

Age trends in tree ring growth and isotopic archives: A case study of *Pinus sylvestris* L. from northwestern Norway

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[1] Measurements of tree ring width and relative density have contributed significantly to many of the large-scale reconstructions of past climatic change, but to extract the climate signal it is first necessary to remove any nonclimatic age-related trends. This detrending can limit the lower-frequency climate information that may be extracted from the archive (the “segment length curse”). This paper uses a data set of ring widths, maximum latewood density and stable carbon and oxygen isotopes from 28 annually resolved series of known-age *Pinus sylvestris* L. trees in northwestern Norway to test whether stable isotopes in tree rings require an equivalent statistical detrending. Results indicate that stable oxygen and carbon isotope ratios from tree rings whose cambial age exceeds *c.*50 years exhibit no significant age trends and thus may be used to reconstruct environmental variability and physiological processes at this site without the potential loss of low-frequency information associated with detrending.

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1. Introduction

[2] It has long been recognized that the physical growth-based proxies from the tree ring archive; ring width (RW) and maximum latewood density (MXD) display trends that are related to tree age. The presence or absence of such age-related trends in tree ring stable isotopes remains, however, a matter of some debate [Esper *et al.*, 2010; Gagen *et al.*, 2007, 2008].

[3] Tree ring properties are often strongly linked (both theoretically and empirically) with climatic variables and this relationship can be quantified using instrumental meteorological data at annual resolution. Replication allows for the calculation of signal strength and statistically defined confidence intervals around any resulting reconstructions of past climate. When, however, RW and MXD are used to reconstruct long-term climate, the age-related trend must first be removed. The effect of this detrending upon the resulting chronology is that the maximum temporal frequency that can be retained is constrained by the length of the individual tree ring series. This “segment length curse” [Cook *et al.*, 1995] is a nontrivial problem as it particularly impacts upon tree ring based climate reconstructions in the lower-frequency

domain, which is of particular interest in the study of long-term climate change. The regional curve standardization (RCS) method [Briffa *et al.*, 1992] was developed to address many of the problems associated with individual curve-fitting approaches. RCS is based upon the principle that where specific sampling conditions are met, a common age-related trend can be identified and applied to all trees growing within an area, regardless of age or growth period. Despite this advance, the possibility remains that many physically based tree ring reconstructions have failed to capture the true long-term variability of late Holocene climate [e.g., Kaufman *et al.*, 2009].

[4] Stable isotopes from tree rings may offer the opportunity to reconstruct climatic variables without recourse to statistical detrending [McCarroll and Loader, 2004; Gagen *et al.*, 2007]. Evidence for the lack of long-term age trends is, however, limited. It is known that stable-carbon isotopes ($\delta^{13}\text{C}$) demonstrate a clear “juvenile” trend during the first (*c.* 50) years of growth, which can be objectively identified and removed from any climate reconstruction [Loader *et al.*, 2007]. Gagen *et al.* [2007] demonstrated that the record beyond this ‘juvenile’ phase of *Pinus sylvestris* L. from northern Finland exhibited no age trends. In contrast, Esper *et al.* [2010] identified a positive age-related trend for $\delta^{13}\text{C}$ from *Pinus uncinata* in the Spanish Pyrenees. Much of this trend, however, appears to be related to a long (*c.* 100 year) ‘juvenile’ phase, which may be site/species specific, as the period from 100 to 390 cambial years shows little or no trend is obvious in their data. Research into age trends in stable oxygen isotopes ($\delta^{18}\text{O}$) is limited, and at present no ‘juvenile’ trend, similar to that observed in $\delta^{13}\text{C}$ has been identified. Treydte *et al.* [2006] identified differing trends between

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biologically older and younger trees covering the same time period, which they suggest may be age-related, but that this had little overall effect on the reconstruction produced. In contrast, *Esper et al.* [2010] have recently reported a significant long-term negative age-related trend for $\delta^{18}\text{O}$ from *Pinus uncinata* located in the Spanish Pyrenees.

[5] The cost and effort of producing a stable isotope chronology is only justifiable as long as environmental information is gained that could not be obtained more easily from ring widths or densities [Hughes, 2002; Gagen et al., 2011]. Retaining the low-frequency component of long-term climate change would certainly justify the extra effort. Equally, if tree ring isotopes do contain long-term age trends then these should be addressed to avoid bias. At present, however, RCS does not provide a solution because it is rarely feasible to produce the highly replicated isotope chronologies that would be required to apply the method properly [Esper et al., 2003]. Conversely, if there are no age-related trends in tree ring isotopes, subjecting them to statistical detrending techniques may introduce the very problems of low frequency signal retention that researchers have, hitherto, sought to avoid.

2. Case Study: Forfjorddalen, NW Norway

[6] Tree cores were collected from an isolated community of Scots pine (*Pinus sylvestris* L.), located close to the northern limit for pine growth, at Forfjorddalen, northwestern Norway (68°48' N and 15°44' E, 50 to 170 m above sea level). Scots pine is the major species used to reconstruct palaeoclimate in northern Fennoscandia, utilizing both growth proxies [Briffa et al., 1990, 1992; Campbell et al., 2007; Eronen et al., 2002; Kirchhefer, 2005; Gouirand et al., 2008; Grudd, 2008; Grudd et al., 2002; Helama et al., 2002; Linderholm et al., 2010; Lindholm et al., 2009; McCarroll et al., 2002; Tuovinen et al., 2009] and isotopic proxies [Hilasvuori et al., 2009; McCarroll et al., 2003, 2011; Sonninen and Jungner, 1995]. The site has been described in detail by Kirchhefer [2001] and Young et al. [2010]. RW, $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ were measured from the annual growth rings of 28 individual trees of mixed ages. MXD measurements were made from 17 of the trees used for the other proxies, but the remainder were not suitable for densitometry. To keep the sample size constant, a further 11 trees were selected for densitometry. The trees were selected to match, as closely as possible, the age and temporal structure of the other data sets. Pith dates were determined by direct measurement or estimates made for each tree core retrieved.

[7] Tree ring $\delta^{13}\text{C}$ records have been directly affected by the changes in the $\delta^{13}\text{C}$ of atmospheric CO_2 since the major onset of industrialization (c. 1850 CE). The correction to preindustrial $\delta^{13}\text{C}$ values of atmospheric CO_2 is additive; the correction values used in this study are those provided by McCarroll and Loader [2004]. It has also become widely accepted that the $\delta^{13}\text{C}$ values from tree rings have been affected by a changing physiological response of trees to increasing atmospheric levels of CO_2 [Saurer et al., 2004; Waterhouse et al., 2004; McCarroll et al., 2009; Treydte et al., 2009]. The values in this study have been corrected using the procedure proposed by McCarroll et al. [2009, 2010] and adopted elsewhere [Loader et al., 2008, 2010;

Kress et al., 2009; Rinne et al., 2010; Sidorova et al., 2010; Young et al., 2010].

3. Methods

[8] Owing to the known presence of the “juvenile effect” in carbon isotopes [Loader et al., 2007] few of the isotope series analyzed were extended earlier than 50 cambial years, and none were analyzed to the pith. Isotope data often exhibit a significant between-tree range in delta (δ) values (2.0‰ is not uncommon for $\delta^{13}\text{C}$ [Loader et al., 2007; McCarroll and Pawellek, 1998, 2001]), although the interannual correlation between trees remains high. This means that to determine a precise mean value, and therefore age trend, a reasonable level of series replication (sample depth) is required. We therefore limited analysis of the isotope series to levels of replication of $n \geq 10$. In order to make direct comparisons between the proxies we treated all the data in the same manner. The data analyzed extend from 50 years from the pith to the year when n is less than 10; a total series length of 296 growth years for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, 358 for ring width and 254 for density.

[9] Each segment was aligned by tree (cambial) age, using the pith dates/pith estimates made for each tree core. The mean of the aligned series was taken and a simple linear function fitted. Ring width and maximum density series are often fitted with more complex (and appropriate) functions to allow accurate detrending that retains the optimum environmental signal, but here we only apply a simple linear fit to identify the presence or absence of trends in these data. To establish whether the slope of the regression line is significantly different from zero, we calculated the p value, with a significance threshold of $p < 0.05$.

4. Results

[10] The results for RW and MXD series (Figure 1) show pronounced and statistically significant ($p < 0.001$) age-related trends over the periods examined, and while negative exponential (RW) and Hegershoff (MXD) functions are more typically employed for detrending [Fritts, 1976; Warren, 1980; Grudd et al., 2002], the linear functions appear to be appropriate for these data.

[11] The results for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ (Figures 2 and 3) suggest that there are no statistically significant age-related trends. The slope of the regression line for $\delta^{13}\text{C}$ is 0.0002 per mille per year and is not statistically significant ($p > 0.05$). In these data the observed trend would result in an isotopic offset of 0.05‰ over the 296 growth years analyzed, which is well within the typical analytical error (± 0.1 per mille) for a single measurement of cellulose $\delta^{13}\text{C}$ [Loader et al., 1997, 2008]. The observed trend for $\delta^{18}\text{O}$ is even smaller, at -0.0001 per mille per year, which would produce a difference of 0.03‰ over 296 years. The typical analytical error for a single measurement of $\delta^{18}\text{O}$ is ± 0.3 ‰ [Loader et al., 2008].

[12] While $\delta^{18}\text{O}$ values are presented in their raw uncorrected form, $\delta^{13}\text{C}_{\text{raw}}$ results have been corrected both for changes in the isotopic ratio of atmospheric CO_2 over the industrial period ($\delta^{13}\text{C}_{\text{atm}}$) and for tree response to increased CO_2 concentration ($\delta^{13}\text{C}_{\text{pin}}$). The first of these corrections is an essential step and uncorrected data cannot be used for calibration or palaeoclimate reconstruction. The second

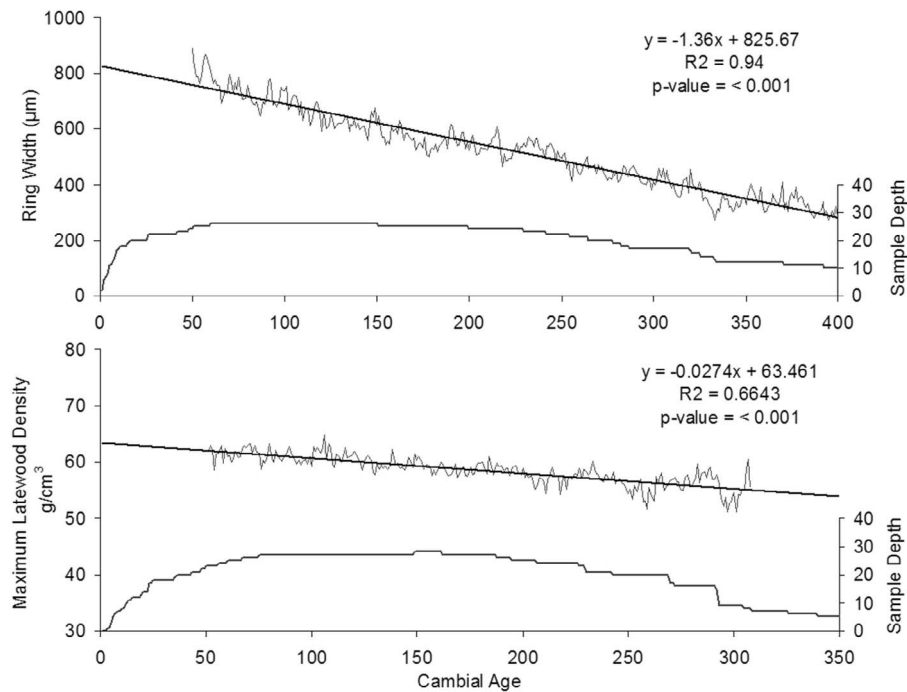


Figure 1. Age trends in the physical proxies aligned by cambial age: (top) ring widths and (bottom) maximum latewood density. Both are the mean of 28 individual series with a linear fit applied to them. Secondary y axes show the sample depth (bold lines). The equations for the linear trend fitted, the squared correlation coefficients (R^2) (between cambial age and the mean series), and the significance of the regression slopes (p value) are displayed.

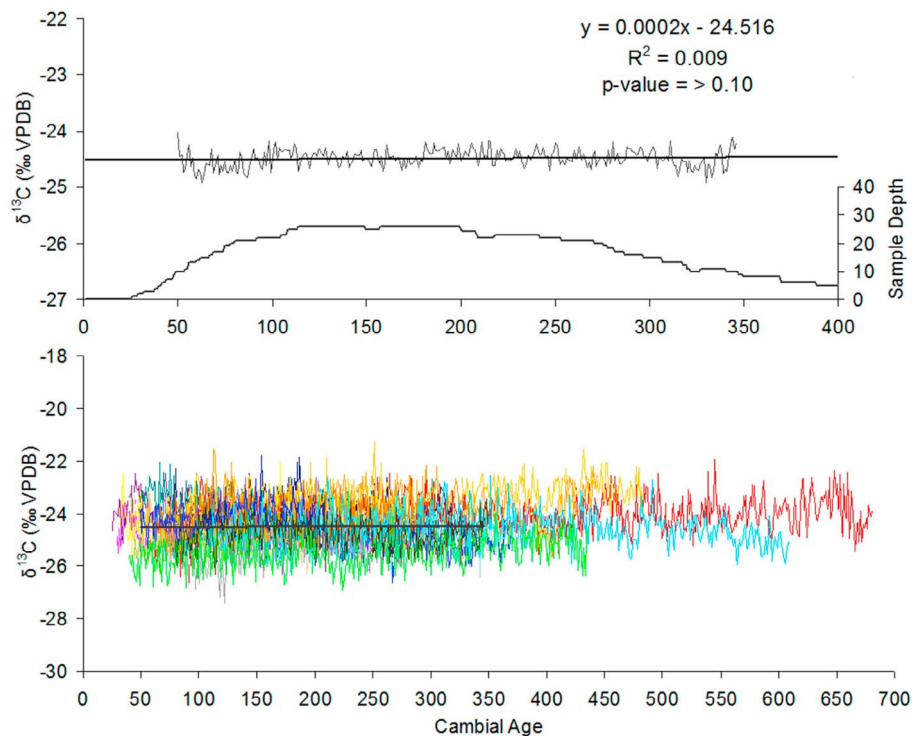


Figure 2. Stable carbon isotope values aligned by cambial age and corrected for both changes in the isotopic ratio and amount of atmospheric CO_2 , since 1850 CE. (top) The mean of 28 individual series with a linear fit applied to it. A secondary y axis shows the sample depth (bold line). (bottom) The regression line from Figure 2, top, superimposed over the individual 28 stable isotope series.

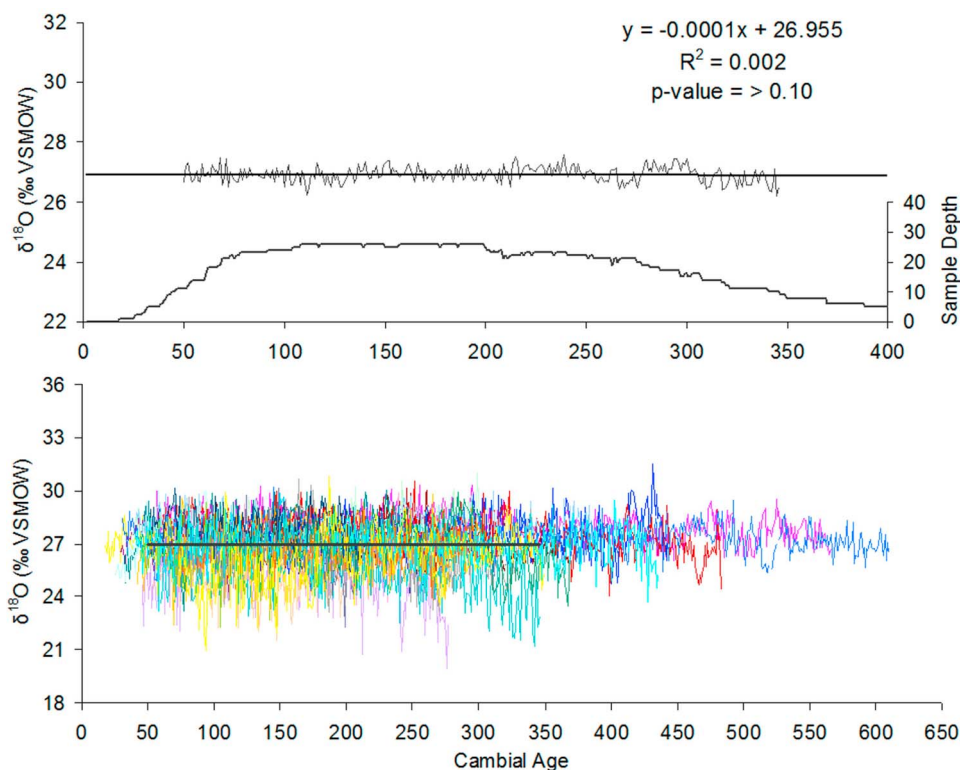


Figure 3. Stable oxygen isotope values aligned by cambial age. (top) The mean of 28 individual series with a linear fit applied to it. A secondary y axis shows the sample depth (bold line). (bottom) The regression line from Figure 3, top, superimposed over the individual 28 stable isotope series.

correction is not a simple additive one and involves an element of detrending, which typically affects only the last few decades of the series, so it is prudent to test whether there is a significant age trend before this correction is applied ($\delta^{13}\text{C}_{\text{atm}}$). When the above exercise was carried out on the $\delta^{13}\text{C}_{\text{atm}}$ data the result was a small but nonsignificant negative slope ($y = -0.0002x - 24.506$; $p > 0.05$) leading to an isotopic offset of -0.05 per mille over 296 years, which is well within the typical analytical error of the method. The results for the $\delta^{13}\text{C}_{\text{atm}}$ data show that even prior to this correction the data, at this location, contain no significant age-related trends.

5. Discussion and Conclusions

[13] The data from the physical growth proxies presented here (Figure 1) display strong age trends that have been reported previously for these proxies. Given sufficient replication such trends can be dealt with successfully using standard dendrochronological methods [Fritts, 1976; Briffa and Jones, 1990; Esper *et al.*, 2003]. The stable isotope series (Figures 2 and 3), in contrast, exhibit no statistically significant age-related trends that would require the application of statistical detrending.

[14] The results presented here suggest that from cambial ages of *c.* 50 to 350 years, stable carbon isotope ratios from northern Fennoscandian Scots pine require no detrending. It therefore seems reasonable to conclude that it is safe to reconstruct climatic variables from this archive without recourse to detrending. These results are in agreement with

those of Gagen *et al.* [2007, 2008] for $\delta^{13}\text{C}$ values from Scots pine in northern Finland. The results for $\delta^{18}\text{O}$ are equally unambiguous. The lack of any significant age trend in the data examined suggests that they can also be used reliably without any detrending. Our findings contrast with those of Esper *et al.* [2010], who found a significant age-related trend in $\delta^{18}\text{O}$ from *Pinus uncinata* located in the Spanish Pyrenees. The reasons for these different findings are not obvious, but could reflect localized site/species effects. The contrast, however, highlights the importance of rigorously interrogating tree ring isotope series prior to climate analysis to identify any such nonclimatic trends. What remains clear is that for the key climate archive species in Fennoscandia (*Pinus sylvestris* L.), at least at this location, no significant age-related trends are apparent in either $\delta^{13}\text{C}$ or $\delta^{18}\text{O}$.

[15] On the basis of the results presented here, and those presented by Gagen *et al.* [2007, 2008], we conclude that the stable carbon and oxygen isotope ratios of Scots pine trees in northern Fennoscandia, after a juvenile phase of about 50 years, do not change significantly with tree age. This means that statistical detrending is not required, thereby removing the attendant risk of loss of long-term, low-frequency climate information. There is, in effect, no ‘segment length curse’ for these archives.

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References

- Briffa, K. R., and P. D. Jones (1990), Basic chronology statistics and assessment, in *Methods of Dendrochronology: Applications in the Environmental Sciences*, edited by E. R. Cook and L. A. Kairiukstis, pp. 137–152, Kluwer Acad., Dordrecht, Netherlands.
- Briffa, K. R., T. S. Bartholin, D. Eckstein, P. D. Jones, W. Karlén, F. H. Schweingruber, and P. Zetterberg (1990), A 1,400-year tree-ring record of summer temperatures in Fennoscandia, *Nature*, **346**, 434–439, doi:10.1038/346434a0.
- Briffa, K. R., P. D. Jones, T. S. Bartholin, D. Eckstein, F. H. Schweingruber, W. Karlén, P. Zetterberg, and M. Eronen (1992), Fennoscandian summers from AD 500: Temperature changes on short and long timescales, *Clim. Dyn.*, **7**, 111–119, doi:10.1007/BF00211153.
- Campbell, R., D. McCarroll, N. J. Loader, H. Grudd, I. Robertson, and R. Jalkanen (2007), Blue intensity in *Pinus sylvestris* tree-rings: Developing a new palaeoclimate proxy, *Holocene*, **17**, 821–828, doi:10.1177/0959683607080523.
- Cook, E. R., K. R. Briffa, D. M. Meko, A. Graybill, and G. Funkhouser (1995), The 'segment length curse' in long tree-ring chronology development for palaeoclimatic studies, *Holocene*, **5**, 229–237, doi:10.1177/095968369500500211.
- Eronen, M., P. Zetterberg, K. R. Briffa, M. Lindholm, J. Meriläinen, and M. Timonen (2002), The supra-long Scots pine tree-ring record for Finnish Lapland: Part 1, chronology construction and initial inferences, *Holocene*, **12**, 673–680, doi:10.1191/0959683602hl580rp.
- Esper, J., E. R. Cook, P. J. Krusic, K. Peters, and F. H. Schweingruber (2003), Tests of the RCS method for preserving low-frequency variability in long tree-ring chronologies, *Tree-Ring Res.*, **59**, 81–98.
- Esper, J., D. C. Frank, G. Battipaglia, U. Büntgen, C. Holert, K. S. Treydte, R. T. W. Siegwolf, and M. Saurer (2010), Low-frequency noise in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ tree ring data: A case study of *Pinus uncinata* in the Spanish Pyrenees, *Global Biogeochem. Cycles*, **24**, GB4018, doi:10.1029/2010GB003772.
- Fritts, H. C. (1976), *Tree Rings and Climate*, 567 pp., Academic, London.
- Gagen, M. H., D. McCarroll, N. J. Loader, I. Robertson, R. Jalkanen, and K. J. Anchukaitis (2007), Exorcising the 'segment length curse': Summer temperature reconstruction since AD 1640 using non-detrended stable carbon isotope ratios from pine trees in northern Finland, *Holocene*, **17**, 435–446, doi:10.1177/0959683607077012.
- Gagen, M. H., D. McCarroll, I. Robertson, N. J. Loader, and R. Jalkanen (2008), Do tree ring $\delta^{13}\text{C}$ series from *Pinus sylvestris* in northern Fennoscandia contain long-term non-climate trends?, *Chem. Geol.*, **252**, 42–51, doi:10.1016/j.chemgeo.2008.01.013.
- Gagen, M. H., D. McCarroll, N. J. Loader, and I. Robertson (2011), Stable isotopes in dendroclimatology: Moving beyond 'potential' in *Developments in Palaeoenvironmental Research*, vol. 11, *Dendroclimatology: Progress and Prospects*, edited by M. K. Hughes et al., pp. 147–172, Springer, New York, doi:10.1007/978-1-4020-5725-0.
- Gouirand, I., H. W. Linderholm, A. Moberg, and B. Wohlfarth (2008), On the spatiotemporal characteristics of Fennoscandian tree-ring based summer temperature reconstructions, *Theor. Appl. Climatol.*, **91**, 1–25, doi:10.1007/s00704-007-0311-7.
- Grudd, H. (2008), Tometrask tree-ring width and density AD 500–2004: A test of climate sensitivity and a new 1500-year reconstruction of north Fennoscandian summers, *Clim. Dyn.*, **31**, 843–857, doi:10.1007/s00382-007-0358-2.
- Grudd, H., K. R. Briffa, W. Karlén, T. S. Bartholin, P. D. Jones, and B. Kromer (2002), A 7400-year tree-ring chronology in northern Swedish Lapland: Natural climatic variability expressed on annual to millennial timescales, *Holocene*, **12**, 657–666, doi:10.1191/0959683602hl578rp.
- Helama, S., M. Lindholm, M. Timonen, J. Meriläinen, and M. Eronen (2002), The supra-long Scots pine tree-ring record for Finnish Lapland: Part 2, interannual to centennial variability in summer temperatures for 7500 years, *Holocene*, **12**, 681–688, doi:10.1191/0959683602hl581rp.
- Hilasvuori, E., F. Berninger, E. Sonninen, H. Tuomenvirta, and H. Jungner (2009), Stability of climate signal in carbon and oxygen isotope records and ring width from Scots pine (*Pinus sylvestris* L.) in Finland, *J. Quat. Sci.*, **24**, 469–480, doi:10.1002/jqs.1260.
- Hughes, M. K. (2002), Dendrochronology in climatology: The state of the art, *Dendrochronologia*, **20**, 95–116, doi:10.1078/1125-7865-00011.
- Kaufman, D. S., D. P. Schneider, N. P. McKay, C. M. Ammann, R. S. Bradley, K. R. Briffa, G. F. Miller, B. L. Otto-Bliesner, J. T. Overpeck, and B. M. Vinther (2009), Recent warming reverses long-term Arctic cooling, *Science*, **325**, 1236–1239, doi:10.1126/science.1173983.
- Kirchhefer, A. J. (2001), Reconstruction of summer temperatures from tree-rings of Scots pine (*Pinus sylvestris* L.) in coastal northern Norway, *Holocene*, **11**, 41–52, doi:10.1191/095968301670181592.
- Kirchhefer, A. J. (2005), A discontinuous tree-ring record AD 320–1994 from Dividalen, Norway: Inferences on climate and treeline history, in *Mountain Ecosystems: Studies in Treeline Ecology*, edited by G. Broll and B. Keplin, pp. 219–236, Springer, Berlin.
- Kress, A., G. H. F. Young, M. Saurer, N. J. Loader, R. T. W. Siegwolf, and D. McCarroll (2009), Stable isotope coherence in the earlywood and latewood of tree line conifers, *Chem. Geol.*, **268**, 52–57, doi:10.1016/j.chemgeo.2009.07.008.
- Linderholm, H. W., J. A. Björklund, K. Seftigen, B. E. Gunnarson, H. Grudd, J. H. Jeong, I. Drobyshev, and Y. Liu (2010), Dendroclimatology in Fennoscandia: From past accomplishments to future potential, *Clim. Past*, **6**, 93–114, doi:10.5194/cp-6-93-2010.
- Lindholm, M., M. Ogurtsov, T. Aalto, R. Jalkanen, and H. Salminen (2009), A summer temperature proxy from height increment of Scots pine since 1561 at the northern timberline in Fennoscandia, *Holocene*, **19**, 1131–1138, doi:10.1177/0959683609345078.
- Loader, N. J., I. Robertson, A. C. Barker, V. R. Switsur, and J. S. Waterhouse (1997), An improved technique for the batch processing of small wholewood samples to α -cellulose, *Chem. Geol.*, **136**, 313–317, doi:10.1016/S0009-2541(96)00133-7.
- Loader, N. J., D. McCarroll, M. H. Gagen, I. Robertson, and R. Jalkanen (2007), Extracting climatic information from stable isotopes in tree rings, in *Isotopes as Indicators of Ecological Change*, edited by R. Siegwolf and T. Dawson, pp. 23–44, Academic, San Diego, Calif.
- Loader, N. J., P. M. Santillo, J. P. Woodman-Ralph, J. E. Rolfe, M. A. Hall, M. Gagen, I. Robertson, R. Wilson, C. A. Froyd, and D. McCarroll (2008), Multiple stable isotopes from oak trees in southwestern Scotland and the potential for stable isotope dendroclimatology in maritime climatic regions, *Chem. Geol.*, **252**, 62–71, doi:10.1016/j.chemgeo.2008.01.006.
- Loader, N. J., G. Helle, S. Los, F. Lehmkuhl, and G. H. Schleser (2010), Twentieth-century summer temperature variability in the southern Altai Mountains: A carbon and oxygen isotope study of tree rings, *Holocene*, doi:10.1177/0959683610369507.
- McCarroll, D., and N. J. Loader (2004), Stable isotopes in tree rings, *Quat. Sci. Rev.*, **23**, 771–801, doi:10.1016/j.quascirev.2003.06.017.
- McCarroll, D., and F. Pawellek (1998), Stable carbon isotope ratios of latewood cellulose in *Pinus sylvestris* from northern Finland: Variability and signal-strength, *Holocene*, **8**, 675–684, doi:10.1191/095968398675987498.
- McCarroll, D., and F. Pawellek (2001), Stable carbon isotope ratios of *Pinus sylvestris* from northern Finland and the potential for extracting a climate signal from long Fennoscandian chronologies, *Holocene*, **11**, 517–526, doi:10.1191/095968301680223477.
- McCarroll, D., E. Pettigrew, A. Luckman, F. Guibal, and J. L. Edouard (2002), Blue reflectance provides a surrogate for latewood density of high-latitude pine tree rings, *Arct. Antarct. Alp. Res.*, **34**, 450–453, doi:10.2307/1552203.
- McCarroll, D., R. Jalkanen, S. Hicks, M. Tuovinen, M. Gagen, F. Pawellek, D. Eckstein, U. Schmitt, J. Autio, and O. Heikkinen (2003), Multiproxy dendroclimatology: A pilot study in northern Finland, *Holocene*, **13**, 829–838, doi:10.1191/0959683603hl668rp.
- McCarroll, D., M. H. Gagen, N. J. Loader, I. Robertson, K. J. Anchukaitis, S. Los, G. H. F. Young, R. Jalkanen, A. J. Kirchhefer, and J. S. Waterhouse (2009), Correction of tree ring stable carbon isotope chronologies for changes in the carbon dioxide content of the atmosphere, *Geochim. Cosmochim. Acta*, **73**, 1539–1547, doi:10.1016/j.gca.2008.11.041.
- McCarroll, D., M. H. Gagen, N. J. Loader, I. Robertson, K. J. Anchukaitis, S. Los, G. H. F. Young, R. Jalkanen, A. J. Kirchhefer, and J. S. Waterhouse (2010), Erratum to "Correction of tree ring stable carbon isotope chronologies for changes in the carbon dioxide content of the atmosphere", *Geochimica et Cosmochimica Acta* **73**, 1539–1547, *Geochim. Cosmochim. Acta*, **74**, 3040, doi:10.1016/j.gca.2009.12.031.
- McCarroll, D., M. Tuovinen, R. Campbell, M. Gagen, H. Grudd, R. Jalkanen, N. J. Loader, and I. Robertson (2011), A critical evaluation of multi-proxy dendroclimatology in northern Finland, *J. Quat. Sci.*, **26**, 7–14, doi:10.1002/jqs.1408.
- Rinne, K. T., N. J. Loader, V. R. Switsur, K. S. Treydte, and J. S. Waterhouse (2010), Investigating the influence of sulphur dioxide (SO_2) on the stable isotope ratios ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) of tree rings, *Geochim. Cosmochim. Acta*, **74**, 2327–2339, doi:10.1016/j.gca.2010.01.021.
- Saurer, M., R. Siegwolf, and F. H. Schweingruber (2004), Carbon isotope discrimination indicates improving water-use efficiency of trees in northern Eurasia over the last 100 years, *Global Change Biol.*, **10**, 2109–2120, doi:10.1111/j.1365-2486.2004.00869.x.
- Sidorova, O. V., R. T. W. Siegwolf, M. Saurer, M. M. Naurzbaev, A. V. Shashkin, and E. A. Vaganov (2010), Spatial patterns of climate changes in the Eurasian north reflected in Siberian larch tree-ring parameters and stable isotopes, *Global Change Biol.*, **16**, 1003–1018, doi:10.1111/j.1365-2486.2009.02008.x.

- Sonninen, E., and H. Jungner (1995), Stable carbon isotopes in the tree rings of a Scots pine (*Pinus sylvestris* L.) from northern Finland, *Paläoklimaforschung*, *15*, 121–128.
- Treydte, K. S., G. H. Schleser, G. Helle, D. C. Frank, M. Winiger, G. H. Haug, and J. Esper (2006), The twentieth century was the wettest period in northern Pakistan over the past millennium, *Nature*, *440*, 1179–1182, doi:10.1038/nature04743.
- Treydte, K. S., D. C. Frank, M. Saurer, G. Helle, G. H. Schleser, and J. Esper (2009), Impact of climate and CO₂ on a millennium-long tree-ring carbon isotope record, *Geochim. Cosmochim. Acta*, *73*, 4635–4647, doi:10.1016/j.gca.2009.05.057.
- Tuovinen, M., D. McCarroll, H. Grudd, R. Jalkanen, and S. Los (2009), Spatial and temporal stability of the climate signal in northern Fennoscandian pine tree-ring width and maximum density, *Boreas*, *38*, 1–12, doi:10.1111/j.1502-3885.2008.00046.x.
- Warren, W. G. (1980), On removing the growth trend from dendrochronological data, *Tree-Ring Bull.*, *40*, 35–44.
- Waterhouse, J. S., V. R. Switsur, A. C. Barker, A. H. C. Carter, D. L. Hemming, N. J. Loader, and I. Robertson (2004), Northern European trees show a progressively diminishing response to increasing atmospheric carbon dioxide concentrations, *Quat. Sci. Rev.*, *23*, 803–810, doi:10.1016/j.quascirev.2003.06.011.
- Young, G. H. F., D. McCarroll, N. J. Loader, and A. J. Kirchhefer (2010), A 500-year record of summer near-ground solar radiation from tree-ring stable carbon isotopes, *Holocene*, *20*, 315–324, doi:10.1177/0959683609351902.
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