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CLIMATE and ATMOSPHERIC CO_2 EFFECTS on IBERIAN PINE FORESTS assessed by TREE-RING CHRONOLOGIES and their potential for CLIMATIC RECONSTRUCTIONS

Efectes del clima i del CO_2 atmosfèric en pinedes ibèriques avaluats mitjançant cronologies d'anells dels arbres i el seu potencial per reconstruir el clima

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PhD DISSERTATION

DISCUSSION

1. EFFECTS OF CLIMATE AND ATMOSPHERIC CO_2 CONCENTRATION ON IBERIAN PINE FORESTS

Some of the most well known shifts embedded in the current global climatic change, mean temperature and atmospheric CO_2 concentration increase, might have opposite effects on plants. Increases in atmospheric CO_2 concentration could provide more substrate for photosynthesis, leading to an enhancement of growth. In contrast, increases in temperature may increase respiration rates, leading to a reduction of growth. The research conducted until now pointed out in different directions. For example, stimulation of net primary productivity in four free-air CO_2 enrichment experiments in forest stands (Norby *et al.* 2005) or decelerating growth in tropical forest trees (Feeley *et al.* 2007). However, there are still many questions related to carbon partitioning and retention that remain unanswered. In Mediterranean climates, atmospheric CO_2 concentration increase will have a fertilizing effect only if temperature and rainfall are not constraining growth by means of water availability. This is only an example to show how, despite the amount of future scenarios simulations (Sabaté *et al.* 2002; Bakkenes *et al.* 2002; Thuiller *et al.* 2003), the effects of climatic change on terrestrial ecosystems are difficult to predict, being also widely heterogeneous around the world (Chapin *et al.* 2000; Walther *et al.* 2002; Root *et al.* 2003; Parmesan 2006).

Tree rings have been extensively used to assess the effects of recent climatic and environmental change on forest ecosystems (Fritts 1976), due to the capacity of trees to register information of climate and CO_2 conditions in their annual growth layers or rings. Using two different variables of tree-ring, width and $\delta^{13}C$ signature, we observed changes along the 20th century in tree-growth variability among thirty-eight forest (*Chapter 1*) and in the water-use efficiency (W_i) of five selected stands (*Chapter 2*), respectively. The first change was related to an increase in mean temperature and climatic variability, while the second was linked to the atmospheric CO_2 concentration increase.

1.1. Climatic effects

Besides the warming effect of greenhouse gases (Mann *et al.* 1998; Crowley 2000; IPCC 2001a; IPCC 2007a), especially in recent decades, scientists are increasingly recognising that short- and long-term variations in the natural climate variability are intrinsically linked to climate change. In this respect, it is expected an increase in limiting climatic conditions over larger scales, and as a consequence more synchronous tree growth among different forest stands.

CHAPTER 1: Climatic effects on regional tree-growth variability in Iberian pine forests

Changes in tree growth pattern

A network of thirty-eight tree-ring width chronologies, composed by three different species, was established at sites with diverse features and under different climatic influences along the north and east of the Peninsula. Despite the wide range of forests, a statistically significant percentage of common variance was shared by all the chronologies (chapter "ch." 1 Fig. 2). On a larger scale, this common variability should be caused by climate, as macroclimate seems the only reliable factor that could have an influence over all the sites across the Iberian Peninsula. However, this variance held in common by the chronologies was not stable throughout time, showing a clear upward shift at the beginning of the second half of the 20th century (ch. 1 Fig. 3). Considering that similarities among chronologies should increase under more limiting climatic conditions (Tardif *et al.* 2003), this higher common variance would indicate that sampled forests were growing more synchronously during the second half of the 20th century. Similarly, the frequency of narrow rings (ch. 1 Fig. 4) and the inter-annual growth variability (ch. 1 Fig. 5a) also rose along the 20th century.

Changes in climatic response

Significant relations were established between the regional chronology of the studied area and Spanish meteorological data (ch. 1 Fig. 7), indicating that radial growth is constrained by summer drought of the previous year, as well as a positive effect of July precipitation during the year of ring formation. However, changes in this climatic response were observed throughout the 20th century (ch. 1 Fig. 8). An extension of the water-stress period from summer to late summer was suggested, as well as strengthening of the relationship between growth and late summer/autumn temperatures of the year before growth. Tree-growth increased its negative correlation with prior August-September temperature and its positive correlation with November temperature, achieving significant correlation values around 1949. This change in the climatic response was produced simultaneously with the change in the tree-growth pattern described above, indicating an increase in water stress effect on radial growth during the last half of the 20th century. Similar findings were reported by other authors (Tardif *et al*. 2003; Macias *et al.* 2006; Wilmking *et al.* 2004).

Agreements between tree-growth patterns and climatic trends

As described above, late summer temperatures of the previous year seems to be one of the climatic drivers of the observed tree-growth pattern change among forests in the Iberian Peninsula. According to that, the upward trends of mean monthly temperature of the 20th century (ch. 1 Fig. 6) could be enhancing water stress at the late summer of the previous year. Precipitation variability during the growth period showed an increasing trend along the 20th century (ch. 1 Fig. 5b), that may be inducing an increase in common tree-growth variation among the forests (ch. 1 Fig. 3), as well as in the tree growth variability (ch. 1: Fig. 4; Fig. 5a). In agreement, precipitation variability was negatively related to radial growth, but positively to tree-growth variability (ch. 1 Fig. 9).

Therefore, at least two climatic factors seem to be responsible of tree growth and driving the observed changes in growth pattern and in their climatic response during the second half of the 20th century: the increasing trends observed in mean temperatures and the increment detected in precipitation variability during the growing period. These results are in agreement with the increase in warmer conditions (IPCC 2001b; Giorgi *et al.* 2004) and climatic variability (Font Tullot 1988; Romero *et al*. 1998; De Luis *et al*. 2000) described in Spain.

Growth pattern changes of three different species were detected in the Iberian Peninsula and climate appears as the main cause because, according to Parmesan and Yohe (2003), non-climatic explanations decline at increasing spatial scale and species number. Climate conditions became more limiting to growth since the mid 20th century, as suggested by an enhancement of growth synchrony among the studied forests. Yearly climatic variability also increased, as illustrated by the higher sensitivity and extreme growth indices recorded by the trees. Of particular interest is the fact that the thirty-eight tree-ring chronologies were not selected to amplify the climatic signal. Despite the network of chronologies was built from three pine species, and from a wide variety of habitats regarding site conditions and climatic influences along the north and east of the Iberian Peninsula, a statistically significant percentage of common variance was shared (32.5%).

The main contribution of *Chapter 1* is to report new evidences of the effects that global climate change is producing on terrestrial ecosystems, adding original information about the responses of Iberian pine forests to these changing climatic conditions. Investigations at specific sites are important to understand the wide range of response observed in biological systems, as well as to achieve a better knowledge of the consequences that climatic change would have over the world. Moreover, stronger effects of climate change were predicted in southern Europe than in more temperate areas (IPCC 2007b). Therefore, studies at regions as the Iberian Peninsula which are already vulnerable due to its intrinsic climatic variability and where many species found the edge of their phytogeographical distribution area (Blanco *et al.* 1997) are even more necessary.

The reported results are also relevant since there is a lack of studies analyzing changes in variability as it was done here. Changes in the mean climate state may be accompanied by changes in short-term (i.e. inter-annual to inter-decadal) variability. The relationship between mean climate state and climate variability has not been extensively investigated, despite the fact that the impacts of climate change on earth systems may derive more from changes in the variability than in the mean (Kutzbach *et al.* 2001). Moreover, the variability increase can be specially critical in regions with highly variable climates as the Mediterranean. Therefore, within the most important contributions of *Chapter 1* is also the validation of the importance of considering the role of climatic variability in studies related with biological changes.

Climatic reconstructions

> Finally, the stability of the significant relationship between current July precipitation and growth highlights the possibility of realistic <u>reconstructions of summer precipitation</u> in the Iberian Peninsula using a network of tree-ring width chronologies. However, special caution should be taken for temperature reconstruction due to the instability of its relationship with radial growth. Similarly, other authors also pointed out that some climate reconstructions based on ring width could miscalibrate past climate (Wilmking *et al.* 2004; Tardif *et al.* 2003).

The occurrence of summer drought, as well as the stability in the relationships found between July precipitation and the regional growth represented by the network of tree ring-width chronologies, points out the Iberian Peninsula as a suitable site for performing summer precipitation reconstruction. According to this, *Chapter 4* presents several preliminary summer precipitation reconstructions in Spain for the last 400 years. As some authors highlight the enormous potential of combining different tree-ring proxies (McCarroll *et al.* 2003; Gagen *et al.* 2006), $\delta^{13}C$ measurements were also used in addition to the classical variable of ring-width in order to improve the reliability of the reconstructions.

1.2. Atmospheric CO_2 concentration effects

Beyond the direct effect of CO_2 concentration as a key driver of climate change, the increase in atmospheric CO_2 concentration plays an important role in tree physiology. High levels of CO_2 concentration might produce a fertilization effect during photosynthetic process leading in higher growth rates. At the same time, high CO_2 levels could also induce a reduction of stomata aperture. This situation would counteract the effect of rising temperatures, as high temperatures heat leaves surface, and consequently stomata must be more open to refrigerate the leaves. However, a decrease in air humidity, linked to temperature increase and/or a precipitation decrease, could reduce stomatal conductance, enhancing also the efficiency in the water use All these reactions represent a big advantage for trees to face environmental stress, as for example summer drought under Mediterranean climate conditions. Nevertheless, how plants and trees in particular are responding and will respond to a CO_2-enriched atmosphere is still an open question in many respects. Considering that tree size imposes obvious limitations to physiological experimental studies, the application of the stable isotope techniques have provided new insights on tree physiology. Trees can register changes of isotopic atmospheric CO_2 composition in their rings with seasonal and annual resolution, allowing the attainment of long records of this environmental variable.

CHAPTER 2: Atmospheric CO_2 concentration effects on five Spanish pine forests

Factors affecting Δ values

By using carbon isotope signatures ($\delta^{13}C$) of tree-ring cellulose, the atmospheric CO_2 concentration (c_a) effect on five pine forest stands of three different species in the Iberian Peninsula (ch. 2 Fig. 1) was analyzed for the last 200 years. Significant differences among discrimination (Δ) values of the chronologies were found probably due to different sites conditions and/or specific characteristics: lowest Δ values belonged to the driest and southernmost site and differences in Δ levels were found between two different species forests separated only by 10 Km (ch. 2 Fig. 3).

The $\delta^{13}C$ declining trend and c_i/c_a (≈Δ) stability

All raw $\delta^{13}C$ chronologies showed a decreasing trend, particular at each stand and most pronouncedly since 1960 (ch. 2: Fig. 2; Fig. 4a), similar to the decrease of the $\delta^{13}C$ of atmospheric CO_2 caused by the rise of $\delta^{13}C$-depleted CO_2 due to fossil fuel burning and deforestation since industrial revolution (ch. 2 Fig. 5a).

The c_i/c_a (≈Δ) ratio remained rather constant since 1800 until the 1960-99 period, where high variability among the c_i/c_a of the chronologies was detected (ch. 2: Fig. 4b; Fig. 5b). However, according to Saurer *et al.* (2004) scenarios, as c_i (leaf intercellular CO_2 concentration) and W_i (water-use efficiency) increases also were observed (ch 2: Fig. 4c-d; Fig. 5c-d), our results suggest a mechanism that keeps c_i/c_a more or less stable which should be interpreted as a regulative adaptation of trees to rising CO_2 (Ehleringer and Cerling 1995). Constancy of c_i/c_a may be achieved by a concurrent reduction of both the stomatal conductance and the photosynthetic capacity in response to higher levels of CO_2 (Saurer *et al.* 2004). The reduced conductance can produce an overall warming contribution for land temperatures through reduction in the evaporative fraction.

Wi improvement was not related to climatic trends

With the rise in c_a, the ratio of c_i/c_a remained more or less constant, resulting in a significant W_i increase from 1960 on all the studied sites (ch. 2: Fig. 4d; Fig. 5d). But was really the c_a increase enhancing W_i? The observed temperature increase, precipitation decrease and vapour pressure deficit (VPD) increase during winter (ch. 2 Fig. 6) did not seem linked to the reported changes. Moreover, these climatic trends did not develop equally at every site, suggesting that these climatic factors can not be responsible for the W_i enhancement detected in the five studied forests. Therefore, these results point out the c_a increase as the most feasible driving force leading to the W_i improvement observed at the end of the 20^{th} century.

Trees under Mediterranean climate conditions must face a trade-off between stomatal conductivity and heat balance of the leaves in order to save water and keep the leave refrigerate. In our study, an enhancement of W_i have been detected in response to higher levels of CO_2, as the c_i/c_a (≈Δ) remained rather constant. Since the c_i/c_a constancy depends on a simultaneous reduction of stomatal conductance and photosynthetic capacity (Saurer *et al.* 2004), we assumed that a decrease in plant transpiration has been produced in our five forest stands. Reduction in plant transpiration could affect hydrological budgets, resulting in drier air and enhanced warming near surfaces (Betts *et al.* 2000). Although consequences of lower conductance are stronger in more continental areas (e.g. Siberia), where a high part of precipitation is generated by transpiration (Saurer *et al.* 2004), the observed physiological response in Spanish forests might cause a vegetation-climate feedback by modifying surface-atmosphere fluxes of energy and moisture. How far this decrease in plant transpiration counteracts the increase in water stress? It remains unclear to what extent and for how long this reduction in plant transpiration can be maintained since, as was described in *Chapter 1*, temperatures are rising and precipitation is becoming more irregular in the Iberian Peninsula and plants will need to open stomata to refrigerate leaves.

Although it must be taken into account that our results are estimations of the W_i (we did not measure real W_i in the field), the observed trends for the two last centuries can be considered relevant as this kind of long time records could only be obtained in this way. Thus, carbon isotope discrimination analysed by tree-rings provides an integrated measure of W_i and also historical records of tree responses to environmental conditions.

In contrast to *Chapter 1* results, in which climate was related to observed changes in tree-growth patterns, *Chapter 2* results showed that climate is not leading the observed trends in W_i, being the atmospheric CO_2 concentration rise the main cause. However, both studies have in common that the strongest changes were observed during the second half of the 20th century, incorporating more evidences of impacts of global change in the Iberian Peninsula and highlighting the complexity of biological systems responses.

2. RECONSTRUCTIONS OF CLIMATE IN SPAIN

2.1. Width and $\delta^{13}C$ sensitivity to climate

The second main objective of this Thesis is to extract the climatic signal registered by the studied forests with the aim of reconstructing past climate. Using the same stands analyzed in *Chapter 2*, the nature and strength of the climatic signal registered by these five Iberian pine forests (ch. 3 Fig. 1) was assessed in *Chapter 3*. In this case, width and $\delta^{13}C$ tree-ring chronologies were analyzed as there was a strong interest in comparing the climatic sensitivity of these both kinds of tree-ring proxies.

CHAPTER 3: Width and $\delta^{13}C$ tree-ring sensitivity to climate in Spanish pine forests

Comparison between width and $\delta^{13}C$

A higher and more homogenous agreement in response to climate was found among carbon isotope records than among ring width series. In a similar frequency domain, correlations among the $\delta^{13}C$ chronologies were higher than between the ring width series (ch. 3: Table 4; Table 5). Accordingly, the variance explained by the PC1 showed that $\delta^{13}C$ variations at different sites presented more similarities than ring width variations (ch. 3 Table 6). The same finding was described by Saurer *et al.* (1995).

Our results also point out that ring-width proxy may reflect local factors, while $\delta^{13}C$ ratios may contain a wider spatial climatic signal. In agreement with this, Gagen *et al.* (2004) found that the $\delta^{13}C$ series is much less sensitive to local conditions than growth proxies, while Robertson *et al.* (1997a, b) studies also demonstrates that more significant climate signals were contained in isotopic measurements than in ring-width.

Correlations (ch. 3 Table 7) and PCs (ch. 3 Fig. 4) revealed a negative relationship between ring-widths and $\delta^{13}C$ values. Although the inter-annual variability of both parameters was related to climatic variations, the same climate variable may have opposite effects on them.

Climatic sensitivity

As inferred from response function analyses, ring-widths and $\delta^{13}C$ showed significant relationships with climate. Each ring-width chronology showed its own particular relationship with climate according to the variety of stand features and local climatic conditions (ch. 3 Fig. 5). In contrast, a common negative response to summer precipitation, as well as a positive response to summer temperature (to a lesser extent) was shared by all $\delta^{13}C$ chronologies (ch. 3 Fig. 6). The finding of a strong dependence of tree-ring $\delta^{13}C$ on water availability, as a strong and consistent climatic control common among all the studied stands, was in agreement with the spatially broad and homogeneous common signal shared by the $\delta^{13}C$ chronologies. Therefore, $\delta^{13}C$ values reflected drought stress signal during summer season better than tree-ring widths, placing $\delta^{13}C$ as a valuable integrator of water availability. This highlights that isotopic ratios are a useful tool for climatic reconstruction when relationships between climate and ring-width are weaker.

Comparisons with other studies revealed a strong precipitation signal in the $\delta^{13}C$ in ring cellulose from trees growing under Mediterranean climate (Feng and Epstein 1995; Swanborough *et al.* 2003; Ferrio and Voltas 2005), but also a high influence of local conditions in $\delta^{13}C$ ratios (Saurer *et al.* 1995; Treydte *et al.* 2001; Gagen *et al.* 2004).

One of the main dendrochronological principles, the assumption that common information shared among trees in a stand can be regarded as climatic information (Cook and Briffa 1990), was extrapolated on a broader scale and used in *Chapter 1* and *Chapter 3*. It was done considering that common variability shared by the thirty-eight tree-ring width chronologies from three different species (*Chapter 1*), five ring width or five $\delta^{13}C$ tree-ring chronologies (*Chapter 3*) across the Iberian Peninsula might be due to climate.

A simple model of the influence of climate on the internal concentration of CO_2 in the stomatal chambers (McCarroll and Pawellek 2001) described that $\delta^{13}C$ values indicate the balance between stomatal conductance (related to air relative humidity and antecedent rainfall) and photosynthetic rate (related to temperature and photon flux). Thus, the sensitivity to precipitation and temperature (linked to air relative humidity) described in *Chapter 3* suggests that $\delta^{13}C$ variability was mainly controlled by stomatal conductance in all the studied sites (although temperature may be also affecting the photosynthetic rate). Findings of *Chapter 2* related a reduction of stomatal conductance with other physiological plant changes as stability in c_i/c_a and W_i rise, as a consequence of the increase in concentration of atmospheric CO_2. Since the aims of these papers were not the same, different methodologies were applied in both chapters, retaining only the low trends of the series in *Chapter 2* and fluctuations of higher frequency domains in *Chapter 3*. In agreement with our results, in literature, low frequency variations in $\delta^{13}C$ of tree-ring series from the late 19th and 20th century were generally linked with physiological responses to increasing atmospheric CO_2 concentrations in conjunction with declining atmospheric $\delta^{13}C$ (e.g. Feng 1998), while high frequency fluctuations in $\delta^{13}C$ were related to climatic parameters (Feng and Epstein 1995; Hemming *et al.* 1998; Tang *et al.* 1999). Therefore, changes in factors as atmospheric CO_2 concentrations, temperature, precipitation, relative humidity or photon flux have an effect on $\delta^{13}C$ ratios, being carbon stable isotopes a useful indicator to reconstruct these different past environmental conditions. However, one of the main goals of the scientific community is being able to separate the climatic signals from those other factors.

2.2. Summer precipitation reconstruction

As *Chapter 3* assessed a significant climatic sensitivity of width and $\delta^{13}C$ tree-ring proxies, we decided to perform a climatic reconstruction for the last 400 years utilizing the three longest chronologies of the studied sites. Water availability during summer season was found to be the most important limiting factor in *Chapter 3* results. Accordingly, preliminary calibration done with monthly (12 variables) and seasonal grouping of this meteorological data (66 combinations) for mean temperature and total precipitation, also found June-July precipitation as one of the best suitable variable to be reconstructed in *Chapter 4*. In contrast, correlations obtained using combinations of temperature variables were lower.

Two different meteorological data sets were used depending on each chapter of this Thesis. Monthly mean temperature and total precipitation of Spain from TYN CY 1.1 data set (Mitchell *et al.* 2003) created by the *Climatic Research Unit* (CRU) was used in *Chapter 1* because the detection of a macroclimate signal registered in the tree ring-width chronology network was one of the main objectives of that paper. In contrast, the nearest data from a Spanish gridded data set (25 x 25 Km grid-box) created by the *Instituto Nacional de Meteorologia* (INM) was used in *Chapter 2* and *Chapter 3* because those papers were focused on more local responses to climate. And finally, both set of meteorological data were used in *Chapter 4* to perform comparisons between these sources of instrumental information. Considering the main objective of that paper was to reconstruct summer precipitation for a regional scale (e.g. Spain), a principal component analyses (PCA) was performed with the three points of the gridded INM data set to get also a regional estimation of Spanish climate. Therefore, some differences between reconstructions done based on these two data sets were expected since they do not represent exactly the same.

CHAPTER 4: Precipitation reconstructions for the last 400 years in Spain

Summer precipitation reconstructions

Reconstructions of June-July precipitation (P0607) in Spain were made back to AD. 1600 using width (ch. 4 Fig. 2) and $\delta^{13}C$ (ch. 4 Fig. 3) tree-ring chronologies established at three different locations (ch. 4 Fig. 1). Prior to establish transfer functions, principal component analyses (PCA) were performed using combinations of the tree-ring chronologies, resulting in different data sets composed by principal components (PCs). The best correlations in the calibration period were obtained using both kinds of tree-ring variables (ch. 4 Table 6). Accordingly to McCarroll *et al.* (2003) and Gagen *et al.* (2006) whom reported that the strength of the climate correlations is increased and the range of extractable parameters extended by combining proxies.

The transfer functions used to estimate P0607 INM (*Instituto Nacional de Meteorologia*) or P0607 CRU (*Climatic Research Unit*) were stepwise multiple regressions based on: (a) standard ring-width and $\delta^{13}C$ series; (b) standard and $\delta^{13}C$ series without autocorrelation; (c) standard and $\delta^{13}C$ series with temporal lags. Strong similarities were found between INM and CRU reconstructions (ch. 4 Fig. 5); although their agreement was lower between reconstructions based on $\delta^{13}C$ series without autocorrelation, and even lower when proxies with temporal lags were used. Larger similarities were observed among INM reconstructions than among CRU reconstructions.

Reliability of P0607 reconstructions

Non-stability between tree-ring proxies and climate was detected, as well as discrepancies among reconstructions in the low frequency domain, introducing questions about the reliability of our reconstructions. However, agreements found with several historical documentary reconstructions during the 17th and 18th century validated somehow our results. In addition, significant relationships between our reconstructions and NAO and SOI indices show a link between our series and general atmospheric phenomena (ch.4: Fig. 6; Fig. 7). However, disagreements were found in the magnitude of their response to NAO and ENSO.

As was concluded in *Chapter 4*, discrepancies found in the long-term trends of the our reconstructions, as well as in the magnitude of their response to large-scale atmospheric phenomena as NAO and ENSO, alert about the need to discuss more about the different statistical treatments applied over the tree-ring proxies prior to be used for reconstructing past climate. This topic is not new in climatic research, as it has been extensively discussed concerning temperature reconstructions. Strong disagreements were reported in the range of amplitude among several high resolution millennial-length reconstructions of past temperatures based on ring width or density measurements (Briffa and Osborn 2002; Esper *et al.* 2004; D'Arrigo *et al.* 2006), although similar variations from multi-decadal to centennial scales were detected after removing their lowest frequency trends (Esper *et al.* 2004). Nevertheless, although the use of stable isotopes reduces statistical standardization methods usually applied to ring-width and density chronologies (McCarroll and Loader 2004; Gagen *et al.* 2007), uncertainties related to the real range of amplitude of temperature or precipitation in the past millennium still remained unsolved. The achievement of this challenge is crucial to provide a better understanding of current climatic fluctuations, as well as to improve the reliability of climate prediction models, determining to what extent present global changes are unusual. In this dissertation Thesis, different statistical treatments were explored, contributing with original results to solve this issue.

Climatic reconstructions with annual resolution, as provided by tree-rings, play an important role in palaeoclimatic investigations because they allow not only the determination of cold/warm or dry/moist periods, but also the detection of climate extreme events occurred in the past. Up to now, not many reconstructions based on tree-ring width chronologies in the Iberian Peninsula have been published (Creus 1991-92, 1995, 1996; Fernández *et al.* 1996; Manrique and Fernández-Cancio 2000), and even only Planells *et al.* (2006) introduced stable isotopes tree-ring chronologies as predictors in a reconstruction of local climate. In this sense, our attempt to reconstruct Spanish precipitation using a combination of ring-width and stable carbon isotope is quite novel.

A multiproxy approach for palaeoclimatic reconstructions is been intensively recommended as a way to improve the reliability of future reconstructions, as it seems that could smooth the particular problems of each kind of proxy (Mann 2002). Indeed, several authors have recently combined different kind of proxies to reconstruct temperatures in Europe during the last millennium (Guiot *et al.* 2005), the Northern Hemisphere temperature by the past 2000 years (Moberg *et al.* 2005) or European precipitation for the last 500 years (Pauling *et al.* 2006). The fact that historical documentary reconstructions and drought indices (Barriendos 1997; Rodrigo *et al.* 1999; Vicente-Serrano and Cuadrat 2007), as well as other climatic proxies studied in lake sediments in Pyrenees (Pla and Catalan 2005) are already available introduce the possibility of performing this kind of multidisciplinary studies in near future for precipitation and temperature reconstructions of the Iberian Peninsula. The geographical location between temperate and tropical climates places the Iberian Peninsula as a transition zone with high complexity of climate. The ecosystems located in transitional zones can be considered ecotones (Lavorel *et al.* 1998) and they are specially sensitive to climate change. Therefore, to determine past climate in this region is important to understand general climate dynamics.

SUMMARY

1. Climate and atmospheric CO_2 concentration effects

1.1. Climatic effects

CHAPTER 1: Climatic effects on regional tree-growth variability in Iberian pine forests

1.1.1. A common macroclimatic signal, expressed by the first principal component, was detected among a network of thirty-eight ring-width pine chronologies along the north and east of the Iberian Peninsula, despite the diversity of species, habitats and climatic regimes.

1.1.2. The variance held in common by the chronologies was not stable throughout time, showing a clear increase at the beginning of the second half of the 20th century. Similarly, the frequency of narrow rings and the inter-annual variability also rose along the 20th century.

1.1.3. Radial growth was constrained by water stress during the summer of the previous year, as well as by lack of water in July during the year of ring formation. Changes in this climatic response were observed throughout the 20th century and were produced synchronously with the change in the tree-growth pattern, indicating an increase in water stress effects on radial growth during the second half of the 20th century.

1.1.4. Two climatic factors could have been affecting tree growth and driving the observed changes in growth pattern and in their climatic response during the second half of the 20th century: the increasing trends in mean temperatures and the increment in precipitation variability during the growing period.

1.2. Atmospheric CO_2 concentration effects

CHAPTER 2: Atmospheric CO_2 concentration effects on five Spanish pine forests

1.2.1. Significant differences among discrimination values of the chronologies were found probably due to habitat and/or specific differences.

1.2.2. All raw $\delta^{13}C$ chronologies showed a decreasing trend, particular at each stand and most pronouncedly since 1960. This declining is similar to the decrease of the $\delta^{13}C$ of atmospheric CO_2 caused by the rise of $\delta^{13}C$-depleted CO_2 due to fossil fuel burning and deforestation since industrial revolution.

1.2.3. The ratio of c_i/c_a (≈discrimination) remained rather constant with the rise in atmospheric CO_2 concentration (c_a), resulting in a significant increase in the intercellular concentration of CO_2 (c_i) and water use efficiency (W_i) since 1960 at all the studied sites.

1.2.4. Neither temperature increase, nor precipitation decrease or vapour pressure deficit (VPD) increase detected during winter seem to be responsible for the W_i enhancement.

2. Reconstructions of climate

2.1. Width and $\delta^{13}C$ sensitivity to climate

CHAPTER 3: Width and $\delta^{13}C$ tree-ring sensitivity to climate in Spanish pine forests

2.1.1. A higher and more homogenous agreement in response to climate was found among carbon isotope records than among ring width series, suggesting that $\delta^{13}C$ ratios may record large scale climatic signals, while ring-width variations may reflect more local factors.

2.1.2. A negative relationship between ring-widths and $\delta^{13}C$ values was revealed, indicating a different relationship with climatic variables.

2.1.3. $\delta^{13}C$ values reflected drought stress signal during summer season better than tree-ring width, being a very valuable integrator of water availability. This highlights isotopic ratios as a useful tool for climatic reconstruction when relationships between climate and ring-width are weak.

2.2. Summer precipitation reconstruction

CHAPTER 4: Precipitation reconstructions for the last 400 years in Spain

2.2.1. Several preliminary reconstructions of June-July precipitation (P0607) based on width and $\delta^{13}C$ tree-ring chronologies were carried out in Spain for the last 400 years.

2.2.2. The best correlations in the calibration period were obtained using both kinds of tree-ring proxies, ring width and $\delta^{13}C$ chronologies. The transfer functions used to estimate P0607 INM (*Instituto Nacional de Meteorologia*) and P0607 CRU (*Climatic Research Unit*) were stepwise multiple regressions.

2.2.3. Strong similarities were found between reconstructions based on INM and CRU data; although their agreement was lower between reconstructions based on $\delta^{13}C$ series without autocorrelation, and even lower when proxies with temporal lags were used. Agreements found with several historical documentary reconstructions during the 17th and 18th century validated somehow our results.

2.2.4. Significant relationships between our reconstructions and large-scale NAO and SOI indices show a link between the reconstructed series and the atmospheric phenomena of NAO and ENSO, as well as their influence over Iberian precipitation.

CONCLUSIONS

- Significant changes in tree-growth variability in a network of thirty-eight forests and in their climatic sensitivity (*Chapter 1*), as well as an increase in water use-efficiency of five selected stands (*Chapter 2*) in the Iberian Peninsula during the second half of the 20th century are unusual relative to the past. Growth pattern changes were related to recent warming and precipitation variability increase, while water-use efficiency trends were related to the rise of atmospheric CO_2 concentration.

- $\delta^{13}C$ values reflected drought stress signal during summer season better than ring width in tree-ring chronologies of five Spanish pine forests (*Chapter 3*). Summer precipitation reconstructions in Spain for the last 400 years were performed based on three width and $\delta^{13}C$ tree-ring chronologies and significant links with large-scale atmospheric phenomenon as NAO and ENSO were established (*Chapter 4*). In addition to the well-known application of dendrochronological techniques to reconstruct past climate, our results highlight the enormous potential of combining different kind of tree-ring proxies in climatic research.