Chapter 20
Stable Isotopes in Tree Rings of Boreal Forests

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Abstract The boreal forests are widely expanded from subarctic forest to tundra, and from taiga to forest-steppe zone (from 50 °N to 70 °N). We reviewed available stable isotope chronologies in tree-ring cellulose ($\delta^{13}C$, $\delta^{18}O$ and $\delta^{2}H$) from 16 sites located in the Russian Federation; 4 research sites from Fennoscandia (Finland, Sweden and Norway); 5 sites from Canada, and 1 site from Alaska (USA) to evaluate impact of climatic changes from seasonal to annual scale across boreal forest ecosystems. Results of our review of carbon isotope data showed that drought conditions (mainly high vapour pressure deficit) are prevalent for western and central regions of Eurasia, Alaska and Canada, while northeastern and eastern sites of Eurasian subarctic are showing water shortage developments resulting from decreasing precipitation. Oxygen isotope chronologies show increasing trends towards the end of the twentieth century mainly for all chronologies, except for the Siberian northern and southern sites. The application of the multiple stable isotope proxies ($\delta^{13}C$, $\delta^{18}O$, $\delta^{2}H$)

Supplementary Information The online version contains supplementary material available at (https://doi.org/10.1007/978-3-030-92698-4_20).

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R. T. W. Siegwolf et al. (eds.), *Stable Isotopes in Tree Rings*, Tree Physiology 8,
https://doi.org/10.1007/978-3-030-92698-4_20

is beneficial to study responses of boreal forests to climate change in temperature-limited environments. However, a deeper knowledge of hydrogen isotope fractionation processes at the tree-ring cellulose level is needed for a sound interpretation and application of δ^2H for climate reconstructions, especially for the boreal forest zone where forest ecosystems are more sensitive to climatic and environmental changes.

20.1 Introduction

The boreal forest, including areas classically known as taiga, is the largest biome on earth (Apps et al. 2006), representing 17% of the earth's terrestrial ecosystems. It holds an estimated ~30% of terrestrial carbon stocks (Pan et al. 2011), making it a significant variable in the global carbon cycle. The boreal forest encompasses a zonal band roughly defined by 50–70 °N and occupies 1.2 billion hectares of land area (Soja et al. 2007), with the Siberian taiga accounting for 70% of this area (Kasischke 2000). The typical boreal climate is subarctic (e.g., Köppen zones Dfc and Dwc). In contrast to tundra areas to the north, the relatively low albedo of the boreal forest plays an important role in regulating the surface energy balance and climate of the subarctic latitudes (Bonan 2008).

Large areas of Fennoscandia, central and eastern Siberia (Russian Federation), northern Canada and Alaska represent the most extensive remaining areas of natural forests on the planet. The boreal forests are globally important for their economic and environmental values. Extensive areas of the boreal forests of Finland, Sweden, and parts of Canada are intensively managed for timber production and contribute 10–30% of the export income of these nations (ACIA 2004).

The study of boreal forest ecosystems is important because of their high sensitivity to regional and global climate changes, and potential to influence ground temperatures and the stability of vast pools of carbon currently locked in permafrost in the subarctic regions (Fig. 20.1a). Permafrost plays an important role in stabilizing the climatic system and climate-albedo feedbacks that are unique to the northern range of the boreal forest (Bonan 2008). Due to climate warming, both vapor-pressure deficit (VPD) and evapotranspiration are expected to increase in the boreal region, which has implications for tree's water relations (Sugimoto et al. 2002; ACIA 2004; Churakova (Sidorova) et al. 2016, 2020).

Many impacts of climate change are already apparent in the boreal forest including:

(i) spatially complex patterns of reduced and increased rates of tree growth (Briffa et al. 1998; Briffa 2000; Lloyd and Bunn 2007); (ii) larger and more extensive fires and insect outbreaks (Soja et al. 2007); and (iii) a range of effects due to permafrost degradation, including new wetland development and subsidence of the ground surface (Turetsky et al. 2019), with the associated loss of trees and ecological succession toward wetland plant communities.

In boreal regions, the traditional tree-ring parameters like tree-ring width and maximum latewood density are typically positively correlated with June-July and

June–August temperatures, and therefore, have been successfully used to reconstruct summer temperatures over the past millennium (Briffa 2000; Sidorova and Naurzbaev 2002; Naurzbaev et al. 2002; Hantemirov et al. 2011; Grudd 2008; Kononov et al. 2009; D'Arrigo et al. 2008; Myglan et al. 2008; Schneider et al. 2015; Büntgen et al. 2021). However, in some areas of Alaska and northwestern Canada where the rate of recent climate warming has been most rapid, the generally reliable association between ring width and summer climate has been demonstrated to break down, potentially linked to warming-induced drought stress (Briffa 2000; Wilmking et al. 2004; D'Arrigo et al. 2008; Porter and Pisaric 2011; Porter et al. 2013). This phenomenon is referred to the "Divergence Problem" (DP) in the dendrochronology literature (D'Arrigo et al. 2008; Camarero et al. 2021). The emergence of the DP has stimulated the search for a more reliable tree-ring climate proxy in affected regions, including tree-ring $\delta^{13}C$ and $\delta^{18}O$ (Barber et al. 2000; Sidorova et al. 2009, 2010; Porter et al. 2009; Zharkov et al. 2021).

20.2 Characteristic of Boreal Zone

20.2.1 Study Sites and Tree Species

Trees in the boreal zone have showed great potential for stable isotope studies due to long-term tree longevity (Sidorova et al. 2008, 2010) and good subfossil wood preservation due to severe climate conditions and permafrost availability (Sidorova et al. 2013a, b; Helama et al. 2018; Churakova (Sidorova) et al. 2019) (Fig. 20.1).

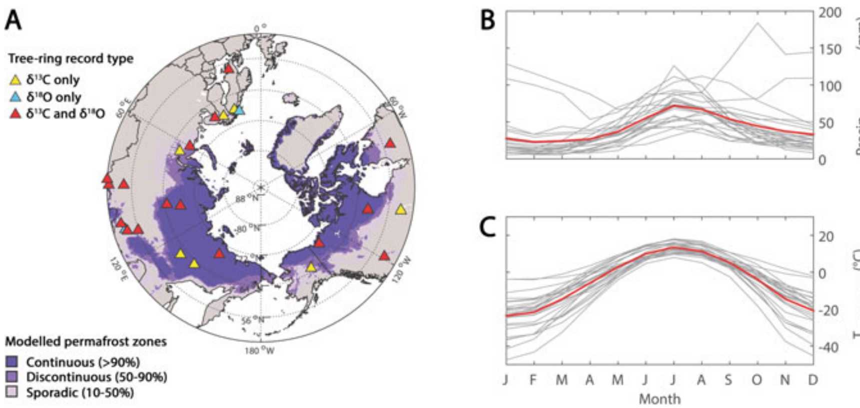

Fig. 20.1 Location of the study sites (Table S20.1) with $\delta^{13}C$ (yellow triangles), $\delta^{18}O$ (light blue triangles) and both $\delta^{13}C$ and $\delta^{18}O$ (red triangles) isotope tree-ring cellulose chronologies (**a**). Monthly precipitation (**b**) and mean air temperature (**c**) climatologies for the common period (1961–1990) for all published sites, calculated from the 10'-spatial resolution dataset by New et al. (2002). Permafrost distribution from continuous to sporadic is available in Obu et al. (2019)

Dominant tree species are white spruce (*Picea glauca*) and black spruce (*Picea mariana* Mill.) in Canada and the USA (Alaska), Scots pine (*Pinus sylvestris* L.) in Fennoscandia, and a variety of larch tree species (*Larix sibirica* Ledeb., *Larix gmelinii* Rupr., *Larix cajanderi* Mayr.) in central, eastern and northeastern Siberia. Previous tree-ring isotope studies in the boreal region have focused mainly on developing stable carbon ($\delta^{13}C$) and oxygen ($\delta^{18}O$) isotope chronologies from cellulose (Fig. 20.1, Table 20.1 and Supplementary Table 20.1). To date there have been only a few studies in the boreal region focusing on hydrogen ($\delta^{2}H$) in tree-ring cellulose (e.g., in Finland, see Hilasvuori 2011). Based on the available literature and knowledge, our review focusses primarily on stable carbon and oxygen isotope studies in tree rings from the boreal zone.

20.2.2 Permafrost

About 80% of the world's boreal forests are located in the circumpolar permafrost zone (Helbig et al. 2016) which makes permafrost a particularly important component of the boreal forest. Boreal forests respond to both the timing and magnitude of changes in soil moisture and soil temperature, nutrient availability, as well as permafrost distribution and dynamics, which themselves are directly affected by snow and vegetation cover, soil texture and geothermal heat flux (ACIA 2004; Cable et al. 2013; Boike et al. 2013). Water released from thawing ice-rich permafrost can be an important moisture source for trees growing in regions with severe temperature limitations and low amount of precipitation (Sidorova et al. 2010; Churakova (Sidorova) et al. 2016; Zhang et al. 2000; Sugimoto et al. 2002; Saurer et al. 2016). Due to low temperatures in the subarctic belt, water loss is not yet as large as observed in European forest ecosystems (Saurer et al. 2014). However, with a continued increase in temperature (Sidorova et al. 2010), drought stress may increase accordingly (Sidorova et al. 2009; Knorre et al. 2010; Bryukhanova et al. 2015; Saurer et al. 2016; Ohta et al. 2019) in the boreal forest regions.

Under the projected climate warming, permafrost is expected to degrade and initially wetland areas (thermokarst lakes) will increase in extent (IPCC 2014), which has the potential to shift the regional carbon balance from a net carbon sink (under productive boreal vegetation) to a carbon source (microbial emission of CO_2 and CH_4 driven by access to thawed permafrost carbon. Lake drainage, hydroclimatic change and ecological succession also have the potential to moderate thermokarst-carbon balance impacts. A number of studies have reported a pronounced increase in the seasonal thaw depth in Western Siberia (Melnikov et al. 2004; Pavlov et al. 2004; Fyodorov-Davydov et al. 2009). Fyodorov-Davydov et al. (2009) investigated the spatial and temporal trends in the active soil layer (ASL) depth in northern Yakutia, Russia (Table S20.1). The ASL is the top layer of soil with high activity of microbial processes and which thaws during summer and freezes back again in autumn.

Seasonal dynamics of the cryosphere also have implications for the phenology of tree growth, on carbon and oxygen isotope ratios in plants due to the influence

Table 20.1 Summary of available stable isotope chronologies in tree rings from the boreal forest

Proxy	Outcome	Tree species	References
$\delta^{13}C$			
Spring temperature	April–May temperature increases towards recent century	*L. sibirica* Ledeb *P. glauca*	Tartakovsky et al. (2012), Porter et al. (2014)
Summer temperature	June–August temperature increases	*L. cajanderi* Mayr *L. gmelinii* Rupr *P. sylvestris* L. *L. sibirica* Ledeb *P. glauca*	Porter et al. (2009), Loader et al. (2010, 2013), Sidorova et al. (2008), Sidorova et al. (2013a, b), Churakova (Sidorova) et al. (2016, 2019), Kononov et al. (2009), personal communication, Tartakovsky et al. (2012), Holzkämper et al. (2008), Gennaretti et al. (2017)
Winter temperature	Annual and decadal temporal resolution Winter (February) temperature trend	*L. gmelinii* Rupr *P. sylvestris* L.	Sidorova et al. (2010), Edwards et al. (2017)
Sunshine duration	Impact of June–August sunshine duration on $\delta^{13}C$ isotope chronologies	*P. sylvestris* L.	Loader et al. (2013)
Cloud cover	July–August percentage of cloud cover suggest strong negative relationship between cloud cover and temperature. High percentage of summer cloud cover during the 14-fifteenth and nineteenth centuries and famines due to crop failures caused by very wet (rather than cold) summer conditions	*P. sylvestris* L.	Young et al. (2012), Loader et al. (2013)
Arctic Oscillation	Recent period becomes cloudier compared to the past millennia	*P. sylvestris* L.	Young et al. (2012)

(continued)

Table 20.1 (continued)

Proxy	Outcome	Tree species	References
Water-use efficiency	Increasing WUE towards the recent decades, Increasing water shortage	*L. gmelinii* Rupr *L. cajanderi* Mayr *L. sibirica* Ledeb	Saurer et al. (2002, 2004, 2014), Churakova (Sidorova) (2018), Siegwolf et al. (2022) Keller et al. (2017)
Vapor pressure deficit	Increasing June-July VPD towards twentieth century over past millennia	*L. cajanderi* Mayr *L. gmelinii* Rupr	Sidorova et al. (2009), Churakova (Sidorova) et al. (2019, 2020) in preparation
Drought reconstruction	Physiological adaptations to drought and correspondence to the drought intervals of the 1790, 1840, 1890, 1930, and 1960–1970	*T. occidentalis*	Au and Tardif (2012)
River flow	Potential for river flow reconstruction	*P. sylvestris*	Waterhouse et al. (2000)
Summer precipitation	June moisture reconstructions Moisture summers during the early millennium and dry summers during the late millennium, twentieth century warm and moist	*P. sylvestris* L.	Edwards et al. (2017)
$\delta^{18}O$			
Summer temperature	Increasing Siberian thaw permafrost depth Link with summer temperature	*L. sibirica* Ledeb, *P. sylvestris* L.	Sidorova et al. (2012), Churakova (Sidorova) et al. (2016, 2019, 2020), Naulier et al. (2015), Porter et al. (2014), Hilasvuori et al. (2009)
Sunshine duration	Recent period becomes sunnier compared to the past century	*L. cajanderi* Mayr;	Churakova (Sidorova) et al. (2019)
Arctic Oscillation	Teleconnection via winter-spring and summer precipitation. Reduction of summer precipitation, triggered by a positive phase of the Arctic Oscillation in May	*L. gmelinii* Rupr	Sidorova et al. (2010), Churakova (Sidorova) et al. (2019, 2021b)

(continued)

Table 20.1 (continued)

Proxy	Outcome	Tree species	References
$\delta^{13}C$ and $\delta^{18}O$			
Mixed signal in spring, summer temperature and precipitation, vapor pressure deficit	Increasing spring and summer temperatures, decreasing July precipitation Increasing drought, limited access to nutrients suggest CO_2 saturation of Siberian larch trees Vegetation period becomes drier in the second half of the twentieth century and the beginning of the twenty-first century due to decreased precipitation. Vegetation period shifted to an earlier date in the course of the last century	*L. gmelinii* Rupr; *P. glauca* *L. sibirica* Ledeb	Sidorova et al. (2009), Knorre et al. (2010), Bryukhanova et al. (2015), Tartakovsky et al. (2012), Holzkämper et al. (2008)
Arctic Oscillation	Teleconnection via precipitation patterns	*L. cajanderi* Mayr; *L. gmelinii* Rupr; *P. sylvestris* L.	Sidorova et al. (2010), Young et al. (2012), Churakova (Sidorova) et al. (2021a)
Relative air humidity, winter temperature and precipitation	Reconstructed relative air humidity reflected the predominating influence of stomatal conductance on carbon-isotope discrimination, while reconstructed winter temperature reflected separation of the $\Delta^{18}O$ record into ΔT-and ΔRH-dependent signals of similar magnitude. High growth season humidity persisted from AD 1900 compared to the Little Ice Age	*P. engelmannii* *P. albicaulus* *L. gmelinii Rupr*	Edwards et al. (2008)

(continued)

Table 20.1 (continued)

Proxy	Outcome	Tree species	References
δ^2H and $\delta^{18}O$			
Cloud cover, temperature, precipitation, relative humidity	The strongest relationship ($r = 0.70$, $P < 0.001$) was observed between $\delta^{18}O$ and cloud cover, yet, r values for $\delta^{18}O$, δ^2H and temperature,$\delta^{18}O$, δ^2H and precipitation, all exceeded 0.5 and were statistically highly significant for the oak tree-ring chronologies from southern Finland Reconstructing relative humidity from plant $\delta^{18}O$ and δ^2H as deuterium deviations from the global meteoric water line	*Quercus robur* L. *P. sylvestris* L. *Quercus macrocarpa* *Q. robur* *Pseudotsuga menziesii*	Hilasvuori (2011), Voelker et al. (2014)

of active layer thaw on soil water availability and plant gas exchange, and on the isotope composition of soil water. The freezing process itself induces a soil water fractionation during the autumn freeze-back period (Lacelle 2011). In a closed system with converging freezing fronts extending downward from the surface and upward from the permafrost table, soil water fractionation is expected to obey Rayleigh distillation principles, with the most enriched ice forming first (i.e., near the surface and at the permafrost table) and progressively more ^{18}O-depleted ice as the two freezing fronts converge roughly at the mid-point of the active layer (Lacelle 2011). This process, therefore, can lead to isotopic stratification of soil water with depth, which has potential implications for the mean isotopic composition of soil water used by trees in the early growing season.

The oxygen isotopic signal in tree-rings of trees growing on permafrost is also masked by the supply of isotopically depleted water from melted frozen soil leading to ‘inverse’ climate to tree-ring isotope relationship, as dry and warm summer conditions result in lower soil, root and wood in $\delta^{18}O$ values (Sugimoto et al. 2002; Saurer et al. 2002, 2016).

A further complication of the isotope composition in tree-rings within the permafrost zone is caused by the impact of forest fires. Wildfires lead to significant changes in active soil layer depth and seasonal dynamics, with potentially long-term consequences for carbon, nutrient and water balance of the ecosystem (Sidorova et al. 2009; Kirdyanov et al. 2020). As both water and nutrient supply for plants predominantly depend on the freeze–thaw processes in the active soil layer (Zhang et al. 2000; Prokushkin et al. 2018), the wildfire-induced changes in isotopic composition of the source water and water availability for trees as well as changes in photosynthesis rate are recorded in tree-ring carbon and oxygen isotopes.

20.2.3 Climate

The major advantage in studying northern forests is their distance to populated regions, allowing the study of tree responses to environmental changes without anthropogenic disturbances. A major disadvantage is the difficult accessibility, especially in northeastern Siberia, and the scarcity of weather stations. Yet, seasonal continuous measurements of climatic parameters are needed for future ecophysiological studies. Gridded large-scale climate data (CRU TS 4.02, $0.5° \times 0.5°$) (New et al. 2002; Harris et al. 2014) can help filling the gaps in the climate data. Gridded temperature and precipitation data are an important source of information to quantify climate reconstructions during the last decade and further back in time (first half of twentieth century). Several studies on stable isotope tree-ring cellulose chronologies for the boreal zone showed good correspondence with temperature signals from both, local weather stations and gridded data (http://climexp.knmi.nl) back in time (>100 years) (Sidorova et al. 2010; Churakova (Sidorova) et al. 2019). However, precipitation signals are better recorded by the local weather stations at the local scale compared to the gridded averaged data at the regional scale.

Sunshine duration and cloud cover are distributed heterogeneously across boreal regions. In summer, light duration lasts longer at high-latitudes than at the southern taiga and forest steppe zone (Young et al. 2012; Gagen et al. 2016; Churakova (Sidorova) et al. 2019).

Depending on the site location and impact of environmental parameters, conifer trees in the boreal zone can adapt to extremely low annual temperatures (−19.2 °C in northeastern Yakutia, data from the local Chokurdach weather station for the period from 1961 to 1990). The climate data obtained from the local weather stations (direct measurements) represent a wide range of minimum and maximum temperature extremes (e.g., −60 °C in Yakutia to +45 °C in Khakassia, Russian Federation). The amount of annual precipitation varies from 236 to 310 mm in northeastern Siberia and Northern America, respectively (Fig. 20.1b) to 502 mm towards Baikalskii ridge (Russian Federation), and further double increases to 1353 mm towards Norway's northeastern coastline.

20.3 Stable Carbon ($\delta^{13}C$) Isotopes

20.3.1 Isotope Ecophysiology

Application of stable carbon isotopes in tree-ring studies for the boreal zone has increased over the past decades because these proxies record information not only about temperature (Knorre et al. 2010; Sidorova et al. 2008, 2009, 2013a, b), but also about moisture changes (Kirdyanov et al. 2008; Sidorova et al. 2010; Tartakovsky et al. 2012; Churakova (Sidorova) et al. 2019, 2020, 2021b), as well as changes in sunshine duration/cloudiness (Young et al. 2012; Loader et al. 2013; Helama et al. 2018) (Table 20.1). Moreover, carbon isotope chronologies in tree-rings also captured signals of atmospheric circulation patterns (Saurer et al. 2004; Sidorova et al. 2010; Gagen et al. 2016) and facilitated the reconstruction of the river flow in Siberia (Waterhouse et al. 2000).

Climatic parameters like temperature, water availability, air humidity and vapor pressure deficit, and the impact of changes in ambient CO_2 concentration on photosynthetic CO_2 assimilation and water balance are reflected in the $\delta^{13}C$ values of plant organic matter and provide an isotopic fingerprint in the wood of tree rings (see Chap. 9). The analysis of tree physiological properties using carbon isotope ratios is particularly useful when combined with a photosynthesis model. This facilitates the functional attribution of meteorological impacts to plant responses, such as stomatal and substomatal conductance vs. ambient CO_2 concentrations (c_i/c_a ratio) (Farquhar and Lloyd 1989). Detailed insight into physiology (see Chap. 9) and resource distribution during tree-ring formation (see Chaps. 3, 13 and 15) may also be obtained through ^{13}C-labeling experiments (Kagawa et al. 2006a, b; Masyagina et al. 2016).

20.3.2 Seasonal Variability

Short growing season (up to 90 days in far North) and harsh climatic conditions of the boreal zone result in low tree stem increment (Vaganov et al. 2006). Compared to temperate trees with wider rings (Leavitt 1993), boreal trees might show a slower carbon turnover rate (Kagawa et al. 2006b). The highly resolved intra-annual measurements of $\delta^{13}C$ within tree rings (earlywood/latewood or laser ablation with the step of 80–200 μm, see Chap. 7) helped to link changes in physiological and metabolic processes and, as a result, tree-ring growth and xylem anatomical structure associated to seasonal climatic variability.

Deciduous and evergreen angiosperms and gymnosperms depend on stored carbohydrates during their first stages of leaves/wood development (Ericsson 1979).

Boreal deciduous (*Betula pubescens* Ehrh., *Populus tremula* L.), conifer deciduous (*Larix gmelinii* (Rupr.) Rupr.) and conifer evergreen species (*Pinus sylvestris* L., *Picea obovata* Ledeb., *Picea abies* (L.) H. Karst.) were used to identify the physiological principle of climate responses related to the phenology and structural–functional features of wood. Intra-annual $\delta^{13}C$ tree-ring analysis of gymnosperm and angiosperm species in Scandinavia (Vaganov et al. 2009), central and eastern Siberia (Kagawa et al. 2006b; Bryukhanova et al. 2011; Rinne et al. 2015; Fonti et al. 2018) and southern Siberia (Voronin et al. 2012) have shown that not only the temperature, but also soil moisture and rainfall might affect the dynamics of $\delta^{13}C$ in tree rings. In particular, $\delta^{13}C$ in latewood of *L. gmelinii* in Yakutia was reported to show better correlations with the growing season precipitation and soil water conditions than $\delta^{13}C$ in earlywood (Kagawa et al. 2003). Variability of tree-ring width and $\delta^{13}C$ under climatic conditions of extreme years in central Siberia indicated that an increased spring temperature initially led to an increase of tree growth. However, due to an increased use of water through transpiration, tree growth could be progressively reduced from temperature to moisture limitation.

To determine the extent to which trees rely on stored carbohydrates from previous years for tree-ring formation and how strongly the current photosynthates were used, the intra-annual $\delta^{13}C$ variability was measured. Samples from *Larix gmelinii* (Rupr.) from two Siberian sites with a different hydro-thermal regime of permafrost soils were analyzed using (a) $\delta^{13}C$-labeling (Kagawa et al. 2006b) and (b) laser ablation coupled to the Compound-Specific Isotope Analysis (CSIA) (Rinne et al. 2015). Kagawa et al. (2006b) showed that latewood in *Larix gmelinii* Rupr. was mainly formed from current-year photoassimilates with minimal carry-over effect of carbohydrates from the previous year, while the early wood is produced from a mixture of current-year photoassimilates and previous-year carbohydrates. In *P. sylvestris* from the same site, $\delta^{13}C$ values of early wood were significantly correlated with the previous year late wood ($r = 0.42$; $P < 0.01$) in a 100-year $\delta^{13}C$ chronology, which is evidence of a carry-over effect. In contrast, Rinne et al. (2015) provided the evidence of a minimal carry-over effect of photosynthates formed during the previous year(s). The combination of different methods, such as CSIA and intra-annual tree-ring isotope analyses will enhance a further mechanistic understanding of the carbon–water relationships within ecosystems, in particular, for the interpretation of retrospective tree-ring analyses (Rinne et al. 2015).

20.3.3 Annual and Decadal Carbon Isotope Variability Over Past 100 Years

The mean $\delta^{13}C$ value in tree-ring cellulose chronologies from Fennoscandia, Yakutia, the high-elevated mountain range in Khibini (Kola Peninsula) and the Altai Mountain range, analysed for the period from 1900 to 1998, showed mean values of $-24‰$. These earlier published chronologies indicated wetter conditions for these sites in the boreal zone compared to the drier northeastern and central sites of Eurasia and Alaska. Based on the available $\delta^{13}C$ tree-ring cellulose chronologies from the southern part

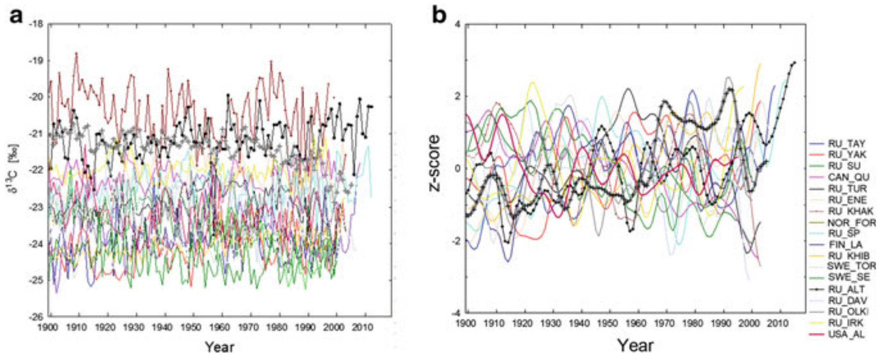

Fig. 20.2 Annual (**a**) and smoothed by a 11-year Hamming window (**b**) $\delta^{13}C$ tree-ring cellulose chronologies obtained from conifer tree species from the boreal zone (for details see supplementary Table S20.1)

(Khakasia, Russian Federation) of the boreal zone, reduced soil moisture availability is reflected by mean $\delta^{13}C$ values of −20.4‰ (Fig. 20.2a).

The $\delta^{13}C$ in tree-ring cellulose chronologies (standardised to z-score) smoothed by a 11-year Hamming window show a general significant increasing trend over the recent decades for all, except for a few sites in northern Eurasia: Davan Pass (Tartakovsky et al. 2012), Khakasia forest steppe (Knorre et al. 2010), Tura (Sidorova et al. 2009) as well as Alaska (Barber et al. 2000), Canada (Porter et al. 2009) and Sweden, Torneträsk (Loader et al. 2013) (Fig. 20.2b).

These decreasing $\delta^{13}C$ trends in tree-ring cellulose chronologies towards recent century from permafrost sites over the past decades were explained as an earlier beginning of the vegetation period in spring and increased use of residual soil carried over from autumn of the previous year (Sidorova et al. 2009; Knorre et al. 2010). Another reason, e.g., physiological effect of increasing atmospheric CO_2, is also responsible for lower $\delta^{13}C$ values. Thus, an earlier start of the vegetation period could lead to tree-ring formation during a period with higher water availability, resulting in stronger isotopic fractionation and ^{13}C depletion (Knorre et al. 2010).

20.4 Stable Oxygen ($\delta^{18}O$) Isotopes

20.4.1 Isotope Ecophysiology

Oxygen isotopes in organic matter are modified by variation in the isotopic composition of source water, which is closely related to that of precipitation and soil water (though modified by evaporation at the soil surface). The $\delta^{18}O$ of meteoric water is directly related to cloud/atmosphere air temperatures (Dansgaard 1964) as well as evaporation and condensation processes in the global water cycle. This is especially true in northern high-latitudes, as has been demonstrated at broad spatial scales across the North American arctic and subarctic based on precipitation isotope data from the Global Network of Isotopes in Precipitation (Porter et al. 2016). An earlier study by Saurer et al. (2002) also showed that average isotope values of 130 trees of a widely distributed genus (*Larix, Picea, Pinus*) within the Eurasian subarctic from Norway to Siberia are highly correlated with the modeled isotope distribution of precipitation showing a large east-to-west gradient (see Chap. 18). Input waters are modified (enrichment in ^{18}O) in the leaf during transpiration, which is imprinted on photosynthates and cellulose through biochemical fractionation and exchange processes. In Siberia, the inter-annual variability of winter precipitation $\delta^{18}O$ is closely related to temperature variability and the North Atlantic Oscillation, while the variability of summer $\delta^{18}O$ appears to be dominated by regional processes involving evaporation and convection (Butzin et al. 2014). Therefore, $\delta^{18}O$ values of tree rings reflect, as a first approximation, average ambient temperatures and humidity. Progress has been made in understanding the fractionation processes, where $H_2{}^{18}O$-molecule goes from soil water to tree-ring cellulose (Craig and Gordon 1965; Dongmann et al. 1974; Farquhar and Lloyd 1989; Roden et al. 2000). These models have been validated with experimental data from deciduous and coniferous tree species. A detailed description of the leaf water enrichment processes is given in Chap. 10.

20.4.2 Seasonal Variability

The highly complex hydrological regime of boreal forests is given by a strong sinusoidal seasonal course of $\delta^{18}O$ imprinted in precipitation water, reflecting the cloud condensation temperatures. Winter precipitation uptake is only possible in the warming spring and summer months after snow melt and active layer thaw. This explains the often good correlation between tree-ring $\delta^{18}O$ values and winter temperature, when this fraction of the annual precipitation becomes available for trees (Sidorova et al. 2010). Oxygen isotopes are then incorporated and become visible in the tree rings. As described in part Sect. 20.2.1 of this chapter the hydrology of forests growing under permafrost conditions, only a shallow layer of soil thaws in summer, each soil layer with its own $\delta^{18}O$ of soil water. This variation of seasonal $\delta^{18}O$ from permafrost water must be taken into account for the evaluation of tree-ring chronologies. It is therefore not surprising that only few studies about the seasonal $\delta^{18}O$ fluctuations in wood are available for the boreal zone, i.e. southern Siberia (Voronin et al. 2012) and central Siberia (Saurer et al. 2016).

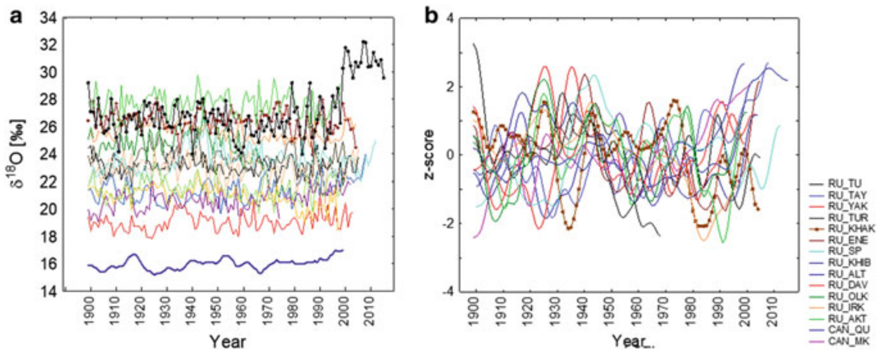

Fig. 20.3 Annual (**a**) and smoothed by a 11-year Hamming window (**b**) $\delta^{18}O$ tree-ring cellulose chronologies obtained from conifer tree species from the boreal zone

20.4.3 Annual and Decadal Oxygen Isotope Variability Over Past 100 Years

Annual $\delta^{18}O$ values in tree-ring cellulose chronologies (Fig. 20.3) showed clear isotopic differences from the coldest sites in northeastern Yakutia (19.0‰) (Sidorova et al. 2008) and Canada (19.1‰) (Porter et al. 2009) towards warmest sites in Russian Altai (up to 27.7‰) (Loader et al. 2010; Sidorova et al. 2012, 2013a, b) and Khakassia (26.4‰) (Knorre et al. 2010). A 5-year block $\delta^{18}O$ tree-ring cellulose chronology of black spruce trees (*Picea mariana* [Mill] B.S.P) from the Québec–Labrador peninsula, northeastern Canada (Naulier et al. 2015) showed the lowest isotopic value (16‰) compared to all other reviewed sites (Fig. 20.3a).

A decreasing $\delta^{18}O$ trend was detected in the early 1900's between 11-year smoothed $\delta^{18}O$ tree-ring cellulose isotope chronologies from Tura site (TUR) (Sidorova et al. 2009) and Canadian site Mackenzie Delta (Porter et al. 2009, 2014). This discrepancy can be explained by cold conditions in Canada compared to warmer periods at Siberian Tura site. Almost all $\delta^{18}O$ values in tree-ring cellulose chronologies showed increasing temperature trends towards the end of the twentieth century, except for the Siberian sites in Yakutsk (Spasskaya Pyad) (Tei et al. 2013) and Khakassia (Knorre et al. 2010) (Fig. 20.3). Decreasing $\delta^{18}O$ values in tree-ring cellulose chronologies can be explained by ^{18}O depleted water from autumn precipitation of the previous year absorbed by the tree rings (Sidorova et al. 2009; Knorre et al. 2010).

The combination of tree-ring and stable isotope parameters (e.g., tree-ring width, cell wall thickness, maximum late wood density, Sidorova et al. 2010, 2012; Churakova (Sidorova) et al. 2019) enhances the strength of our interpretations and need to be pursued where possible.

20.5 Stable Hydrogen (δ^2H) Isotopes

As the oxygen and hydrogen isotopic composition of precipitation was already recognized to be related to temperature (Dansgaard 1964), early work on oxygen and hydrogen in plant material was conducted with the aim of using tree rings as an isotopic thermometer. Although the fractionation mechanisms in leaf water are the same for δ^2H as for $\delta^{18}O$, the incorporation of hydrogen follows a different metabolic pathway. Therefore, correlation analyses with tree-ring hydrogen isotope time series and annual temperature records have been less successful (Epstein et al. 1976; Waterhouse et al. 2002; Augusti et al. 2006). Most recent studies by Voelker et al. (2014) showed potential for reconstruction of relative humidity from plant δ^2H and $\delta^{18}O$ as deuterium deviations from the global meteoric water line (GMWL).

The analysis of δ^2H in tree-rings is still in an explorative stage (Kimak and Leuenberger 2015; Cormier et al. 2019; Lehman et al. 2021; Churakova (Sidorova) et al. 2021a; Schuler et al. 2022), but the application of the dual stable isotope approach ($\delta^{18}O$ and δ^2H) in tree-ring analyses is promising and will strengthen our future isotope interpretation. Chapter 11 discusses the principles of δ^2H in tree rings in detail.

20.6 Conclusion and Outlook

Carbon isotopes proved to be a reliable proxy for spring and summer temperature, vapor pressure deficit, sunshine duration/cloud cover and soil moisture changes. Oxygen isotopes were not only a temperature proxy but also an indicator for air humidity and water origin, showing also teleconnection with Arctic Oscillation via precipitation patterns. A mixed temperature and precipitation signal is mainly recorded for subarctic regions, covered by permafrost (Chap. 18).

The dual carbon and oxygen isotope approach is highly recommended for the interpretation of stable isotope chronologies from the boreal forest due to often mixed signals recorded in tree rings and the complex hydrology, which can be analyzed best by using dual or even triple isotopes ($\delta^{13}C$, $\delta^{18}O$, δ^2H).

Based on the available stable carbon and oxygen isotope data sets across the boreal forest zone, we conclude that trees from western and central regions of Eurasia, Alaska and Canada are exposed to drought conditions, while no strong evidence for drought is observed at the northeastern and eastern sites of the Eurasian subarctic.

There are only few nitrogen isotope measurements in tree tissues, mainly in needles of conifer trees (Mack et al. 2004; Prokushkin et al. 2018) and in soil samples, e.g., northern Sweden (Högberg et al. 2006). So far, no data is available for $\delta^{15}N$ in tree-ring chronologies from the boreal zone, because no strong $\delta^{15}N$ signal in tree rings was found.

Trees growing at the circumpolar zone are a valuable archive and monitoring system for information not only about temperature but also about currently ongoing hydrological changes. A multi-proxy approach as a combination of stable isotopes and tree-ring parameters, new approaches (intra annual tree-ring analyses, δ^2H and CSIA), and eco-physiological modelling ($\delta^{13}C$, $\delta^{18}O$, δ^2H) will strengthen our interpretations and improve the quality of available climate reconstructions with annual time resolution.

Acknowledgements This work was supported by the *Russian Science Foundation (RSF) (project 21-17-00006) granted to O.C. (S.)* and *(project* 19-14-00028) granted to V.M.

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