ORIGINAL PAPER

Influence of micro-site conditions on tree-ring climate signals and trends in central and northern Sweden

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Abstract Tree-ring chronologies are important indicators of pre-instrumental, natural climate variability. Some of the longest chronologies are from northern Fennoscandia, where ring width measurement series from living trees are combined with series from sub-fossil trees, preserved in shallow lakes, to form millennial-length records. We here assess the recent ends of such timeseries by comparing climate signals and growth characteristics in central and northern Sweden, of (1) trees growing at lakeshore micro-sites (representing the source of sub-fossil material of supra-long chronologies), with (2) trees collected in dryer micro-sites several meters "inland". Calibration trials reveal a predominating June–September temperature signal in N-Sweden and a weaker but significant May–September precipitation signal in C-Sweden. At the micro-site level, the temperature signal in N-Sweden is stronger in the lakeshore trees compared to the inland trees, whereas the precipitation signal in C-Sweden remains unchanged among the lakeshore and inland trees. Tree-rings at cambial ages >40 years are also substantially wider in the lakeshore micro-site in C-Sweden, and juvenile rings are more variable (and wider) in the dryer micro-site in N-Sweden (compared to the adjacent micro-sites). By combining the data of the various micro-sites with relict samples spanning the past 1,000 years, we demonstrate that growth rate differences at the micro-site scale can affect the low frequency trends of millennial-length chronologies. For the supra-long chronologies from northern Fennoscandia, that are derived from sub-fossil lake material, it is recommended to combine these data with measurement series from only lakeshore trees.

Keywords Tree growth · Tree-ring width · *Pinus sylvestris* L. · Climate reconstruction · Dendroclimatology · Scandinavia

Introduction

Large-scale temperature reconstructions derived from tree-ring chronologies are important indicators of long-term climate variations over the past centuries to millennia (Briffa et al. 1998; Esper et al. 2002; D'Arrigo et al. 2006; Frank et al. 2007; Christiansen and Ljungqvist 2012). Particularly trees from sites near the northern distribution limit show a strong sensitivity to temperature variations (Esper et al. 2010) and are included in the hemispheric reconstructions (Solomon et al. 2007). Among these, tree-ring chronologies from northern Fennoscandia have been used to construct some of the world's longest continuous tree-ring width (TRW) and maximum latewood density (MXD) chronologies (Schweingruber et al. 1988; Eronen et al. 2002; Grudd et al. 2002; Esper et al. 2012b). Such records are generally developed by combining TRW and MXD measurement series from living trees either with dry dead wood from the ground (or historical buildings; Büntgen et al. 2006, 2007) or with sub-fossil material from

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lakes (Kultti et al. 2006) or peat bogs (Nicolussi et al. 2009), for example (overview in Esper et al. 2002).

The climate signal inherent to these long tree-ring chronologies is typically assessed by comparison of twentieth century TRW (or MXD) measurements—derived from living trees—with instrumental climate data (Fritts 1976). Through this "calibration process", a linear model between tree-ring proxy and a leading climatic variable (e.g. summer temperature in northern environments) is established and subsequently used to transfer a TRW chronology into estimates of temperature variability over the past centuries to millennia (Esper et al. 2005). This calibration and transfer scheme rests on the assumption that a statistically derived association between living trees and twentieth century climate data is equally valid for the pre-instrumental portion of a long chronology derived from historical or sub-fossil wood samples (the principle of "uniformitarianism", e.g. Speer 2010).

In case of the supra-long chronologies from northern Fennoscandia, different wood sources, including sub-fossil material from lakes and dry dead wood from the ground, were combined with samples from living trees to form timeseries spanning the past 7,400 years in Swedish Lapland (Grudd et al. 2002) and 7,519 years in Finnish Lapland (Eronen et al. 2002). The recent portions of these records are represented by living trees sampled in relatively dry micro-sites in varying distances to the lakes. The coherence of growth characteristics among the relatively wet lakeshore sites that represent the source habitats of the sub-fossil material of much of the supra-long chronologies, and the relatively dry inland sites remained largely unexplored, however (Esper et al. 2012b).

We here assess the potential influence of varying micro-site conditions on long tree-ring records by analyzing climate signals and growth trends of *Pinus sylvestris* L. trees collected at lakeshores and several meters inland in northern and central Sweden. It is presumed that the central sites, located near Stockholm, contain a predominating drought signal, whereas the northern sites, located near Kiruna, contain a predominating temperature signal (Linderholm et al. 2010). Climate signals of TRW chronologies from six lakeshore and inland micro-sites are evaluated through comparison with regional instrumental climate data, and growth trends assessed by combining these living tree records with existing relict data from the Torneträsk region in northern Sweden and the Gotland Island located southeast of Stockholm. In this paper, we first provide detail on the sampling regions and micro-sites, as well as the detrending and calibration techniques, then present the results on the common climate signals in northern and central Sweden, followed by a detailed assessment of the climate signals inherent to lakeshore and inland micro-sites. Varying growth trends of these micro-sites are

discussed after combining the data with relict material from Torneträsk and Gotland considering different tree-ring detrending techniques.

Materials and methods

Sampling regions and micro-sites

Three hundred and eighty-five *P. sylvestris* L. core samples were collected in northern Sweden 12 km northwest of Kiruna (KIR: 67.95°N, 20.03°E) and in central Sweden 11 km north of Stockholm (STO: 59.44°N, 17.99°E; Fig. 1). KIR is located about 50 km south of Lake Torneträsk near the northern distribution limit of tree growth where pines and birches (*Betula pubescens*) are the predominating forest species. The area is characterized by a short growing season of only ~120 days with mean annual and July–September (JAS) temperatures of −2.6 and 10 °C, respectively. Due to its position east of the Scandinavian Mountains, in the rain shadow of the prevailing influence of the North Atlantic Oscillation (Linderholm et al. 2010), the northern sampling site receives relatively low summer precipitation sums (~200 mm). The Torneträsk/Kiruna area is situated in the transition zone between the tundra and a humid snow climate with cool summers classified as ET and Dfc, respectively, according to Kottek et al. (2006).

STO is located at Lake Rösjön, ~950 km south of KIR, in a transition zone from boreal to temperate forests predominated by mixed coniferous and deciduous species including pine, spruce (*Picea abies* L.), oak (*Quercus robur*), and beech (*Fagus sylvatica*). Mean annual and JAS temperatures reach 6.6C and 15.3 °C, respectively, and
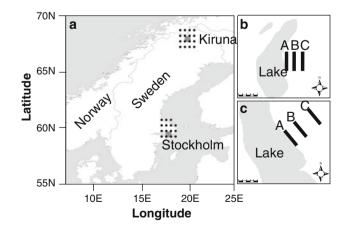

Fig. 1 Map showing the tree-ring sampling sites in northern and central Sweden (**a**, *gray dots*) and the lakeshore (*A*), intermediate (*B*), and inland micro-sites (*C*) (**b** and **c**) in KIR and STO. *Black dots* in **a** indicate the position of the climate data grid points used for calibration of the tree-ring data

summer precipitation equals ∼190 mm. The growing season is ∼60 days longer than in the northern sampling area, though much less photosynthetically significant, direct and diffuse, sunlight is received during "nighttime". The Stockholm region is located at the transition between a humid snow climate with warm summers (Dfb) and a warm, temperate and humid climate with warm summers (Cfb) typical for much of Central Europe (Kottek et al. 2006). Overall growth rates are higher at the central STO site (1.19 mm/year) compared to the colder KIR site (0.85 mm/year).

In both the sampling sites, KIR and STO, *P. sylvestris* was sampled in three distinct micro-sites—lakeshore (A), intermediate (B), and inland (C)—characterized by varying distances to the lakes (Fig. 1b, c). The micro-sites are oriented along transects starting at the lakeshores, where conditions are wetter and trees have access to groundwater that is largely in balance with the lake levels, towards locally dryer conditions some meters above the lakes. In KIR, the transect reaches from 451 to 471 m asl., tree girths vary between 0.13 and 1.37 m, and tree heights range from 3 to 13 m. In STO, the transect reaches from 20 to 60 m asl., tree girths vary between 0.2 and 1.85 m, and tree heights range from 2 to 18 m. Transect expositions are west in KIR and southwest in STO. Distances between the single micro-sites are all ≥15 m.

Tree-ring data and chronology development

To develop well-replicated sub-site chronologies, ∼40 Scots pines (mostly two cores per tree) were sampled in each micro-site in KIR and STO (Table 1). Ring widths

Table 1 Sampling site characteristics

	KIR	KIR-A	KIR-B	KIR-C
Number of samples	195	68	67	60
Rbar (1901–2009)	0.40	0.40	0.39	0.47
EPS (1901–2009)	0.99	0.98	0.98	0.98
Mean growth rate (mm/year)	0.85	0.83	0.78	0.97
Segmenth length (years)	93.33	83.22	78.21	77.08
	STO	STO-A	STO-B	STO-C
Number of samples	190	69	63	58
Rbar (1901–2009)	0.23	0.27	0.41	0.42
EPS (1901–2009)	0.98	0.96	0.98	0.98
Mean growth rate (mm/year)	1.19	1.15	1.48	1.00
Segmenth length (years)	96.81	119.71	74.92	93.33

Number of measurement series (*n*) of the Kir and Sto sites, as wells as the lakeshore (KIR-A, STO-A), intermediate (KIR-B, STO-B), and inland (KIR-C, STO-C) micro-sites. Rbar is the interseries correlation, and EPS the expressed population signal, both calculated of the 1901–2009 period

were measured with an accuracy of 1/100 mm and cross-checked with the programs LinTab and Cofecha (Holmes 1983). Samples were taken in pre-defined plots to ensure representation of micro-site conditions including all age classes (Esper et al. 2012a).

Age trend, which is the decreasing width (and variance) associated with increasing tree girth (Fritts 1976), was removed by (1) calculating ratios from negative exponential functions (NegExp) fit to each individual TRW measurement series (Cook and Peters 1997), and (2) removing the trend common to all trees within KIR and STO using the regional curve standardization (RCS) technique (Esper et al. 2003). Every micro-site was detrended with its own regional curve. All measurement series were power transformed prior to index calculation to remove variance changes (i.e., generally more variable juvenile and less variable adult TRW values) inherent to the raw TRW data (Cook and Peters 1997). Sub-site chronologies were developed by averaging the detrended TRW series for each micro-site integrating between 58 and 69 core samples, and removing temporal variance changes that typically arise from changes in interseries correlation and replication (Frank et al. 2007). We additionally averaged all tree-ring data in KIR and STO to assess the common climate forcing at the regional scale (Table 1). Common variance inherent to the chronologies and the effectiveness of samples to represent theoretically infinite populations were estimated using the interseries correlation (Rbar) and Expressed Population Statistics (EPS) calculated over the 1901–2009 calibration period (Wigley et al. 1984).

Besides calculating site and micro-site chronologies, the living tree data were also combined with relict material from the Torneträsk (Grudd et al. 2002) and Gotland (Esper et al. 2002) regions to assess the influence of growth rate changes—at the micro-site level—on the long-term trends of millennial scale chronologies (Esper et al. 2012b). While this could effectively also be achieved using artificial data that mirror the properties of TRW data from central and northern Sweden, the combination of living trees representing distinct micro-sites with existing relict samples from a given region reflects common praxis of developing long-term climate reconstructions in dendrochronology (Tegel et al. 2010). In this approach, the TRW data were detrended using either NegExp or RCS to assess the significance of standardization methodology on the integration of relict and living tree samples.

Climate data and calibration

TRW data were calibrated against gridded meteorological data (version CRU TS 3.1 at 0.5° resolution; (Mitchell and Jones 2005) to assess the climate–growth relationships at the site and micro-site scales. The northern KIR

chronologies were compared with temperature and precipitation data of 16 grid points averaged over the 67–69°N and 19–21°E area; and the central STO sites using 15 grid points averaged over the 59–61°N and 17–19°E area (see the black dots in Fig. 1a). Pearson correlations were calculated among tree-ring chronologies and monthly and seasonally (JAS and MJJAS) averaged climate data over the 1901–2009 common period. 30-year running correlations were computed to assess the temporal variability of climate signals throughout the twentieth and early twenty-first centuries. Correlation significance was estimated using the standard error [$SE = (1-r^2)/\sqrt{(1-n)}$] considering first-order autocorrelation inherent to the proxy and climate data (Cook and Kairiukstis 1990).
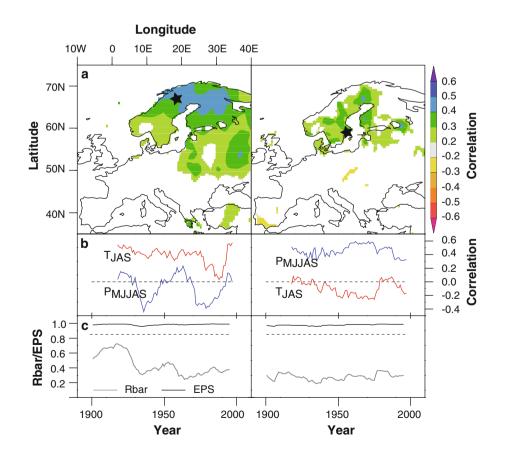
Results

Regional climate signals

Whereas *P. sylvestris* growth in northern Sweden is controlled by temperature, the pines in central Sweden are influenced by precipitation (Helama and Lindholm 2003; Drobyshev et al. 2011). Calibration of the well-replicated RCS site chronologies revealed a stronger JJA temperature signal in KIR ($r_{1901–2009} = 0.44$) and a weaker but significant MJJAS

precipitation signal in STO ($r_{1901–2009} = 0.36$). The spatial pattern of the temperature signal covers much of northern Fennoscandia (at $r > 0.40$) and extends south towards a line from northern Denmark into western Russia (Fig. 2; $p < 0.05$). The spatial pattern of the precipitation signal is patchier (Büntgen et al. 2010) and limited to a region west of the Scandinavian Mountains reaching into Helsinki/St. Petersburg area and south towards Denmark. The seasonal climate signal patterns were similar between the RCS and NegExp detrended micro-site chronologies.

Assessment of the temporal characteristics of these climate signals indicated overall stable associations between the northern and central pine sites and the leading JJA temperature and MJJAS precipitation climatic variables, respectively, though the KIR site shows an increased variability—including exceptionally low and high correlations—towards the late twentieth and early twenty-first centuries (Fig. 2b). In contrast, correlations with precipitation in the northern site and with temperature in the central site fluctuate around zero, validating that *P. sylvestris* at the two sites contain distinctly differing climate signals. The EPS results indicate that both the KIR and STO collections reflect representative samples throughout the twentieth century. The interseries correlation (Rbar) is overall higher in KIR (0.40) compared to STO (0.23). KIR Rbar values are increasing back in time, likely due to a

Fig. 2 Tree-ring climate signals in northern and central Sweden. **a** Spatial correlation patterns ($p < 0.05$) of RCS-detrended TRW chronologies from KIR (*left*; against JAS temperature) and STO (*right*; against MJJAS precipitation) with CRU TS3.1 climate data over the 1901–2009 period. **b** 30-year running correlations with JAS temperatures (*red*) and MJJAS precipitation (*blue*) derived from nearby grid points (see Fig. 1). **c** 30-year running Rbar and EPS statistics of the RCS-detrended KIR and STO chronologies (*dashed line* indicates the 0.85 value)

growing influence of low sample replications (see Fig. 2c, and bottom panels in Fig. 3).

Micro-site coherence and climate signals

Cross-correlations among the micro-site chronologies are substantially lower in STO ($r_{1901-2009} = 0.53$) compared to KIR ($r_{1901-2009} = 0.85$) indicating an increased, and differentiating, influence of micro-site conditions in the central sampling area. The Rbar result of the STO-A lakeshore micro-site is also deviating from its intermediate and inland counterparts (STO-B and STO-C), which is likely related to individually differing (at the tree-to-tree level) root access to groundwater (Table 1). These differences are also reflected in the micro-site chronologies as displayed in Fig. 3 showing largely synchronous TRW variations between the lakeshore and inland KIR micro-sites, but larger deviations and differing variances between the STO micro-sites. Again all micro-site chronologies analyzed here show EPS values exceeding the commonly accepted 0.85 threshold throughout the 1901–2009 period, similar replication changes, and comparable Rbar results (except for STO-A).

The micro-site climate–growth relationships are largely in line with the results obtained at the site level (see above), i.e., a dominating temperature signal is found in the North, and a less strong, though significant ($p < 0.05$), precipitation signal is found in central Sweden (Fig. 4). Associated precipitation and temperature signals are insignificant in the North and in the central part, respectively. However, whereas the correlation coefficients are balanced ($r \sim 0.32$) among the STO micro-sites, the temperature signal in the North is decreasing from KIR-A ($r = 0.50$) to KIR-B ($r = 0.44$) to KIR-C ($r = 0.43$). While these differences in KIR micro-site climate signals are again insignificant (note the SE error bars in Fig. 4), this finding indicates that the sub-fossil Pine stems preserved in northern Swedish lakes contain a slightly stronger temperature signal compared to the dryer, inland trees.
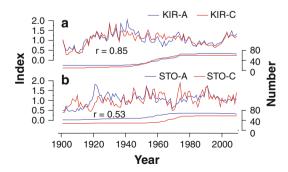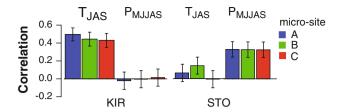

Fig. 4 Tree-ring climate signals. Correlation coefficients derived from calibrating the RCS-detrended lakeshore (*A, blue*), intermediate (*B, green*), inland (*C, red*) micro-site chronologies from KIR (*left*) and STO (*right*) against gridded regional JAS temperature data over the 1901–2009 common period. *Error bars* indicate the SE of the correlation coefficients

Micro-site growth trends

Besides the differences in climate signals, the TRW data indicate deviating growth levels and trends between the lakeshore and inland micro-sites (Fig. 5). Mean growth rates differ by 0.19 mm among the KIR and 0.47 mm among the STO micro-sites (Table 1). These differences are in part related to the varying segment lengths (that is the mean tree age; Cook et al. 1995) that are comparable among the northern micro-sites but range from ~90 years in STO-C to ~120 years in STO-A.

In both KIR and STO, age trends are overall more balanced and less steep in the lakeshore micro-sites compared to their inland counterparts. Juvenile growth (up to an age of 20–30 years) is more rapid in the inland micro-sites (Helama et al. 2004), followed by a scarped age trend until cambial ages of ~90 years in KIR-C and ~70 years in STO-C, where these inland growth curves approach levels clearly below the lakeshore micro-sites. Whereas the steep age trends inherent to the inland micro-sites are likely related to increasing inter-tree competition (and limited access to soil water in the southern site), the subsequent growth increases, up to an age of ~120 years in KIR-C

Fig. 3 Lakeshore and inland chronologies. RCS-detrended micro-site chronologies from KIR-A and KIR-C (**a**) and STO-A and STO-C (**b**) over the 1901–2009 period. *Bottom panels* show the replication curves of the lakeshore (*blue*) and inland (*red*) chronologies
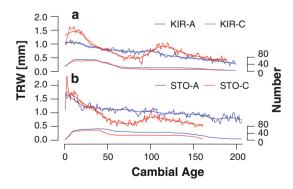

Fig. 5 Growth levels and trends in lakeshore and inland micro-sites. Original and 40-year smoothed regional curves (that is the arithmetic mean of the age-aligned TRW data) of the KIR-A and KIR-C (**a**) and STO-A and STO-C (**b**) micro-sites. *Bottom panels* show the replication curves of the lakeshore (*blue*) and inland (*red*) data

and ∼100 years in STO-C, which appears unexpected. Stem wood production of old trees (>120 years) remains larger at the southern lakeshore site (STO-A) compared to its inland counterpart (STO-C; Fig. 5).

Effects on long chronologies

Combination and joined detrending of the micro-site datasets together with the relict material from northern and central Sweden enable an assessment of the effects of differing growth rates, inherent to the living tree data, on the long-term trends of millennial scale records. In these experiments, we combined the living tree data from the northern lakeshore and inland micro-sites (KIR-A and KIR-C) with the relict TRW data from the widely cited Torneträsk chronology (Schweingruber et al. 1988; Esper et al. 2002; Grudd et al. 2002) downloaded from the International Tree-Ring Databank: file swed019), and the data from the central lakeshore and inland micro-sites (STO-A and STO-C) with the relict TRW data from Gotland (Esper et al. 2002; file swed022). The resulting (combined) RCS and NegExp detrended chronologies were (1) truncated at AD 1146 where the Gotland data reaches a minimum replication of five TRW series, and (2) normalized over the 1146–1859 period covered by only the relict wood samples (Fig. 6). The chronologies are based on only living tree samples (from the various micro-sites) over the recent 1901–2009

period, and on a mix of living tree and relict wood samples over the 1860–1900 period (see the replication curves at the bottom of Fig. 6 panels). Data integration of these records is conceptually similar to any millennial scale tree-ring record integrating TRW data from living and relict trees, with the exception that we have full control of the varying micro-site conditions over the recent period of these timeseries (Christiansen and Ljungqvist 2012).

The varying combinations of relict with living tree datasets result in only minor differences, if NegExp detrending is considered, i.e., the blue (lakeshore) and red (inland) recent 'tails' of the millennial scale chronologies display similar variability (Fig. 6). This conclusion changes considerably, however, if the combined datasets are detrended using RCS. The chronologies not only contain more low frequency variability (as expected; see Esper et al. 2002), but also deviate substantially during the twentieth century: (a) the Tor-RCS record is picking up more variability if combined with the inland KIR-C micro-site data (compared to Tor + KIR-A); (b) the Got-RCS record shows much larger recent values if combined with the lakeshore STO-C micro-site data (compared to Got + STO-A).

The foundation for these differing twentieth century trends is the varying growth levels of the lakeshore and inland micro-site data in KIR and STO. The overall wider rings in STO-A (see above, Fig. 5) translate into increased, recent, chronology values after combination and joined RCS
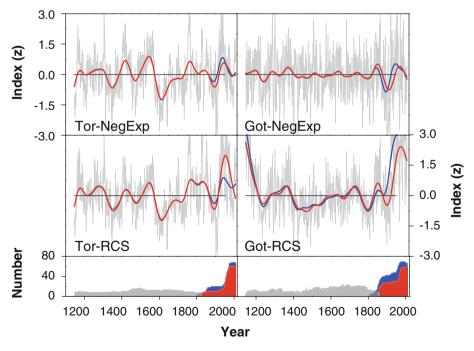

Fig. 6 Influence of micro-site conditions on TRW chronology trends. Millennial scale chronologies derived from combining relict TRW data from Torneträsk (Tor) and Gotland (Got) with living tree data from KIR-A and KIR-C (*left panels*) and STO-A and STO-C (*right panels*). Smoothed (100-year low pass filter) composite chronologies integrating living tree lakeshore data (TorA and GotA)

are shown in *blue*; chronologies integrating inland data shown in *red* (TorC and GotC). *Top* and *middle panels* show the NegExp and RCS-detrended chronologies, respectively. All records were normalized over the 1146–1859 period covered by only the relict wood samples. *Bottom panels* show the replication of combined datasets
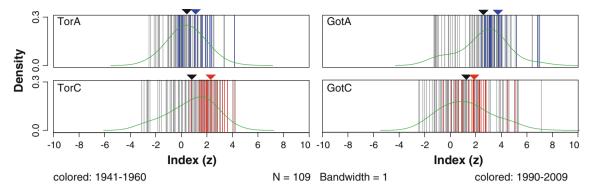
Fig. 7 Influence of micro-site conditions on twentieth century chronology values. Distribution of the RCS-detrended chronology values of the combined millennial-length timeseries shown in Fig. 6. *Black lines* indicate the 1901–2009 index values; and *colored lines* of specific 20-year periods (1941–1960 in TorA and TorC; 1990–2009 in GotA and GotC) discussed in the text. Mean values of the longer and shorter periods are indicated with *black* and *colored* (*blue* and *red*) *triangles*. *Green curves* indicate probability density functions derived from kernel estimates (bandwidth = 1)

detrending with the relict Got data. Whereas the smoothed twentieth century index values of the combined GotA chronology exceed 3.0 throughout most of the twentieth century, the record obtained from combining relict with inland data remains below 2.42 during this period. For the northern Swedish data, the increased variance of the KIR-C inland micro-site (compared to KIR-A) translates into a more variable twentieth century 'tail' after combination and joined RCS detrending with Tor. The mid-twentieth century index values of this record exceed 1.5, whereas the twentieth century values of the combined TorA record do not exceed the variance recorded during earlier centuries.

These differences are further emphasized in the twentieth century value distributions of the combined RCS chronologies, with the chronology values during the identified, deviating periods (1941–1960 in the northern, and 1990–2009 in the central region) being highlighted in blue and red (Fig. 7). Whereas the northern RCS chronologies indicate a slight shift towards more positive values when considering the inland micro-site data (twentieth century mean values change from 0.43 to 0.82; see the black triangles in Fig. 7), integration of lakeshore instead of inland data results in a substantial shift in the mean value (from 1.27 in GotC to 2.59 in GotA) in the southern Gotland chronology. The northern chronology also indicates differences in the value distributions. Compared to Tor A, the distribution of TorC is negatively skewed towards larger values, but these changes appear overall minor compared to the distributions differences between GotA and GotC. In these latter chronologies, the 1990–2009 mean values change from 1.88 in GotC to 3.73 in GotA.
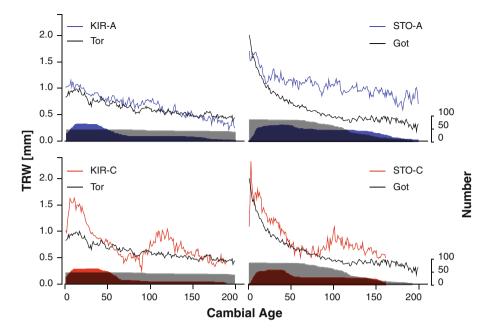
Discussion

Our high replication micro-site chronologies shed light on the sensitivity of established climate–growth relationships.

We identified differences in growth behavior and sensitivity to various climate parameters between the lakeshore and inland micro-sites. These differences arise from varying growth patterns between different micro-sites in one sampling area. While hydrological conditions were expected to be more favorable for tree growth at lakeshores, effective growth rates were higher at the inland sites, in both northern and central Sweden, for the first decades of growth. We assume that the young trees cannot deal with the perhumid conditions surrounding their root system and anaerobic conditions slow down the growth rate at the lakeshore. For a more detailed analysis, soil water content and temperature measurements on a micro-site level are required. Also the climate–growth relationships differ between the micro-sites. Even in the high latitude study area, where overall growth conditions are harsh, there are differences, at the micro-site scale, in the response to climate. Similar processes have been revealed in altitudinal micro-site studies (Liang et al. 2010). In central Sweden, the precipitation signal is similar among the micro-sites. The stronger temperature signal recorded towards the lakeshore in the far northern environment is a new aspect that could help to improve long-term reconstructions from such regions.

Our results show that *P. sylvestris* growth in northern and central Sweden is controlled by different climate parameters; temperature in the North and precipitation/drought in the central part. The identified relationships offer the possibility to reconstruct temperature and drought variations over longer timescales in these regions. The higher growth rate in the central sampling area is affiliated with an extended growing season period and overall more favorable growing conditions. However, the lower correlations among micro-sites in central Sweden indicates that growth is less affected by external, and unifying, factors compared to the northern micro-site chronologies. This conclusion is supported by the stronger response to climate

Fig. 8 Growth levels and trends of relict and living tree TRW data. Regional curves of the lakeshore (*blue*) and inland (*red*) micro-sites from KIR and STO shown together with the data relict data from Torneträsk and Gotland (*black*). *Lower panel* shows the replication

parameters in northern Sweden, where more TRW variance is explained by summer temperature (compared to the southern sites and precipitation). The northern micro-sites also contain a gradual decrease from higher temperature signals at the lakeshore to weaker signals towards inland, which could be related to short-term drought conditions disturbing the temperature signal in the dryer inland micro-sites. It therefore appears likely that sub-fossil material, from trees originally growing at the lakeshores, and used for developing millennial-length chronologies, contains a stronger climate signal than currently believed. Since the climate–growth relationships differ between the micro-site habitats, we recommend using living trees from only lakeshore sites for calibration purposes of these supra-long chronologies.

While varying temperature signals among pine micro-sites can affect the climatically explained variance and uncertainty estimates of combined (living + relict material) chronologies, the plain growth rate differences among micro-sites can affect the long-term course of millennial scale records (Fig. 7). If an individual detrending scheme (NegExp) is applied to the combined datasets, the differences between relict + lakeshore and relict + inland chronologies are negligible. However, if we apply a detrending method that enables preserving low frequency (centennial scale) variance over the past millennium (Esper et al. 2003), the growth rate differences between lakeshore and inland micro-sites translate into varying long-term trends that can alter conclusions on twentieth century warming with respect to the preceding centuries of the past millennium. In the northern study area, the wet micro-site matches the growth curve of the relict wood quite closely, while the inland growth curve trends to

differ substantially, during certain periods (0–40 and 100–160 years), from the Torneträsk relict material (Fig. 8). In the southern study area, lakeshore micro-site growth is much faster, explaining the severely increased recent trends after combination with the Gotland relict data and RCS detrending. It is thus recommended to study the growth rates and changes with aging, as expressed in the growth curves, when combining living tree data with measurements series from relict material. Our study thereby not only reinforced the importance of analyzing the age structure and growth variations of subsets integrated in millennial scale chronologies, but also emphasized that growth rate (and climate signal) differences at the micro-site scale can affect the conclusion derived from long-term climate reconstructions.

Conclusions

Comparisons of well-replicated micro-site chronologies (lakeshore and several meters inland) from northern and central Sweden showed stronger temperature signals in trees growing directly at the lakeshore, compared to the inland counterparts, in northern Sweden. Besides the differing climate signal strengths, we found varying growth rates (and trends) among the lakeshore and inland micro-sites in both study regions. These differences appear to be unimportant, if individual detrending techniques (e.g. NegExp), that remove growth rate differences among single measurement series, are applied. Micro-site differences are important, however, when RCS detrending is applied, resulting in differing long-term trends in millennial-length chronologies.

Concerning the discussion on twentieth century temperature trends, this study detailed novel approaches to improve existing long-term tree-ring chronologies and derived temperature reconstructions. In line with recommendations to more carefully choose (and combine) living tree with historical wood samples (Tegel et al. 2010), the results presented herein revealed supra-long tree-ring chronologies from northern Fennoscandia should be combined with living tree data from lakeshore micro-sites only. Doing so will not only result in a better assessment of the climate signal retained in these long records, but also improve our understanding of recent climate change with respect to pre-instrumental variations and trends over the past several 100 years to millennia.

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