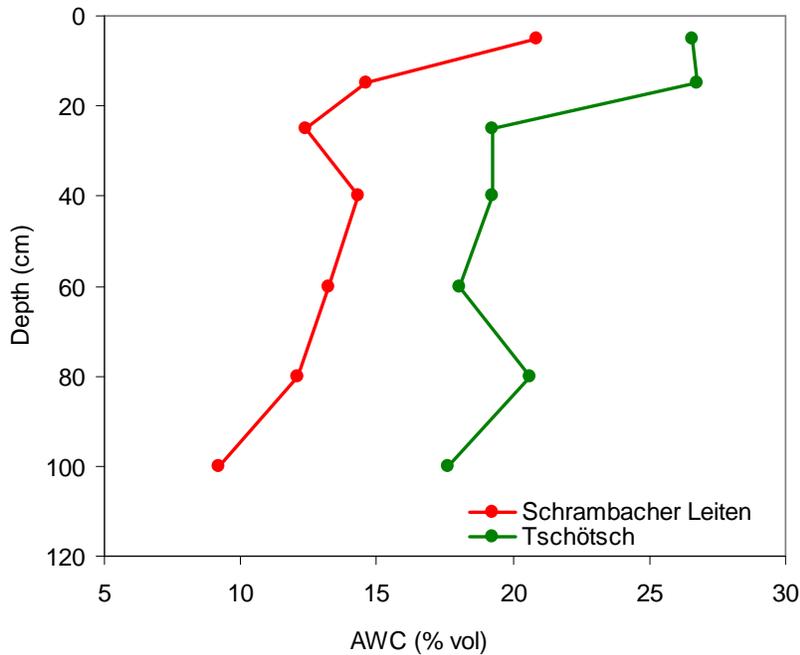


Fig. 11  
Vertical profile of available water capacity (AWC) in a range of potential between the field capacity (pF 1.7) and the wilting point (pF 4.2).

Using the data for the vertical profile of available water capacity (AWC) given in Fig.13, the AWC values cumulated over the whole profile (Tab.4) were calculated in mm of water.

As can be observed, the soil at the Tschötsch site has maximum water reserves of **203mm** compared to **146mm** at Schrambacher Leiten.

Tab. 4  
Values of Available Water Capacity (AWC) observed at the two experimental plots.

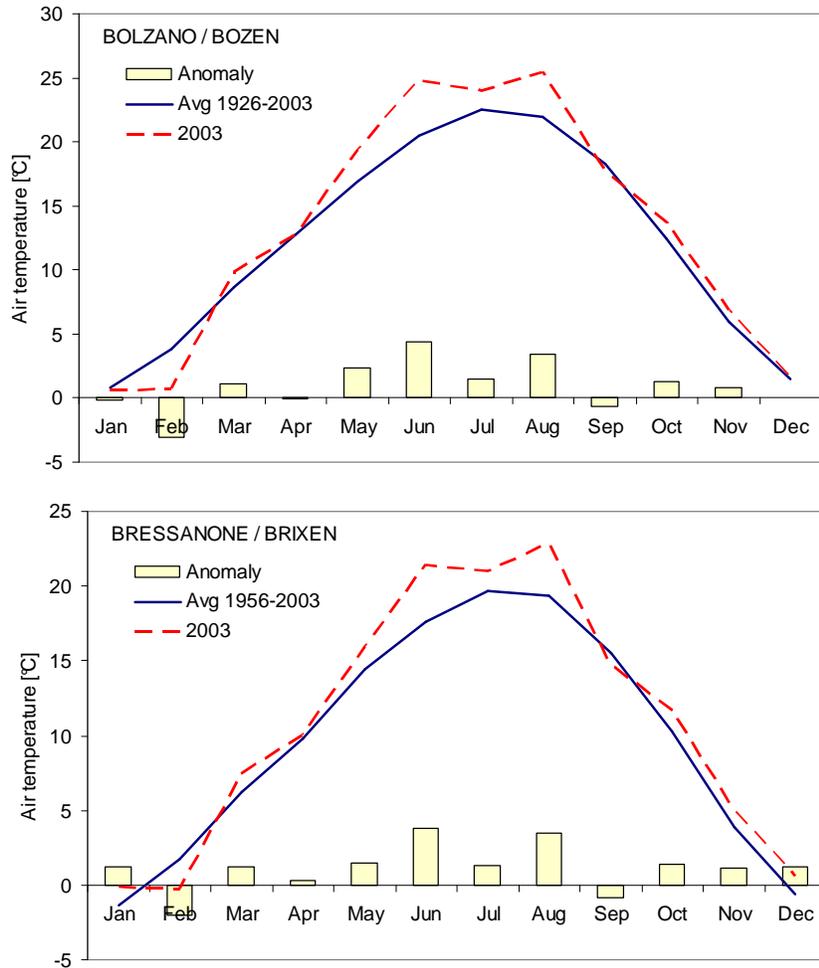
Experimental sites	Profile 1	Profile 2	Average
Tschötsch	216.62	189.26	202.94
Schrambacher Leiten	152.54	138.56	145.55

### 3.2 Climate analysis

The summer of 2003 was characterised by prolonged heatwaves throughout the European continent accompanied by rather scarce precipitations, which caused widespread drought. The extent to which this climatic event was exceptional for climatology in the province of Bolzano was evaluated using the data recorded at the meteorological stations of Bolzano, which has the longest time series (1926-2003) among those near the study area,

and Bressanone, which is the nearest to the dying tree stands. By comparing the mean monthly temperatures in 2003 with the mean for the whole of the long period (Fig.12), a strong thermal anomaly of 1.5 – 4.4°C during the summer months can be observed. As well as the particular intensity of the thermal anomaly, its duration is also to be noted (four months from May to August).

Fig. 12  
Trends of monthly mean temperatures in the period 1926 -2003 and of the year 2003 for the meteorological station of Bolzano, and of the period 1956 -2003 for the meteorological station of Bressanone. Yellow bars show the 2003 temperature anomaly that during May-August varied between 1.5 and 4.4 °C.



From analysis of the time series, the period May-August 2003 was found to be the warmest since recordings of meteorological data began at both the Bolzano station and that of Bressanone (Figs.13, 14). Moreover, from sorting of the warmest years it seems clear that there has been

a considerable increase in summer temperatures in the last ten years, so much so that in Bolzano eight of the thirteen warmest years since 1926 and in Bressanone ten of the fifteen with the warmest summers since 1956 fall within the period 1993-2003.

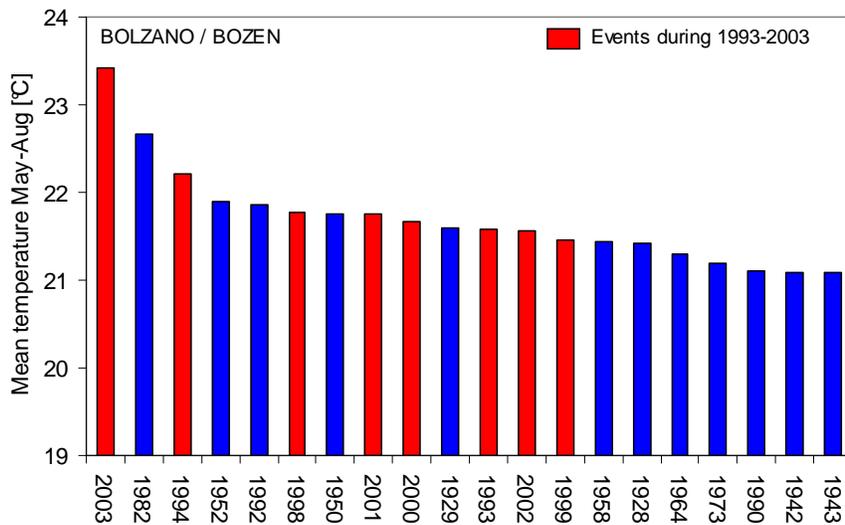


Fig. 13  
Sorting of years between 1926 and 2003 for the mean temperature of the period May-August at the meteorological station of Bolzano. Eight of the thirteen warmest years since 1926 occurred in the last decade (red bars).

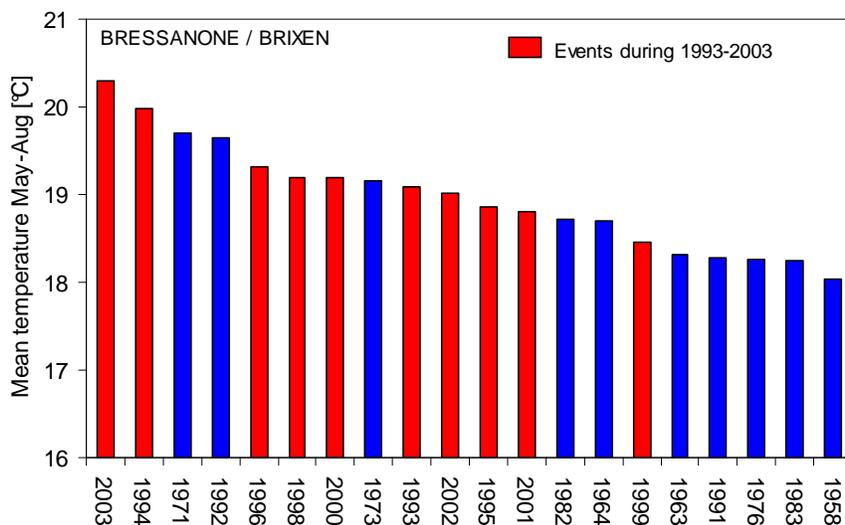


Fig. 14  
Sorting of years between 1956 and 2003 for the mean temperature of the period May-August at the meteorological station of Bressanone. Ten out of the fifteen warmest years since 1926 occurred in the last decade (red bars).

Thermal conditions during the most important period for tree growth (May-August) have therefore changed considerably in the last ten years.

The monthly values shown in Fig.15 show how 2003 summer precipitations were below average

for both the Bolzano and Bressanone stations, with the single exception of the month of July. Altogether in the period May-August, precipitations in 2003 were only 65% of mean precipitation, followed by a particularly dry September (precipitations 16% of the average).

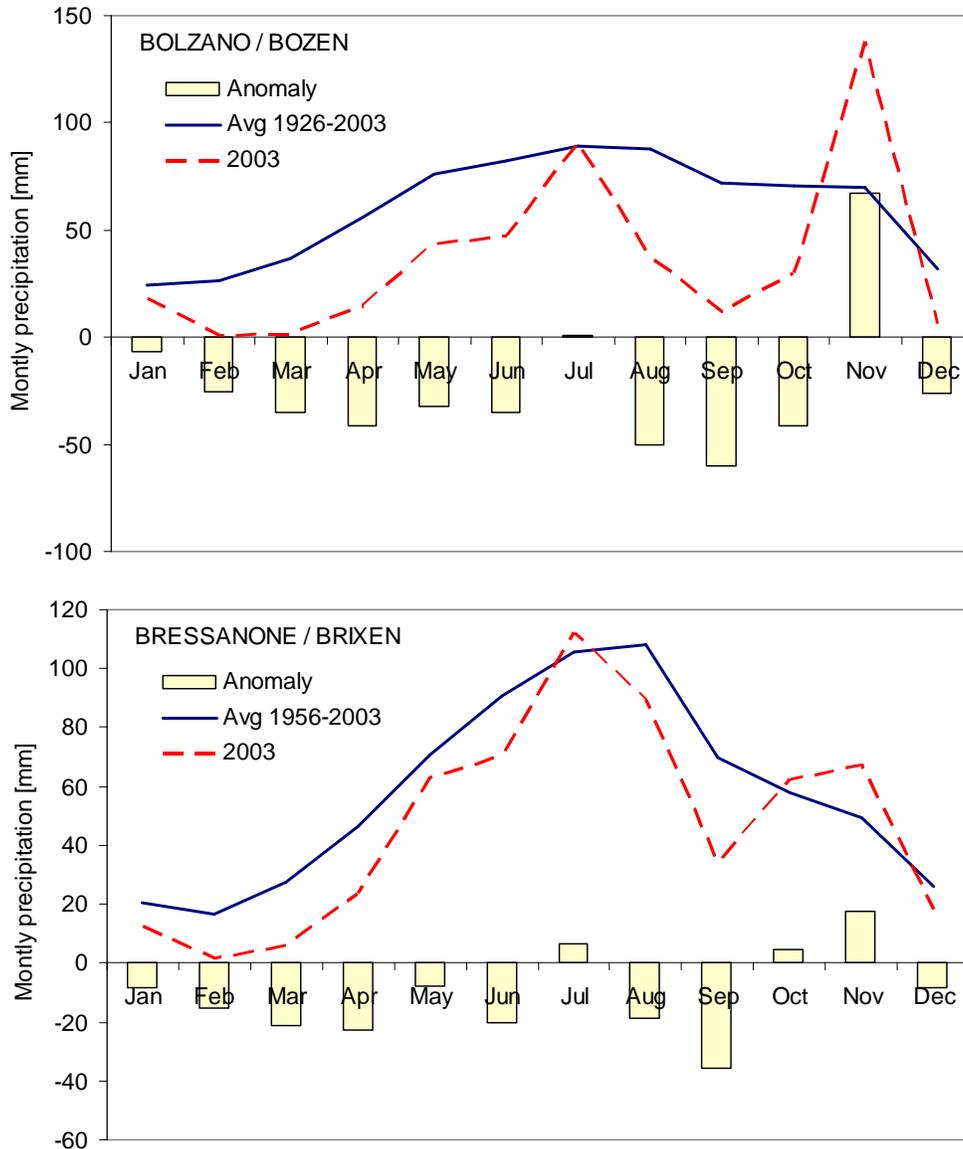


Fig. 15 Trends of the mean monthly precipitation for the period 1926 -2003 and of the monthly precipitation of 2003 at the meteorological station of Bolzano and for the period 1956 -2003 at the station of Bressanone. Yellow bars show the 2003 precipitation anomaly, which varied from -50 to 1 mm during May-August. Precipitation in Bolzano in 2003 was 439 mm in comparison with a long-term average of 724 mm (reduction of 40 %), and of 560 mm in comparison with an average of 690 mm at Bressanone.

In Bolzano the summer of 2003 was therefore the second driest since recordings began, while in Bressanone it is only in fourteenth place. In contrast with temperature observations, the rising order of rainy summers shown in Figs. 16 and 17 shows that the last ten years were

not characterised by particularly dry summers. So a trend of abundant summer precipitations is associated with the general trend of warming observed in the last ten years (progressive oceanisation of the climate).

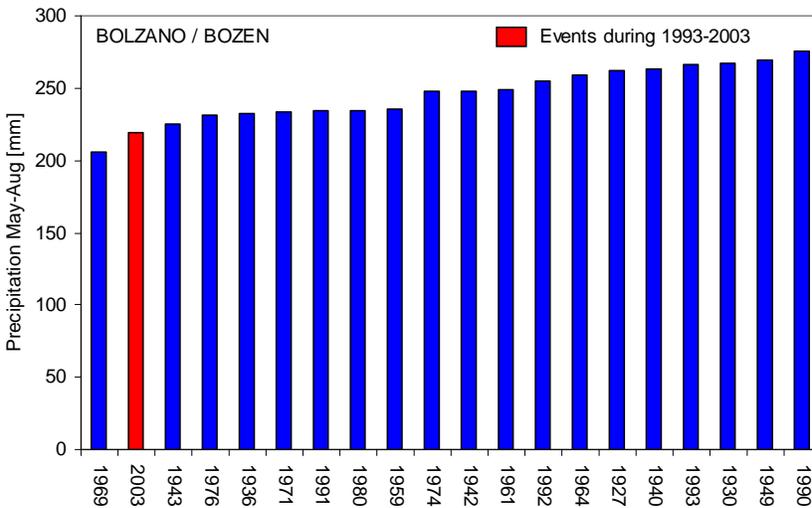


Fig. 16  
Sorting of years for the precipitation of the period May- August between 1926 -2003 at the meteorological station of Bolzano. Only 2003 in the last decade falls within the 20 driest summers (red bar).

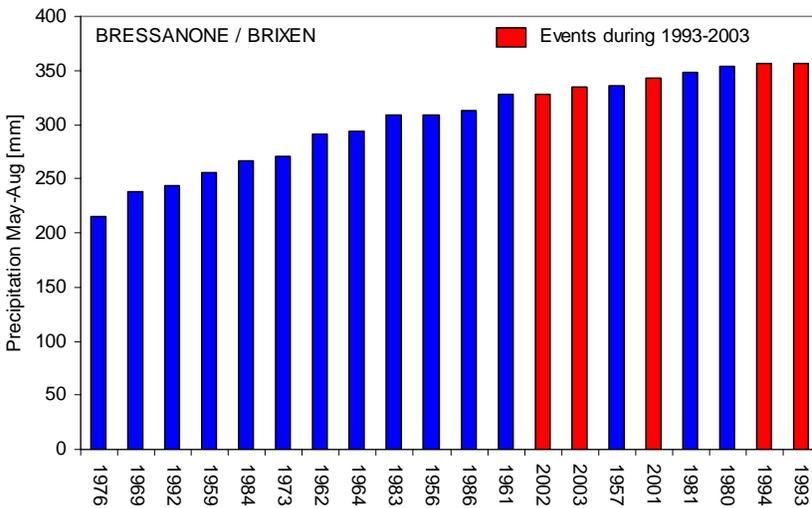
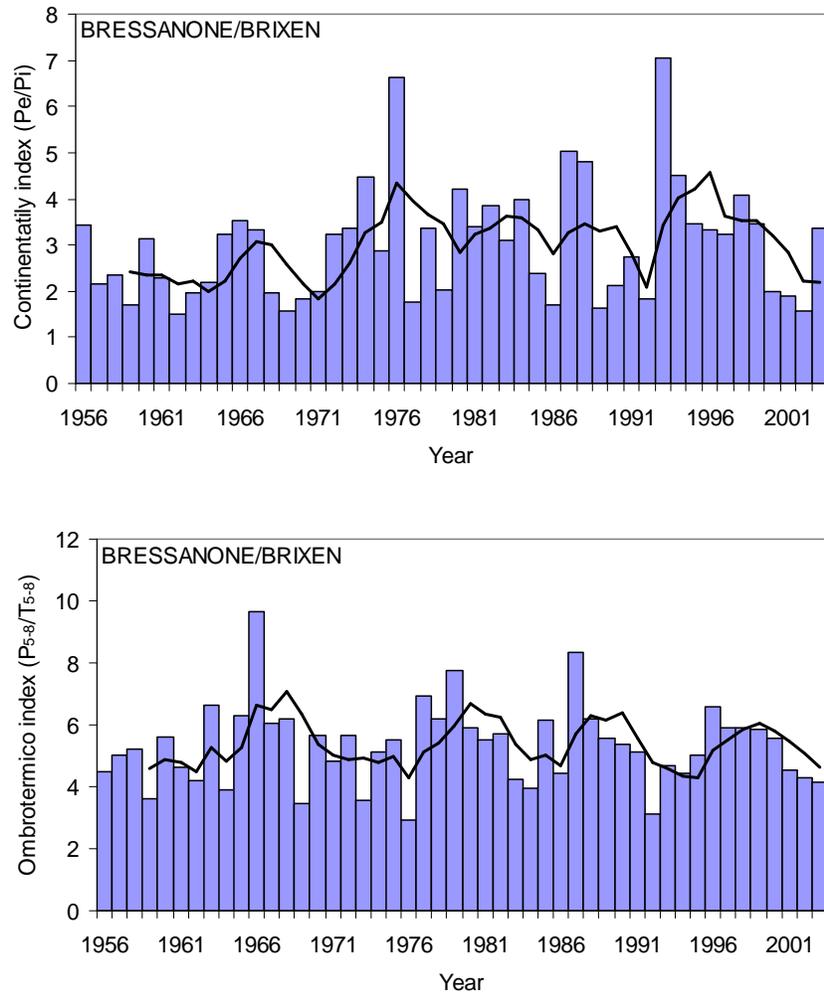


Fig. 17  
Sorting of years for the precipitation of the period May- August between 1956- 2003 at the meteorological station of Bressanone.

The variation in the seasonal distribution of precipitations was examined using the pluviol continentality index, given by the relationship between summer precipitations (May-October) and winter precipitations (November-April). The index is interpreted assuming a prealpine distribution for values below 1.45, alpine in the 1.45-2.25 range and intra-alpine for values above 2.25. As can be observed in Fig.18, precipitations in the Bressanone area vary

between periods with a typically intra-alpine distribution to others with a prealpine distribution. The time series shows how the 1990s were characterised by marked “continentality” of precipitation distribution while the first years of the 21<sup>st</sup> century show index values typical of a prealpine situation. Moreover, the moving average trend shows that the changeover from one kind of distribution to the other typically seems to occur in a cycle of about 10 years.

Fig. 18  
 Time series and moving averages (four-year interval) of the continentality climatic index and of the umbrothermic index for the period May-August.



The second climate index shown in Fig.18 is given by the relationship between precipitations and the mean temperature in the period May-August. This relationship defines the summer umbrothermic index of Rivas-Martinez (RIVAS-MARTINEZ 1990) and makes it possible to give a synthetic representation of the relationship between water availability and evaporative stress. Index values below 3.5 indicate a xeric climate while values above 6 indicate a humid climate.

The time series given in Fig.18 shows how 2003 was the third consecutive year with an index value below 4.5 while the previous decade was characterised by a much higher index, one typical of subhumid climates. This index confirms the observations made from temperature and precipitation trends, that is, that

2003 was characterised by an exceptionally warm and dry summer after a decade of warm but relatively humid summers, thanks to an intra-alpine type of precipitation distribution (summer maximum).

A more detailed analysis of the climatology of the areas affected by dieback was developed with the application of Newhall's water balance model, which can simulate the evapotranspirative process and soil water conditions.

Fig.19 gives the historical trend in the last twenty years (1983-2003) of the main variables in the balance, in particular the mean temperature and summer precipitation, and the simulated values for water deficit and real evapotranspiration in the period May-August.

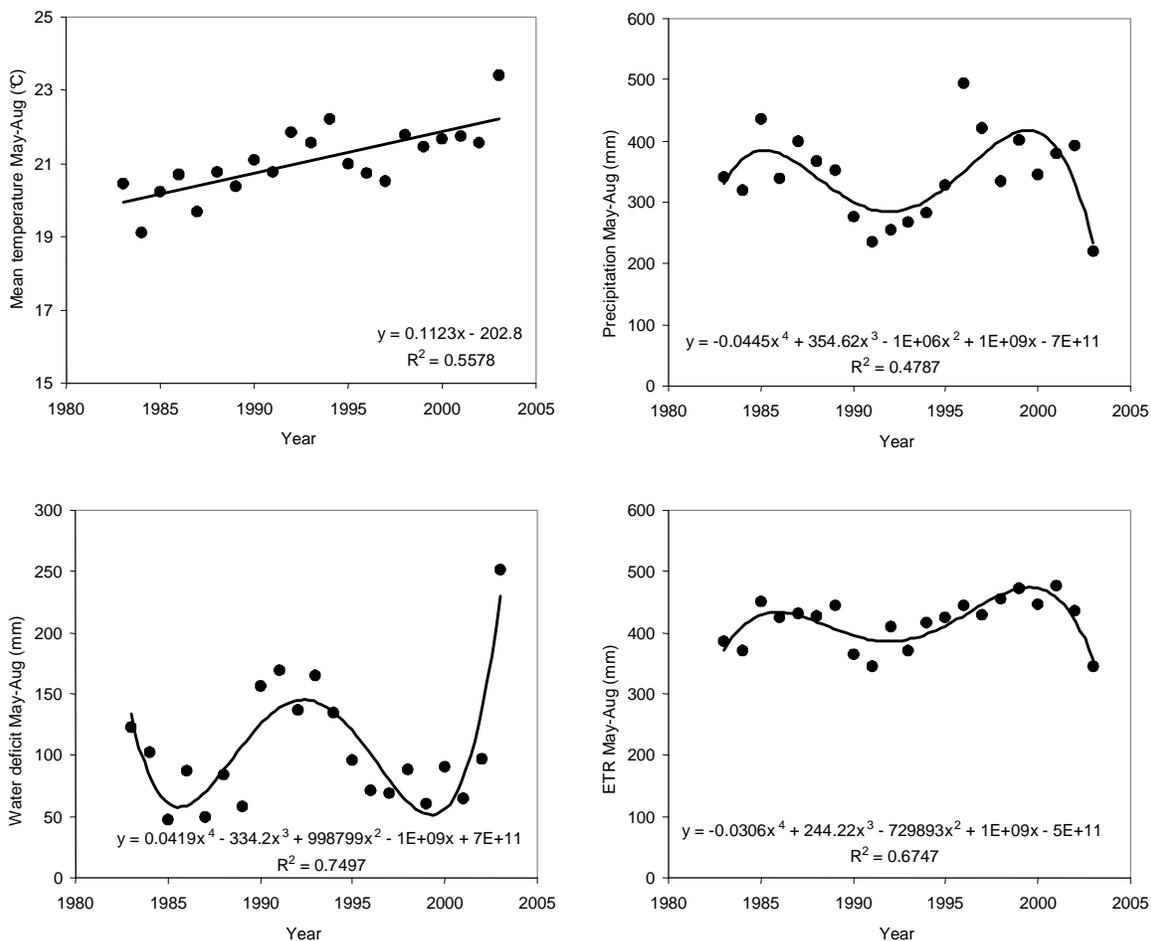


Fig. 19  
Time series of temperature, precipitation and parameters of the water balance during the period 1983-2003 at the meteorological station of Bolzano.

The strong and significant upward trend in summer temperatures in the twenty-year period ( $R^2 = 0.55$ ) combined with a cyclical trend in summer precipitation, with a minimum at the beginning of the 1990s and a second minimum in 2003, resulted in a severe water deficit in the early 1990s and a particularly intense water deficit event (about 250mm of water) in 2003. With regard to the potential effects of these periods of water stress on the state of health of forest formations, it must be remembered that in

the Alps the early 1990s were characterised by widespread cases of dying trees and by parasitic attacks by hymenoptera of the genus *Cephalcia* and the moth black arches, *Lymantria Monacha* (MARCHISIO, 1994).

Figs.20-21 show the mean water balance and that for 2003 at the Schrambacher Leiten station calculated on the basis of the results of pedological investigations and using the meteorological series of Bolzano.

	Gen	Feb	Mar	Apr	Mag	Giù	Lug	Agò	Set	Ott	Nov	Dic	ANNO
Temperature medie	0.8	3.9	8.7	12.8	16.9	20.5	22.5	22.0	18.3	12.5	6.0	1.5	12.2
ETP	1	8	32	58	98	128	147	131	88	47	14	2	755
Precipitazioni	25	26	37	56	76	82	89	88	72	71	70	32	724
Riserve	145	145	139	130	113	81	52	41	41	67	123	145	
Variazioni riserve	0	0	-6	-9	-17	-32	-29	-12	1	26	55	23	
ETR	1	8	31	58	93	115	118	99	71	45	14	2	655
Deficit idrico	0	0	1	0	4	14	29	32	17	2	0	0	99
Surplus	23	18	12	7	0	0	0	0	0	0	0	7	69

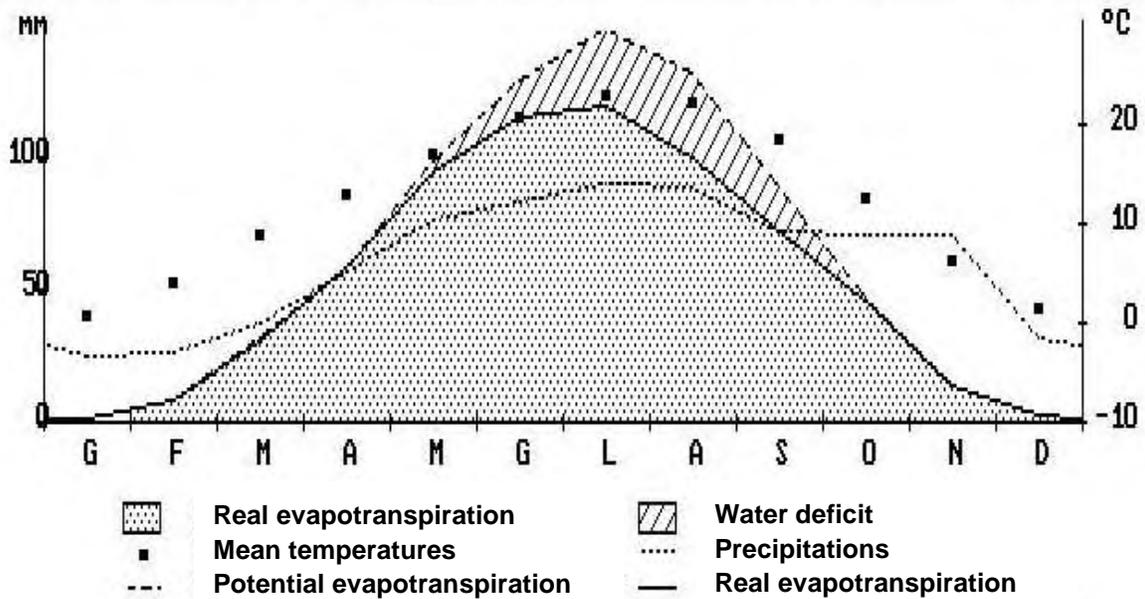
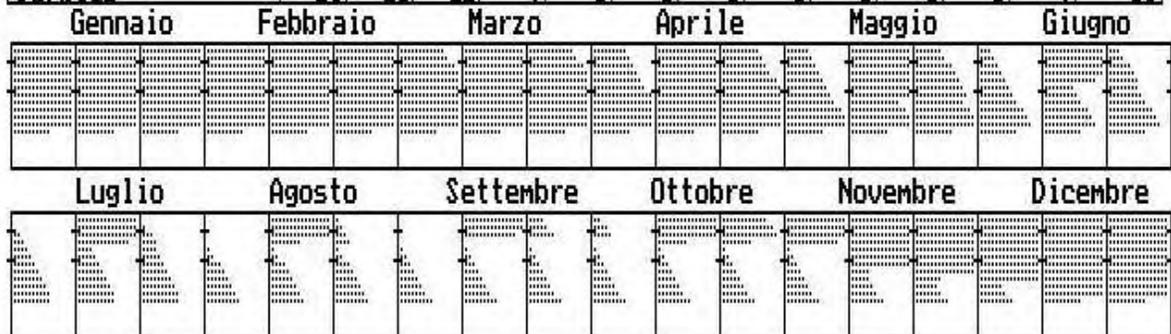


Fig. 20  
Average water balance for the period 1923-2003 at the Schrambacher Leiten experimental site, according to the meteorological data of Bolzano

By comparing the data of Fig.20 and that of Fig.21, it seems clear how on average the climatology of the Schrambacher Leiten station is able to guarantee sufficient water in summer to keep water reserves in the soil above 40mm. In contrast, during 2003 the lack of spring precipitations resulted in a considerable reduction in water reserves from the beginning of summer, when high temperatures combined

with scarce precipitations resulted in prolonged drying up of the soil (July-October). In this situation of extreme drought, only those trees with root systems most developed in cracks in the soil and a more balanced relationship between root systems and photosynthesising surfaces were able to stand the severe water stress.

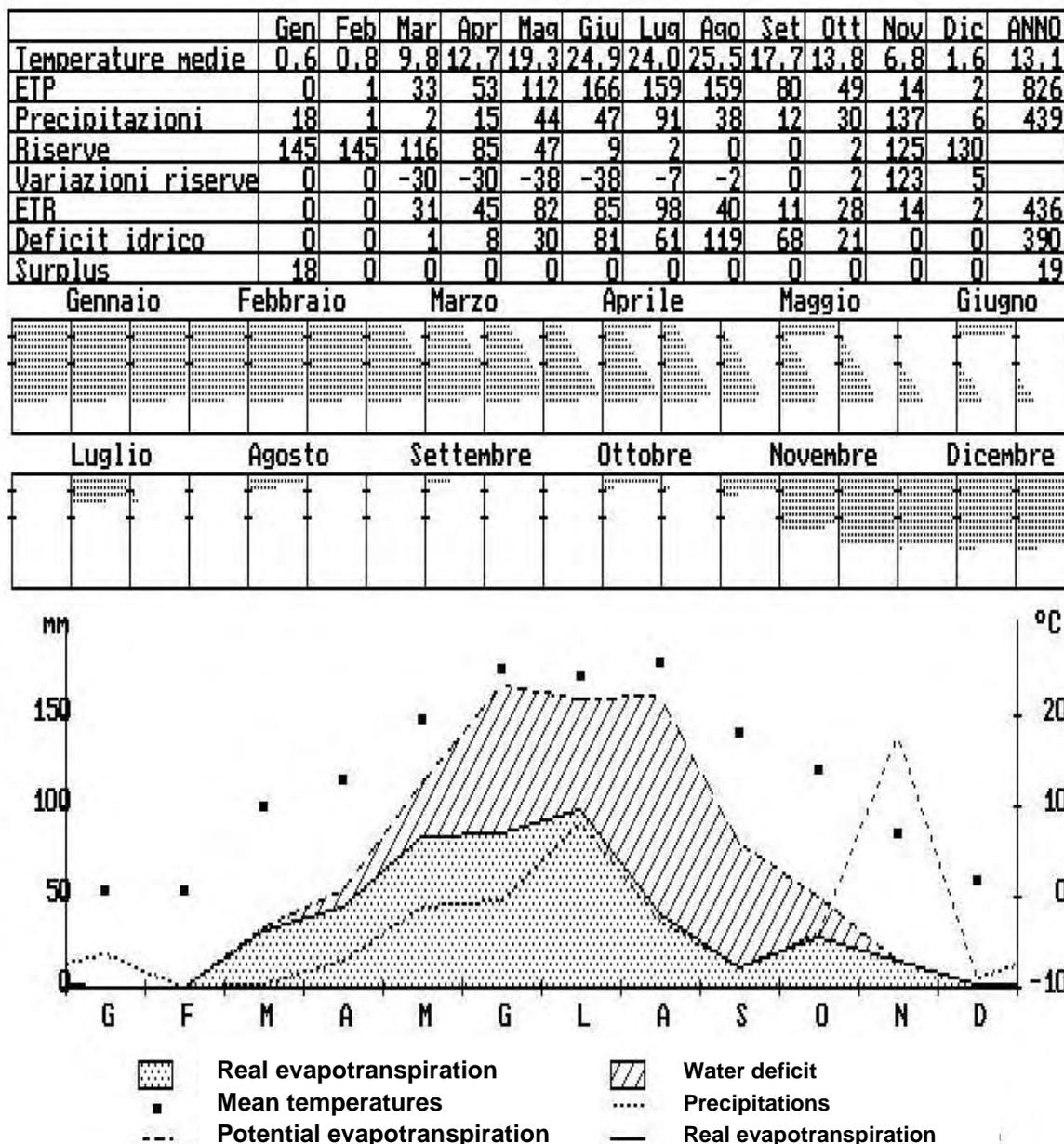


Fig. 21 Water balance for the year 2003 at the Schrambacher Leiten experimental site, according to the meteorological data of Bolzano.

Fig.22 gives the data for the mean water balance for the Schrambacher Leiten station for the period 1956-2003 and Fig.23 the balance for 2003 using the meteorology of the Bressanone station.

On average it was found that the Schrambacher Leiten site is not affected by severe summer water stress and that the control plot (area with

maximum root absorption) of the pedological profile is always supplied with water. In 2003 the persistence of high evaporative stress caused by the high temperature led to the complete emptying of the control plot in late summer. It is precisely the great difference in the soil water regime in 2003 from the average situation that may have led to dieback in the Scots pine stands.

	Gen	Feb	Mar	Apr	Mag	Giu	Lug	Ago	Set	Ott	Nov	Dic	ANNO
Temperature medie	-1.4	1.8	6.2	9.8	14.5	17.6	19.7	19.3	15.5	10.3	3.9	-0.6	9.7
ETP	0	5	27	49	88	112	129	116	77	43	12	0	658
Precipitazioni	21	17	27	46	71	91	106	108	70	58	49	26	689
Riserve	145	145	139	133	118	103	91	93	91	106	144	145	
Variazioni riserve	0	0	-6	-6	-15	-15	-12	2	-2	16	38	2	
ETR	0	5	26	48	85	105	118	106	72	42	12	0	620
Deficit idrico	0	0	0	1	3	7	11	10	5	1	0	0	38
Surplus	20	12	7	4	0	0	0	0	0	0	0	25	69

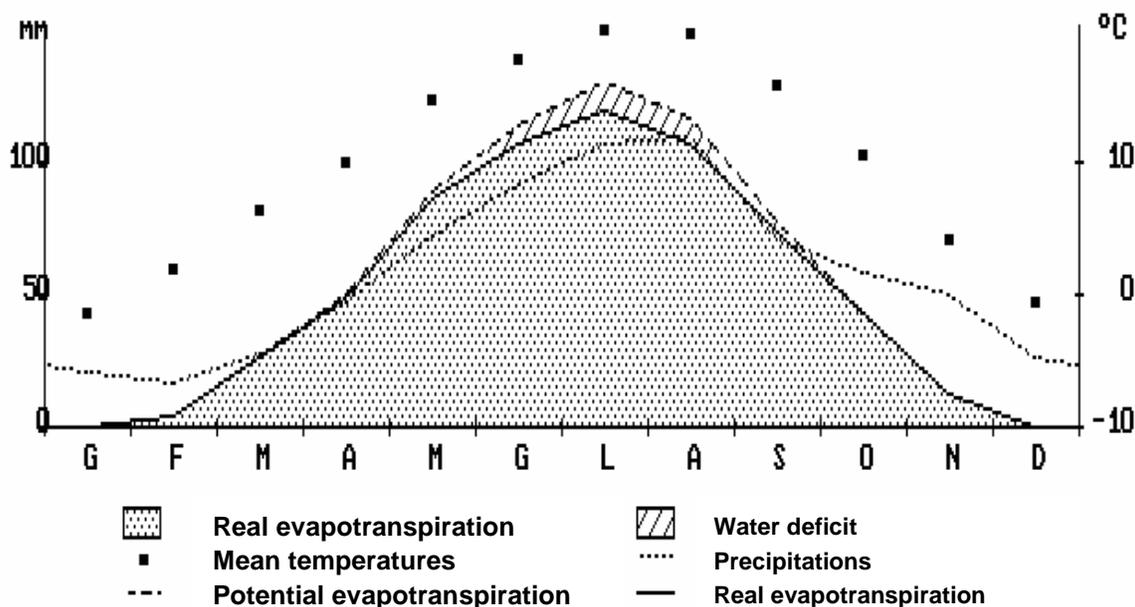
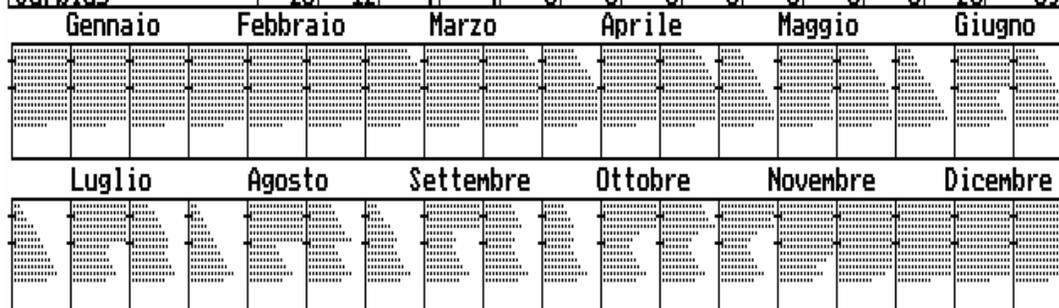


Fig. 22 Average water balance for the period 1956-2003 at the Schrambacher Leiten experimental site, according to the meteorological data of Bressanone.

	Gen	Feb	Mar	Apr	Mag	Giu	Lug	Ago	Set	Ott	Nov	Dic	ANNO
Temperature medie	-0.1	-0.3	7.5	10.1	15.9	21.4	21.0	22.8	14.7	11.7	5.0	0.6	10.9
ETP	0	0	29	46	94	139	137	139	69	46	13	1	712
Precipitazioni	12	2	6	24	63	70	112	89	34	62	67	18	560
Riserve	145	145	123	104	83	47	50	33	22	44	98	114	
Variazioni riserve	0	0	-22	-20	-21	-36	3	-17	-11	22	54	16	
ETR	0	0	28	43	84	106	109	106	45	41	13	1	577
Deficit idrico	0	0	1	3	10	32	27	33	23	6	0	0	135
Surplus	12	2	0	0	0	0	0	0	0	0	0	1	15

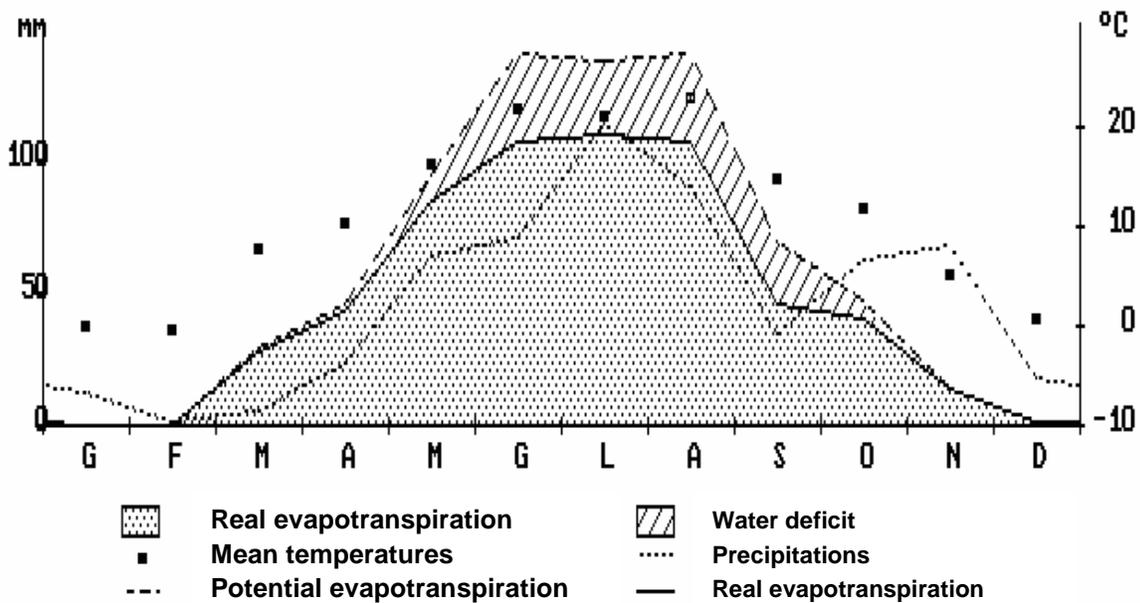
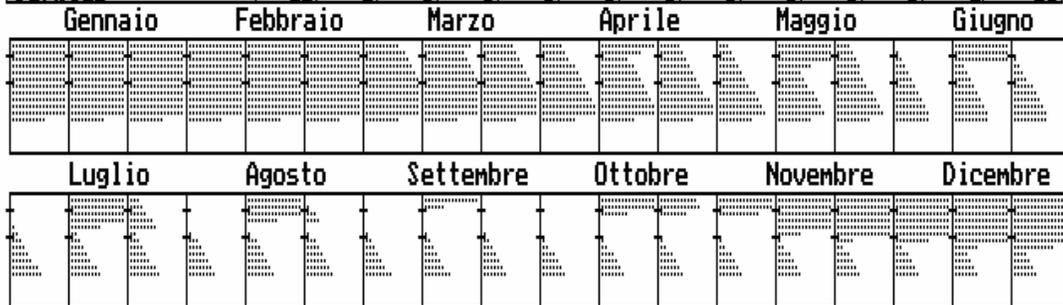


Fig. 23  
Water balance for the year 2003 at the Schrambacher Leiten experimental site, according to the meteorological data of Bressanone.

The mean value of the water deficit (the difference between potential evaporation and real evaporation) observed in the period 1926-2003 at the Bolzano station and in the period 1956-2003 at the Bressanone station was compared with the deficit observed

in 2003 (Fig.24). The anomaly between the long term average and the summer of 2003 is of almost 80mm in June and August in Bolzano and of 18mm in Bressanone, so great as to create the highest water deficit value for the period May-August since records.

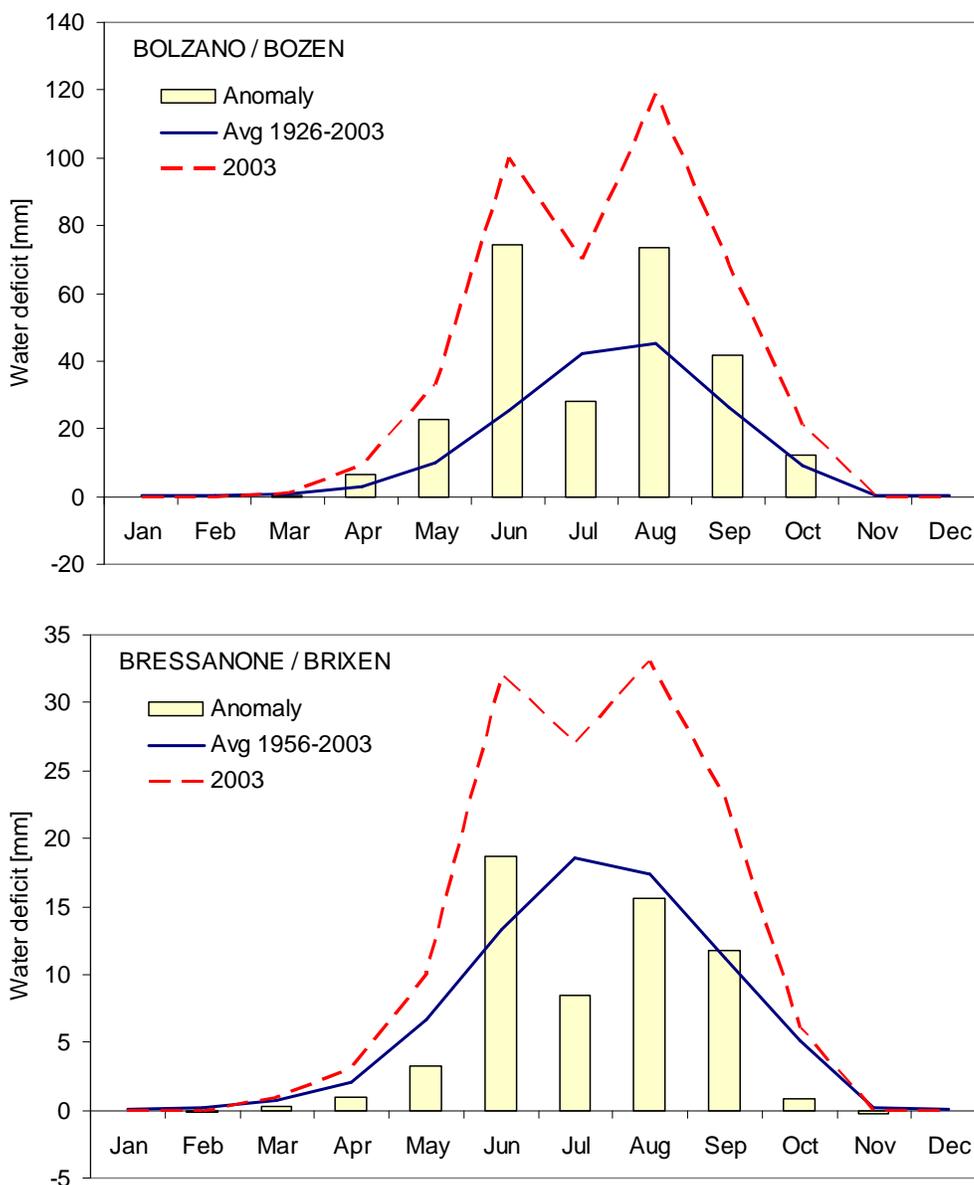


Fig. 24 Trends of the mean monthly water deficit for the period 1926 -2003 at the Bolzano station and for the period 1956 -2003 at the Bressanone station. Yellow bars show the 2003 anomaly that, during May-August, ranged from 23 to 73 mm.

From analysis of the Bolzano series, sorted by the years with the highest summer water deficit values since 1926, apart from 2003, in the last decade only 1993 and 1994 fall within the twenty driest years. This fact confirms the observations based on thermal and pluviometric trends and on climate indices.

2003 was characterised by a very severe water deficit that followed a decade of vegetative seasons characterised by good water availability in spite of the upward trend of summer temperatures (Fig.26).

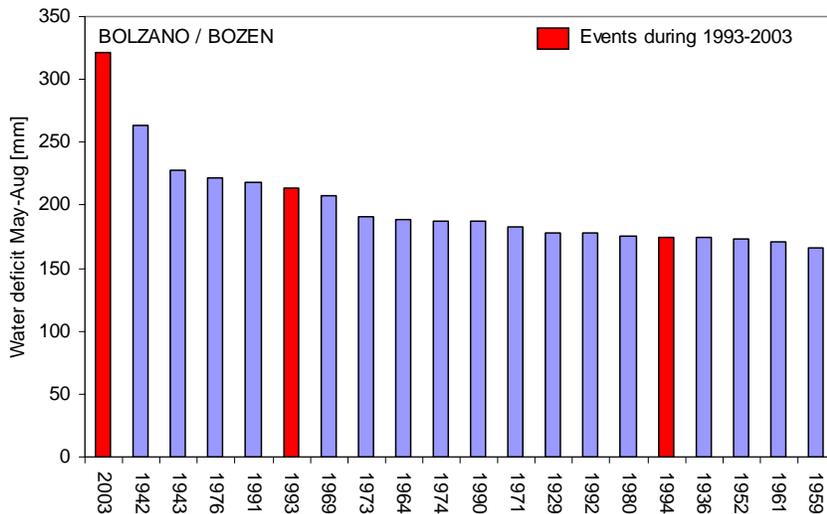


Fig. 25  
Sorting of the year 1926-2003 for decreasing water stress in the period May-August at the Bolzano station and of the year 1956 -2003 at the Bressanone station. 2003 was the driest year since 1926 in Bolzano (-322 mm) and the fifth driest year since 1956 in Bressanone.

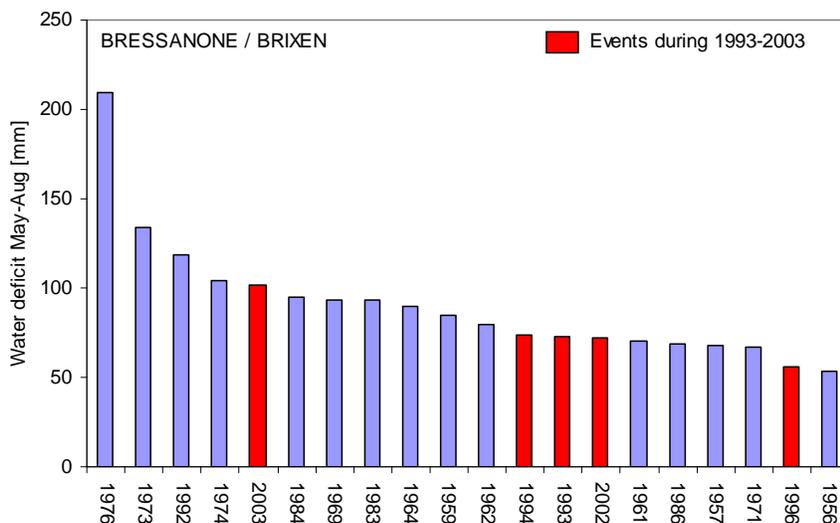
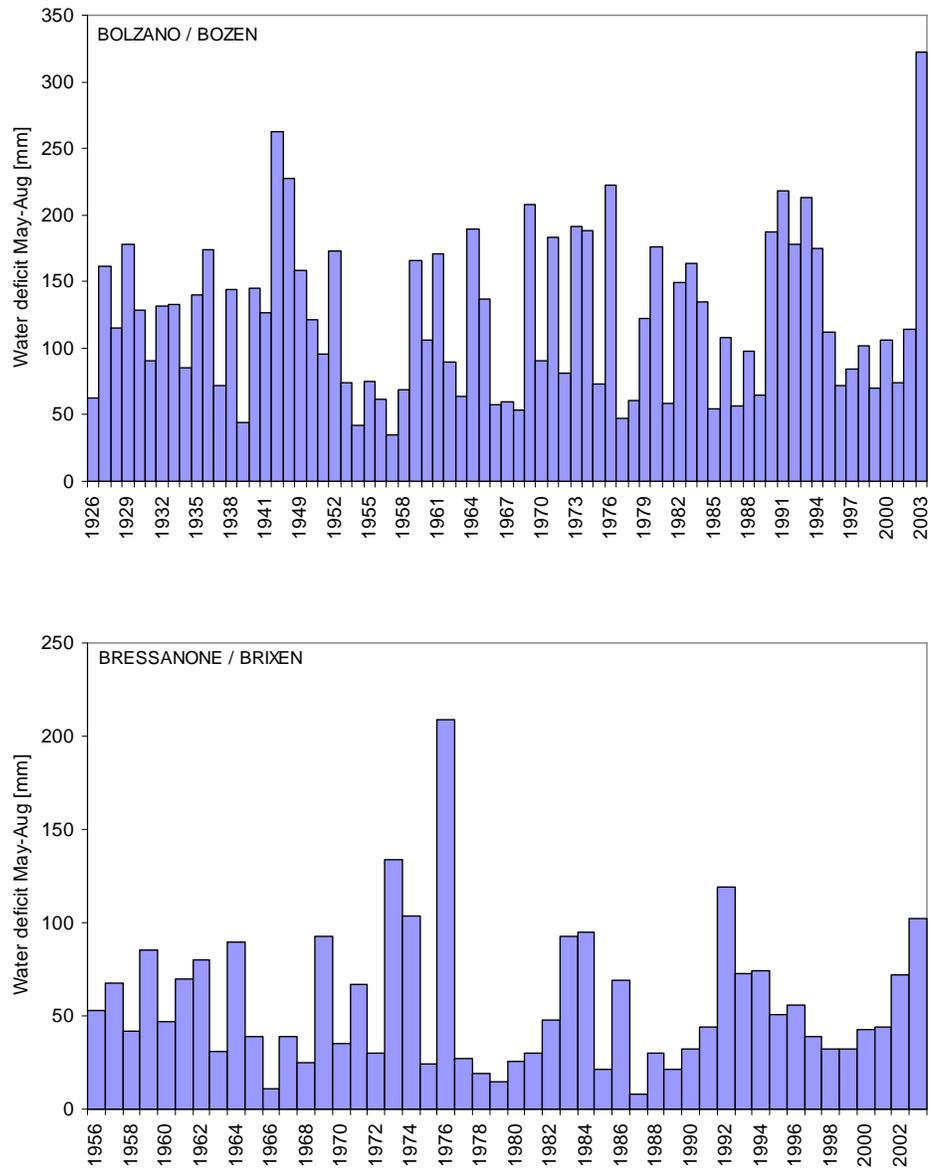


Fig. 26  
 Time series of water deficit (May-August) for the period 1926-2003 at the meteorological station of Bolzano and for the period 1956-2003 at the meteorological station of Bressanone.



To summarize, from the analysis of climate trends at the study areas, the following emerges. In the last twenty years a trend of significant increase in mean summer temperatures was observed (Fig.19), to the extent that of the 13 years with the warmest summers since 1926, no fewer than 8 fall within the last decade. (Figs.13 – 14). During 2003 the thermal anomaly in summer was particularly large (1.5 – 4.4°C during the summer months; Fig.12), so much so that the average temperature for the months May-August was 3°C higher than the long-term average (23.4 instead of 20.4 for the period 1926-2003).

The upward trend in the summer temperature in the last decade was offset by good water availability, so much so that only 2003 falls within the twenty driest summers since 1926 (Fig.16). The pluviometric regime in the 1990s was characterised by continental distribution, while in the first years of the 21<sup>st</sup> century this has changed to equinoctial distribution, typical of intra-alpine areas (Fig.18). Good water availability in the 1990s guaranteed a sub-humid climate.

In general, while the last decade had warmer than average summers, but with a tendency to greater

humidity, the combination of high temperature and, in countertendency, low rainfall, resulted in a vegetative season typical of xeric climates (Fig.18). The precipitation anomaly in the summer of 2003 amounts to a reduction of 40% of mean long-term water availability.

The application of a detailed water balance model showed that in 2003 the combined effect of high temperature and low precipitation caused conditions

of severe stress for vegetation, with a water stress that in the four months May-August exceeded 300mm, compared with a long-term average of 123 (Fig.24). This concurrence of events brought about the most marked period of water stress since 1926 and resulted in almost total drought at the study sites, which continued for about 3 months (Fig.21, Fig.23).

### 3.3 Dendrochronological investigations

#### 3.3.1 Mean age of sample examined

Generally speaking it seems that the dead plants are only a slightly older than the living ones as, for

reasons due to the investigation methodology, the cores of the latter do not always include the central annual rings.

Tab. 5

Mean age of the dying and living sampled trees for the different experimental sites.

Experimental sites	Dying	Living
Nössing-Büchel	90	50-75
Tschötsch	60	55
Schrambacher Leiten	55	45 (80)
Rotwand	55-100	-

#### 3.3.2 Statistical analysis

For each site the mean tree-ring width curve was worked out and then compared with the curves of single trees.

At Nössing-Büchel the coefficient of coincidence between the single curves is high.

Apart from one plant with  $P \leq 0.05$  (where P indicates the likelihood that the correlation between the curves is not statistically different from zero), 83% of the curves show a highly significant correlation ( $P \leq 0.001$ ).

At Tschötsch the correlation between the single

curves and the mean curve is highly significant ( $P \leq 0.001$ ) for 33%, for another 33% it is  $P \leq 0.01$ , while for the remaining 33% it is  $P \leq 0.05$ . Compared to the other sites there is a lower level of correspondence between the curves.

At Schrambacher Leiten the correlation is high ( $P \leq 0.001$ ) for 55% of the curves, for 36% it is  $P \leq 0.01$ , while for the remaining 9% it is  $P \leq 5$ .

At Rotwand the correlation is very significant ( $P \leq 0.001$ ) for 80% of the curves. For the remaining 20% it is  $P \leq 0.01$ . This site gives the best correlation between the tree-ring width curves.

### 3.3.3 Tree-ring width curves

#### Nössing-Büchel

Negative characteristic years: 1944, 1952, 1976, 1986

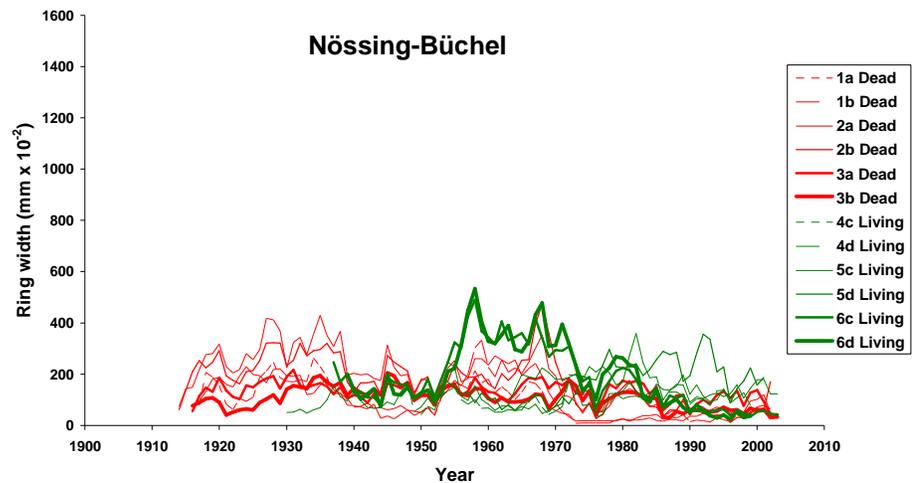
Positive characteristic years: 1935, 1958, 1968

The dating of the curves is very good, as confirmed by synchrony with the characteristic years 1952 and 1976.

In this time interval, all six sampled trees show a good level of growth, on average (with one

exception) higher for the plants that subsequently died than for the living ones. However, after 1976, a notoriously dry year, the latter show better reactive capacities with growth markedly greater compared to the damaged ones, whose situation worsens progressively from 1986. From 1990 the living trees also show lower growth rates.

Fig. 27  
Nössing-Büchel  
Time series of tree-ring width.



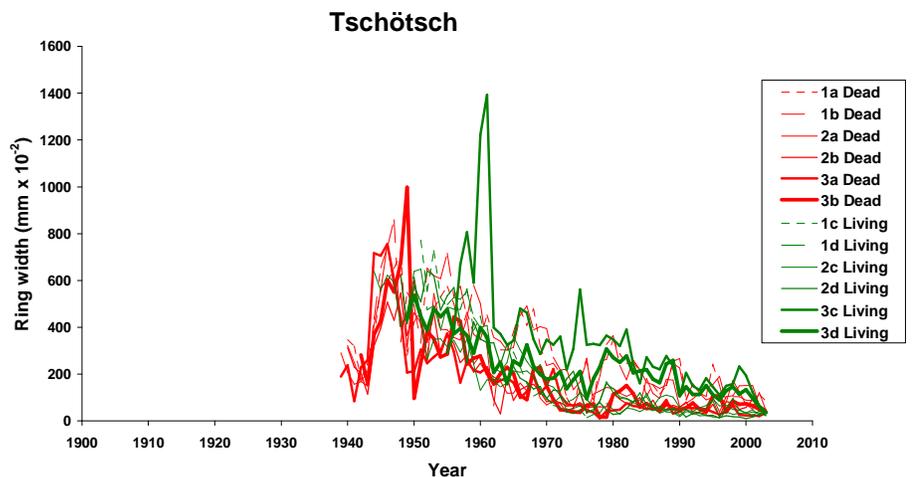
#### Tschötsch

No characteristic years are apparent.

Not every single tree reacts to the drought of 1976. From the end of the 1970s there is a generalised reduction of growth, although less marked for two trees.

At the Tschötsch site it is not possible to distinguish different growth behaviour between the two groups.

Fig. 28  
Tschötsch  
Time series of tree-ring width.

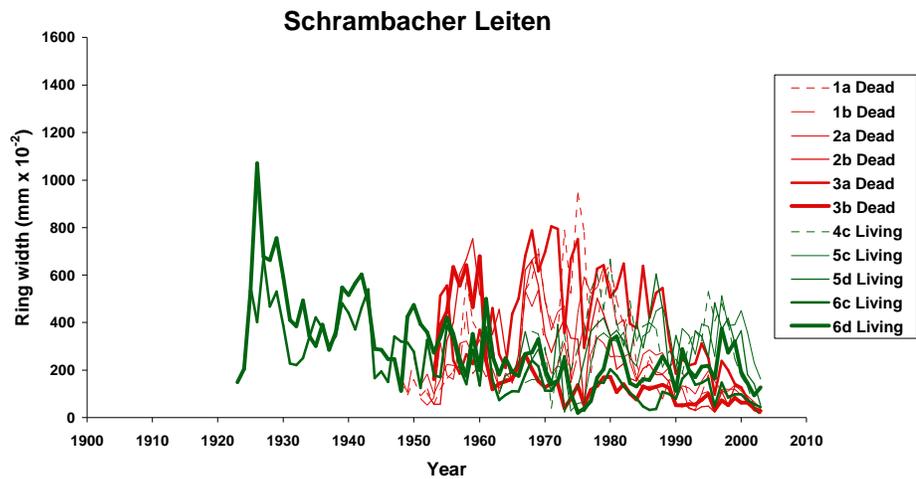


**Schrambacher Leiten**

Negative characteristic years: 1963, 1976, 1990  
 Positive characteristic years: 1958, 1968,  
 In the period 1950-1970 the trees now dead  
 show better growth compared to those still alive.  
 From 1990 the situation changes in favour of the

latter. Clearly the characteristics of the soil, of average depth and looseness, favoured the growth of the trees that subsequently died only so long as climatic conditions guaranteed sufficient availability of water in the soil.

Fig. 29  
 Schrambacher Leiten  
 Time series of tree-ring width.

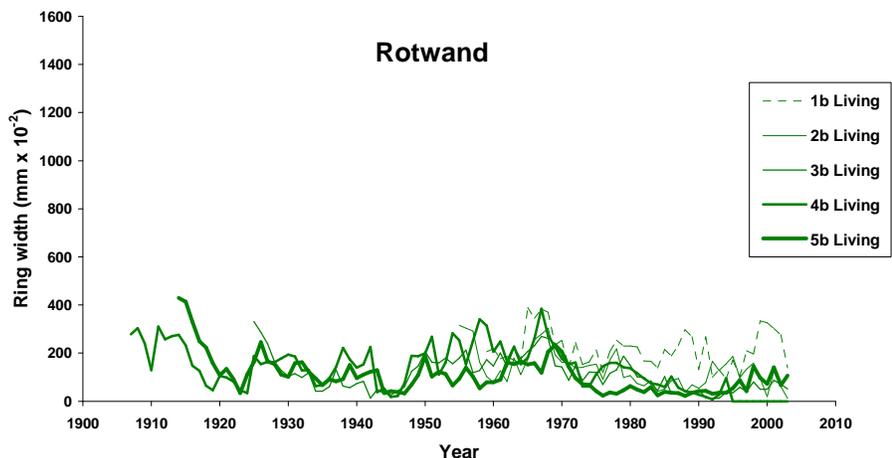


**Rotwand**

Negative characteristic years: 1944-1946, 1976, 1984  
 Positive characteristic years: 1967  
 The tree-ring width curves do not correlate with the corresponding ones at other sites. Both for

the period 1944-1946 and for the year 1976, low growth rates can be attributed to drought. Apart from one individual, for all the sampled trees, after a slight recovery in the following two years, growth does not return to previous values.

Fig. 30  
 Rotwand  
 Time series of tree-ring width

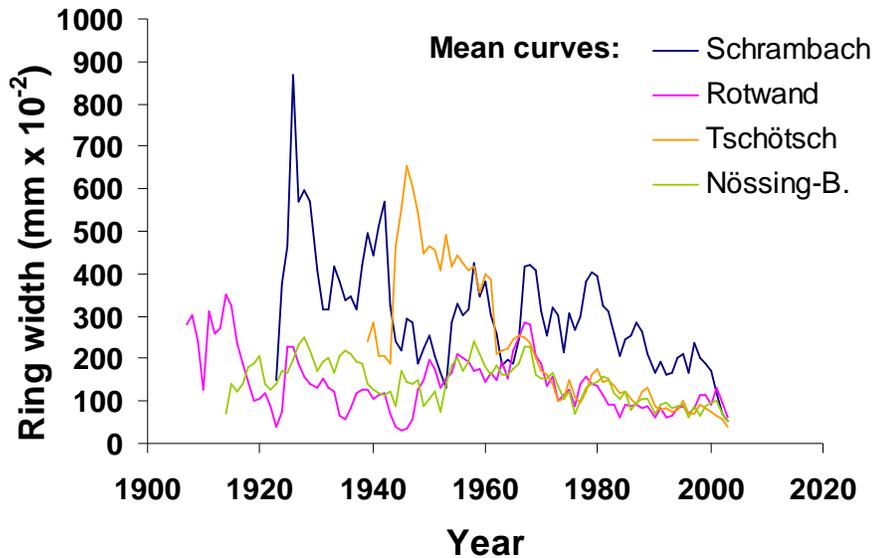


### 3.3.4 Comparison between mean ring width curves

The synchronicity of the mean curves for the four sites shown in Fig.31 indicates that they are properly dated. At Schrambacher Leiten, compared to the other sites the trees grew significantly better during the whole period under consideration.

A common element, on the other hand, is the limited growth that characterises all the sites in the years 1964 and 1976. Afterwards all the trees show a slight recovery in growth that then diminishes progressively in the following decade.

Fig. 31  
Comparison of mean ring width trends at the four experimental sites

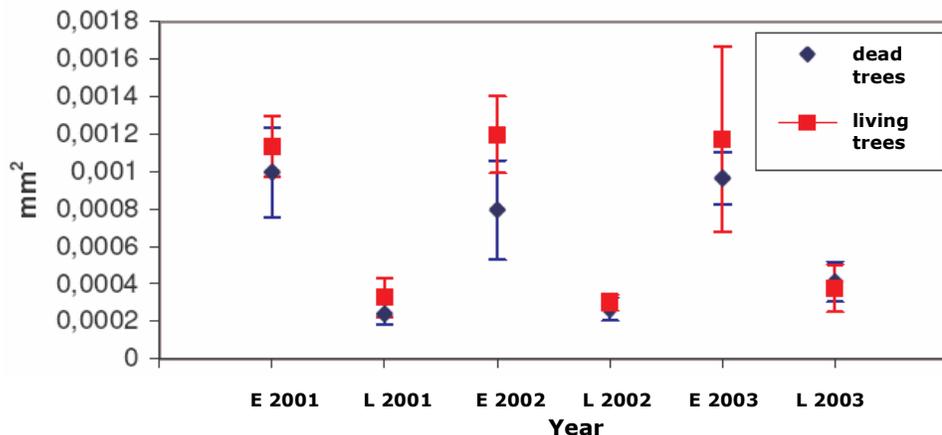


### 3.3.5 Anatomical wood analysis using image analysis

The width of the tracheid lumen does not differ significantly between dead and living trees, even though in the latter the lumen surface is on

average greater, while, as expected, the greater surface of the tracheid lumen in spring wood compared to late wood in all the plants examined seems significant.

Fig. 32  
Mean surface of the tracheid lumen of early (E) and late wood (L) in living and dead trees at the Nössing-Büchel site for the period 2001-2003



### 3.4 Interactions between climate and tree physiology

The joint study of meteorology and carbon and oxygen isotope discrimination in the series of wood rings makes it possible to analyse the physiological reaction of plants in relation to changes in climate.

#### 3.4.1 Carbon isotope discrimination

The depletion of the  $^{13}\text{C}$  isotope in carbohydrates fixed by photosynthesis depends on the concentration of  $\text{CO}_2$  inside the leaf, that is, on stomatal conductance and therefore on the water potential of the soil-plant system.

In Fig.33 the time series for carbon isotope discrimination in spring and summer wood is given separately for the different investigation sites and for living and dead trees.

From the diagrams several significant aspects can be inferred.

The values of  $\delta^{13}\text{C}$  are systematically higher (tending to approach the ratio in the atmosphere) in dying and dead trees (on average  $-24.5\text{‰}$ ) than in living ones (on average  $-25\div-26\text{‰}$ ), with values that become increasingly different in

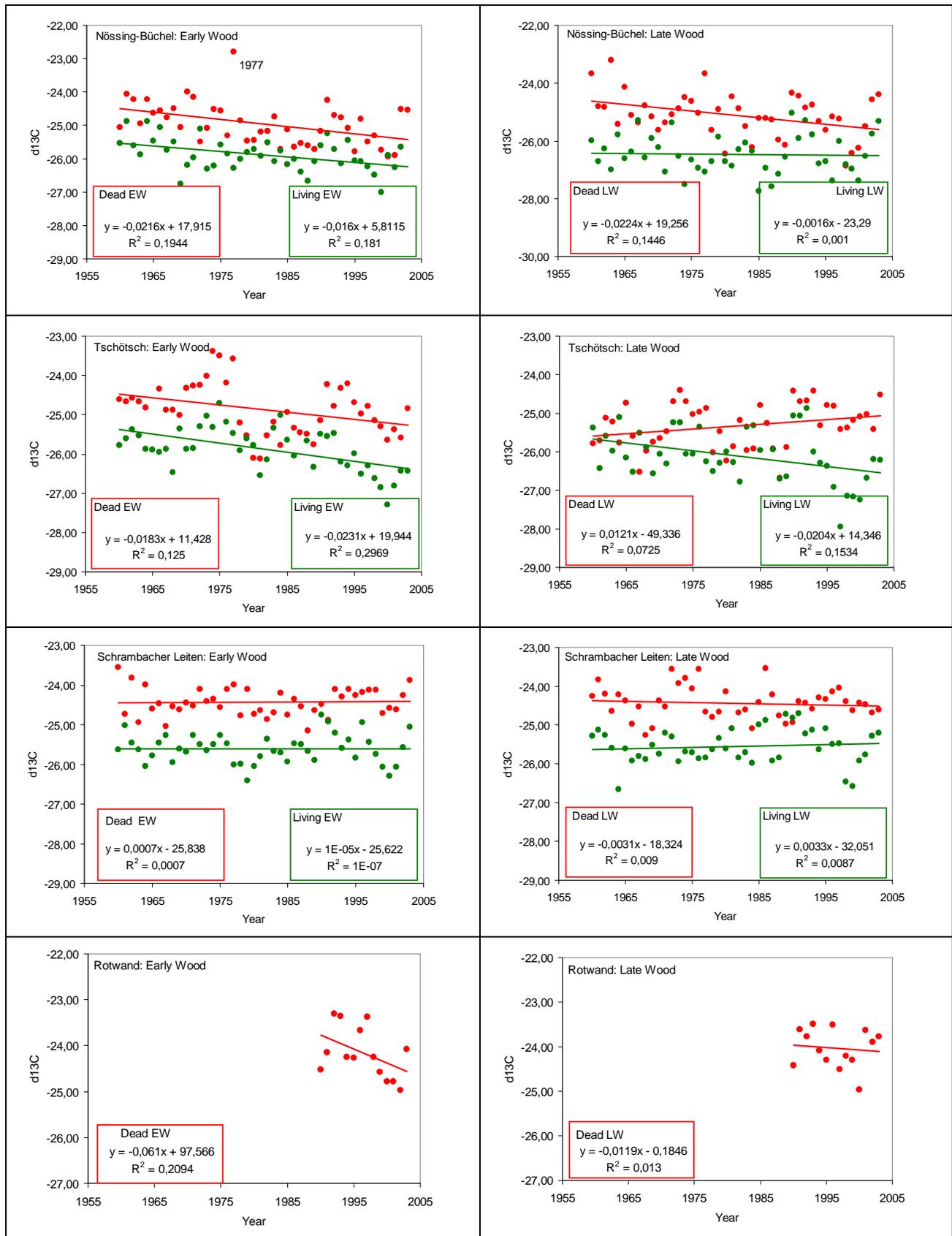
the last decade until it is in effect possible to differentiate between two different tree populations. This aspect is more marked from 1992 on the Tschötsch and Schrambacher Leiten sites that are characterised by more widespread deaths.

A tendency towards a reduction in  $\delta^{13}\text{C}$  values in the last twenty years can be noted which can only in part be explained by the reduction of the isotope discrimination of atmospheric carbon dioxide. These negative trends indicate a tendential reduction in water use efficiency linked with an increase in water availability during the vegetative period. This trend does not emerge for the dead trees on the Schrambacher Leiten site and is in any case lower than that observed in living trees.

The latter also show greater fluctuations in isotope discrimination values in response to the various levels of water availability, and consequently an unchanged degree of vitality compared to the dead trees, whose lower sensitivity and reactivity are evidence of a physiological decline already in progress for some time.

Fig. 33

Time series of carbon isotope discrimination ( $\delta^{13}\text{C}$ ) in early (EW) and late wood (LW) for living and dead trees in Isarco Valley.



### 3.4.2 Oxygen isotope discrimination

The analysis considered the periods 1990-2003 for Nössing-Büchel and 1960-2003 for Tschötsch and Schrambacher Leiten.

Fig.34 separately shows the time series for the three sites of oxygen isotope discrimination on the basis of the ratio  $^{18}\text{O}/^{16}\text{O}$  for spring wood

(EW) and summer wood (LW) and for living trees and dead trees. Already from the beginning of the 1960s the latter are differentiated by considerably higher values, in particular for late wood (Tschötsch and Schrambacher Leiten), which reflects growth conditions during the vegetative period.

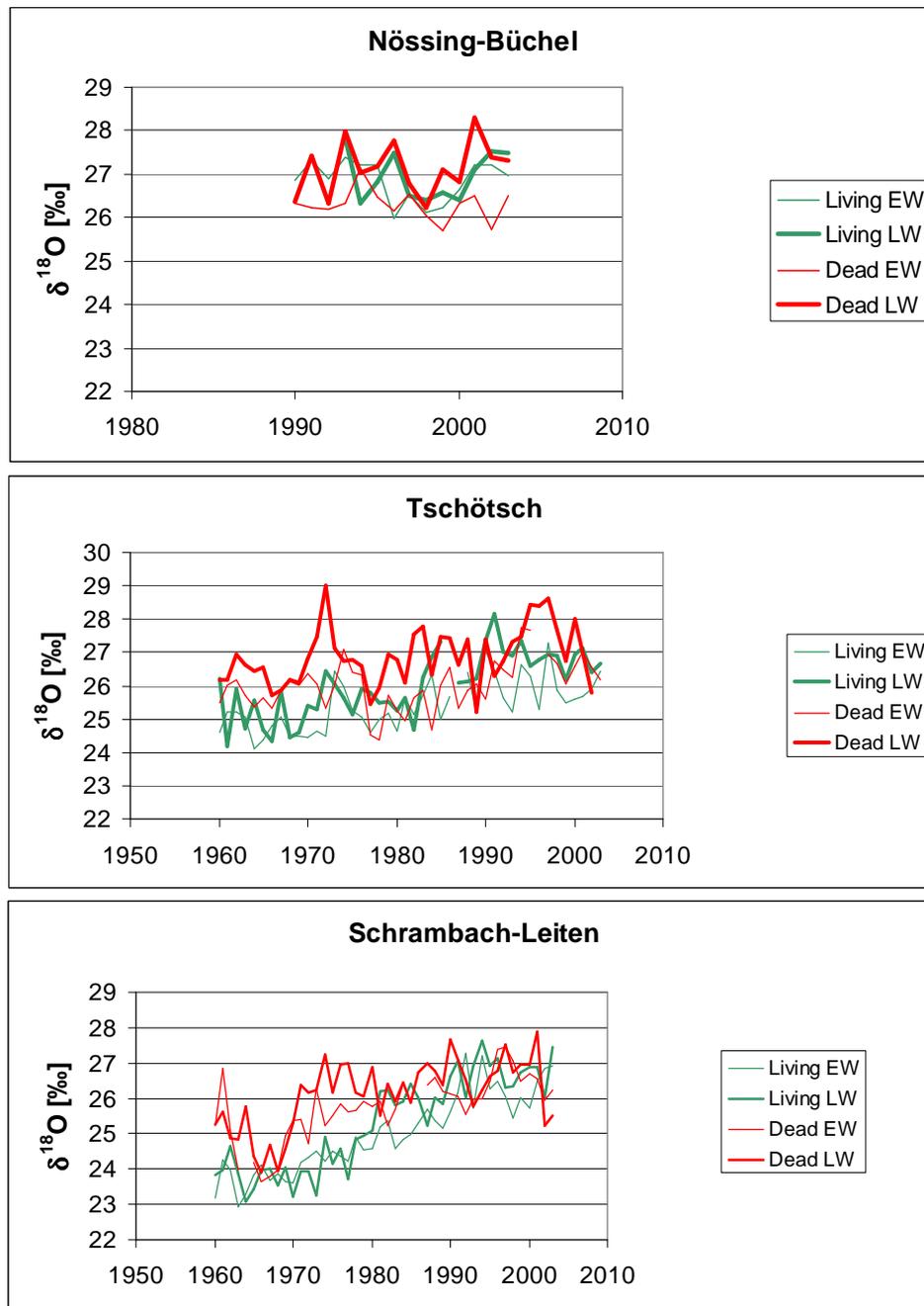


Fig. 34 Time series of oxygen discrimination ( $\delta^{18}\text{O}$ ) at three experimental sites separately for early and late wood and for dead and living trees

The initial difference between the two groups is marked but then progressively diminishes until it disappears in the 1990s. This reduction is better quantified in Fig.35 by the comparison between the values averaged out of the ratio  $\delta^{18}\text{O}$  in spring and summer wood for each population.

The highest values of  $^{18}\text{O}$  indicate lower transpirative activity in the dead trees as a result

of the low stomatal conductance already also revealed by analysis of the carbon isotopes. The lower degree of transpiration may likewise depend more in general on lower assimilation, given that the two processes are often correlated. In any case the ailing trees were not able to accumulate reserves in the last years and subsequently this turned out to be fatal with the occurrence of dry periods in the 1990s.

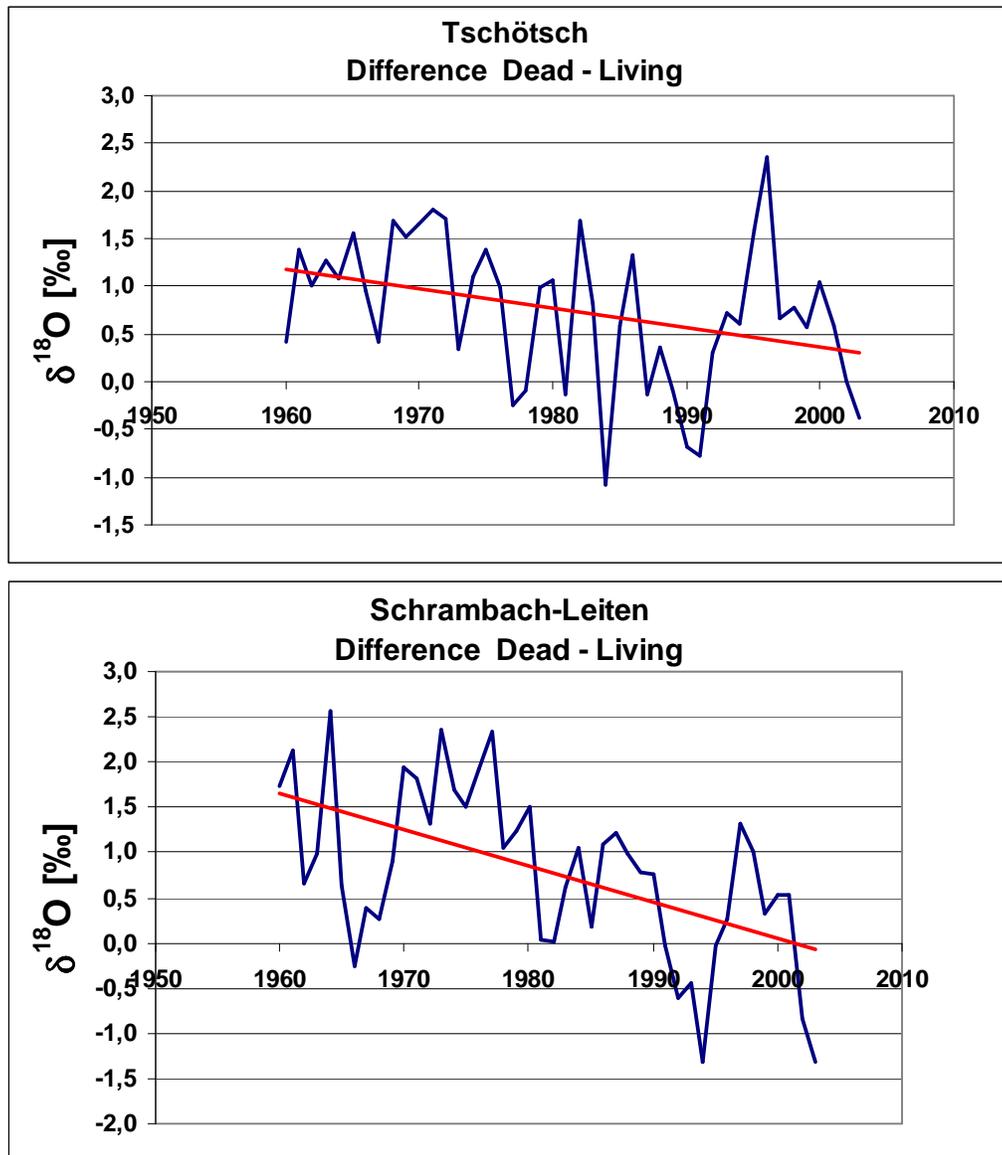


Fig. 35 Time series of the differences in  $\delta^{18}\text{O}$  between dead and living trees in two sampling areas.

### 3.4.3 Analysis of variance

To establish whether the  $\delta^{13}\text{C}$  differences between living trees and dead ones and between sites are statistically significant, Analysis of variance (ANOVA) was performed on the data for the period 1990-2003, using as classification factors the site, summer and spring wood and the health of the plant.

The ANOVA results reported in Tab.6 show that the differences in  $\delta^{13}\text{C}$  between the sites and between states of health are highly significant.

Specifically the differences between  $\delta^{13}\text{C}$  values for living trees and dead trees have been found to be significant, while the values for summer wood and spring wood are not statistically significant.

As regards the sites, a statistically significant difference can be detected between the Schrambacher Leiten site and the others. It was not possible to include the Rotwand site in the analysis as at this site sampling involved only dying trees and so the experimental design was incomplete.

Tab. 6

Results of the ANOVA on the values of  $\delta^{13}\text{C}$  between sites and tree state. Both factors are statistically significant ( $P < 0.00$ ), while the interaction between the two is not significant.

**ANOVA** multifactorial.

Factor	GDL	MS	F	p
Status	3	18.24481	55.62642	1.83E-24
Site	2	9.352988	28.51623	2.85E-11
Interaction	6	0.333874	1.017945	0.415713

Post-doc comparisons based on Staffe-test (\* differences with  $p < 0.05$ ).

State of health		Sites	
Living trees, early wood	*	Nössing-Büchel	*
Living trees, late wood	*	Tschötsch	*
Dead trees, early wood	**	Schrambacher Leiten	**
Dead trees, late wood	**		

In Fig.36-37 the mean values  $\pm ES \pm DS$  of  $\delta^{13}C$  for the different sites show how in the period 1990-2003 the dying trees have systematically higher mean  $\delta^{13}C$  values and less variability than the living trees. In addition, in the living plants  $\delta^{13}C$  variability in summer wood is higher than variability in spring wood.

As shown in Fig.33, the differences between living and dead trees are much more marked at the Tschötsch and Schrambacher Leiten sites than at the Nössing-Büchel site. The dead trees at the Schrambacher Leiten site in particular show the most critical discrimination values of the different sites analysed.

Fig. 36  
Mean values of  $\delta^{13}C$  ( $\pm$  standard error  $\pm$  standard deviation) for the different sites and tree states (V= living trees, M= dying trees, P= early wood, E= late wood).

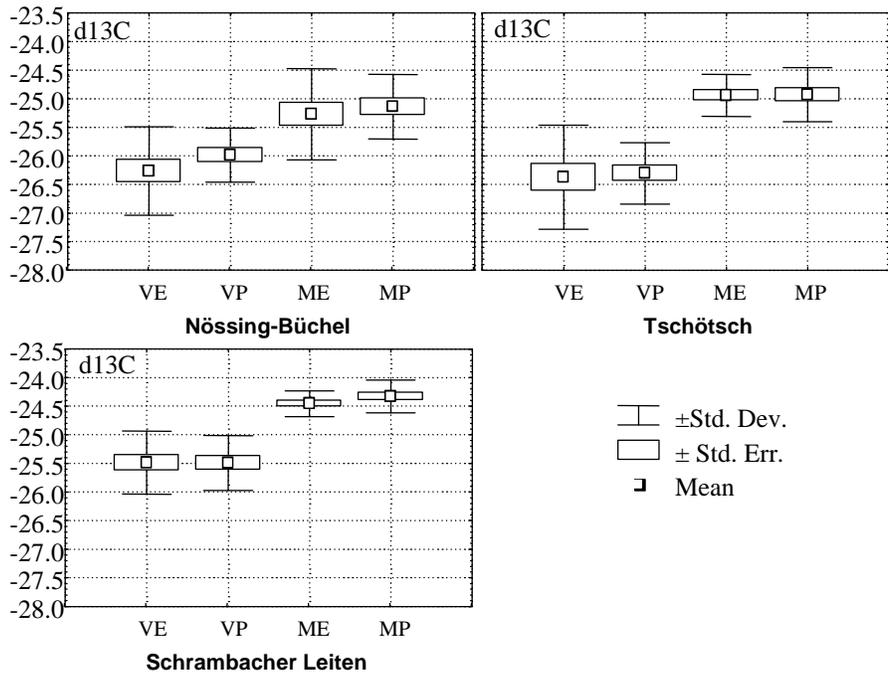
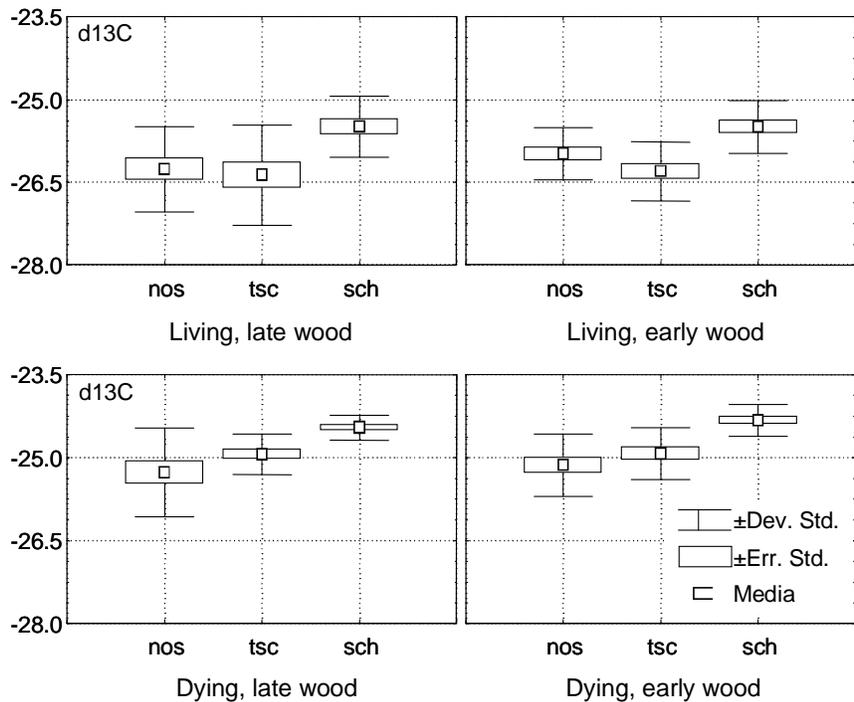


Fig. 37  
Mean values of  $\delta^{13}C$  ( $\pm$  standard error  $\pm$  standard deviation) for the different sites and tree states. nos = Nössing-Büchel, tsc = Tschötsch, sch = Schrambacher Leiten)



Relations between  $\delta^{13}\text{C}$  and water deficit in the vegetative season (April-September) show statistically significant positive relations at all the investigation sites (Fig.38-40). Relations seem to be stronger for the trees still living than for the dead ones and also stronger for summer wood than for spring wood.

These relations show how a reduction in water availability results in a reduction in stomatal conductance and hence in photosynthesis, indicated by the systematic increase in  $\delta^{13}\text{C}$ . The isotopic ratio can therefore be used as a synthetic indicator of the water state of the soil-plant system.

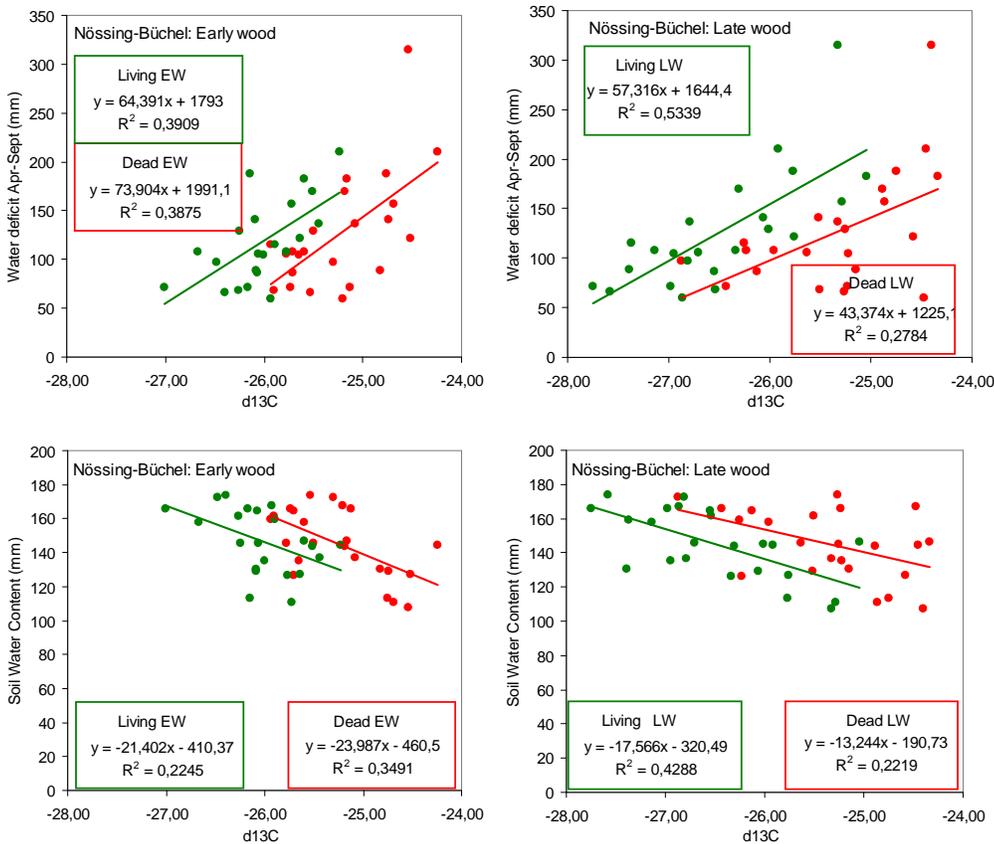


Fig. 38 Relations between carbon discrimination  $\delta^{13}\text{C}$  and the microclimatic parameters, water deficit and soil water content, during the period April-September at Nössing-Büchel. Data are shown separately for dead and living trees and for early and late wood.

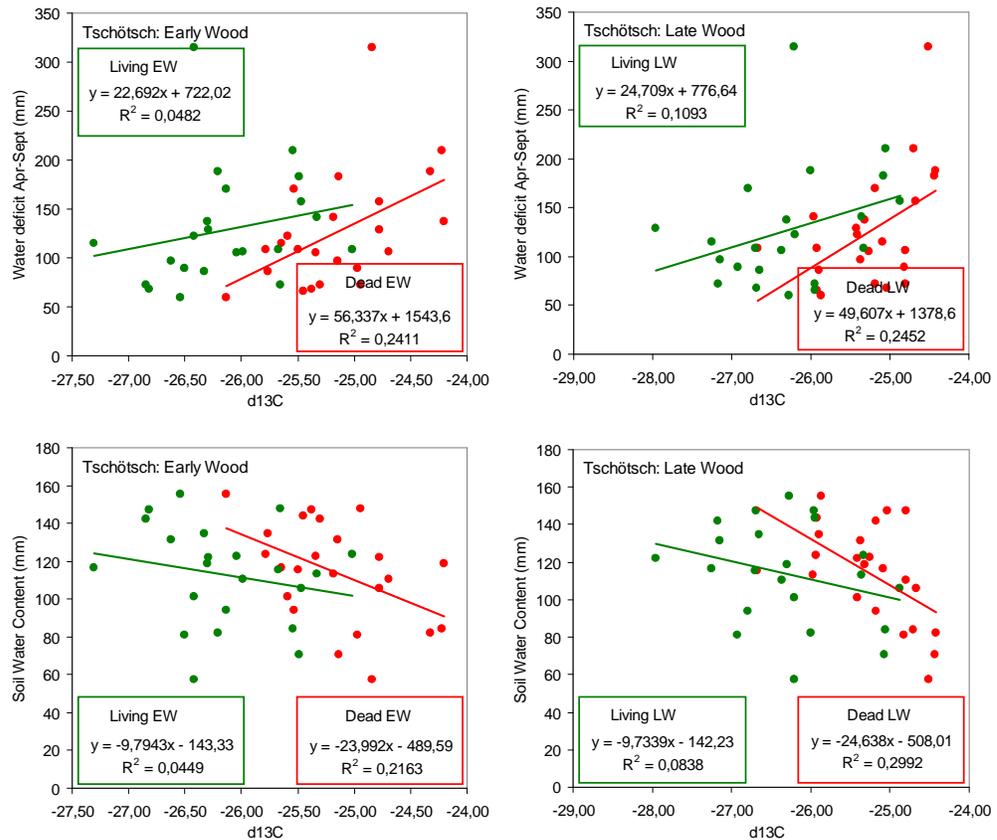
Figs.38-40 also give the relations between  $\delta^{13}\text{C}$  and soil water content expressed in mm of rain. In this case the relations at all the investigated sites are negative, that is, with an increase in the mean soil water content during the vegetative season, an increase in the  $\text{CO}_2$  concentration inside the leaves is observed, with consequent greater discrimination against  $^{13}\text{C}$ . It is of particular interest that although showing analogous sensitivity to environmental parameters, the dead trees and those still alive form two clearly distinct clusters of points in the graphs.

This is to be interpreted as the result of a microclimatic differentiation in the ecological niches in which these trees are living, and in general of a different set-up between water provision processes and those of evapotranspiration. As was noted in Fig.33, the stands of dead trees and of those that survived the drought have differed for more than a decade in a statistically significant way in their capacity for water provision at all the investigation sites (Fig.36).

The extreme water stress event that occurred in 2003 has therefore caused the death of trees whose water balance had already been

weakened, leading to a natural selection of tree cover in favour of trees with better access to water resources.

**Fig. 39**  
Relations between the carbon discrimination  $\delta^{13}\text{C}$  value and the microclimatic parameters of water deficit and soil water content during the period April-September at Tschötsch  
Data are shown separately for dying and living trees and for early and late wood.



An aspect of particular interest for understanding the physiological response of vegetation to variability of climate concerns the dynamic of carbohydrate reserves, whose storage in the root systems at the end of the autumn is of fundamental importance for vegetative renewal in the following season. This aspect was analysed at the various investigation sites by comparing the level of isotope discrimination in summer wood with that of spring wood in the following season (Fig.41). The figure shows how, at the sites less affected

by die-back such as Nössing-Büchel, there are no significant differences between living and dead trees, while at the hardest-hit sites (Tschötsch and Schrambacher Leiten) the dead trees have a lower correlation in  $\delta^{13}\text{C}$  than living trees. In practice only living trees were able to mobilise the previous year's reserves. The dying trees, on the contrary, had difficulty (low photosynthetic activity) forming the carbohydrate reserves necessary to sustain the process of vegetative renewal and growth in the following year.

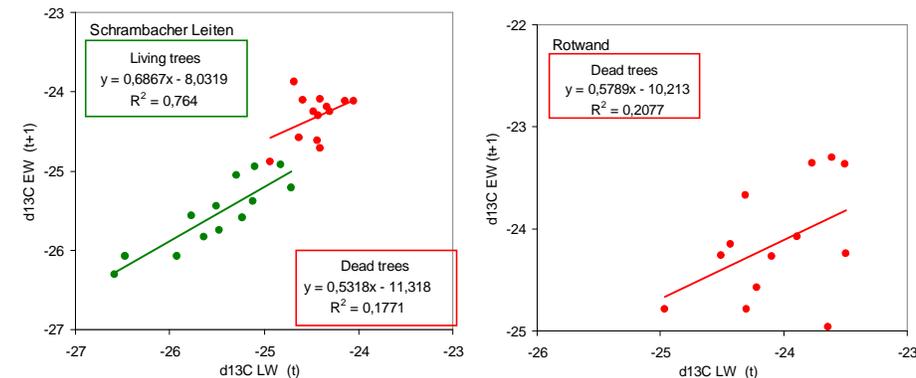
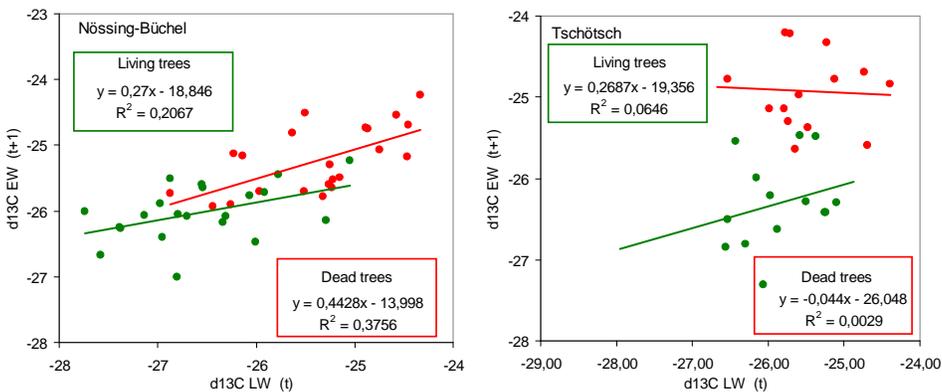
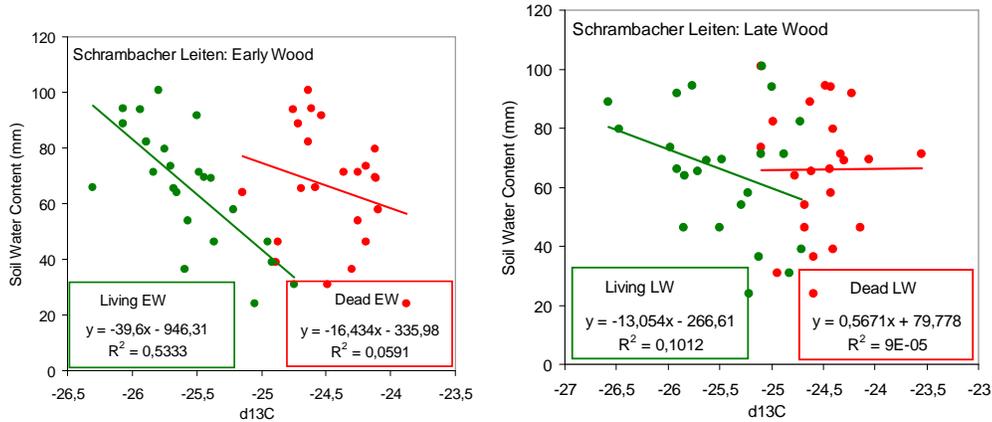
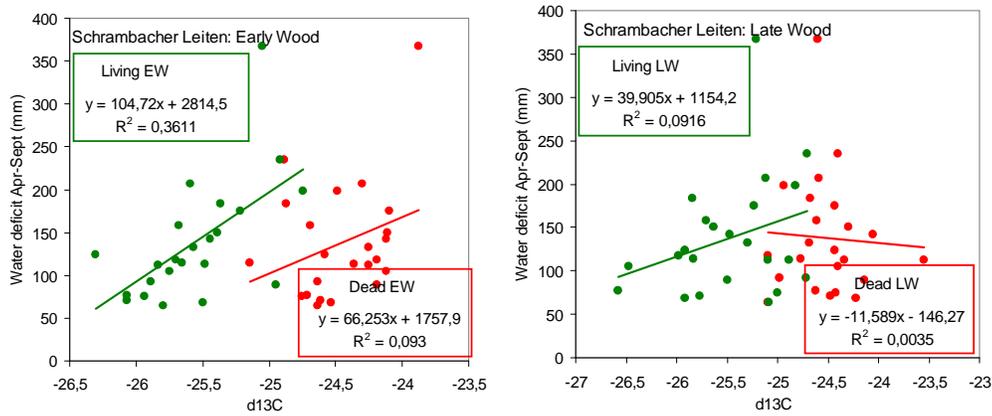


Fig. 40 Relations between carbon discrimination  $\delta^{13}C$  and the microclimatic parameters of water deficit and soil water content during the period April-September at Schrambacher Leiten. Data are shown separately for dying and living trees and for early and late wood.

Fig. 41 Relation between carbon discrimination  $\delta^{13}C$  in late wood and early wood on the following growing season at the four study sites.

### 3.5 Phytopathological investigation

In November 2004, a year after the first signs of dieback, further entomological and phytopathological investigations were made to assess any possible development of secondary diseases.

At the Tschötsch site the samples of dead and/or dying pines examined indicate as a constant the almost total absence of primary insect attacks, in particular, of scolytidae (bark beetle), a typical potential cause of pine dieback. All the insects discovered, classified in part on the basis of the specimens (larvae or adults) found and for the most part on the basis of the typical larval galleries on branches and trunks, have a typically secondary ethology. Their distribution for a standard sample tree is given in Tab.7. The upper parts of the crown, from which dieback began, include a greater diversity of insect species, but with a small number of individuals. Thus, for example, numerous larval galleries of the cerambycida (longhorn beetle) *Pogonochaerus fasciculatus* can be found on some already dead branches, while only one living specimen of the rarer *Pogonochaerus decoratus* was found. The same is also true for other xylophagous insects found in the upper parts of the trees, such as the buprestidae coleoptera (metallic wood-boring beetle) *Chrysobothris solieri* and *Anthaxia godeti* (a species related to the *A. quadripunctata* of the spruce), and the curculionidae (weevils) *Magdalis frontalis* (similar to the *M. violace*) and *Magdalis rufa*, and *Pissodes piniphilus* and *Pissodes notatus*, whose presence is widespread but by no means in large numbers.

Leaving aside their usual behaviour as secondary parasites, because of their small number alone they could not, in any case, have been the cause of the death of the pines. This is also true of the very few galleries of secondary scolytidae found on some branches.

The presence of the cerambycida *Rhagium inquisitor* (ribbed pine borer) – a species considered typically secondary, which normally develops in old tree stumps – is likewise limited. The contemporaneous presence of mature larvae and pupae, but also of developed adults, shows that the attacked plants – although still having some branches with green needles – must have

already been dying for some time. This also reduces the significance of the role of the curculionida *Pissodes pini* (Pissodes weevil) – a secondary parasite even if it is partial to the still fresh and robust parts of the bark – present in various parts of the trunk in galleries under the bark in various larval stages of development, but not yet in the stage of an adult insect. On the other hand, the development on the trunk of galleries under the bark of some xylophagous insects is considerable. Of these, the galleries under the bark – in great numbers! – of the buprestidae coleoptera *Phaenops cyanea* (blue pine wood borer) and of the cerambycida *Acanthocinus aedilis* in particular are conspicuous. Both species typically colonise dying pines.

It is also surprising how various scolytidae, although present in the ecosystem, as is shown by the remains in the wood of previous attacks (dead branches and tops on the ground) – e.g. *Tomicus minor* (lesser pine shoot beetle) in the parts of the trunk with thin bark and *Tomicus piniperda* (common pine shoot beetle) in the shorter ones with thicker bark – have not taken advantage of this “good opportunity” for an outbreak. No trace of them was found on the pines that died recently. The same is true for *Ips acuminatus* (engraver beetle).

The presence of fungal infections of the crown, *Cenangium ferruginosum* (Cenangium limb canker) and *Sphaeropsis sapinea* (Sphaeropsis shoot blight), previously the cause of severe infections in the 1990s in these areas, was also found to be sporadic and irrelevant in the general context (Fig.48). On the other hand, the development of blue stain fungi in the sapwood at various levels of the trunk is a common feature (Fig.49).

In addition, almost the entire mature population shows a generalised and high level of colonisation by *Viscum album* (European mistletoe), an epiphyte that has progressively become the main factor of death in recent years (Fig.50-51). This constitutes a decisive co-acting factor in the development of the etiopathological situation as it further reduces the assimilatory surface of trees already weakened by inadequate

development of their aerial structure as a physiological reduction of the leaf mass caused by water stress (RIGLING *et al.* 2006).  
 consequence of high population density, the consequence of lack of thinning in the past, and the

Tab. 7

<b>Pinus sylvestris Scots pine</b>	<b>mt</b>	<b><u>INSECTS</u></b>	<b><u>FUNGI - EPIPHYTA</u></b>
		<i>Pogonochaerus fasciculatus</i> ( <i>Cerambycidae</i> - longhorn beetle)	
		<i>Pogonochaerus decoratus</i> ( <i>Cerambycidae</i> - longhorn beetles)	<i>Viscum album</i> ( <i>European mistletoe</i> )
		<i>Chrysobotris solieri</i> ( <i>Buprestidae</i> - metallic wood-boring beetles)	<i>Cenangium ferruginosum</i> ( <i>Cenangium limb canker</i> )
		<i>Anthaxia godeti</i> ( <i>Buprestidae</i> - metallic wood-boring beetles)	<i>Sphaeropsis sapinea</i> ( <i>Sphaeropsis shoot blight</i> )
		<i>Magdalis frontalis</i> ( <i>Curculionidae</i> - weevils)	
	12	<i>Magdalis rufa</i> ( <i>Curculionidae</i> - weevils)	
		<i>Pissodes piniphilus</i> ( <i>Curculionidae</i> - weevils)	
		<i>Acanthocinus aedilis</i> ( <i>Cerambycidae</i> - longhorn beetles)	
		<i>Rhagium inquisitor</i> - ribbed pine borer ( <i>Cerambycidae</i> - longhorn beetles)	<i>Blue Stain Fungi</i>
		<i>Pissodes notatus</i> ( <i>Curculionidae</i> - weevils)	
	8	<i>Pissodes pini</i> ( <i>Curculionidae</i> - weevils)	
		<i>Acanthocinus aedilis</i> ( <i>Cerambycidae</i> - longhorn beetles)	
		<i>Phaenops cyanea</i> - blue pine wood borer ( <i>Buprestidae</i> - metallic wood-boring beetles)	<i>Blue Stain Fungi</i>
		<i>Rhagium inquisitor</i> - ribbed pine borer ( <i>Cerambycidae</i> - longhorn beetles)	
	4	<i>Pissodes pini</i> ( <i>Curculionidae</i> - weevils)	
	<i>Phaenops cyanea</i> - blue pine wood borer ( <i>Buprestidae</i> - metallic wood-boring beetles)	<i>Blue Stain Fungi</i>	
	<i>Rhagium inquisitor</i> - ribbed pine borer ( <i>Cerambycidae</i> - longhorn beetles)		
0			

Tschötsch 04.11.2004



Fig. 42 a  
Fig. 42 b  
*Magdalis frontalis*



Fig. 43  
*Pissodes notatus*

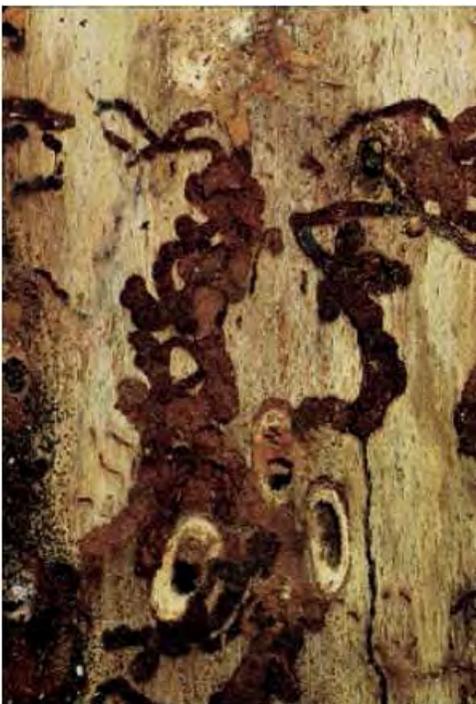


Fig. 44 a  
*Pissodes* sp.  
larval galleries



Fig. 44 b  
*Pissodes pini*  
*Pissodes* weevil



Fig. 45 a  
*Rhagium inquisitor* - ribbed pine borer, Larvae



Fig. 45 b  
*Rhagium inquisitor* - ribbed pine borer



Fig. 46 a  
*Acanthocinus aedilis*, Larvae



Fig. 46 b  
*Acanthocinus aedilis* ♂ + ♀



Fig. 47 a *Phaenops cyanea* - blue pine wood borer, Larva



Fig. 48  
*Cenangium ferruginosum*  
Cenangium limb canker



Fig. 47 b *Phaenops cyanea* - blue pine wood borer



Fig. 49  
Blue stain fungus

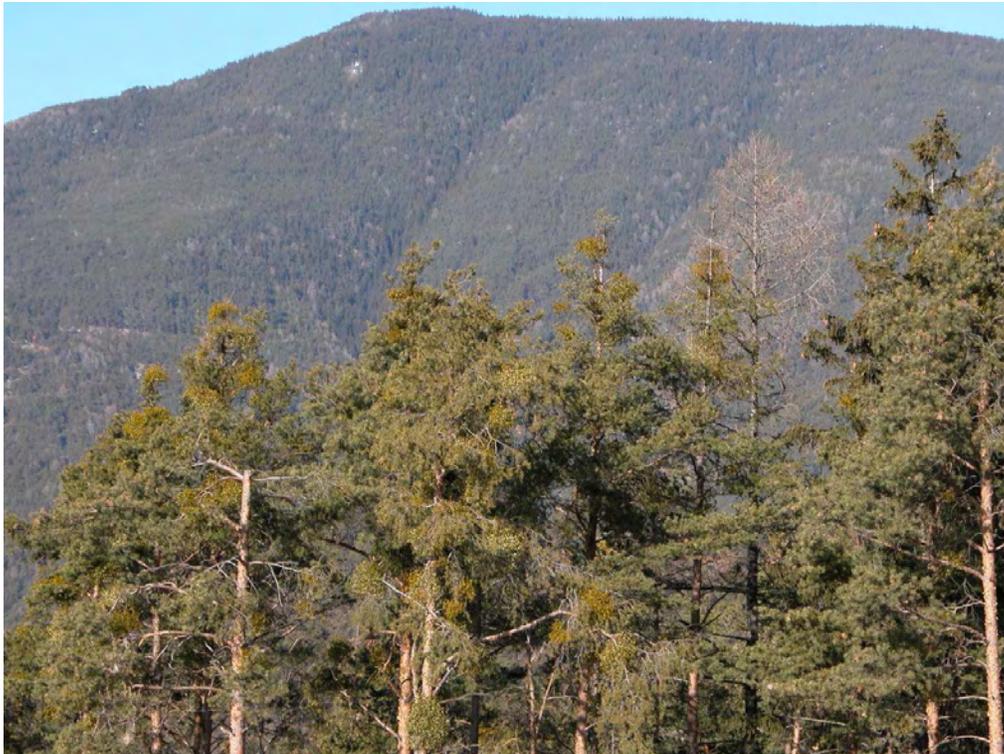


Fig. 50 Mistletoe (*Viscum*) growing on pine

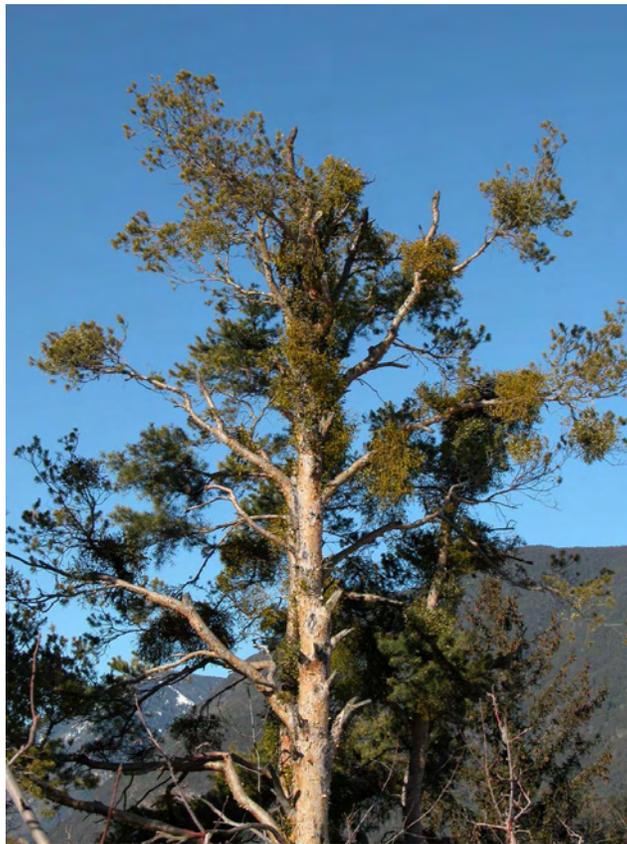


Fig. 51 Mistletoe substitutes the pine crown

## 4 Conclusions

The rapid dehydration of the bark tissues due to the exceptional intensity and suddenness of the drought of 2003 combined with its late-summer timing had the effect of preventing the development of secondary pathogens (*Tomicus minor* - lesser pine shoot beetle, *Ips acuminatus* - engraver beetle) and of weakness (*Cenangium ferruginosum* - Cenangium limb canker, *Sphaeropsis sapinea* - Sphaeropsis shoot blight, *Armillaria* sp. - Armillaria root-rot fungus), both immediately and in the following year.

This situation was therefore an ideal opportunity for verifying whether biotic factors were indeed to be excluded as a cause of the death of the Scots pine in the Isarco Valley on such a vast scale, in other words, for circumscribing and ascribing the phenomenon to the more strictly climatic, edaphic and physiological spheres.

The fact that damage was exclusive to the Scots pine is explained by various factors: the precarious pre-existing health status of the trees, the extreme extent of the water deficit that turned out to be fatal even for this species, which is able to colonise xerophyllous environments, precisely those avoided by other conifers, and not last the unfavourable microsite conditions at sites characterised by soil that on the one hand was of average depth but on the other hand had low water retention capacity, with the pine obviously unable to adapt its root system to the lowering of the groundwater level in the space of just a few weeks.

On the contrary, the consequences were limited on rocky substrata where root systems, which have already penetrated down into the cracks in the rock, guarantee sufficient water provision (Fig.52).



Fig. 52  
Pines at the edge of a rocky slope survived the summer drought in 2003 without damage.

Dendrochronological investigations trace back to 1976 – indicated then as “the driest year of the century” – the common beginning of the physiological collapse of the pine forests in terms of growth. After this, the structural and ecological stability of these stands was markedly affected by the repeated years of drought and record heat that followed one another in the following decades (1983 – 2003) as well as by lack of care in cultivation, which weakened their general state of health, as shown by the endemic prior presence of numerous parasites and epiphytes.

In confirming the degenerative tendencies in the dried up plants, the  $^{13}\text{C}$  and  $^{18}\text{O}$  isotope analyses emphasise the strong connection with site water balance and consequently with water stress induced by climatic trends.

In particular the predictive ability of oxygen isotope discrimination is shown with regard to negative effects on the transpirative and assimilative processes of Scots pine stands: the critical phase in which this species finds itself in Alto Adige and throughout the Alps is shown in Fig.34 and Fig.35, where the trend lines join dead trees and those still living in a common destiny, outlining future scenarios in which it will be progressively replaced by other tree species.

This is the fundamentally useful indication for management that emerges from the analyses made and that the natural population dynamics already highlights with the spontaneous recolonisation of the dominated plane by the manna ash and other shrubs (Fig.53).



Fig. 53  
Extensive flowering of manna ash (*Fraxinus ornus* L.) following the thinning of a pine stand after the drought (17.05.2006)

From the point of view of plant health, as there is no need for rapid removal of the dried-up trees, given the low level of reactivity of the secondary pathogens, interventions are limited only to accessible areas.

Where convenient, the mature pine stand is removed to allow the development of spontaneous broadleaves already present there – manna ash, downy oak and hop-hornbeam, and on cooler sites, chestnut, cherry, trembling poplar and birch – differentiating and modulating the extent of interventions according to the type of forest (BOLZANO FORESTS DEPARTMENT, 2006; RIGLING *et al.* 2006).

Considering the current edaphic and climatic characteristics and future *global change* scenarios, these are the species that undoubtedly adapt better to local site requirements and that, we believe, will largely replace the current pine forests over the next decade, modifying the appearance of the valley landscape. The consequence of these dynamics on the landscape also have an impact from a touristic-recreational point of view, as demonstrated by the concern aroused in the tourism and hotel sectors as a result of the reddening of crowns in the autumn of 2003, thus showing the importance of the axiom “a healthy wood means healthy air”.

For the purpose of hydrogeological protection it will therefore be necessary to ensure that cultivation is managed in such a way as to favour the development of the tall-trunk tree mixed with broadleaves in areas with the right soil conditions, also through the introduction of high-value species, with the economic aim of improving the quality of the vegetation and of sequestering carbon in a lasting form, leaving the task of covering the ground in marginal and more xeric areas to coppices.

The drought of 2003 was followed by the development of parasites and pathogens of the Scots pine in many other wooded areas of the Alto Adige: since 2004 an infestation of coccids (*Leucaspis* sp.) has affected hundreds of hectares of mixed woods in the Adige Valley on the mountain slopes to the west of Bolzano and Merano (the communes of Caldaro, Appiano, Andrano and Prissiano), while the presence of

*Cenangium ferruginosum* (cenangium limb canker) and *Sphaeropsis sapinea* (sphaeropsis shoot blight) after the infestation that, in 1997, as a result of damage caused by winter drought, affected a total area of 1000 ha., is still endemic. Hundreds more hectares were damaged by *Leucaspis* in Venosta Valley where, already since 1992, about 1000 ha had been affected by pine dieback.

Attacks by *Ips acuminatus* (engraver beetle) and *Ips typographus* (eight-toothed bark beetle) have also increased throughout the Alto Adige, mainly on slopes exposed to the sun.: +60% in 2004 and 2005 compared to 2003 (AUTONOMOUS PROVINCE OF BOLZANO, 2005).

This description shows the Scots pine to be in a terminal historic phase, documented furthermore throughout the Alps (RIGLING & CHERUBINI 1999) that gives rise to considerations of plant health and forestry that are of obvious supraregional importance.

Mostly it concerns populations subjected in the past to various forms of human pressure, in which the pine, having established itself spontaneously or because it was artificially favoured as a consequence of irrational past forms of management (grazing in woods, collection of brushwood, razing during the two world wars to gather firewood) is replaced by the original species (broadleaves), now reconquering the space they are due. The Scots pine will obviously not disappear from the Alps. Its domination of the formation of forest stands will just be considerably reduced.

However, behind what today might seem to be a normal succession in the sphere of the natural cycles of forest ecosystems, there could lurk a deviant dynamic caused by climate changes whose future scenarios can only in part be forecast. This requires a more attentive and constant surveillance of those wooded areas that are more sensitive and play a prominent protective role, in order to rapidly implement those measures that guarantee their ecological and structural stability (plurispecificity) or to fight and contain the appearance of pathogens. – And then, after the Scots pine, which species will be next?

## Acknowledgements

The authors would like to thank the staff of the forest stations of Bressanone and Chiusa

for their support and the valuable assistance given with investigations in the countryside.

## Riassunto

### **La siccità dell'estate 2003 causa di disseccamenti del Pino Silvestre in Val d'Isarco**

Estesi fenomeni di deperimento si sono manifestati a carico dei soprassuoli boscati di pino silvestre, siti sui versanti più soleggiati ed aridi della Val d'Isarco, in seguito all'intensa e prolungata siccità che nell'estate 2003 ha investito il continente europeo. Gli accertamenti condotti a cura della Ripartizione Foreste di Bolzano secondo un approccio interdisciplinare, sono stati finalizzati all'acquisizione di elementi diagnostici discriminanti a diversi livelli funzionali dell'ecosistema e della specie in oggetto, proprio in quanto particolarmente sensitiva nei riguardi di andamenti climatici stagionali. I risultati conseguiti hanno fornito una chiave scientifica d'interpretazione del fenomeno, riconducibile a scompensi idrici piuttosto che ad altre cause di danno, come pure utili indicazioni ai fini dei necessari ed indifferibili interventi di carattere fitosanitario e per la futura gestione selvicolturale.

## Zusammenfassung

### **Sommertrocknis 2003, als Ursache des Kiefernsterbens im Eisacktal**

Zu ausgedehnten Absterbenserscheinungen war es in Weißföhrenbeständen in sonnenexponierten Lagen des Eisacktales gekommen, infolge der anhaltenden Trockenperiode, von der im Sommer 2003 weite Teile Europas betroffen waren. Von der Abteilung Forstwirtschaft Bozen wurde eine interdisziplinäre Untersuchung eingeleitet, mit dem Ziel durch diagnostisch-differenzierte Erhebungen in verschiedenen Fachbereichen (Bodenuntersuchungen, Analyse von Witterungsfaktoren und Wasserbilanz, dendrochronologische Jahrringsuntersuchungen, Schädlingsauftreten etc.) zu wissenschaftlich fundierten Aussagen und Schlußfolgerungen zu kommen über das betroffene Ökosystem und die auf Klimaeinflüsse besonders sensibel reagierende Weißföhre. Aus den wissenschaftlich gestützten Ergebnissen lassen sich als primäre Ursachen des Phänomens vor allem Störungen des Wasserhaushaltes ableiten, während anderweitige Schadensursachen mehr sekundär erscheinen. Aus den Erhebungen lassen sich auch wichtige Erkenntnisse über erforderliche phytosanitäre sowie für künftige waldbaulischen Maßnahmen ableiten.

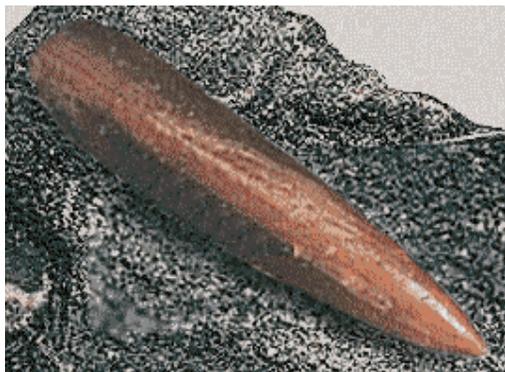
## Appendix:

The following sections briefly illustrate the technique and principles on which the methodology is based.

### Carbon isotope discrimination

The two stable carbon isotopes  $^{12}\text{C}$  and  $^{13}\text{C}$  occur in nature in proportions of 98.99% and 1.11% respectively. The ratio between these isotopes in the atmosphere is not, however, perfectly constant but is variable, depending on physical and biochemical processes as well as the use of fossil fuels.

Therefore the ratio  $\delta$  between  $^{13}\text{C}$  and  $^{12}\text{C}$  present in the atmosphere as  $\text{CO}_2$  averages  $-7\text{‰}$  in relation to an international reference standard **PDB** (Peedee Belemnite), that is, in relation to the isotopic ratio measured in a fossil sample of calcium carbonate taken from the rostrum of the cephalopod "American belemnite" coming from the Peedee Formation (Cretaceous) in South Carolina, USA.



[www.cretaceousfossils.com/invertebrates/belemnites/belemnitella\\_americana.htm](http://www.cretaceousfossils.com/invertebrates/belemnites/belemnitella_americana.htm)  
[virtual.clemson.edu/Geomuseum/bcgm2419.html](http://virtual.clemson.edu/Geomuseum/bcgm2419.html)  
[ethomas.web.wesleyan.edu/ees123/belemnite.htm](http://ethomas.web.wesleyan.edu/ees123/belemnite.htm)  
[fossilcollections.co.uk](http://fossilcollections.co.uk)

Fossil of Belemnite rostrum

During the process of photosynthesis a twofold discrimination takes place in the absorption of the two stable carbon isotopes depending on photosynthetic capacity and the extent of stomatal aperture. Consequently preference is given to the assimilation of the carbon dioxide composed of  $^{12}\text{C}$ :

- the first discrimination is physical, connected, that is, to the smaller atomic mass of  $^{12}\text{C}$  compared to  $^{13}\text{C}$ , as a result of which it diffuses more easily as  $\text{CO}_2$  through the stomatal apertures, into the substomatal chamber and, through the mesophyll, to the chloroplasts;

The level of discrimination in the plant  $\delta^{13}\text{C}_p$  depends on the isotopic composition of the atmosphere  $\delta^{13}\text{C}_a$  and on the partial pressure of carbon dioxide in the intercellular spaces of the foliar mesophyll (**ci**) in relation to partial atmospheric pressure (**ca**). Discrimination against  $^{13}\text{C}$  grows with the growth of partial carbon dioxide pressure in the foliar mesophyll and hence with the growth of stomatal conductance according to the expression (GRIFFITHS, 1993):

$$\delta^{13}\text{C}_p = \delta^{13}\text{C}_a + 4.4 \cdot (\text{ca} - \text{ci}) / (1000 \cdot \text{ca}) + 27 \cdot \text{ci} / (1000 \cdot \text{ca})$$

- the second discrimination is biochemical: it takes place during enzymatic carboxylation and depends on the greater affinity between the  $^{12}\text{C}$  and the ribulose enzyme-1.5-biphosphate-carboxylase/-oxygenase (=rubisco).

Therefore, as the  $^{12}\text{C}$  is selectively fixed in the carbohydrates synthesised by photosynthesis, the vegetal tissues are as a rule impoverished, or "lightened" (negative value) compared to  $^{13}\text{C}$ , according to a mean value for plants with C3 metabolism of a  $\delta^{13}\text{C}$  of about  $-25\div-30\text{‰}$  of the **standard isotopic concentration PDB**.

The index of carbon isotope concentration is as follows:

$$\delta^{13}\text{C} = \left( \frac{^{13}\text{C}/^{12}\text{C} \text{ of sample}}{^{13}\text{C}/^{12}\text{C} \text{ standard}} - 1 \right) 1000$$

from which it is possible to estimate the balance of stomatal and biochemical limitations on photosynthesis and of the effects exerted by environmental stress on the productivity of plants.

When there are episodes of water stress, the plants with C3 metabolism immediately reduce stomatal conductance (closure of the stomas) in order to minimise water losses through transpiration and guarantee the plant's survival. This causes a reduction in partial CO<sub>2</sub> pressure in the carboxylation sites, while the <sup>13</sup>C/<sup>12</sup>C ratio increases (in favour of the <sup>13</sup>C, whose partial pressure increases inside the intercellular spaces of the foliar mesophyll).

The result is a reduction in the discriminatory action of the rubisco enzyme in favour of the <sup>12</sup>C with the consequent use of all the CO<sub>2</sub> present in the air contained in the substomatal chamber and in the intercellular spaces of the foliar mesophyll, <sup>13</sup>C included, which is therefore assimilated in a greater amount, as shown by higher values in the δ<sup>13</sup>C ratio in the vegetal tissues.

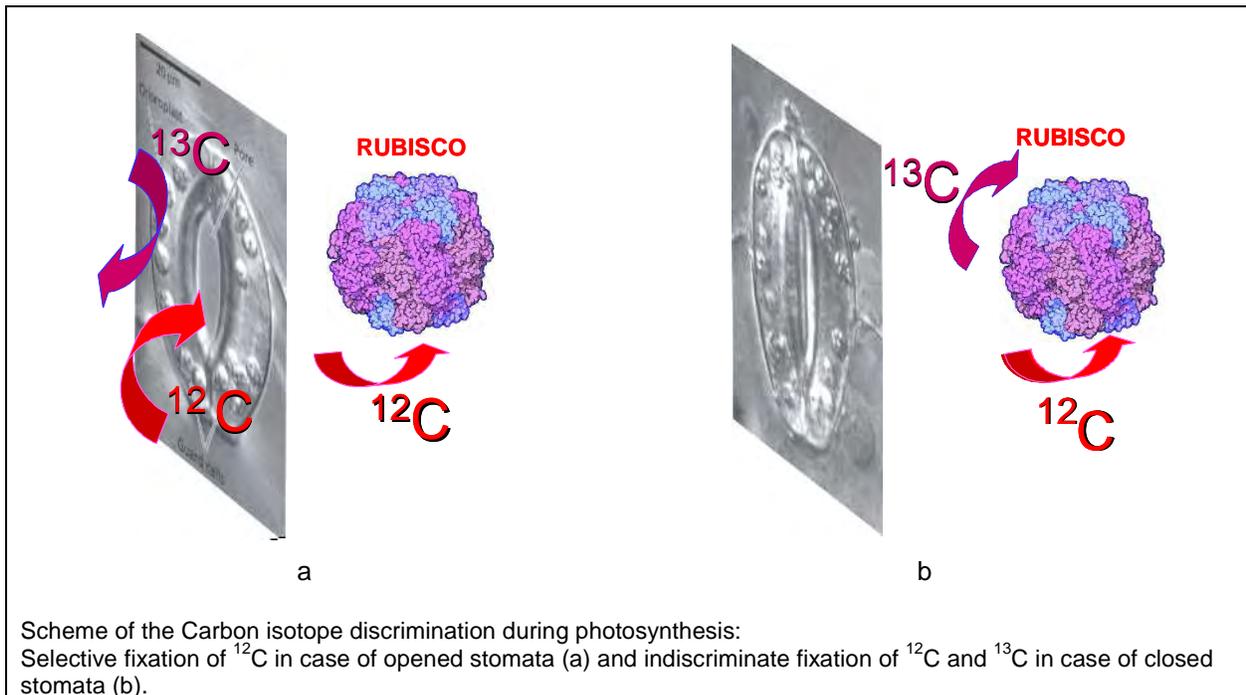
Therefore higher values of concentration of <sup>13</sup>C than those for unstressed plants accompany a state of water deficit in the soil/plant system.

Vice versa low values in the ratio indicate a favourable year with abundant precipitations sufficient for water provision. These are the ideal conditions for growth, as subsequently shown by the greater width of the annual ring, itself an indicator of optimal vegetative conditions for the plant.

Below are listed some of the factors which, by acting on stomatal conductance, affect the δ<sup>13</sup>C ratio.

Effect of specific factors on δ<sup>13</sup>C (SIEGWOLF & SAURER, 2000):

Factor	δ <sup>13</sup> C (↓negative, ↑positive)
Drought, water stress, high temperatures	↑↑
Nutrient shortage (particularly N)	↓
Air pollution	↓↑
Shading	↓
Increase in atmospheric CO <sub>2</sub> concentration	↓
High stock density, competition	↓
Management	↓↑
Metabolic status	↓↑



Scheme of the Carbon isotope discrimination during photosynthesis: Selective fixation of <sup>12</sup>C in case of opened stomata (a) and indiscriminate fixation of <sup>12</sup>C and <sup>13</sup>C in case of closed stomata (b).

### **Water Use Efficiency**

For C3 plants carbon isotope discrimination during synthesis is inversely correlated with Water Use Efficiency (WUE) (Brugnoli et al., 2003), given by the molar ratio between assimilated carbon dioxide and evaporated water (assimilation/transpiration).

In fact, WUE depends on the difference in carbon dioxide concentration (ca-ci) and the difference in the water saturation deficit (Dw) inside and outside the leaf according to the ratio (GRIFFITHS, 1993):

$$WUE = (ca-ci)/(Dw*1.6)$$

Therefore if water resources are sufficient, assimilation takes place with open stomata and high evapotranspiration ratios, that is, the quantity of water used per unit of carbon assimilated (mole on mole) is high (waste of water!), viceversa with closed stomata the plant is forced to use the available water more efficiently.

### **Oxygen isotope discrimination**

Oxygen present in nature is represented by three stable isotopes according to the following abundance values (GARLICK, 1969 in: GERMANI & ANGIOLINI, 2003):  $^{16}\text{O}$  99.763%,  $^{17}\text{O}$  0.0375%,  $^{18}\text{O}$  0.1995%.

Plants take in  $^{18}\text{O}$  only through soil water. Foliar water, and consequently vegetal tissues, contain more  $^{18}\text{O}$  than soil water, as water molecules containing  $^{16}\text{O}$ , being lighter, evaporate more rapidly than those containing  $^{18}\text{O}$ .

This process is affected by various environmental factors (temperature, relative humidity of the atmosphere, etc.), but it is stomatal conductance that, by regulating the speed of transpiration in response to the environment, determines enrichment in  $^{18}\text{O}$  of foliar water (BRUGNOLI et al. 2003).

However, this is true only for low or moderate transpiration values. If transpiration and consequently tree water consumption increase, foliar water cannot become completely enriched in  $^{18}\text{O}$  as it is diluted by soil water. In other words, the less transpiration there is, the greater is the ratio  $^{18}\text{O}/^{16}\text{O}$ .

The ratio  $^{18}\text{O}/^{16}\text{O}$  in wood growth rings can therefore be taken as an indicator of the plant's transpiration processes and indirectly of stomatal conductance.

This value is then compared with the reference value given by the mean current isotopic composition of ocean waters (SMOW – Standard Mean Ocean Water).

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