Measured and modelled source water δ\(^{18}\)O based on tree-ring cellulose of larch and pine trees from the permafrost zone

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To identify source water for trees growing on permafrost in Siberia, we applied mechanistic models that quantify physical and biochemical fractionation processes, leading to oxygen isotope variation (δ\(^{18}\)O) in plant organic matter. These models allowed us to investigate the influence of a variety of climatic factors on tree-ring cellulose from two dominant species: *Larix cajanderi* Mayr. from northeastern Yakutia (69° 22' N, 148° 25' E, - 250 m a.s.l.) and *Pinus sylvestris* L. from Central Yakutia (62° 14' N, 129° 37' E, - 220 m a.s.l.). The climate of the region is highly continental with short growing seasons, low amount of precipitation and these forest ecosystems are growing on permafrost, which in turn impact the water cycle and climate variation in the δ\(^{18}\)O of source water. We compared outputs of the Land surface Processes and exchanges (LPX-Bern v. 1.3), and Roden-Lin-Ehleringer (RLE) models for the common period from 1945 to 2004. Based on our findings, trees from northeastern and central Yakutia may have access to additional thawed permafrost water during dry summer periods. Owing to differences in the soil structure, active thaw soil depth and root systems of trees at two Siberian sites, *Larix cajanderi* Mayr. trees can access water not more than from 50 cm depth, in contrast to *Pinus sylvestris* L. in Central Yakutia which can acquire water from up to 80 cm soil depth. The results enhance our understanding of the growth and survival of the trees in this extreme environment.

**Keywords:** Conifers, Climate, Drought, Permafrost Thaw Depth, Siberia, δ\(^{18}\)O of Source Water

**Introduction**

Modern climatic changes are leading to significant air temperature increase in the Eurasian subarctic at even faster rates compared to the global average (Overland et al. 2018, Fischer et al. 2018). Siberian forests respond to both the timing and magnitude of changes in soil moisture as well as to soil temperature, permafrost thickness and distribution, which is in turn affected by snow and vegetation cover, soil texture and geothermal heat flux as well as atmospheric dryness (Cable et al. 2014, Boike et al. 2013, Churakova-Sidorova et al. 2019, Kropp et al. 2019). Therefore, the fate of trees growing on permafrost undergoing climatic changes is of great interest, owing to the important role of permafrost in these ecosystems: (i) as additional water source (Sugimoto et al. 2002, Cable et al. 2014, Churakova-Sidorova et al. 2016a, Young-Robertson et al. 2017) for trees during droughts; and (ii) for the large amounts of carbon stored in these soils, which essentially contribute to the global carbon and water budget (Cable et al. 2014).

Increasing temperatures at higher latitudes, especially in areas with low precipitation inputs such as parts of Yakutia (200-250 mm year\(^{-1}\)), enhance the risks of tree decline and mortality in boreal forests (Sidorova et al. 2010, Boike et al. 2013, Churakova-Sidorova et al. 2016a, Timofeeva 2017). A number of studies report a pronounced increase of seasonal permafrost thaw depth in western Siberia (Sugimoto et al. 2002, Melnikov et al. 2004, Pavlov et al. 2004, Fyodorov-Davydov et al. 2008). Sugimoto et al. (2002) reported, that the active soil layer depth at the central Yakutia can reach up to 1.4 m making thawed permafrost water available for *Larix gmelinii* Rupr. Moreover, the authors demonstrated that during wet summers in central Yakutia *Larix gmelinii* Rupr. can use rain water, while thawed permafrost water can be used by trees mainly during drought summers. Fyodorov-Davydov et al. (2008) investigated the spatial and temporal trends in active soil layer for northern Yakutia and its relation to landscape and climate variables. The soil layer thaws during June-August and freezes again in autumn, defying the length of the short growing season. The few studies in Siberian regions show significant differences between sites in hydrological and geomorphological characteristics, which should be taken into account. To our knowledge, there are no direct seasonal or long-term measurements of the thawing depth of the active soil layer for northeastern Yakutia, which is the driest forested area in the world. Precipitation and thawed permafrost water are particularly crucial for trees growing in this region with severe temperature limitations and low amounts of precipitation (Arnett...
et al. 2002, Sidorova et al. 2008, 2010).

Based on isotopic differences between precipitation and permafrost, variations of stable oxygen isotopes (δ¹⁸O) may help to reveal water relations in deep-rooted plants (Saurer et al. 2016). Oxygen isotopes in plant organic matter are influenced by variations in the isotopic composition of the water source, which is closely related to the precipitation and soil water (after modification by evaporation at the soil surface and due to the shallow active layer depth). In this study, we aim to determine the source water of Larix cajanderi Mayr. and Pinus sylvestris L. trees from the Siberian subarctic using measured and modeled δ¹⁸O variation in annual tree-ring cellulose at two contrasting study sites (northeastern and central Yakutia).

Materials and Methods

Study sites

Both study sites are located in the broad permafrost zone in northeastern Siberia: in northeastern Yakutia (NE – 69°22’ N, 148°25’ E – 250 m a.s.l.) and Central Yakutia (CE – 62°14’ N, 129°37’ E – 220 m a.s.l.) in Russia.

The mean winter temperatures (December-February) averaged for the period from 1948 to 2004 are -36 °C and -38 °C and in summer (June-July) +12 °C and +19 °C for NE and CE, respectively. However, minimum temperature range during winter can vary between -38 °C and -46 °C, while maximum day time summer temperatures range from +27 °C to +42 °C. Larix cajanderi Mayr. and Pinus sylvvestris L. trees are the dominant tree species in NE and CE respectively. The growing period is rather short for trees at both sites and lasts around 60 days (Abaimov et al. 1997).

Low precipitation inputs are typical for both regions (200-250 mm year⁻¹) and most of the precipitation falls in summer. The main difference between the two sites are soil conditions. Larix cajanderi Mayr. trees in NE are mainly growing on stones, rocks and mixtures of clay (Sidorova et al. 2008), while Pinus sylvestris L. in CE are growing on mixtures of sand and clay soils (Nikolaev 2003). The root system is also different between these species as they adapt to site-specific edaphic conditions. Larix cajanderi Mayr. roots are shallower than those of Pinus sylvestris L., which tend to be slightly deeper and more extensive in spread.

Local climate data

To drivers the δ¹⁸O variation in tree-ring cellulose for measured and modeled datasets, we used daily maximum and minimum temperature, daily precipitation and daily relative humidity data from the Chokurdach weather station (70°30’ N, 148°08’ E – 250-300 m a.s.l.) located close to the north-eastern site (NE) for the period from 1948 to 2004. For Central Yakutia (CE) we used data from the weather station in Yakutsk (62°02’ N, 129°44’ E – 220 m a.s.l.) for the period from 1966 to 2004.

Annual δ¹⁸O in tree-ring cellulose chronologies

As a reference, we used δ¹⁸O values of Larix cajanderi Mayr. cellulose chronologies, which were constructed based on individually analysed annual tree rings from four trees from the NE site (Sidorova et al. 2008) for the period from 1880 to 2004 and from five trees for the period from 1900 to 2013 from the CE sites (Timefroeva 2017). These measured δ¹⁸O chronologies were used for comparative analyses with the LPX-Bern modeled data of the source water, δ¹⁸O of cellulose, and thaw depths for the common period (from 1901 to 2004) for both sites.

Cellulose samples from both study sites (NE and CE) were measured at the Stable Isotope Research Facility of the Paul Scherrer Institute (Villigen, Switzerland). For measurements of the oxygen isotope ratios from NE, cellulose samples were pyrolyzed to CO at 1080 °C (Saurer et al. 2016) using RLE model and from CE at 1420 °C (Elementar, Germany). The CE samples were pyrolyzed using PYRO-cube® at 1420 °C (Elementar, Hanau, Germany) and analyzed with a Delta Plus XL® Mass spectrometer (Thermo Finnigan, Bremen, Germany).

Leaf water is xylem water and leaf water (δ¹⁸Olx) was modeled as a function of both the isotopic ratio of the source substrate and the temperature dependent enrichment fractionation of evaporation (Δ 27‰ -28 to -25‰), assuming a 42% enrichment fractionation of evaporation from source (Fan et al. 2018). The δ¹⁸Olx of xylem cellulose (δ¹⁸Ocx) was predicted as a function of both the isotopic ratio of the substrate source and of the medium water at the site of cellulose synthesis, root, or xylem as part of the treering (Roden et al. 2000). The δ¹⁸O in tree-ring cellulose is calculated as (eqn. 2):
Simulating δ18O in LPX Bern

The Land surface Processes and eXanges (LPX-Bern v. 1.3) model (Keller et al. 2012) is a dynamic global vegetation model and features a process-based representation of the coupled terrestrial nitrogen, carbon and water cycle. Here only a natural vegetation, consisting of ten Plant Functional Types (PFTs) competing for resources and confined by bioclimatic limits, is considered. The δ18O isotope enabled version of the LPX-Bern model is introduced and discussed in detail by Keel et al. (2016), which helps to reduce uncertainties in the interpretation of raw measured δ18O chronologies for investigating different temporal scales of the oxygen isotope patterns in tree rings. The δ18O_int (stem cellulose isotope composition) was calculated based on eqn. 3.

The δ18O_int is calculated according to eqn. 3, but modified by including the Péclet effect (Farquhar & Lloyd 1993) using the modeled rate of transpiration (eqn. 5):

$$\delta^{18}O_{\text{int}} = \delta^{18}O_{\text{source}} + (\delta^{18}O_{\text{Péclet}} - \delta^{18}O_{\text{source}}) \cdot (1 - e^{-D/\lambda})/\lambda$$

where P = EL/CD; L is mixing path length (m); E is the rate of transpiration (mol m⁻² s⁻¹); C is the concentration of water 5.55 · 10⁻¹⁰ mol m⁻³; D is the diffusivity of H₂O in water 2.66 · 10⁻⁵ m² s⁻¹; P is the Péclet number (Ikedda 1983); δ18O_Péclet is the Péclet corrected leaf water enrichment; δ18O_int is the enrichment of the leaf water at the surface of evaporation.

In this study, the model runs for both study sites with a single grid cell configuration from 1901 to 2004. Monthly temperature, precipitation, cloud cover and number of wet days data are extracted from the 0.5° latitude/longitude grid cells closest to the study cells locations of the global CRU-TS3.22 climate dataset (Harris et al. 2014). Internally, the meteorological data are interpolated to a daily time-step, except for precipitation, where a stochastic weather generator is applied to compute daily precipitation according to Gerten et al. (2004). The temperature and precipitation data correspond well (r = 0.96; p < 0.05) with the local weather stations (see above) from 1966 to 2004. Similarly, nitrogen deposition is supplied to the model (Lamarque et al. 2013). Furthermore, the oxygen module requires input values for the δ18O of soil water and water vapor, as well as relative humidity data, which are extracted from global transient isotope-enabled simulations of the coupled atmosphere-land surface model ECHAM5-JS Bach (Haese et al. 2013). Since the simulation only spans the period 1960-2012, earlier years are approximated by the values of the year 1960. Identiﬁcal atmospheric CO₂ concentrations are prescribed to both study sites from a global reconstruction (Etheridge et al. 1998, Francey et al. 1999, MacFarling Meure et al. 2006).

The LPX-Bern δ18O simulations are useful for investigating different temporal scales of the oxygen isotope patterns in tree-ring, which help to reduce uncertainties in the interpretation of raw measured δ18O chronologies.

Climatological and statistical analyses

Pearson correlation coefﬁcients were calculated between local weather station data and the CRU-TS3.22 climate dataset were calculated (Harris et al. 2014). Statistical calculations were performed in licensed version of the software Statistica® v. 13.3 (StatSoft, Tulsa, OK, USA).

Results

Modeled and measured δ18O tree-ring cellulose data

Using the LPX-Bern (Keel et al. 2016) and RLE (Rodén et al. 2000) models, we obtained modeled δ18O tree-ring cellulose values for the NE (Fig. 1a) and CE (Fig. 1b) study sites in Yakutia.

Modeled LPX-Bern thaw depth varied much stronger for the NE site (in the range 50-100 cm) compared to the modeled soil depth at the CE site (50-70 cm). Modeled values and data for δ18O in cellulose agree in so far that the tree-ring cellulose is more depleted in the heavier 18O isotope at the NE site than at the CE.

Measured δ18O data from the NE and CE are signiﬁcantly correlated with RLE (r = 0.92 and r = 0.74, p < 0.05) and LPX-Bern (r = 0.59 and r = 0.46, p < 0.05), respectively for both studied regions. On average the offset between modeled RLE and measured δ18O data for both NE and CE is low (less than 1‰).

The LPX-Bern modeled thaw depth (maximum values) correlates signiﬁcantly (r = -0.29, p < 0.05) with measured NE δ18O data only. The δ18O measured data from the NE and CE correlated signiﬁcantly between each other (r = 0.20, p < 0.05) for the common period from 1901 to 2004, although

Fig. 1 - The δ18O in tree-ring cellulose measured and modeled using LPX-Bern and RLE models. Modeled thaw depth as output parameter of the LPX model is presented for the (a) northeastern (NE) and (b) Central (CE) sites in Yakutia. Maximal seasonal thaw depth (LPX-TD_max) simulated by LPX-Bern model is presented in black lines for both sites (a, b).
The δ¹⁸O leaf water in the RLE is calculated based on the isotopic composition of leaf water at the site of evaporation, which is not the same as bulk leaf water due to the contribution of non-evaporative vein water and tissues (Yakir et al. 1993) and the “Péclet effect” (Farquhar & Lloyd 1993, which describe the convective/diffusive mixing between evaporatively enriched and un-enriched source water from the xylem).

A strong increase in estimated isotopic composition of the source water after the 1990s for NE was revealed, while an overall declining trend for CE was found (Fig. 2). Correlation coefficients between source water δ¹⁸O and July precipitation were significant at NE ($r = -0.27, p < 0.05$) and for May precipitation ($r = -0.28, p < 0.05$) at the CE site. However, the negative correlation with July precipitation was weak.

A decrease in July precipitation at the NE site was detected after the year 2000, which is consistent with the modeled δ¹⁸O source water values.

**Discussion and conclusion**

Simulations of thawing depth and δ¹⁸O values in tree-ring cellulose, using the output of the RLE model as a proxy for source water over time, indicate that thawed permafrost water is available for trees from NE in addition to precipitation water. Based on this analysis we conclude that thawed permafrost water could be an important water source for trees, especially for periods when the amount of precipitation is lower than the evaporative water loss. Our model simulation is in line with earlier findings by Sugimoto et al. (2002) for the central part of Yakutia, confirming that trees from the CE could use thawed permafrost water during dry events. Yet the question remains whether *Larix cajanderi* Mayr. from the NE site can utilize thawed permafrost water. There was also an indication of source water enrichment (¹⁸O) increased over time. This could be caused by rising temperatures resulting in higher evapotranspiration due to higher vapor pressure deficit (VPD) during drought conditions (Yuan et al. 2019), but may also be the result of a diminishing influence of thawed permafrost water, which has a more negative isotope ratio than rain water (Saurer et al. 2016).

Precipitation or snowmelt can be stored in soils or lost as run off, depending on permafrost depth. Source water for *Pinus sylvestris* L. trees from the CE site did not indicate a strong increase of thawed permafrost use as an additional water source as it was found at the NE. Opposite to the NE, trees from the CE have limited water availability caused by drought conditions in this area.

Our study showed that trees from NE and CE might have access to additional thawed permafrost water during dry summer periods, which is in line with the study by Sugimoto et al. 2002. Due to differences in the soil structure, active thaw soil depth and root systems of trees at two Siberian sites, *Larix cajanderi* Mayr. trees cannot access water deeper than 50 cm, while *Pinus sylvestris* L. in Central Yakutia can access water as deep as 80 cm. This is opposite to the finding of Sugimoto et al. (2002), who showed possible water access up to 1.4 m. These differences can be explained by different soil structures (sand in central Yakutia and rocks in northeastern Yakutia) as well as with species-specific rooting distributions, resulting in different rooting depths. Thus, trees have different access to water sources depending on their root distribution, i.e., surface rooting system (*Larix cajanderi* Mayr.) vs. roots proliferated to deeper soil layers (*Pinus sylvestris* L. – Sidorova et al. 2008, Körner 2012, Churakova-Sidorova et al. 2016b, Saurer et al. 2016, Kropp et al. 2019).

We could show that the application of different oxygen isotope models (Keel et al. 2016, Roden et al. 2000) helps to reveal the impact of important hydro-climatic factors such as the interplay between water sources, e.g., precipitation, soil moisture and frozen soil water and soil thawing depth, influencing tree-growth and physiology in an ecosystem under permafrost conditions. The discrepancies between modeled and measured data are in part due to different parameterizations, but more so due to different model designs for different scales, from whole plant to ecosystems. So far, direct seasonal measurement...
for the thawed permafrost depth or measurement for stomatal conductance at the remote study site, like NE are rare due to the harsh climatic conditions leading to costly and complex fieldwork at this region. Therefore, the modeling approach can be a powerful tool for the investigation of the influence of a variety of climatic factors on Siberian forest ecosystem water relations that impact on isotope fractionations in tree-ring cellulose from remote Siberian sites. Furthermore, we must keep in mind that the heterogeneous soil structure will result in a great variation of δ18O values of the xylem water, especially with regard to time gaps between the isotopic signals of precipitation and what we find in xylem water. Depending on the depth of the active soil layer (where trees can access water) and its structure, these time gaps can be considerable (Allen et al. 2015). Such structural variations are difficult to take into account in any modeling approach. Further studies on adjustments and harmonization between LPX-Bern and RLE models and their parameterization based on a wider pool of measured data will provide the basis to enhance the relevance of these models to a powerful analytical tool. Although each model has its strengths and weaknesses, making use of their complementarity and strengths facilitates the enhancement of our understanding of the source water availability and its the complexity for trees in these boreal ecosystems under permafrost dynamics. For instance, the use of a process-based model, such as the LPX-Bern (Keel et al. 2016), allows investigating δ18O signals in tree rings as a proxy for hydrological and climate dynamics on a regional or global scale. Furthermore, factorial simulations (where each parameter is modified specifically) are a potential avenue to further improve our understanding of the linkage between the vegetation cover, climatic drivers and permafrost dynamics.

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Author Contributions
OCh did the measurements and data interpretations for the NE Yakutia, and applied the RLE model to both studied sites. GT performed the experiments at the CE Yakutia site. SL modeled δ18O and thaw depth for both NE and CE sites. All authors significantly contributed to the writing of the manuscript.

Conflicts of Interest
The authors declare no conflict of interest.

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