Contents lists available at SciVerse ScienceDirect

Global and Planetary Change

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Declining pine growth in Central Spain coincides with increasing diurnal temperature range since the 1970s



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ARTICLE INFO

Article history: Received 13 May 2013 Accepted 22 May 2013 Available online 30 May 2013

Keywords: climate change dendroecology diurnal temperature range ecosystem response forest growth Mediterranean Basin

ABSTRACT

Growing evidence suggests environmental change to be most severe across the semi-arid subtropics, with past, present and projected drying of the Mediterranean Basin posing a key multidisciplinary challenge. Consideration of a single climatic factor, however, often fails to explain spatiotemporal growth dynamics of drought-prone ecosystems. Here, we present annually resolved and absolutely dated ring width measurements of 871 Scots pines (*Pinus sylvestris*) from 18 individual plot sites in the Central Spanish Pinar Grande forest reserve. Although comprising tree ages from 6 to 175 years, this network correlates surprisingly well with the inverse May–July diurnal temperature range (r = 0.84; $p < 0.0001_{1956-2011}$). Ring width extremes were triggered by pressure anomalies of the North Atlantic Oscillation, and the long-term growth decline co-incided with Iberian-wide drying since the mid-1970s. Climate model simulations not only confirm this negative trend over the last decades but also project drought to continuously increase over the 21st century. Associated ecological effects and socio-economic consequences should be considered to improve adaptation strategies of agricultural and forest management, as well as biodiversity conservation and ecosystem service. © 2013 Elsevier B.V. All rights reserved.

1. Introduction

Indication of past, present and projected climate change is particularly strong for the western Mediterranean Basin (Luterbacher et al., 2012), where future rates of temperature increase and precipitation decrease will likely accelerate aridification (Fischer and Schär, 2010; Hoerling et al., 2012; Xoplaki et al., 2012). Associated effects on biodiversity and ecosystem functioning (Carnicer et al., 2011; Anderegg et al., 2013), including phenological alterations (Peñuelas et al., 2002), species-specific range shifts (Peñuelas et al., 2007), decreasing forest production (Martínez-Vilalta and Piñol, 2002; Jump et al., 2006; Galiano et al., 2010; Linares and Camarero, 2012), and subsequent reductions in carbon accumulation (Vayreda et al., 2012), are often attributed to warming-induced desiccation (Zhao and Running, 2010; Galiano et al., 2011). The relative roles of temperature-driven evaporative demand and precipitation or their amalgamation on tree growth and mortality, however, are not yet fully understood (Allen et al., 2010; Choat et al., 2012; Williams et al., 2012).

Economic consequences of a drought-induced decline in forest ecosystem productivity and functioning are expected to increase under projected climate change and may even contain a valuable shift from traditional timber harvest to the utilization of other forest resources (Hanewinkel et al., 2012). Socio-economic consequences of a Mediterranean long-term drying, including associated effects on tourism and hydropower, will subsequently require future drought risk and water resource management strategies as part of any public policy and scientific activity (Courtenay-Botterill and Hayes, 2012).

Insight on how trees respond to climate can originate from annual variations in their radial stem thickening. Ring widths retain past environmental conditions that occurred during a tree's lifespan and therefore constitute a unique high-resolution archive. Nevertheless, most of the existing tree-ring studies focused on species-specific distribution limits, and dendroclimatological evidence from less extreme woodlands is sparse. Many tree-ring chronologies are often also constrained by a rather low sample replication weighted towards long-lived, isolated individuals from open stands that do not necessarily reflect putative growth-climate response patterns of different age

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^{0921-8181/\$ -} see front matter © 2013 Elsevier B.V. All rights reserved. http://dx.doi.org/10.1016/j.gloplacha.2013.05.013

classes coexisting in natural forests (Esper et al., 2008). Further uncertainties related to growth–climate response analyses can arise from the meteorological target measurements themselves (Frank et al., 2007a; Büntgen et al., 2008b; Esper et al., 2010). Particularly severe spatiotemporal heterogeneity in the relationship between tree growth and climate has been reported for Mediterranean sites (Tardif et al., 2003; Büntgen et al., 2010a, 2010b, 2012b; Seim et al., 2012), where the proper recording of sporadic local rainfall events is additionally hampered by a historical instrumental record that is generally too short in length and too coarse in spatial resolution (Brunet et al., 2006).

In seeking to enhance knowledge on interannual to multi-decadal lberian forest growth dynamics, we compiled a unique ring width network of Scots pine plot chronologies across a homogeneous forest region in Central Spain. European-scale gridded meteorological parameters, as well as state-of-the-art climate model simulations were used for comparison. Results were placed in a socio-economic context and discussed in light of continuous future drying.

2. Materials and methods

This study was conducted in a natural Scots pine (*Pinus sylvestris* L.) forest in the Central Spanish province of Soria (Fig. 1). This habitat, called Pinar Grande (hereinafter PG), is located between ~1100 and 1500 m asl, roughly covers an area of 12,533 ha, and mainly contains acidic brown soils or alluvial with acid and sandy loam or sandy soils (pH 4–5). The semi-arid climate is continental Mediterranean with a mean annual rainfall and temperature of 530 mm and 10.6 °C, respectively (computed over the 41.5–42.0° N and 2.5–3.0° W region and the 1961–1990 period). Although yearly values are fairly moderate, June–August summer precipitation totals of 87 mm and a corresponding temperature mean of 18.7 °C are indicative for a drought-prone ecosystem.

Core samples were collected from a total of 871 pines in 18 individual forest plots (Fig. 1, Table 1). These fenced protection areas of 150 m² each were installed in 1995 to systematically monitor mushroom productivity and phenology (Martínez-Peña et al., 2011). The resulting dendro network of 18 disjunct plot chronologies includes a unique distribution of tree ages that range between 6 and 175 years (Fig. 2a). Mean segment length (MSL) and average growth rate (AGR) values of each individual sample of the 18 different plots reveal a clear relationship between total increment and lifespan at the network level (Fig. 2b).

To remove non-climatic, biological-induced growth trends (so-called age trends) from the raw ring width measurements, two conceptually different detrending techniques were applied at the plot-scale level: Cubic smoothing splines with 50% frequency-response cutoff at 10 years (SPL; Cook and Peters, 1981), and the Regional Curve Standardization (RCS; Esper et al., 2003). To ensure an appropriate operation of the RCS method, we estimated the pith offset for each sample, that is the number of innermost missing rings per core sample, following a simple though straightforward standard technique (Table 1). The two detrending methods either pinpoint year-to-year (high-frequency) variability (SPL) or allow possible lower frequency information to be preserved for growth-climate response analyses and climate reconstructions (RCS). Both detrending techniques were performed after power-transformation (PT; Cook and Peters, 1997), and the corresponding index values were calculated as residuals between the original measurements and their corresponding curve fits. Mean plot chronologies were calculated using a bi-weight robust mean and their variance was stabilized over time (Frank et al., 2007b). The Expressed Population Signal (EPS; Wigley et al., 1984) was applied for additional quality control, as it represents a summary measure of chronology uncertainty that determines how well a dataset, based on a finite number of samples, estimates the theoretical population chronology from which it was drawn. EPS statistics and inter-series correlation coefficients (RBAR) were computed over statistically meaningful 30-year windows lagged by 15 years along the various chronologies.

After exploring the plot-specific chronology behavior, we developed the Pinar Grande RCS master chronology (PGRCS; containing all 871 samples and using RCS detrending). Robust growth–climate response analyses were subsequently computed for PGRCS using monthly and seasonal averages of station-based gridded $(0.5^{\circ} \times 0.5^{\circ})$ meteorological parameters (CRU TS3.1 available at http://www.knmi.nl/). Considering data from the European landmass back to 1901, we supplemented



Fig. 1. (a) Spatial distribution of natural and artificial Scots pine forests in Spain, with the light blue square referring to the PG reserve located at ~41°53′ E, 2°56′ W and 1225 m asl. (b) Location of the PG reserve within the European distribution area of Scots pine (http://www.euforgen.org/distribution_maps.html), and (c) the precise location of the 18 individual sampling plots (green squares) northwest of the regional capital Soria.

Table 1

(a) Plot location (30UTM), elevation (m asl), slope (%), aspect (°), and stand density (stem ha¹) of the sampling plots. (b) Corresponding tree-ring characteristics of each plot: series (number of samples), average growth rate (AGR; mm year¹), mean segment length (MSL; years), first order autocorrelation (AC1; correlation coefficient), start and end date, as well as length per plot chronology (years), and the mean sample pith offset per plot (MPO; years).

	(A)		Site conditions				(B)		Tree ring characteristics					
Plot	UTM X	UTM Y	m asl	Slope	Aspect	Density	Series	AGR	MSL	AC1	Start	End	Length	MPO
p 1	506,017	4,634,878	1119	1	0	21687	138	2.090	18	0.515	1990	2011	22	1.167
p 2	509,016	4,634,502	1119	5	315	7175	80	2.910	16	0.554	1992	2011	20	1.400
р 3	505,718	4,636,688	1139	4	135	9050	117	2.427	12	0.405	1997	2011	15	0.667
p 4	501,744	4,634,727	1159	2	315	3037	70	2.082	30	0.840	1975	2001	37	1.714
р 5	508,458	4,633,559	1109	5	45	2212	43	2.828	26	0.733	1979	2011	33	1.093
р6	508,573	4,630,911	1149	1	45	587	54	3.594	23	0.685	1982	2011	30	1.769
р7	506,913	4,636,147	1129	2	135	2012	40	2.381	37	0.784	1960	2011	52	1.725
p 8	514,134	4,633,290	1089	3	45	962	22	2.787	47	0.806	1955	2011	57	3.409
р9	505,783	4,632,826	1149	1	45	1825	64	1.661	40	0.826	1960	2011	52	1.469
p 10	503,763	4,632,476	1149	4	45	1350	30	1.579	58	0.847	1943	2011	69	2.167
p 11	502,323	4,634,355	1149	1	235	812	35	1.294	80	0.675	1906	2011	106	2.886
p 12	511,152	4,634,309	1119	4	45	1162	26	1.481	54	0.704	1937	2011	75	4.154
p 13	504,769	4,632,409	1149	1	45	312	32	1.664	82	0.727	1875	2011	137	6.156
p 14	508,983	4,630,489	1149	1	315	450	24	1.285	102	0.801	1886	2011	126	5.125
p 15	505,348	4,634,911	1129	1	45	487	30	1.761	86	0.807	1909	2011	103	4.200
p 16	503,968	4,632,035	1159	4	45	712	27	1.209	110	0.762	1848	2011	164	5.926
p 17	514,087	4,633,335	1089	1	0	525	16	1.028	109	0.734	1837	2011	175	29.563
p 18	504,464	4,633,864	1129	2	135	512	23	1.636	91	0.771	1898	2011	114	8.565
mp 1-18	506,956	4,633,651	1132	2	111	3048	871	2.163	40	0.662	1837	2011	175	4.620

temperature means and precipitation totals with more integrative indices of the self-calibrated Palmer Drought Severity Index (scPDSI; Wells et al., 2004), as well as the diurnal temperature range (DTR; Easterling et al., 1997). A composite analysis of gridded 500-hPageopotential height fields over the North Atlantic/European sector (Luterbacher et al., 2002) was additionally calculated for the 20 most positive and negative ring width anomalies back to 1876. This extra-verification of putative relationships between tree growth and climate variability further helps assessing possible impacts of large-scale circulation patterns on the observed ring width extremes (Büntgen et al., 2010c).

An ensemble of 12 state-of-the-art regional climate models (RCMs) of the period 1950–2099 AD was selected (Fischer and Schär, 2010). The RCMs were driven by six different General Circulation Models (GCMs) forced with the SRES A1B emission scenario within the European multi-model experiment ENSEMBLES (see van der Linden and Mitchell, 2009 for details). The ensemble mean of the DTR, merged over the May–July seasonal window, was obtained from first averaging

across all RCMs driven by the same GCM in order to give all the six GCMs equal weight — a technique already successfully implemented in Büntgen et al. (2012a). Model output was selected over the 41.5–42.0° N and 2.5–3.0° W region, and subsequently employed for comparison with the observational tree-ring and instrumental station records back to 1950. Moreover, model output further predicts trends of the DTR until 2099. Multi-model ensemble mean changes in the DTR between 2070 and 2099 were plotted at the European-scale to assess its spatial patterns with respect to 1960–1989.

3. Results

Plot-specific growth trends, commonly resembling negative exponential functions (Fig. 3a), not only describe an ideal target for fitting a Regional Curve (and subsequently allow RCS detrending), but also reveal a wide range in the absolute width of the individual tree-ring samples (again, fulfilling a prerequisite for RCS detrending). Differences in ring width variability among the 18 sampling plots are most



Fig. 2. (a) Temporal distribution of 871 individual Scots pine ring width core samples (blue bars) from 18 plots in the PG reserve, and (b) the relationship between mean segment length (MSL; years) and average growth rate (AGR; mm year¹ of all samples (blue dots), with the red lines referring to their mean).



Fig. 3. (a) Plot-specific growth trends expressed by the mean of all age-aligned ring width series per plot and after truncation <20 series. (b) Average ring width growth levels (mm) of the 18 plots computed over the first 14 and 28 years of juvenile growth.

obvious during the first years of juvenile tree growth (Fig. 3b). A suite of site-specific parameters including plot location, elevation, exposition, inclination and stand density was found to be non-important for the observed variations and trends in pine growth (Table 1).

Despite plot-specific differences in the absolute growth level and trend, all SPL chronologies share an exceptionally high year-to-year coherency over their common period 2002–2011 (Fig. 4a). The strongest growth depressions commonly occurred across all plot sites during



Fig. 4. (a) The 18 plot tree-ring width (TRW) indexed chronologies after power-transformation and 10-year spline detrending (SPL) shown over their common period 1998–2011, during which each record is replicated by at least five series. (b) The same chronologies shown over their individual full periods (1937 refers to the most distinct growth depression on record), and (c) their temporal coverage. (d) The corresponding EPS and RBAR statistics calculated over 30 years lagged by 15 years.

the severe droughts in 2005 and 2009. Slightly less ring width agreement was found during years with overall positive growth anomalies, a well-known feature of dendrochronological time-series behavior. Enhanced growth agreement also occurred after 2002, whereas less similarity characterized the chronologies' early and less replicated portions. Long-term, network-internal growth synchrony is further indicated over the individual maximum time spans of each plot chronology back to 1880 (Fig. 4b). It should be noted that the constant decrease of plot chronologies is not affecting the inter-plot growth synchrony (Fig. 4c). RBAR and EPS statistics further denote an exceptionally high plot-internal growth agreement (Fig. 4d).

Growth-climate response patterns between the PGRCS chronology and local to regional-scale climate variability (i.e. temperature, precipitation, and scPDSI) of the 20th century reveal some sort of spatiotemporal instability (Fig. 5). While negative relationships with temperature appear most distinct for May, June and July, as well as their seasonal mean, are positive though less pronounced correlations obvious for summer precipitation and scPDSI. On the other side was a much more consistent relationship found between the PGRCS chronology and the DTR (Fig. 6). Significant positive correlations exist between the inverse DTR averaged over the May-July season (MJ) and Scots pine growth over the past 60 years (r = 0.80; p < 0.0001). Even higher correlation of 0.84 was found over the slightly shorter period back to 1956 (Fig. 6c). As a decade, the 1970s is branded by a cool and wet climate across Spain, which allowed for a high level of net primary productivity. Since then, decreasing tree-ring width values match the inverse MJ DTR. An assessment of the spatial significance of the MJ DTR signal further shows reasonable agreement (r > 0.60) over most of the Central Iberian Peninsula and Southern France (Fig. 6d). A composite analysis of the 20 most extreme growth anomalies confirms the synoptic pressure fields and demonstrates the temporal robustness of the obtained relationship back to 1876 (Fig. 7).

4. Discussion

The wide range in plot-specific growth trends and levels (Fig. 3) likely reflects differences in stand age, soil chemistry and water availability between the 18 individual sampling sites, and somehow contradicts the outstanding growth coherency (Fig. 4). In fact, the observed ring width synchrony is particularly surprising, because the 18 plots do not represent (obvious) species-specific distribution limits where one single dominant climatic parameter is assumed to drive tree growth. Moreover, our ring width dataset comprises a substantial amount of juvenile wood that constantly enters the chronology throughout the entire 20th century and is generally assumed to contain a relative high fraction of individual noise rather than an externally-driven environmental signal (Esper et al., 2008). Our results, however, demonstrate that replication can compensate for both factors, and that the species-specific physiological capability and subsequent drought tolerance was possibly nearly reached in the two extreme drought years of 2005 and 2009, for instance.

Significant positive correlations (p < 0.001) between the inverse DTR and pine growth (Fig. 6) are particularly important since the traditional meteorological parameters, such as temperature means, precipitation totals and drought indices were not successful in explaining PG forest vigor (Fig. 5), in line with previous evidence from many parts of the Mediterranean Basin (Büntgen et al., 2010a, 2010b; Seim et al., 2012). Inverse temperature means are inadequate hydroclimatic surrogates and precipitation totals are spatially very heterogeneous. Hence, the daily difference between minimum and maximum temperatures, the DTR, a spatially reliable measure of cloudiness ideally constitutes a hydroclimatic target for the calibration of tree-ring proxy records. A high DTR during the spring-summer season refers more to a cloud-free sky related to high pressure (Easterling et al., 1997), which generally corresponds to reduced soil moisture availability triggered by warm temperatures, little rainfall and enhanced evapotranspiration. Such circumstances control forest growth in sites subject to continental Mediterranean conditions (Camarero et al., 2010). Conversely, cloudy, mild and wet conditions during spring and summer linked to low DTR values likely enhance photosynthetic activity and biomass productivity (Gimeno et al., 2012).

Caution is, however, advised as the gridded DTR is derived only from those stations that simultaneously report daily minimum and maximum temperatures and were included in the CRU TS3.1 network (Jones et al., 2012). Yet, there are only eight stations available within the 38-45° N and 6°W to 1° E domain that fulfill all criteria after homogenization (Fig. 6a). Moreover, none of these records is covering the entire 20th century, and decreasing station replication coincides with increasing station distance (Fig. 6a). The overall amount of uncertainty in daily station measurements also increases back in time (Brunet et al., 2006). Temporal inconsistency in the quality and quantity of meteorological observations is well known to particularly affect the relationships between early instrumental targets and their corresponding tree-ring proxies (Frank et al., 2007a). In case of the Iberian Peninsula, this issue was likely most critical during the first half of the 20th century when Spanish meteorological readings were less systematic (Büntgen et al., 2008a), and differences between the ancient Montsouri shelter and the modern Stevenson screen for daily maximum and minimum temperatures directly affected the DTR (Brunet et al., 2011).



Fig. 5. Correlation coefficients between monthly (January–December) and seasonal (May–July) resolved (a) temperature means, (b) precipitation totals and (c) scPDSI indices, calculated over the 1901–2009, 1946–2009 and 1966–2009 periods (first, second and third bar).



Fig. 6. (a) Temporal coverage of eight individual meteorological stations in Spain and southern France (gray bars) that were used for calculating the DTR, plus the mean distance of these stations to the PG forest. (b) The inverse DTR of May–July averaged over the 41.5–42.0° N and 2.5–3.0° W region (red back to 1946 and light orange back to 1901), and the PGRCS chronology (blue), which was scaled to the DTR data over the 1901–2009 period. (c) Correlations between monthly (January–December) and seasonal (May–July) resolved (inverse) DTR values and the PGRCS chronology computed over four different periods (colors). The horizontal lines mark the corresponding 99.9% confidence limits after correction for first order autocorrelation in each time-series. (d) Spatial field correlations between gridded 0.5°×0.5° May–July DTR indices (inverse) and the PGRCS chronology computed over the PGRCS chronology computed over the 1966–2009 period. White star denotes the PG sampling region.

An additional factor that can impact terrestrial biomass productivity and may therefore imply some instability in the observed relationship between pine growth and springtime hydroclimate possibly derives from changes in the ratio between diffuse and direct solar radiation at the Earth's surface (Wild et al., 2005), which would also result from a changing DTR. Lower rates of diffuse radiation under clear sky conditions, expressed by a greater DTR are expected to decrease plant photosynthesis (Gu et al., 2003), whereas a turbid sky likely enhances canopy photosynthesis. Quantification of possible negative effects of a recent global brightening (Wild, 2009) on Mediterranean forest growth and overall ecosystem productivity, however, remains subject to further analyses.

A distinctively positive phase of the North Atlantic Oscillation (NAO; Hurrell, 1995), depicted by a pronounced Azores High and Icelandic Low coincided with the 20 most negative growth anomalies (Fig. 7), whereas low pressure over the Azores and high pressure over Eurasia corresponded to enhanced pine growth. This dominant and NAO-related synoptic driver of Iberian pine growth has previously been reported (Camarero, 2011), and was subsequently related to wet and mild conditions in the winter and spring months before



Fig. 7. Composite analysis of (a) the 20 most negative and (b) the 20 most positive pine ring width extremes computed against May–July 500-hPa-geopotential height (gpm) data back to 1876.

tree-ring formation usually associated to negative NAO phases (Pasho et al., 2011). Positive winter–spring NAO phases are associated with clear sky conditions over the central and western Iberian Peninsula and such below-normal cloud cover is linked to a high DTR and thus low pine growth. These observations are in line with the overall assumption that recent changes in atmospheric circulation patterns are partially responsible for declining precipitation trends and major drought episodes over the western Mediterranean Basin (Xoplaki et al., 2012).

The herein observed continuous long-term decline in continental lberian forest growth since the mid-1970s (Fig. 6), which was a decade of cool and wet climate across Spain (de Luis et al., 2010; del Rio et al., 2011), supplements a recently discussed reduction of Périgord truffle (*Tuber melanosporum*) yield (Büntgen et al., 2012a), and coincides well with decreasing discharge rates of the upper Duero River in the vicinity of the PG sampling sites (Lorenzo-Lacruz et al., 2012).

The observed warming and drought intensification over the Central Iberian Peninsula from the mid-1970s is consistent with the increase in DTR in an ensemble of regional climate models (RCMs), which further projects its continuation until the end of the 21st century (Fig. 8). Despite wide uncertainty ranges discussed with climate model output for the semi-arid Mediterranean Basin (Boberg and Christensen, 2012), a well-defined envelope of the 12 utilized RCMs ensemble members evidently projects a rising MJ DTR of ~1.2 K until 2099 with respect to the 1960–1989 mean (Fig. 8a). Less cloud cover and less precipitation together with higher temperatures and more evapotranspiration are circumstances that likely cause this longterm increase of the DTR, which will probably translate into more drought conditions and a critical impact on forest growth. Furthermore, during the past century the increase in DTR over the Iberian Peninsula has been mainly caused by a stronger warming trend of the maximum (day) than the minimum (night) temperatures (Brunet et al., 2006).

If and how the PG forest structure will change in a drier future with a wider thermal amplitude remains unclear, but other studies have already reported climate-driven vegetation shifts from initial (sub-boreal) Scots pine dominance to more drought-tolerant (sub-Mediterranean) pubescent oaks in the Spanish Pyrenees (Galiano et al., 2010) and in the dry inner-Alpine forests of Switzerland (Rigling et al., 2012), alternations in the quality and quantity of wood formation (Eilmann et al., 2011) and adjustments in hydraulic architecture in the concerned forests, as well as increased mortality rates of Austrian Scots pine sites that were most drought exposed (Oberhuber, 2001). The predicted climate change will likely affect the metabolism of trees (McDowell, 2011), including hydraulic failure (Choat et al., 2012) and reduction of carbon uptake or increasing respiration costs and subsequent carbon starvation (McDowell, 2011), which will subsequently transfer in higher mortality rates (Allen et al., 2010) and a decreasing capacity of water-limited Spanish forests to accumulate carbon (Vayreda et al., 2012).

Socio-economic consequences of the predicted hydroclimatic changes in continental lberia and their devastating effects on forest ecosystems may cover a wide range of complex issues including wildfire, settlement, agriculture, water management, recreation, tourism, and environmental protection, together with biological conservation (Hanewinkel et al., 2012). Social vulnerability is anticipated to be particularly severe in rural areas (Samils et al., 2008), where hydroclimatic changes not only have stronger consequences for wide-spread domestic water supply but also for subsistence agricultural irrigation. An array of ecological, societal and economic impacts emphasizes the eminent need to increase our knowledge on global climate change.

The necessity of interdisciplinary collaboration towards drought adaptation and mitigation, however, becomes a challenging task when political and cultural demands are intertwined with socio-economic interests (Hanewinkel et al., 2012). Additional scientific complexity originates from land-atmosphere couplings between soil moisture, vegetation structure and cloud cover (Senevirante et al., 2006), among other factors. These intertwined subjects illustrate how the impacts to any component within an ecosystem cascade throughout the entire ecosystem, and the continental Iberian forests are no exception. The specific economic, social, and environmental impacts are local and can exhibit strong spatial variability. For this reason, a proactive approach to address these ongoing and potential future impacts is recommended, beginning with their detailed assessment among various spatiotemporal scales (Hayes et al., 2004).

5. Conclusions

This study comprises a total of 871 Scots pine ring width samples from 18 individual plot sites collected in a continental Mediterranean forest ecosystems in Central Spain. Highly synchronized growth variations at the network level were triggered by changes in springtime DTR between May and July. Positive and negative growth extremes



Fig. 8. Simulated temporal changes of the May–July DTR (color lines) over the 41.5–42.0° N and 2.5–3.0° W region in Spain and between 1950 and 2099 AD, with all time-series being expressed as 15-year running means with respect to the 1960–1989 reference period. The black line shows the multi-model mean and the gray band a range of \pm 1.0 standard deviation. The right map denotes simulated spatial patterns of the May–July DTR for 2070–2099 with respect to 1960–1989 and using the ensemble mean. The white star refers to the PG sampling region.

coincided with anomalous low- and high-pressure patterns over the Azores Islands, which mainly depend on alternating NAO phases. Declining forest vigor of the PG reserve parallels a long-term warming and drying of the Central Iberian Peninsula since the mid-1970s. This trend, predicted to continue under future climate change, not only downgrades local timber and fungi harvest, but likely also weakens ecosystem-dependent enterprises caused by a potential cascade of impacts. Adaptation strategies of forest management and agricultural systems, as well as environmental protection and biodiversity conservation, are recommended to take these linkages into account when preparing for the future.

Acknowledgments

Supported by the WSL-internal DITREC project, the Eva Mayr-Stihl Foundation, the project AGL2012-40035-C03-01 (Ministerio de Economía y Competitividad of Spain, Secretaría de Estado de Investigación, Desarrollo e Innovación), the Micosylva project (Interreg IVB SUDOE SOE1/P2/E069), and the Government of Castilla y León. Staff of CIF Valonsadero contributed to the network maintenance, and the Czech project "Building up a multidisciplinary scientific team focused on drought" (No. CZ.1.07/2.3.00/20.0248).

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