Stem growth and stem sap flow measurements of three conifer tree species in Siberia

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Abstract. This work is targeted to evaluate the reaction of individual trees against periodic and punctual environmental stressing events with a network of long-term monitoring of tree water/growth-related processes in various geographic and climatic areas. Instrumental measurements of stem circumferential/radial size changes (dRc/dR) using band/point dendrometers and stem sap flow rates (Q) using a trunk segment heat balance method in Scots pine, Siberian larch, and Dahurian larch trees have been carried out at three research sites in Krasnoyarsk Krai, Russia. Analysis of perennia\(l\) dRc/dR and seasonal Q data obtained in 2015-2019 allows us to characterize the seasonality and features of the tree stem growth and stem water transport rates specific for each of the studied conifer species and on different temporal scales (diurnal, inter/intra-seasonal, and annual). The archived in-situ data are used to verify the efficiency of some process-based BS- and stochastic VS- tree growth and phenology models for Siberian larch and Scots pine trees. The results have confirmed the realistic nature of the simulation and have shown certain drawbacks of these models.

1. Introduction

Current climate change alters the sustainability of forest ecosystems worldwide [1]. Boreal forests in Siberia are particularly vulnerable due to the increased impact of regional anomalies of seasonal weather conditions within the last decades [2]. Multiple negative climatic factors, prolonged droughts, heavy rains, and temperature extremes affect the gross/net productivity, water balance [3, 4], and the phenology of forests [5]. Therefore, it is important to estimate and understand the physiological response of boreal forests against periodic and punctual environmental stress events on the level from individual trees to ecosystems.

Advances in the modern knowledge of weather and climate impacts on forest ecosystem components in terms of their interactive processes is possible through analysis of relevant quantitative data acquired by complex environmental monitoring systems. Versatile estimation of the links between tree water regime and tree stem radial growth depending on variations of local weather and soil hydrothermal conditions in Central Siberia on different time scales (diurnal, inter- and intra-seasonal, annual) is the main idea of this work. The basic material in this study is in-situ data acquired by equipment sets (sensors and devices) for automated measurements of tree stem circumferential or

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radial size variations (dendrometer data as a dynamic characteristic of tree growth rate) and vertical water transport in the stem xylem (sap flow rate data as a dynamic characteristic of tree water regime), with adjacent records of micrometeorological variables.

In a variety of published studies on tree physiology, researchers used different types of dendrometers [6] and sap flow sensors [7, 8, 9] as tools for the monitoring of dynamic vital processes in a tree. Point dendrometers installed on tree stems measure temporal changes of their radial size ($dR$) at one point of the stem basically with sub-daily (often with sub-hourly) resolution, while band dendrometers record stem circumferential size changes ($dRc$) as an integral value of $dR$ along the stem circumferential surface at a certain height of a tree. Dendrometer data show contractions (shrinkages) and expansions (swellings) of a tree stem in radial dimensions caused by multiple factors including stem growth (formation of new xylem cells), stem water fluxes (sap flow), the influence of air temperature and bark growth (under a tape of band dendrometers). Tree stem sap flow measurements, based on several methods of detection of water-induced heat transfer in sapwood [8, 9], can be used as a stand-alone facility in tree water balance related studies and can be combined with many other methods, often including application of dendrometers. Therefore, acquisition and analysis of long-term dendrometer/sap-flow measurements allow studying the tree growth stages and cycles [10, 11], canopy transpiration [12, 13], tree water balance [14, 15, 16], phenology [17], and wood anatomy formation [17, 18].

Thus, the creation of a network of long-term instrumental monitoring of tree growth and water transport processes in the main forest-forming tree genera in Siberia in geographically and climatically distinct areas was the scope of our work. In particular, we aimed to recognize, characterize, and compare seasonal patterns of growth, transpiration, and drought stress reaction of three conifer species: Scots pine, Siberian and Gmelin larch trees.

2. Research sites
This study was based on miscellaneous local in-situ data including dendrometer and sap flow measurements in conifer trees at three research sites in Central Siberia within the territory of Krasnoyarsk Krai in Russia: the “NARIM” research station in the national park “Krasnoyarsk Stolby”, the “Pogorelsky bor” (PogBor) research station (both near the city of Krasnoyarsk) and the Zotino Tall Tower Observatory (ZOTTO) international research station (near the village of Zotino). According to the Köppen classification, the climate conditions at all sites belong to the cold continental climate zone but differ in seasonal weather characteristics and forest composition.

The territory of the national park “Krasnoyarsk Stolby” with intact forest ecosystems is divided into two altitudinal belts: a low-mountain belt with elevations from 200 to 500 m a.s.l. consist of a light needle and parvifoliate forest, while dark needle taiga covers the mid-mountain belt with elevation from 500 to 800 meters a.s.l. NARIM is located in the mountain area at 538 m a.s.l. in a mixed boreal forest, where for the study we selected $\approx$116 year old Scots pine (Pinus sylvestris L.) and $\approx$140 year old Siberian larch (Larix sibirica Ledeb.) trees which co-occur with silver birch (Betula pendula Roth) and Siberian fir (Abies sibirica Ledeb.) trees. The long-term mean annual air temperature (MAT) in NARIM calculated from the local meteorological station data was 0.1°C, the while mean annual precipitation (MAP) was 668 mm for 1960–2017.

The “Pogorelsky Bor” research station of the Sukachev Institute of Forest (of the Siberian Branch of the Russian Academy of Sciences) is also located in the south taiga zone (at 243 m a.s.l.) of boreal forest. The studied trees in PogBor were chosen from two species of a larch provenance trial plot, selectively from planted Dahurian larch (Larix gmelinii Rupr. from Chernyshevsky District of Zabaykalsky Kray, Russia) trees and Siberian larch (Larix sibirica Ledeb. from Motyginsky District of Krasnoyarsk Kray, Russia) trees and, additionally, from a native Scots pine (Pinus sylvestris L.) stand. Tentative larch and native pine trees were planted at neighboring sites in 1969-1970 as three-year-old seedlings; the age of the stand was 47-48 years at the beginning of our measurements in 2014-2015. The local climatic conditions were as follows: MAT was 1.3 °C, MAP was 537 mm for 1960–2017.
The most northern site in our study was at ZOTTO research station which is situated on the western side of the Yenisei River basin in the middle taiga subzone [19] at 114 m a.s.l. Dendrometer measurements were performed in a ≈100-year old monoculture homogeneous Scots pine forest growing on alluvial sandy mineral soil with no underlying permafrost [20]. The long-term MAT was about -3.5 °C and MAP was 530 mm [19].

3. Equipment and data
Most devices and components in the equipment complexes used in our study were produced by the Environmental Measuring Systems company (EMS Brno, CZ, www.emsbrno.cz). Automated self-logging band dendrometers EMS DRL-26A were used in measuring and recording temporal changes in the stem circumferential size (dRe, in mm) of six Scots pine trees in ZOTTO from May 2013 to October 2018 and five Scots pines in NARIM since November 2018 (until present) with 1 µm resolution. Dendrometers of the same design with wire signal output (EMS DR-26) are used in measuring dRe of five Scots pine and Siberian/Gmelin larch trees in PogBor (Figure 1) from May 2015 until present. Variations in the stem radial size (dR, in mm) of four Siberian larch trees in NARIM are measured since May 2015 by using self-made analog point dendrometers based on the LM10 linear conductive 5kΩ potentiometer (RS PRO, UK). The outer bark layer of all monitored trees was partially removed (thinned) to minimize the dRe/dR variability component caused by bark shrinkage and swelling. Totally in 2013-2019 we recorded dRe data from 25 trees (17 pines, 8 larches) and dR from 4 larches.

Sap flow rates (Q, in kg/cm/h) in tree stems at ≈1.3 m height above ground were measured in three tree species during several vegetation seasons with a trunk segment heat balance (THB) method [8] by using two models of EMS sap flow meters: analog EMS SF-51 control units (+TC-120 thermocouples) and self-logging EMS Microset 8x units (+SF-81 thermocouples). Stem sap flow rates in the Siberian larch trees were recorded in PogBor (in 2015-2017) and in NARIM (in 2018), in the Gmelin larch trees in PogBor (in 2016-2019), in the Scots pine trees in PogBor (2015-2019) and in ZOTTO (in 2015).

Micrometeorological data like air temperature (Tair, in °C), relative humidity (Rh, in %), and photosynthetically active radiation (PAR, in µmol/m²) at 2-meter height in PogBor were collected by a triple self-logging EMS Minikin QTHi sensor. Liquid precipitation (P, in mm) in PogBor was measured each year in 2014-2019 from April to mid-October with a Pronamic Rain-O-Matic Professional rain gauge (orifice 200 cm²). The main meteorological variables in NARIM were
obtained by using the weather station Vantage Pro 2 (Davis Instruments, USA). Data on the volumetric soil water content ($W_s$, in m$^3$/m$^3$) at depths of 10/20/45 cm in PogBor and at depths of 10/20/30 cm in NARIM were acquired by using WaterScout ST100 sensors (Spectrum Technologies, USA). The soil temperature ($T_s$, in °C) was measured by using EMS PT100 sensors at depths of 10/20 cm in NARIM and at depth of 10/20/40/60 cm in PogBor. The soil water potential was measured in PogBor with GB-2 gypsum sensors (Delmhorst Instrument, USA) at 10/20/45 cm in depth. Analog output signals from the wire connected sensors and devices in PogBor and ZOTTO were recorded to EMS RailBox E1532V4P data loggers; $dR$ and $T_s$ in NARIM to EMS EdgeBox V8 logger, $W_s$ in NARIM to EMS MicroLog SP3 logger. In ZOTTO, a large equipment complex consists of multiple components for acquisition of many environmental variables including all meteorological readings, soil conditions, and atmospheric gas exchange measurements with eddy-covariance techniques [19, 20].

Raw measurements data were acquired with a temporal resolution from 10 to 60 minutes and stored in hardware-specific file formats (.hex, .dev). Onward, raw data were verified and pre-processed in the EMS Mini32 software consisting of the following procedures: removal of incorrect values, adjustment of data timing, compilation of successive data parts into entire time-series, correction of $Q$ values considering heat losses (known as the sap flow baseline [21]), noise reduction by averaging $dR/dRc/Q$ to hourly mean values, and data conversion to basic file formats. The data post-processing stage included computation of several derivative variables and statistics from previously prepared data. From diurnal $dR/dRc$ values we calculated daily absolute tree stem radial size variations ($dRabs$, in mm, Figure 2) and accumulated stem growth curves ($dRaccu$, in mm, Figure 2). Further, we defined the annual timing of the main vegetation season phases in terms of dendrometer data: start, end, and duration of tree growth periods (SoGS, EoGS, DoGS, correspondingly, in days of the year) and their inter-annual shifts. The same was done in terms of sap flow data. Additionally, we defined theoretically normal patterns of seasonal stem growth curves (without the influence of drought) for the Scots pines in PogBor, which then were used in the calculation of daily stem shrinkage values ($dRshr$, in mm) induced by environmental drought.

4. Results and conclusions
Analysis of the above-obtained dendrometer and sap flow data with weather condition readings allowed us to get some results. Long-term time series of $dR/dRc$ values for all tree species show specific data patterns on hourly, daily, and seasonal temporal scales. In winter time, daily and diurnal $dR/dRc$ highly correlate with air temperature dynamics. This corresponds to the dormant state of the trees. Within the vegetation season, the diurnal variability of $dR/dRc$ is mainly related to the intensity of the stem water transport driven by canopy transpiration. On the daily scale, $dR/dRc$ values indicated a progression of stem growth between SoGS and EoGS dates in each of the vegetation seasons. The daily absolute ($dRabs$) and accumulated ($dRaccu$) stem growth values differed in magnitude but showed high synchronicity among the neighboring trees at each of the research sites and high variability of the temporal distribution within all vegetation seasons. One example of the $dRabs$ and $dRaccu$ dynamics in 2016 from three Scots pines in PogBor is shown in Figure 2, where the initial point of the $dRaccu$ increase is set from the SoGS date, while $dRabs$ is shown from March to October. The inter-seasonal tree stem growth curves also show annual similarities to the intra-seasonal patterns. Usually the main period of continuous tree growth lasts from mid-May to mid-July with a mean annual SoGS variability of 3-7 days. The different length periods of physiological drought in trees mainly occur from mid-June to September, where negligible or negative $dRabs$ values occur, corresponding to a decline in the daily $Q$ in these periods.
Figure 2. Time series of daily absolute ($dR_{abs}$, in mm, upper panel) and accumulated ($dR_{accu}$, in mm, bottom panel) stem radial growth rates of three Scots pine trees (PP1-3) in 2016 at PogBor. Data from different trees are shown in different colors of the lines.

Daily transpiration and soil moisture dynamics simulated using the process-based eco-physiological Benkova-Shashkin model have been compared with in-situ data. This allowed us to verify the model efficiency and determine its drawbacks and advantages [22]. This research suggested that continuous measurements of $Q$ allow a study of phenological cycles (phases) of trees with various growth rates, particularly determining the timing (dates) of start/end of the vegetation seasons. Similar work was done to validate tree ring growth start timing using the Vaganov-Shashkin stochastic tree grow model (VS-oscilloscope). An analysis comparing the simulated daily tree growth rates from the VS-model output versus the dendrometer-derived $dR_{abs}$ and $dR_{accu}$ values for pine at PogBor (2015-2019) has shown discrepancies between the model output and the stem growth rates caused by the not sensitive parameters of tree growth limitation by soil moisture. However, the VS-model produces sufficiently realistic $dR_{accu}$ output.

The $Q$ data obtained from PogBor and NARIM show significant differences in the stem water transport seasonal timing related to the start/end dates and duration of the vegetation season among the sites and the tree species. Particularly, at PogBor two stands of Scots pine and Siberian larch with similar age and taxonomic properties exhibited very different transpiration rates and response mechanisms to environmental signals [12]. The stand water use was higher for larch than for pine, despite the fact that the transpiration for the deciduous larch trees occurred in shorter time periods [12]. The cumulative annual transpiration of the Siberian larch stand was 284 ± 4 mm in the growing seasons of 2015–2016, while for pine it was 20% lower [12]. The seasonal transpiration was 50% and 40% of the reference evapotranspiration and 91% and 67% of the growing season precipitation for larch and pine, respectively [12]. We also compared $Q$, growth, and water use efficiency of stem growth (WUE) in three equal age stands of Siberian/Gmelin larch and Scots pine in PogBor and showed that the pine stand maintained a higher WUE than both larch stands [13]. WUE of stem biomass production was the lowest in Siberian larch trees and the highest in Scots pines [13].
Figure 3. Sap flow data time series ($Q$, in kg/cm/day) of the Scots pine trees at PogBor in 2018 (upper panel) and 2019 (bottom panel). Colors of the lines show data from different trees.

The collected data archive of the perennial $dRc/dR$ and seasonal $Q$ from the three research sites will be freely available as a database “Kras_DendroSap” [23] (under the terms of the CC-BY-SA-NC 3.0 international license) at the scientific data portal Elsevier Mendeley Data (www.data.mendeley.com/datasets/266c9tzg2c). This database consists of three parts: one dataset for each research site with the data arranged by tree genera (Larix/Pinus) in separate MS Excel files. The specification files for each dataset in the corresponding data folders provide some descriptive information about the sites: research plots in detail, inventory parameters of the trees, equipment, data pre-processing stages, data gaps, some data visualization in figures and tables, and useful references.

A conclusion and a general overview: The long-term tree stem growth and sap flow monitoring with micrometeorological records based on a network of research sites with different tree species has an immense potential of research applications. The dendrometer and sap flow data can be used in stand-alone investigations related to the ecosystem/region specific of tree water/growth processes or can be a supplementary component in complex monitoring systems with comprehensive possibilities of environmental studies.

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