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Global and Planetary Change 40 (2004) 129–139

GLOBAL AND PLANETARY CHANGE

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Climate from dendrochronology: latest developments and results

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Received 19 December 2002; accepted 7 May 2003

Abstract

This review deals with the latest developments in dendroclimatology focused on climate reconstruction. It presents results from research carried out during the period 1992–2001, when both the geographical and chronological extension of tree-ring data were greatly improved. Research projects are presently being carried out in nearly all the main forest land areas of the Subarctic and Subantarctic zones, outside the traditional regions of research in North America and Europe, and about 150 tree-ring chronologies over 1000 years in length have been developed. Special attention is paid to data from Southern Europe and the Mediterranean area, where a detailed temperature reconstruction has been completed back to A.D. 970.

Research carried out in Italy and France provides useful information on climate change and CO_2. The aim of this research consists of evaluating whether in the radial tree growth of recent decades, there might be a part unexplained by climate and due directly to increasing atmospheric CO_2 fertilisation. These studies show that many wooden species in various ecosystems show different responses of ring width to increasing atmospheric CO_2. Finally, new scenarios of vegetation distribution and carbon sequestering, due both to positive or negative response from the trees, are offered by studies that reconstruct the expected radial growth of trees in situations of atmospheric CO_2 doubling.

Keywords: Tree rings; Dendroclimatology; Climate reconstruction; Atmospheric CO_2 fertilisation; Southern Europe, Mediterranean area

1. Introduction

Dendrochronology has attained a more and more increasing influence in paleoenvironmental studies, primarily because it not only provides annually resolved records, but also deals with decadal to century time scales that are appropriate for global climate change studies.

This review on recent developments and results in dendroclimatology and climate reconstruction from tree rings deals with research carried out between 1992 and 2001. It has as a starting point the situation illustrated by E. Corona during the Conference on "Cambiamento globale del clima: stato della ricerca italiana" held at Lincei in Rome in 1991 (Corona, 1992). The paper focuses primarily on two themes: climate reconstructions developed for Southern Europe and studies concerning fertilising effect on tree growth due to atmospheric CO_2.

2. Recent developments in climate reconstruction from tree rings

Climate reconstruction from tree rings has improved noticeably during the last 10 years, although the principles and methods of this kind of research

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doi:10.1016/S0921-8181(03)00103-6

had already been standardised and established in 1991—when Corona spoke at Lincei (Corona, 1992)—as Fritts (1976, 1991) and Cook and Kairiukstis (1990) had already published their basic works on the subject.

These books include exhaustive descriptions of methods and techniques useful for extracting climatic information from tree rings, from the first step of data collection to sample and data processing and finally to climatic reconstruction through the sophisticated statistical procedures of transfer functions.

Nevertheless, in recent years, the dendrochronological community has made increasing efforts to refine the methodology being used, in order to provide more detailed, more reliable, and especially more easily intercomparable data sets for climatology, especially for studying recent climatic global changes. These improvements may be noted both in methodology and in the results obtained.

In-depth discussion on recent improvements in data analysis techniques is beyond the scope of this paper; therefore, we refer to the works quoted *passim* along the text.

Regarding the improvement of the data set, special emphasis has been placed recently on broad geographical distributions of dendrochronological series, because detailed spatial reconstructions require suitable networks of tree-ring chronologies from all over the world. Research projects are presently being carried out in nearly all the main forested areas of the Subarctic and Subantarctic zones, outside the traditional regions of research in North America and Europe (Dean et al., 1996). The disparity in land area at the high latitudes of both hemispheres may account for the different amount of research results obtained (Boninsegna and Villalba, 1996).

Some recent studies conducted in tropical areas revealed that species living in tropical environments are also sensitive to climatic factors and are therefore suitable for climate reconstruction. Among the zones recently interested by dendroclimatological studies are the Himalaya (Esper et al., 1995), the Tibetan Plateau (Wu and Shao, 1995), southern Africa (D'Arrigo et al., 1996), Thailand, Indonesia, and the Pacific area (Otha et al., 1996). Tropical trees producing annual-like rings also permit the reconstruction of climatic variables (Boninsegna and Villalba, 1996).

The improvement of the data set concerns also its extension back in time. To detect whether recent climatic changes are due to anthropogenic effects, or are still within the range of natural variability, very long precisely dated annual tree-ring chronologies are needed. About 150 tree-ring chronologies over 1000 years in length have been constructed to date all over the world; more than 80 of these chronologies are referred to the southwestern United States (Briffa, 2000), 25 are from South America (Boninsegna and Villalba, 1996). Nevertheless, their analysis brought to less than 20 climatic reconstructions, which extend for more than 1000 years (Serre-Bachet, 1994b; Jacoby and D'Arrigo, 1997; Briffa, 2000; D'Arrigo et al., 2001) (Table 1; Fig. 1). There are two major problems with the use of millennia-long curves: firstly, the series usually presents bad replication at the beginning; the second problem is the lack of modern analogues to detect climate–growth relationships for some of the series.

Millennia-long temperature reconstructions, with the exception of those from South America (D'Arrigo et al., 1996) and Southern Alaska (Barclay et al., 1999), usually show evident warming during recent decades. Opinions vary with regard to the detection of whether recent warming is unusual in relation to previous centuries and millennia, although there is a general agreement in defining that none of the temperature maxima of the last millennium reached the levels of warmth seen at the end of the 20th century (Briffa and Osborn, 1999, 2000; D'Arrigo et al., 2001). In the reconstructed annual mean temperature series for the Northern Hemisphere calculated by Mann et al. (1998), it appears that the years 1990, 1995, and 1997 show the greatest anomalies back to A.D. 1400. One of the longest temperature reconstructions at our disposal, that based on Huon pine from Tasmania, ca. 3600 years long, shows marked and abrupt warming, comparable to that of recent decades only back in the 4th and in the 1st centuries B.C. (D'Arrigo et al., 1996).

Today, the widespread network of tree-ring chronologies available, together with the prolongation of their temporal validity, allows the association with changes in general atmospheric circulation patterns, such as El Niño/Southern Oscillation (ENSO) and the (NAO) (D'Arrigo et al., 1993; Stahle and Cleaveland,

Table 1
List of tree-ring reconstructions which are over 1000 years in length; (*) T/P = Inferred climatic variables: Precipitation (P) or Temperature (T), DSI = Palmer Drought Severity Index

Number	Site	Region	State	(*) T/P	First year	Species (E.)	Species (L.)	References
1	Prince William Sound	Southern Alaska	Alaska, USA	T	873 A.D.	hemlock	*Tsuga* sp.	Barclay et al., 1999
2	Southern Sierra Nevada	Sierra Nevada	California, USA	T	1 A.D.	foxtail pine	*Pinus balfouriana*	Scuderi, 1993
3	Southern Sierra Nevada	Sierra Nevada	California, USA	T and P	800 A.D.	foxtail pine western juniper	*Pinus balfouriana* *Juniperus occident.* ssp. *australis*	Graumlich, 1993
4	Methuselah Walk	White Mountains	Nevada, USA	P	6050 B.C.	bristlecone pine	*Pinus longaeva*	Hughes and Graumlich, 1996
5	San Francisco Peaks	Northern Arizona	Arizona, USA	T	663 B.C.	bristlecone pine	*Pinus longaeva*	Salzer, 2000
6	El Malpais	Northwestern New Mexico	New Mexico	P	136 B.C.	Douglas fir ponderosa pine	*Pseudotsuga menziesii* *Pinus ponderosa*	Grissino-Mayer, 1996
7	Tidewater	Tidewater Regions	North Carolina, USA	P (DSI)	372 A.D.	bald cypress	*Taxodium distichum*	Stahle et al., 1988
8	Lenca	Northern Patagonia	Chile	T	1630 B.C.	alerce	*Fitzroya cupressoides*	Lara and Villalba, 1993
9	Rio Alerce	Northern Patagonia	Argentina	T	864 A.D.	alerce	*Fitzroya cupressoides*	Villalba, 1990
10	Merveilles	French Alps	France	T	970 A.D.	larch	*Larix decidua*	Serre-Bachet, 1994b
11	Trentino-Alto Adige	Central Alps	Italy	T	970 A.D.	larch	*Larix decidua*	Serre-Bachet, 1994b
12	Tornetrask	Northern Sweden	Sweden	T	500 A.D.	Scots pine	*Pinus sylvestris*	Briffa et al., 1990
13	Salekhard	Urals	Russia	T	914 A.D.	Siberian larch	*Larix sibirica*	Briffa et al., 1995
14	Yamal	Western Siberia	Russia	T	1250 B.C.	Siberian larch	*Larix sibirica*	Briffa et al., 1995; Briffa, 2000
15	Taimyr	Central Siberia	Russia	T	1 A.D.	Siberian larch	*Larix sibirica*	Briffa et al., 1995; Briffa, 2000
16	Solongotyn Davaa	Tarvagatay Mountains	Mongolia	T	262 A.D.	Siberian pine	*Pinus sibirica*	D'Arrigo et al., 2001
17	Lake Johnston	Western Tasmania	Australia	T	1600 B.C.	Huon pine	*Lagarostrobos franklinii*	Cook et al., 1992; Briffa, 2000

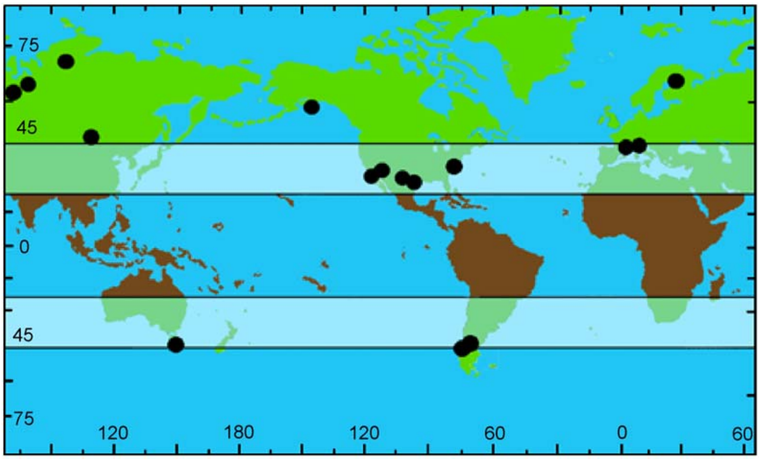

Fig. 1. Locations of tree-ring reconstructions which are over one 1000 years in length.

1993; Boninsegna and Villalba, 1996; Mann et al., 1998; Briffa, 2000).

This latter direction of research addresses the global-scale reconstruction of climate together with the use of other proxy data with a synoptic approach (“synoptic dendroclimatology”). We may also observe another type of approach focused on regional or local-scale studies in order to give us a greater understanding of the mechanisms involved in tree-growth response to climate. These local-scale studies allow the evaluation of magnitude (Hughes et al., 1999), timing (Vaganov et al., 1999), and spatial patterns of different factors affecting tree growth, such as volcanic eruptions (Yamaguchi et al., 1993; Jacoby et al., 1999), glacier fluctuations (Luckman, 2000), fire regimes (Grissino-Mayer and Swetnam, 2000), and drought occurrences (Stahle et al., 1998).

3. Climate reconstructions for Southern Europe and the Mediterranean area

In Europe, a third problem is present in working with long chronologies, related to the scarcity of long-lived trees. Long tree-ring series are often built from wood samples of varied and unknown provenances (i.e., from archaeological or historical contexts) and are hardly suitable for reconstruction purposes. Nevertheless, long climate series have been inferred for Southern Europe and the Mediterranean area.

The longest reconstructions for Southern Europe were developed by Serre-Bachet (1994b) on the basis of long tree-ring-width series established by the Laboratoire de Botanique Historique et Palynologie in Marseille (France) and the Istituto Italiano di Dendrocronologia in Verona (Italy). These show the evolution of the April to September mean temperatures from A.D. 970 to 1970, calculated by means of transfer functions, for three points (45°N10°E, 40°N10°E, 35°N10°E), corresponding to some of the points within the 5° latitude × 10° longitude-grid published by Jones et al. (1985).

A broader research carried out in Marseille provides both mean annual and summer temperature reconstructions for western and southwestern Europe and northern Africa for the period A.D. 1500–1969 (Serre-Bachet, 1994a). Twenty-two temperature reconstructions were developed for 17 points ranging from 30°N to 55°N and from 10°W to 10°E. One of these points corresponds to Rome, the other to some of the points published by Jones et al. (1985). The reconstructions are based on 25 different predictors: 15 are tree-ring series, 3 correspond to the three first principal components of the 17 longest ring-width series of cedars from Morocco, the others are historical proxy series (archive data) or isotopic series ^{18}O data in the Arctic ice.

The detailed analysis of temperature estimates, restricted to the five grid points for which both mean annual and summer temperature were calculated, gives evidence of the presence of a rather cold period (with high frequency of negative anomalies) from ca. 1700 to approximately 1800 (corresponding in part to the so-called Little Ice Age) for the latitudes 50, 45, and 40 across nearly all longitudes, which is clearly suggested by the mean annual temperature reconstruction. This period is preceded by two successive cold (1560–1590) and warm (1610–1680) phases and is followed by several short warm episodes, among which, the strongest is that of 1940–1950. Only the warm 1610–1680 episode is notable at 35°N latitude (Serre-Bachet, 1994a).

The first phase of this study has been dealing directly with temperature reconstruction from coniferous ring widths for the Italian area (Serre-Bachet et al., 1991). April to September mean temperatures were reconstructed for the province of Veneto and for the nearby grid point located at 45°N10°E in Italy. It was possible to determine the presence in Italy of strong and frequent negative anomalies from 1536 to 1574, from 1694 to 1735, from 1812 to 1826, and from 1832 to 1844, which also correspond in part to the so-called Little Ice Age (Fig. 2). Reconstructed temperature anomalies since the year 1500 correspond to anomalies reported for Europe. A predominance of cold periods between A.D. 1550 and 1850 is also shown by nine of the European temperature series summarized by Serre-Bachet (1997).

Reconstructions of total precipitation calculated for the Mediterranean area are less abundant than temperature reconstructions. There are two major reasons for this: the first is the great variation in precipitation from one place to another that makes it difficult to find a homogeneous response of ring-width to this factor; the second is that long-lived trees useful for this research usually grew in areas where precipitation is not a limiting factor.

Reconstructions of precipitations were made for Marseille (Serre-Bachet, 1997), NE Spain (Serre-

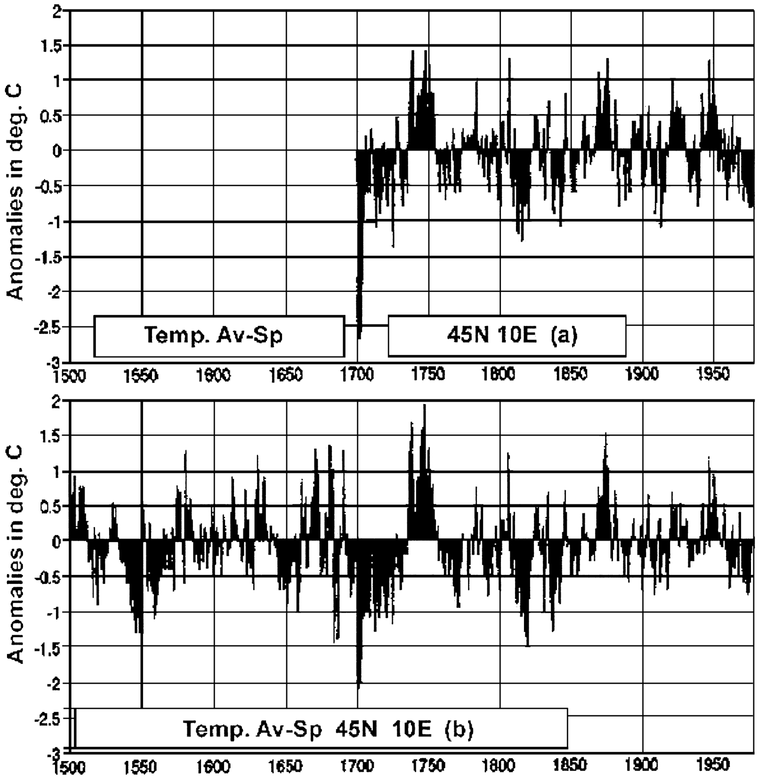

Fig. 2. Reconstructed temperatures at the 45°N10°E grid point of Jones et al. (1985) network expressed as departures from the average value of the periods. (a) Period 1700–1979 (seven tree-ring-width series). (b) Period 1500–1979 (five tree-ring-width series) (from Serre-Bachet et al., 1991).

Bachet et al., 1992), Central Spain (Fernandez et al., 1996), and Morocco, the latter spanning from A.D. 1100 (Till and Guiot, 1990). These are more difficult to interpret than temperature reconstructions, but we can note that in Morocco, the Little Ice Age coincided with severe drought periods, present from 1700. The precipitation reconstructed series from central Spain also shows a general decreasing trend from 1770 (Fernandez et al., 1996).

A recent reconstruction both for temperature and precipitation for the Southwestern Alps seems to indicate that the longest cold periods were humid as well (1680–1695; 1710–1720; 1760–1780; 1885–1915), and the longest warm periods were often dry (1735–1755; 1915–1930), but from 1780 to 1880, the climate seems to have been unstable (Belingard et al., 1996).

4. Studies on radial tree growth and increase of atmospheric CO_2

Tree rings may be used to reconstruct past climates as well as to estimate the effects of recent climatic and environmental change on tree growth. Tree-ring analysis may provide information about climate and CO_2 by evaluating whether increased radial growth during recent decades may be unexplained by climate and might instead be related to 'fertilisation' due to increased atmospheric CO_2 or other greenhouse gases.

Research carried out in France and Italy plays an important role in the study of climate change correlated with atmospheric CO_2 levels, as a new nonlinear method for such a purpose has been recently introduced: the artificial neural network (ANN). This new nonlinear technique seems to have improved the response and transfer functions significantly and to be reliable in detecting nonclimatic signals (Guiot et al., 1995).

This new method was applied in a study carried out for the Alpine region and the Apennines by the laboratory of Dendrodata s.a.s. in Verona (Italy), cofinanced by ENEL (the Italian electricity company) and the European Commission (Martinelli et al., 2001).

The study includes 15 forest stands located in six areas, with Norway spruce and larch as the main species, located on the southern slopes of the Alps, at an elevation generally between 1600 m a.s.l. and the upper vegetation limit and in two beech stands of the Northern Appenines. The beech stands are located on Mt. Abetone at an elevation of 1330 m and on Mt. Ventasso at 1400 m a.s.l.

The analyses carried out in the Alpine stands show an increase of radial tree growth in the last decades in 7 of the 15 site chronologies in the form of annular surfaces mean series. Tree growth–climate relationships were defined by response functions in the period preceding the growth increase, to be used subsequently as predictive models for the reconstruction of growth trends. Comparing the observed and the estimated growth rates through transfer functions, the latter calculated by using the ANN technique from the available climatic data, a positive trend independent from climatic factors could be identified (Fig. 3). This trend can be noticed beginning from the forties of the 20th century and becomes more pronounced during the sixties. It might be related to the growth of industrialisation and to the increase of CO_2 concentrations in the atmosphere. Nonetheless, a combined effect with other factors of human origin such as woodland management procedures and the emission of air pollutants with a fertilising effect cannot be excluded. Moreover, we have to stress the fact that in one site (Val Sesia 1), the growth rate is lower than predicted (Fig. 4).

Referring to the beech stands, the absence of clear relationships between climatic factors and tree growth did not allow reliable reconstructions for the last decades to be obtained. An increase in tree growth, however, can be observed in the last decades for the dendrochronological series located at Mt. Abetone.

Recent widespread diffusion of similar research on many wooden species growing in natural vegetation in various ecosystems shows quite different responses of ring width to increasing atmospheric CO_2 (Graumlich, 1991; Jacoby and D'Arrigo, 1997). From some studies, it appears clear that the negative impact of drought stress on tree growth in many regions during the warming in the last decades overcomes the positive fertilizing effect of CO_2 and may induce a reduced sensitivity of tree growth to temperature (Barber et al., 2000; Keller et al., 2000).

Briffa et al. (1998) could identify a decrease in Northern Hemisphere tree growth after 1940 due to the reduced sensitivity to temperature by comparing

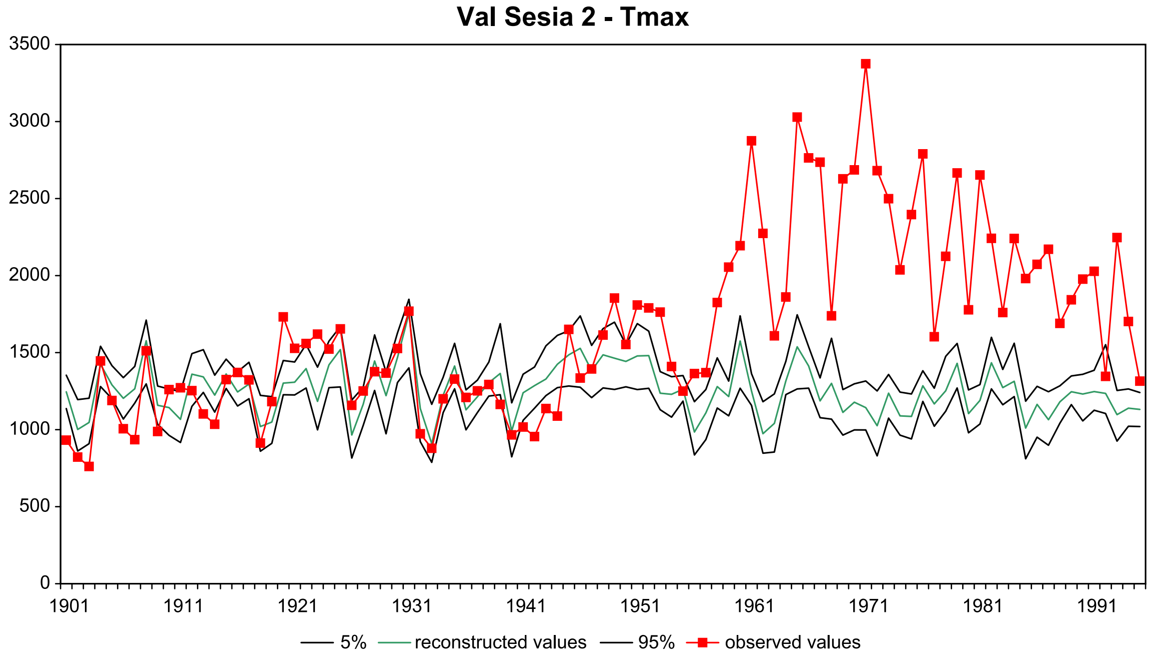

Fig. 3. Site Val Sesia 2 (Northern Italy)—comparison between the observed values (in the form of annular surfaces) and the values inferred on the basis of temperatures (T_{max}).

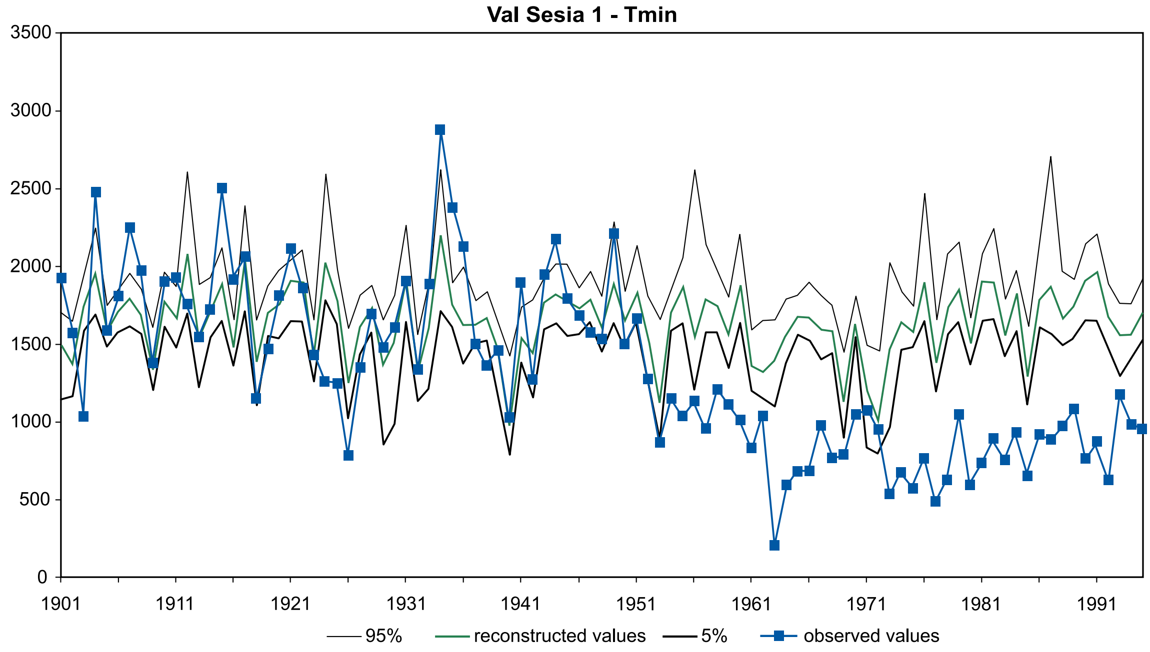

Fig. 4. Site Val Sesia 1 (Northern Italy)—comparison between the observed values (in the form of annular surfaces) and the values inferred on the basis of temperatures (T_{min}).

the decadal trends in recorded summer temperatures with averaged ring density and ring width from more than 300 locations. The reason of this phenomenon—which seems to have begun in the 1930s—is not known, but its syncronicity in all the investigated areas suggests the involvement of factors with a hemispheric-scale influence.

The hypothesis that warmer temperatures and enhanced atmospheric CO_2 have promoted increases in plant growth during summer in the northern high latitudes may no longer be retained without further support, although evidence from satellite data also shows that outside the tropics photosynthetic activity of terrestrial vegetation increased in recent years (Myneni et al., 1997).

New scenarios of vegetation distribution, due both to a positive or negative response from the trees, are offered by studies that reconstruct the expected tree-radial-growth in the situation of CO_2 doubling. Recent studies have been carried out in Marseille in order to estimate the growth induced by climatic change scenarios by using an atmospheric general circulation model (AGCM) (Keller et al., 2000; Rathgeber et al., 2000). The climatic perturbation induced by a hypothetical atmospheric CO_2 doubling was given by the ARPEGE model of Meteo-France.

Keller et al. (2000) determined that 6 of the 24 population chronologies studied in Southern France are sensitive to climate change. The CO_2 doubling would induce a growth increase for all the high-altitude populations (1600–2200 m) with the exception of one population. This southernmost Scots pine population reacts with a severe growth rate reduction, as it is in critical conditions with regard to the water

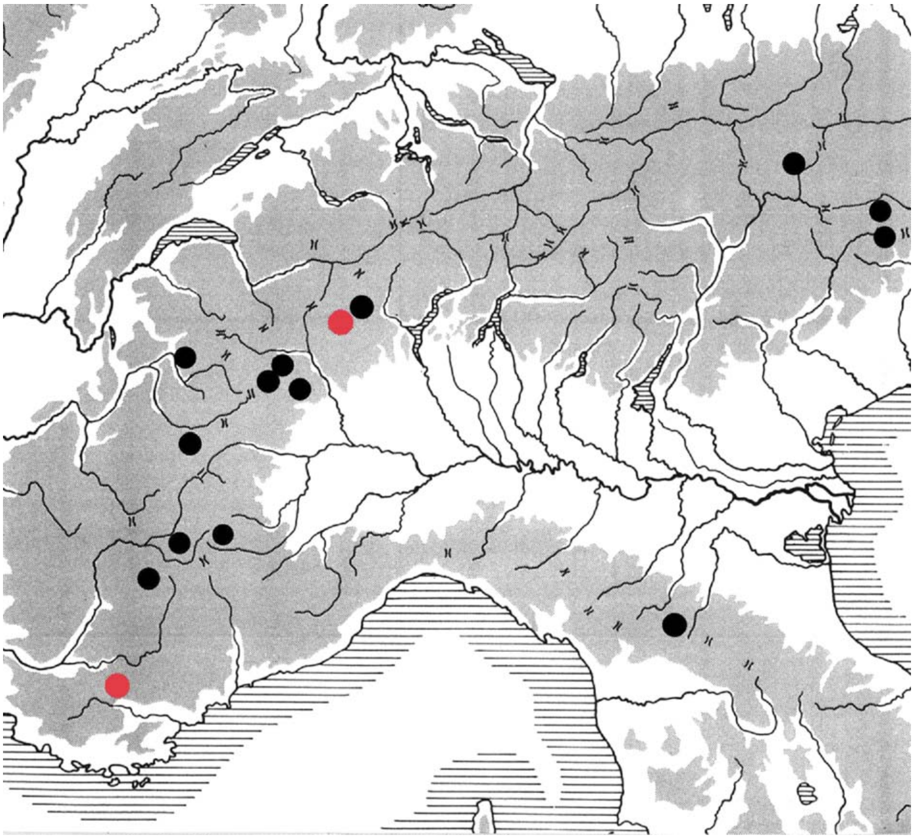

Fig. 5. Western and central Alps—location of sites where a positive (black dots) or negative (gray dots) trend independent from climatic factors was detected (summarized from Keller et al., 2000 and Martinelli et al., 2001).

Table 2
Some recent studies on radial tree growth and increase of atmospheric CO_2

References	Region	State	Species (E.)	Growth trends unexplained by climate	Methods of evaluation
La Marche et al., 1984	White Mountains	California, USA	bristlecone pine	positive in the two sites	visual comparison
Cook et al., 1992	Tasmania	Australia	Huon pine	positive in the site	visual comparison
Graumlich, 1991	Sierra Nevada	California, USA	foxtail pine lodgepole pine, Western juniper	positive in two of the five sites	growth prediction (regression analysis and response surfaces)
Nicolussi et al., 1995	Tyrol	Austria	stone pine	positive in the mean curve of the five sites	comparison in periods of similar temperature
Rolland et al., 1998	French Alps	France	larch Norway spruce stone pine mountain pine	positive in the four species mean curves	stepwise regression
Keller et al., 2000	French Alps and Provence	France	Scots pine mountain pine Norway spruce larch	positive in five sites negative in one site	transfer functions
Martinelli et al., 2001	Central Alps and Appennines	Italy	larch stone pine Norway spruce beech	Positive in seven sites negative in one site	transfer functions

factor. The increasing evapotranspiration would induce a more important water stress. Results show that the sensitive populations are located near the limit of the geographic distribution area of each species. In the new scenarios of atmospheric CO_2 doubling, species now widely distributed in Provence, such as Scots pine, risk to be replaced by other Mediterranean species such as Aleppo pine. Meanwhile, larch populations, now present in the Alps usually up to 2000 m, might reach higher altitudes and increase their productivity (Fig. 5).

These studies contribute in re-estimating the positive influence of atmospheric CO_2 on wood production (Jacoby and D'Arrigo, 1997) (Table 2). This change in tree-growth response has important implications for studies of past and future climate change.

On a global scale, this supposed positive influence on wood production and forest regeneration was thought to have the possibility of balancing the CO_2 increase by carbon sequestering through photosynthesis. On the contrary, tree-ring records indicate that, under recent climate warming, drought may have been an important factor in limiting carbon uptake in a large portion of the boreal forest, one of the planet's major potential carbon sinks. If this limitation in growth due to drought stress is sustained, the future capacity of northern latitudes to sequester carbon may be less than currently expected (Barber et al., 2000).

5. Conclusions

We have briefly described some of the latest dendroclimatological studies carried out to reconstruct past climate and to estimate whether recent climate changes are unusual relative to the past and might have a direct fertilizing effect on tree growth due to greenhouse gases. This research does not provide conclusive evidence, but shows that long high-temporal resolution climatic series from tree rings are essential for studying late Holocene climate variation.

Acknowledgements

I am very grateful to Henri Grissino-Mayer and Frederic Guibal, whose detailed and competent advice were invaluable in preparing this paper.

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