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Large-scale estimation of xylem phenology in black spruce through remote sensing

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ABSTRACT

There is a growing need for understanding the timing of wood formation in relation to the dynamics of bud phenology at wide geographical scale. This study analysed the relationships between long-term chronologies of xylem growth and the timing of plant phenology detected by Normalized Difference Vegetation Index (NDVI) in five permanent stands across the latitudinal distribution of black spruce [*Picea mariana* (Mill.) BPS] in the boreal forest of Quebec, Canada. Xylogenesis was studied weekly from April to October for thirteen years (2002–2014) on anatomical sections derived by wood microcores. The timing of the growing season detected by remote sensing was extracted from MODerate resolution Imaging Spectroradiometer (MODIS) 250 m 16-days NDVI data. The NDVI time-series were fitted using a double-logistic curve. Phenological chronologies from remote sensing and xylem phenology showed a latitudinal trend. The models correlating the data inferred from satellite sensors and the spring observations of xylem phenology were significant ($p < 0.0001$). The length of NDVI growing season and the duration of xylogenesis showed a close correlation. This study demonstrated that the timing of xylem formation could be suitably estimated at wide geographical scale using remote sensing data. However, the inter-annual phenological variability remained unexplained, which might limit the application of the models only to the years considered by our chronologies.

1. Introduction

Phenology is the study of recurring biological events, such as growth reactivation or flowering, and their connection with environmental factors (Cleland et al., 2007). Forests are the most important ecosystems for the terrestrial carbon budget (Pan et al., 2011), and the cyclic dynamics of wood formation represent the primary biological process through which carbon is sequestered in plants. Wood formation, or xylogenesis, occurs annually in trees of temperate and cold climates according to the cycles of summer and winter, producing a distinct pattern in the wood conferred by the tree rings (Rossi et al., 2014). Xylogenesis lasts from a few weeks to several months, according to species and individual growth rate, and, more specifically, to climate (Schmitt et al., 2004; Rathgeber et al., 2011; Treml et al., 2015; Vieira et al., 2015). The wide variation in timing of wood formation observed across geographical regions demonstrates the high plasticity of trees in adapting their growth to local environmental conditions (Cuny et al., 2015; Rossi et al., 2016). In cold ecosystems, trees display conservative responses to temperature to minimize the risk of late (spring) or early (autumn) frost. A better understanding of variability in growth resumption and cessation of trees is necessary for identifying the period of wood formation and carbon sequestration in temperate and boreal ecosystems. Seasonal dynamics of wood formation is largely dependent on temperature (Cocozza et al., 2016). Understanding how the thermal conditions, which occur during spring and summer, affect the timing and dynamics of wood formation has great ecological and economic relevance in a region as the boreal forest (Balducci et al., 2014). Indeed, productivity and growth are directly mediated

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by phenology at scales from the cell to ecosystem. There is therefore a growing need to identify the timing of wood formation by means of phenological investigations at wide geographical scale.

Optical satellite observations of land surface reflectance and their combinations in the form of vegetation indices are associated with the biophysical and biochemical properties of vegetation (Wu et al., 2014). Nowadays, it is possible to study vegetation phenology from field measurements and through satellite observations (Piao et al., 2015), because remote sensing of phenology using time-series of vegetation indices is based on the intra-annual changes of canopy greenness. These methods generally use time-series of Normalized Difference Vegetation Index (NDVI) data from different sensors. The NDVI is an effective parameter for monitoring the spatio-temporal patterns of vegetation phenology because it is related to the amount of green-leaf biomass (Lillesand and Kiefer, 2000). Due to its close relationship with plant activity, NDVI has been considered a good proxy for investigating the impact of climate change on tree phenology at regional to continental scale (Peng et al., 2013; Piao et al., 2015). NDVI correlates directly with vegetation productivity (Reed et al., 1994); there are numerous applications of this index for ecological purposes, and specifically for detecting changes in vegetation phenology, estimating biomass and net primary productivity, or assessing vegetation's response to climate (Wu et al., 2014; Balzarolo et al., 2016). Plant phenology is studied at different spatial scales, from plant to landscape (Antonucci et al., 2015; Richardson et al., 2013). Obviously, each scale of investigation produces results with specific resolution. How much can these different spatial scales be integrated? In particular, we raise the question whether and at what strength the phenological data inferred by remote sensing represents the dynamics of wood formation.

In this study, along a latitudinal gradient covering the entire closed boreal forest of Quebec (Canada), we analysed the relationships between phenology detected by NDVI and a long-term chronology of black spruce [*Picea mariana* (Mill.) BPS] xylem formation, divided into the different phases of xylem growth, ending in tree ring formation. Boreal forests are undergoing rapid northward shifts as a result of warming climate, which can influence vegetation patterns and growth responses by modifying the start and duration of the growing season. Although these shifts appear first at the biome's margins (Beck et al., 2011), it also clear that the effects of climate warming on growth dynamics vary across the distribution range of a species (Gazol et al., 2015). A hypothesis is proposed that different phases of xylem phenology are correlated with NDVI data. Linking landscape-level vegetation measurements of detailed time-series analysis derived from remotely sensed data to xylem phenology may provide an innovative tool to estimate the timing of xylem formation and carbon sequestration in wood at wide geographical scale. This approach may also elucidate the interdependence of foliage and xylem phenological phases and their interrelationships with regional temperature trends through a remote sensing approach.

2. Material and methods

2.1. Study area

The study was conducted in the boreal forest of Quebec, Canada, at five permanent sites located between the 48th and 53rd parallels across the latitudinal distribution of black spruce: Simoncouche (abbreviated as SIM), Bernatchez (BER), Mistassibi (MIS), Camp Daniel (DAN) and Mirage (MIR) (Table 1, Fig. 1). SIM and BER were in the balsam fir-white birch bioclimatic domain, MIS and DAN were in black spruce-moss bioclimatic domain, and MIR was in the black spruce-lichen bioclimatic domain. All sites consisted of coniferous stands dominated by mature and even-aged black spruce. Other coniferous or broadleaf species were rare or missing (Rossi et al., 2013). The climate of the area is typically boreal, with cool summers and very cold winters. The mean annual temperature varied between −1.6 and 4.1 °C, with the highest values recorded in the southern site. Winter temperatures attained a minimum ranging between −29.8 and −47.1 °C, while May-September mean temperature was 12.1 °C.

Table 1
Location of the five study sites across the latitudinal distribution of black spruce in the boreal forest of Quebec, Canada.

ID	Site	Latitude (°N)	Longitude (°W)	Altitude (m a.s.l.)
SIM	Simoncouche	48° 22′	71° 25′	338
BER	Bernatchez	48° 86′	70° 34′	611
MIS	Mistassibi	49° 73′	71° 94′	342
DAN	Camp Daniel	50° 69′	72° 18′	487
MIR	Mirage	53° 79′	72° 86′	384

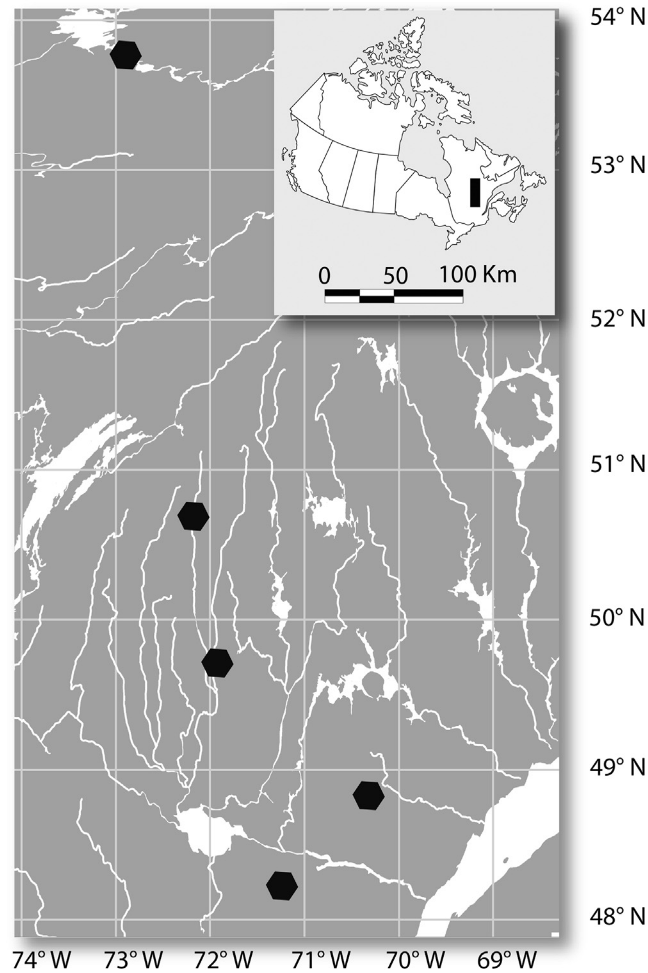

Fig. 1. Location of the five study sites in the boreal forest of Quebec, Canada.

2.2. Assessing xylem phenology

Ten dominant or co-dominant trees were chosen in each site. Tree-ring formation was studied from April to October 2002–2014 in all sites, except for MIR, where the study lasted from 2012 to 2014. Wood microcores were collected weekly following a spiral trajectory on the stem from 30 cm below to 30 cm above breast height (1.3 m) using Trephor (Rossi et al., 2006a). Trephor is a chisel-