

Chapter 16

Smartforests Canada: A Network of Monitoring Plots for Forest Management Under Environmental Change



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Abstract Monitoring of forest response to gradual environmental changes or abrupt disturbances provides insights into how forested ecosystems operate and allows for quantification of forest health. In this chapter, we provide an overview of *Smartforests* Canada, a national-scale research network consisting of regional investigators who support a wealth of existing and new monitoring sites. The objectives of *Smartforests* are threefold: (1) establish and coordinate a network of high-precision monitoring plots across a 4400 km gradient of environmental and forest conditions, (2) synthesize the collected multivariate observations to examine the effects of global changes on complex above- and belowground forest dynamics

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and resilience, and (3) analyze the collected data to guide the development of the next-generation forest growth models and inform policy-makers on best forest management and adaptation strategies. We present the methodological framework implemented in *Smartforests* to fulfill the aforementioned objectives. We then use an example from a temperate hardwood *Smartforests* site in Quebec to illustrate our approach for climate-smart forestry. We conclude by discussing how information from the *Smartforests* network can be integrated with existing data streams, from within Canada and abroad, guiding forest management and the development of climate change adaptation strategies.

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16.1 Introduction

Canada is the third most forested country in the world with 347 million ha of forest land (The State of Canada's Forests 2020). This vast forest provides habitat for flora and fauna as well as crucial ecological, social, and economic services. Canadian forests contribute over \$25 billion to Canada's gross domestic product and directly employ ca. 210,000 people in the forest industry (The State of Canada's Forests 2020). In addition to these direct economic benefits, forests provide critical ecological, social, and spiritual services. Furthermore, Canadian forests play a key role in the global carbon balance and thus affect Canada's international commitments regarding net carbon emissions (Luyssaert et al. 2008; Pan et al. 2011; Le Quéré et al. 2018; Baldocchi and Penuelas 2019).

However, the sustainability and resilience of forests are increasingly threatened by climate change as well as natural and anthropogenic disturbances, especially in high-latitude forests (ACIA 2005; Soja et al. 2007; Brandt et al. 2013; Gauthier et al. 2015; Trumbore et al. 2015; Brecka et al. 2020; DeSoto et al. 2020). Climate change will cause gradual long-term changes as well as increased frequency and severity of extreme events. These changes will contribute to increased uncertainty about future forest conditions that threaten the long-term viability of the forest sector and of human well-being (IPCC 2013; Brecka et al. 2020). Warming climate, drought stress, increasing frequency and severity of wildfires, and unprecedented outbreaks of insects and diseases are expected to reduce forest productivity and dramatically change forest composition, with concomitant impacts on biodiversity and ecosystem function, including the net carbon balance (Seidl et al. 2017; Navarro et al. 2018; Pugh et al. 2019).

While Canadian forest landscapes have always been dynamic due to the influence of a wide variety of natural biotic and abiotic disturbances, recent global changes are likely to alter the frequency and severity of these disturbances and lead to new disturbances not previously encountered. Increases in mean annual air temperature of 2.0 °C have been reported in western Canada during the period 1950–2003, compared with increases of only 0.5 °C in eastern Canada (Price et al. 2013). Similar discrepancies in precipitation have also been observed between eastern and western regions of Canada. In some areas, drought stress will reduce forest productivity and could threaten many ecosystem services. Given the vast extent of Canadian forests, effects of climate change will vary with geographic location, topography, forest composition, and local conditions. For example, western boreal forests are already drier than eastern boreal forests. Thus, slight increases in temperature or small decreases in precipitation may cause drought stress, reduced growth, increased tree mortality, and shifts in tree species composition, particularly in species-poor forests in western regions (Hogg et al. 2008; Michaelian et al. 2011; Peng et al. 2011; Chen et al. 2017; Cortini et al. 2017; Hisano et al. 2017; Searle and Chen 2017; Pappas et al. 2018). Another example is novel insect outbreaks, such as the invasion of the western boreal forest by the mountain pine beetle (Safranyik et al. 2010). However, in eastern boreal forests, warmer and drier conditions may

increase tree growth (D'Orangeville et al. 2016, 2018). Several studies point toward a positive effect of the increased concentration of atmospheric CO₂ on tree growth (e.g., Tagesson et al. 2020), but reverse patterns have also been reported (Girardin et al. 2016). Translating how a carbon source (i.e., photosynthesis) is converted to a tree carbon sink (i.e., growth) remains challenging (Fatichi et al. 2019; Walker et al. 2020). Regional variation in forest responses to air temperature or precipitation change is also expected along a North-South gradient (Huang et al. 2010; Hogg et al. 2013; Chen et al. 2017). Projected increases in atmospheric CO₂ concentration, air temperature, evaporative demand, and surface net radiation are expected to intensify climate extremes, such as atmospheric and soil droughts (Held and Soden 2006; Dai 2012; Cook et al. 2014), with pronounced commensurate impacts on forest composition, structure, and function (Allen et al. 2015; Novick et al. 2016). Site-specific conditions will shape the impacts of climate change on forest function. Management options should be tailored accordingly by implementing case-specific solutions. Changes in soil conditions (nutrient concentrations, organic layer, permafrost) could scale up to long-term losses in productivity. Similarly, shifts in phenology can alter the synchrony between tree hosts and insect pests, potentially leading to increased damage to trees (Pureswaran et al. 2015). As a result, small-scale changes can have large consequences for forests, particularly when conditions are close to critical thresholds (Allen et al. 2015; Reyer et al. 2015; Trumbore et al. 2015).

Climate-smart forestry in the era of rapidly changing environmental conditions should provide tailored solutions for sustainable forest management based on a mechanistic understanding of forest function and of the influence of environmental stressors (Bowditch et al. 2020; Verkerk et al. 2020). This can be achieved by collecting and analyzing multivariate and multiscale observations of forest function (e.g., from the cell to the organism and to the ecosystem level) together with advanced understanding and numerical modelling of processes. Forest monitoring thus plays a central role in providing data to: (i) build improved knowledge on forest function at multiple spatiotemporal scales, as well as forest health and resilience to environmental change, and (ii) design and validate predictive modelling through numerical experiments. Precise temporal data, which are representative of the dynamic responses of forests in real time, are crucial for understanding and predicting the effects of global change (Kayler et al. 2015; Sass-Klaassen et al. 2016; Steppe et al. 2016). Accurate forest modelling, with state-of-the-art process-based simulation tools, allows for hypothesis testing and evaluating risk and uncertainty by conducting numerical experiments with hypothetical, yet realistic, scenarios of future climate conditions and/or forest stand composition (Fatichi et al. 2016; Mencuccini et al. 2019; Mastrotheodoros et al. 2020). To ensure the long-term viability of the forest sector, we also need well-coordinated research efforts that span a wide range of forest ecosystems and climatic conditions. While there have been many local-scale studies of changes associated with climate, we are lacking a comprehensive understanding of ecological responses and how these vary across the major forest types in Canada. We urgently need a Canada-wide concerted effort to document effects of climate variability, to experiment with different species mixes, and to model forest responses across large climatic gradients and forest types.

Smartforests Canada (<https://smartforest.uqam.ca/>) is a national project designed to address this gap through the establishment of a Canada-wide network of monitoring sites covering a wide spectrum of forest biomes and environmental conditions. More specifically, *Smartforests* aims to provide an improved understanding of how ecosystems, species, populations, and individual trees are influenced by changes in both physical (climate, soil) and biotic (competition, facilitation) environmental factors as well as interactions between these factors. The objectives of *Smartforests* are threefold: (1) establish a network of high-precision forest monitoring plots across a gradient of forest types and environmental conditions to examine the effects of global changes on complex above- and belowground forest dynamics, (2) synthesize multivariate data collected across the monitored forest stands to assess ecosystem functioning and resilience, and (3) assimilate the data and understanding of processes to guide the development of the next generation of forest growth simulation models and inform policy-making toward the best management and adaptation strategies for our forests.

In this chapter, we provide an overview of the *Smartforests* methodological approach and network of sites, and illustrate this multivariate and cross-scale *Smartforests* framework with an example of a temperate hardwood forest site in Quebec, Canada. We conclude with an outlook on how the *Smartforests* toolbox, based on state-of-the-art technology with automated and campaign-based measurements, can be deployed to quantify the multifaceted aspects of forest functioning and resilience under climate change. This holistic approach is firmly based on a balanced experimental design, which includes belowground, understory, and overstory forest components as well as biotic and abiotic factors affecting forest function. Information from the multivariate, multilevel *Smartforests* data streams can be integrated with global observation networks, where Canadian forests are currently underrepresented, and can be used for advanced forest growth modelling to guide forest management and the development of climate change adaptation strategies.

16.2 Methodological Framework

16.2.1 High-Precision Monitoring Plots

The backbone of the *Smartforests* approach is based on a Canada-wide network of high-precision forest monitoring plots (Fig. 16.1). These plots are designed to provide intensive and detailed spatiotemporal data on meteorological and soil conditions as well as various forest functions that are necessary to understand the response of forests to environmental stressors (Fig. 16.2). A tree-centered approach underlies the experimental design and instrumentation (Sass-Klaassen et al. 2016). Detailed observations are collected at different levels of spatial organization, spanning from the cell (e.g., plant tissue) to the organism (e.g., tree), the forest stand, and the landscape, and include campaign-based but also automated observations, coupled with

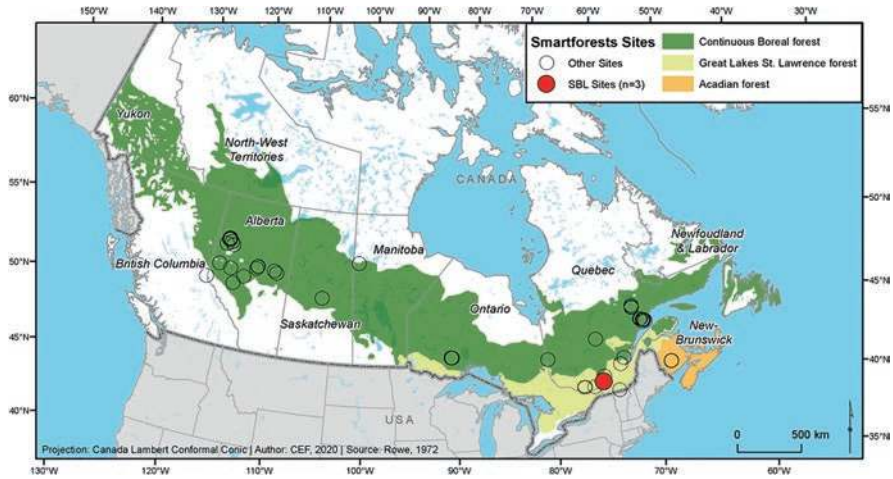


Fig. 16.1 An overview of the *Smartforests* network of sites. The strategically selected sites cover a wide range of environmental conditions as well as distinct forest types and vegetation characteristics. Point clusters occur in certain areas since, within each region, several monitoring plots are established to cover local-scale climatic gradients and environmental conditions. The case study used here to illustrate the implemented *Smartforests* approach is highlighted in red (Station de biologie des Laurentides; SBL)

remote sensing data (Fig. 16.2). It is important to underline that instrumentation and observed variables are not necessarily homogeneous across the network. Site-level priorities and specific research questions have resulted in tailored experimental designs to address the needs of specific research groups. Measured variables include meteorological (e.g., precipitation, air temperature, radiation, wind speed and direction, relative humidity) and soil conditions (temperature, water and nutrient availability), in addition to information on tree growth, reproduction, mortality, phenological changes in organisms, community turnover rates, net primary productivity, and trophic interactions. These high-precision monitoring plots allow us to: (1) collect long-term biological, ecological, and environmental data to document and understand changes in forest functioning with climate variability, (2) develop a network promoting ecological research and stimulating collaborations at national and international levels, and (3) provide a unique setting not only for research but also for educational activities, such as hosting teaching seminars, field classes, and facilitating student engagement through exposure to the scientific method.

The methodological design and the deployed instruments are tailored to cover a wide range of relevant ecophysiological and ecological processes and to quantify forest function including belowground as well as the understory and overstory components (Fig. 16.2). In the overstory, for example, we focus on measuring key biogeochemical processes describing the exchange of carbon, water, and energy in the soil-plant-atmosphere continuum, including measurements at the leaf level (e.g., leaf gas exchanges) and tree level (e.g., stem water fluxes and growth) but also at the landscape level (e.g., airborne thermal imaging), focusing on species interactions

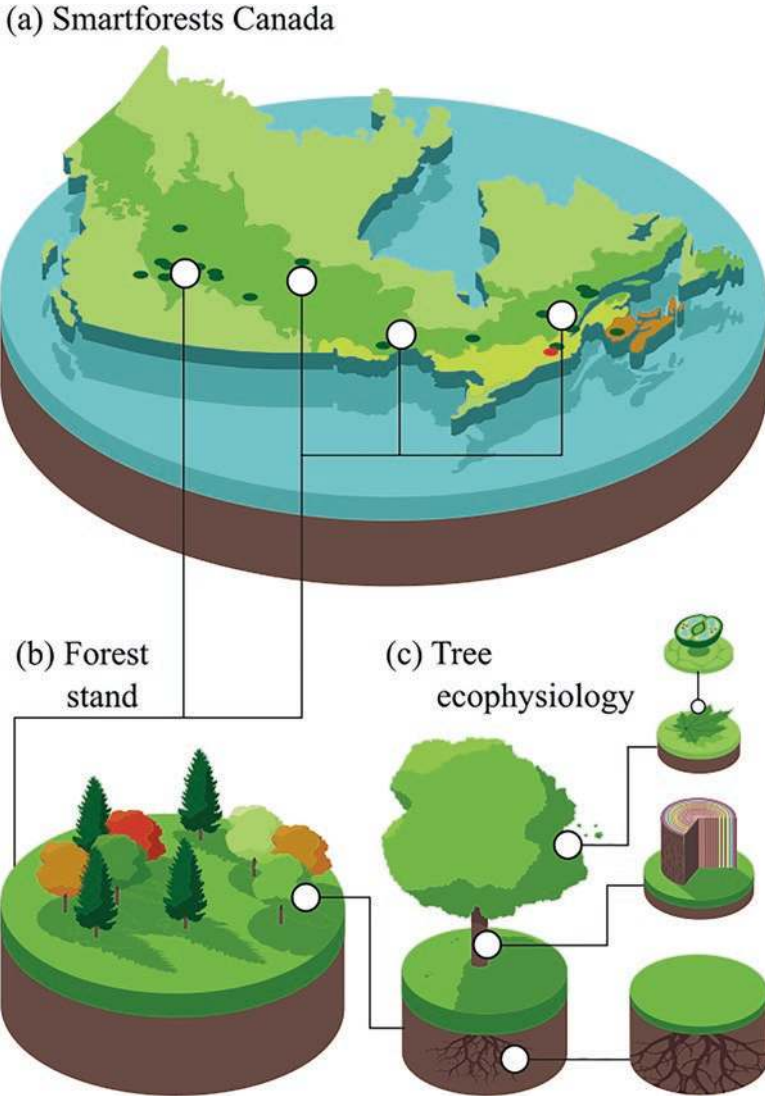


Fig. 16.2 The tree-centered approach implemented in the *Smartforests* network for tackling pressing environmental change questions in Canadian forests. Detailed tree ecophysiological observations are collected at the cell and whole plant level (subplot c). Plant ecophysiological insights and tree-level process understanding are upscaled to the forest stand level using information on stand demography and airborne imaging (subplot b). Findings at the forest stand level are synthesized across the *Smartforests* network of sites to better understand and model forest structure and function, health, and resilience to environmental change and provide Canada-wide guidance for forest management and policy-making (subplot a)

(Fig. 16.2). Understory vegetation is also monitored to quantify species demography and growth dynamics (Landuyt et al. 2019). Finally, soil conditions and below-ground processes (e.g., temperature, water and nutrient availability, fine root growth, soil respiration, litter decomposition) are also explicitly monitored, acknowledging the fundamental role of soil biogeochemistry and belowground processes to tree growth and forest health (Vicca et al. 2012; Clemmensen et al. 2013).

16.2.2 The Smartforests Canada Network of Sites

The *Smartforests* network includes more than 100 high-precision forest monitoring plots spread across Canada (Figs. 16.1 and 16.3). The research efforts at these sites are geared toward pressing environmental change questions, in accordance with the *Smartforests* objectives, yet instrumentation and specific research questions explored at each site may vary. These forest plots cover a wide range of environmental conditions and include major North American forest types with widespread common tree species. The established network spans a temperature gradient of about 8 °C, i.e., mean annual air temperature across sites ranges from −3 °C to 5 °C. The gradient of monitoring plots covers forests from southern shade-tolerant

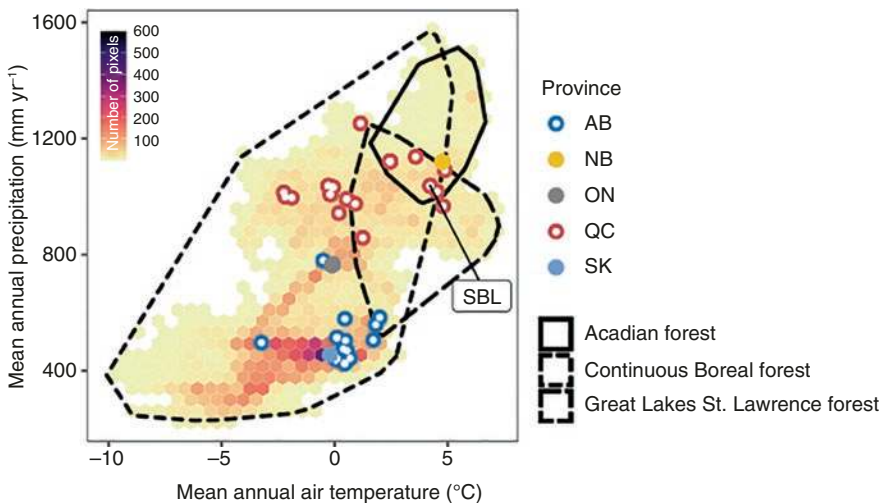


Fig. 16.3 Climate envelope of the forest types covered by the *Smartforests* network (color-coded dots denote the province, namely, Alberta, AB; New Brunswick, NB; Ontario, ON; Quebec, QC; Saskatchewan, SK; see also Fig. 16.1; for clarity, filled and open circles are used). Hexagons, color-coded with the density of 10⁷ resolution pixels, define the climate space of mean annual air temperature and total precipitation, as quantified using the WorldClim dataset (Fick and Hijmans 2017). Polygons show the specific forest types, as classified by Rowe 1972, which overlap the *Smartforests* network of sites. The case study used here to illustrate the implemented *Smartforests* approach is also highlighted (Station de biologie des Laurentides; SBL)

hardwoods to the boreal region along an East-West moisture gradient across the country, with mean annual total precipitation ranging from 380 mm in the West to 1252 mm in the East (Fig. 16.3). The latitudinal North-South gradient includes temperate shade-tolerant hardwood forests in southern Quebec, mixed temperate and temperate-boreal transition zone forests, as well as mixedwood and black spruce boreal forests in the Abitibi region. The East-West moisture gradient extends from the Acadian forest in New Brunswick to boreal forest plots on the North Shore of Quebec and to a series of boreal plots across Ontario, Manitoba, Saskatchewan, and Alberta. The wide range of environmental conditions and forest types covered by this network allows us to quantify forest dynamics, health, and resilience at the forest stand level and assess climate-change impacts by combining insights from the temperate, temperate/boreal transition, and boreal forest zones. The *Smartforests* network includes long-term monitoring sites, with more than a decade of detailed forest monitoring, as well as recently established research sites. The spatial and temporal gradient being covered by this network allows us to detect long-term effects of small changes in productivity or community relationships, including the influence of extreme events that may only affect a small number of sites, as a result of inter- and intraspecific differences in tree species, as well as adaptations of tree functioning to prevailing environmental conditions, e.g., species-specific responses of tree water use in humid forest stands of Eastern Canada (Oogathoo et al. 2020) vs. responses of the same species in drier sites in Central Canada (Pappas et al. 2018). Description of the design and efficacy of a network of observational plots across European mountain regions is presented in Chap. 5 of this book (Pretzsch et al. 2021).

16.3 Climate-Smart Forestry with High-Precision Monitoring Plots

16.3.1 From Forest Function to Forest Health and Resilience

Robust quantification of forest function including below- and aboveground components with processes occurring at cell, organism, and ecosystem levels provides the basis for assessing forest health and resilience to ongoing environmental change (Reyer et al. 2015). For example, tree growth is an indicator of tree age and vitality that is influenced by ontogeny, local competition, and climate (Dobbertin 2005). Temporal data on tree growth (e.g., annual tree ring widths, seasonal dendrometer-derived growth signals) can be used to characterize tree performance, vulnerability, and resilience to environmental changes over time (Lloret et al. 2011; Rogers et al. 2018; Pappas et al. 2020b). Moreover, tree water use and storage are indicators of drought-induced tree mortality risk (Martinez-Vilalta et al. 2018), and when combined with tree growth measurements, interspecific differences in species resilience could be quantified (Pappas et al. 2020b). Combining tree-level ecophysiological

observations with remote sensing products covering forest landscapes provides a large-scale perspective of forest health that is useful in deriving early warning signals of critical transitions in forested ecosystems, e.g., drought-induced tree mortality (Camarero et al. 2015; Rogers et al. 2018; Cailleret et al. 2019). Discussion on how to implement tree-based monitoring platforms and large-scale forest observations is presented in Chaps. 10 and 11 of this book (respectively, Tognetti et al. 2021; Torresan et al. 2021). Thus, the *Smartforests* toolbox is geared to develop a quantitative and process-based understanding linking forest function under recent past and present environmental conditions with forest health and resilience to climate change using mechanistic understanding and modelling tools to predict future forest responses to environmental stressors.

16.3.2 Modelling and Adapting Forests to Climate Change

A comprehensive understanding of the interactions between forest dynamics, climate change, and management requires the use of simulation models optimized on robust data. Current tools employed by managers are still strongly influenced by the idea that forest ecosystems are at equilibrium with environmental conditions and tend to ignore the effects of changing environmental factors and vegetation acclimation and adaptation. The data collected under *Smartforests* are tailored to provide the necessary information to parameterize and validate state-of-the-art process-based models of forest growth and vegetation functioning (Fatichi et al. 2016; Prentice et al. 2015; Gennaretti et al. 2017). Process-based models facilitate prognostic simulations with a scenario analysis approach to evaluate, both at stand and landscape level, the benefits, compromises, and uncertainties associated with different management strategies and climate change scenarios. Simulation models constitute a relevant approach to investigate the dynamics, function, and structure of forests at scales that may be difficult to capture via experimental field research alone.

In addition, models are powerful tools for evaluating the long-term consequences of variation in baseline conditions and management strategies on forests at different spatial scales (Elkin et al. 2013; Bugmann et al. 2019). This approach is becoming more relevant with the acknowledged need to develop management strategies that will ensure that forest ecosystems maintain the variety of services on which our society depends, despite uncertainties associated with rapidly changing ecological, climatic, and economic conditions (Albrich et al. 2020). Managers and decision-makers already rely on simulation models, for example, to determine annual allowable cut levels. In many regions of Canada, forests are now being managed as ecosystems rather than just for fiber. While this approach is a large step forward in that it considers multiple values, it still often fails to consider changing forest conditions and natural disturbance regimes. As such, the effects of climate change are not considered in simulation models used for determining the annual allowable cut, which may overestimate timber supply. There is, therefore, an urgent need to adapt current simulation models and develop new models that better integrate uncertainty in resource availability, risk management in planning processes, and the multiple

spatial and temporal scales over which climate change influences forests (Boucher et al. 2018; Boulanger et al. 2019; Gauthier et al. 2015; Mina et al. 2020).

Models that represent key ecosystem processes and are parameterized, calibrated, and validated with multivariate observations from the *Smartforests* network can be used to test and compare scenarios for developing adaptive forest management strategies. The data collected with *Smartforests* will contribute to the improvement of parameter estimates and to the accuracy of the processes being modelled, such as tree water use and growth, tree mortality, plant phenology, plant nutrition, natural disturbance dynamics, plant succession, plant inter- and intraspecific interactions, plant-microbe interactions, as well as the effect of climate change on these processes. Simulation results from these models provide virtual numerical experiments which can be used to inform managers and decision-makers on the best strategies to use in order to mitigate the negative impacts of global change and to adapt to and exploit opportunities linked with future environmental conditions. The models will be crucial to evaluating the consequences of alternative management approaches under different climate scenarios and thus providing managers with means of incorporating newly acquired data into decision-making. A review of mechanistic and empirical models, which are currently available to predict forest growth, is presented in Chap. 7 of this book (Bosela et al. 2021).

16.4 A *Smartforests* Case Study

16.4.1 Site Description

To illustrate the *Smartforests* methodological approach, we used the established high-precision monitoring plots at the Station de biologie des Laurentides (SBL; 45.987 N, 74.005 E), which is located within the temperate hardwood forest of the Great Lakes – St. Laurent region of Quebec (Figs. 16.1 and 16.4). The SBL site is a 16.4 km² research and teaching forest operated by the Université de Montréal (<https://sbl.umontreal.ca/>) and is situated in a transitional mixedwood forest within the southern Laurentians region (Fig. 16.4). The area is characterized by a continental climate with a mean annual air temperature of 5.5 °C and total precipitation of 1050 mm (long-term 1980–2010 averages from meteorological observations in St. Jerome; Environment and Climate Change Canada). Overstory vegetation includes common tree species in North America's temperate, boreal, and temperate/boreal transition zone (Table 16.1). Due to its geographic position, topography, and disturbance history, the area has developed into a mosaic of tree species, with dominant species being sugar and red maple (*Acer saccharum* Marsh. and *Acer rubrum* L.) mixed with American beech (*Fagus grandifolia* Ehrh.), white and yellow birch (*Betula papyrifera* Marsh. and *Betula alleghaniensis* Britt.), balsam fir (*Abies balsamea* (L.) Mill.), and bigtooth aspen (*Populus grandidentata* Michx.). Patches of forest stands dominated with red oak (*Quercus rubra* L.) occur at the southeast edge of the SBL region, corresponding to the northern species distribution range (Fig. 16.4). Understory vegetation consists primarily of striped maple (*Acer*

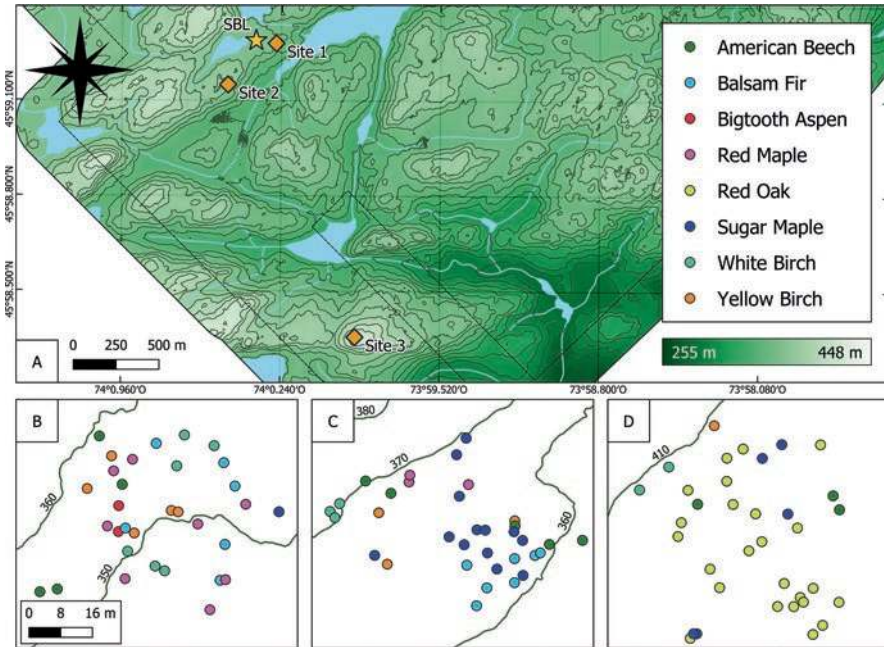


Fig. 16.4 Location of the three forest plots at the Station de biologie des Laurentides (SBL) together with the exact locations of the trees selected for continuous monitoring of stem growth and water use, color-coded according to species

pensylvanicum L.), hobblebush (*Viburnum lantanoides* Michx.), wood fern (*Dryopteris* spp.), and lycopods (*Lycopodium* spp.). The forest floor is a moder humus form, and most of the soils, which are thin, are well-drained Orthic Ferro-Humic or Humo-Ferric Podzols (Soil Classification Working Group 1998). To better capture local-scale topographic gradients and heterogeneity related to vegetation composition, three distinct forest plots were established within the SBL region for automated monitoring and campaign-based surveys (Fig. 16.4, Table 16.1). Average stand age, density, and basal area of overstory tree species (i.e., stem diameter ≥ 5 cm) in these plots are around 80 year, 1060 stems ha^{-1} and 33 $\text{m}^2 \text{ha}^{-1}$, respectively (Table 16.1).

16.4.2 Automated Measurements of Forest Functioning

Tree-level ecophysiological measurements are collected with automated equipment at the three forest plots at SBL and, together with concurrently recorded environmental variables (e.g., meteorological and soil conditions), are used to characterize tree and forest growth dynamics and water use (Fig. 16.2). Meteorological variables include hourly recorded rainfall, snow depth, albedo, relative humidity, air

Table 16.1 An overview of the tree species at Station de biologie des Laurentides (SBL) selected for continuous monitoring of stem growth and water use, together with their leaf type, taxon group, wood anatomy, and stand demography (stem density and basal area for overstorey trees with DBH \geq 5.0 cm)

Species name	Common name	Leaf type	Taxon group	Wood anatomy	Density [stems ha ⁻¹]; Basal area [m ² ha ⁻¹]
<i>Abies balsamea</i>	Balsam fir	Needle-leaved	Gymnosperm	Tracheids	91; 0.9
<i>Acer rubrum</i>	Red maple	Broad-leaved	Angiosperm	Diffuse-porous	152; 2.7
<i>Acer saccharum</i>	Sugar maple	Broad-leaved	Angiosperm	Diffuse-porous	315; 4.5
<i>Betula alleghaniensis</i>	Yellow birch	Broad-leaved	Angiosperm	Diffuse-porous	24.3; 1.2
<i>Betula papyrifera</i>	White birch	Broad-leaved	Angiosperm	Diffuse-porous	67; 5.6
<i>Fagus grandifolia</i>	American beech	Broad-leaved	Angiosperm	Diffuse-porous	30; 0.4
<i>Quercus rubra</i>	Red oak	Broad-leaved	Angiosperm	Ring-porous	224; 16.2

temperature (above and below the canopy), wind speed and direction, and solar radiation, while soil conditions are characterized by hourly measurements of soil volumetric water content (VWC), water potential, and temperature recorded at a depth of approximately 10 cm (Fig. 16.5; Spectrum Technologies, Aurora, IL, US). Across the study region, 48 micro-stations are deployed. For each micro-station, two replicates of two soil variables are included (i.e., soil temperature and VWC or soil temperature and water potential) for a robust characterization of local-scale environmental heterogeneity (Fig. 16.5).

Tree ecophysiological monitoring includes: (1) sap flow measurements with both custom-made thermal dissipation sensors (20 mm long stainless-steel probes, with a 2 mm diameter; Granier 1987; Lu et al. 2004; Pappas et al. 2018) and commercial sensors (3-N, East 30, Pullman, WA, USA) measuring sap flow with the heat ratio method (Burgess et al. 2001) and (2) stem radius change measurements with two types of high-frequency and precision stem dendrometers (DC3, Ecomatik, Munich, Germany; DRL26C, Environmental Measuring Systems, Brno, Czech Republic). More than 100 trees are instrumented with sap flow and stem dendrometers in the three study plots, and all dominant tree species in the area are represented in the measurements being conducted (Fig. 16.4). This large sample size allows for detailed quantification of temporal dynamics in tree growth and water use and their inter- and intraspecific differences as well as for upscaling estimates to the forest stand level (Fig. 16.2). Measuring sap flow with two different methods allows us to infer sap flow at different sapwood depths and to derive species-specific radial profiles of sap ascent in tree stems (Fig. 16.6). Such information not only is useful for

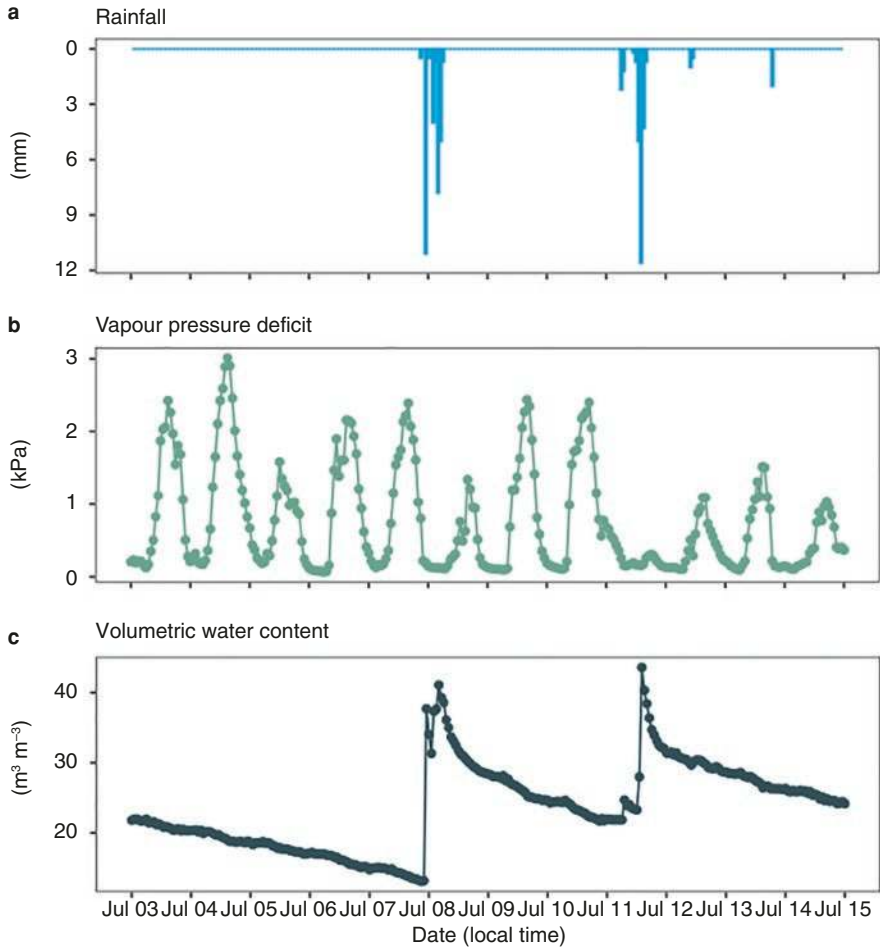


Fig. 16.5 Hourly time series for key meteorological and soil variables at the Station de biologie des Laurentides (SBL, Site 2; Fig. 16.4) for the period July 3 to July 15, 2020. Rainfall events (subplot a) resulted in drops in daytime vapor pressure deficit (subplot b) and concurrently increased soil water content (subplot c)

pinpointing interspecific differences in stem hydraulics and water use but also allows for robust transpiration estimates at the forest stand level (Berdanier et al. 2016). Further, combining constant heat (thermal dissipation method) and pulse-based (heat ratio method) sap flow measuring techniques allows us to minimize uncertainties related to method-specific assumptions and limitations (Steppe et al. 2010; Rabbel et al. 2016; Peters et al. 2018, 2020; Flo et al. 2019). By doing so, tree water use and transpiration rates can be assessed in terms of both temporal dynamics and absolute rates. Moreover, when combining tree-level data using different measuring techniques with forest stand characteristics (e.g., stem density) and

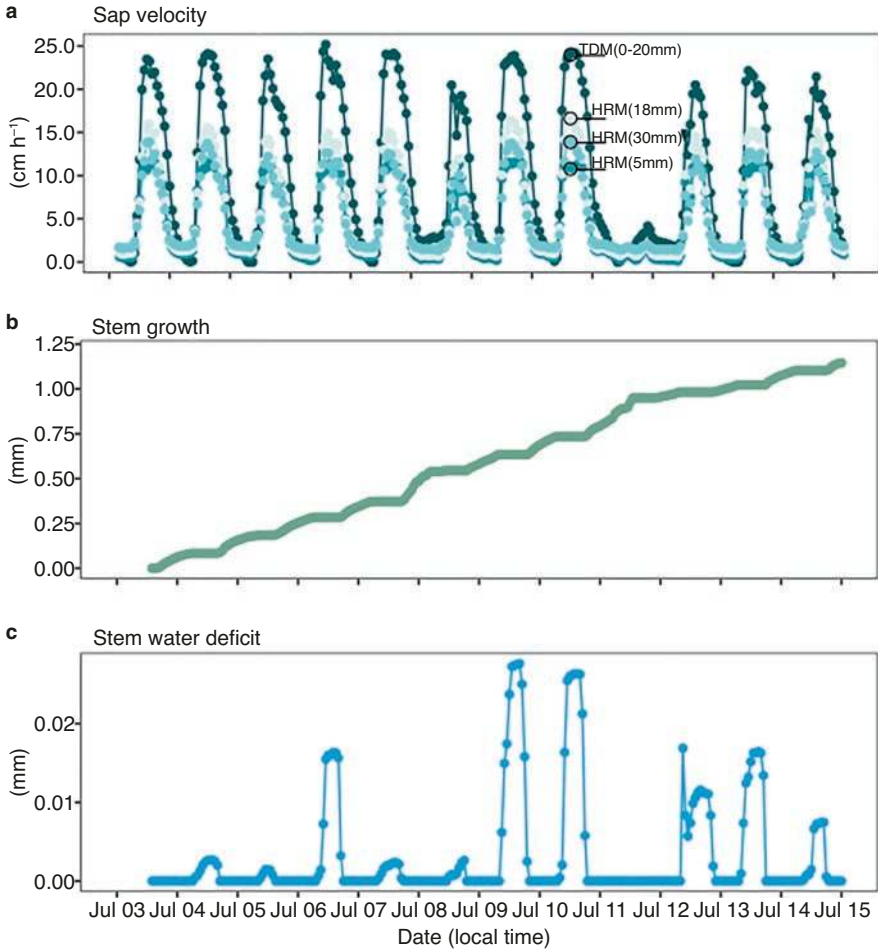


Fig. 16.6 Hourly time series of concurrently recorded ecophysiological variables using sap flow and dendrometer sensors affixed to the stem of an American beech (*Fagus grandifolia*) with DBH = 15.1 cm and sapwood depth, $S_d = 3.9$ cm, at the Station de biologie des Laurentides (SBL, Site 2; Fig. 16.4) for the period July 3 to July 15, 2020. Continuous ecophysiological monitoring includes sap velocity (subplot a) measured with two approaches, namely, the thermal dissipation method (TDM; 20 mm long probes; data processed with the *TREX* R Package; Peters et al. 2020) and the heat ratio method (HRM; at 5 mm, 18 mm, and 30 mm sapwood depths), and stem radius changes, used to derive stem growth (subplot b) and stem water status (stem water deficit; subplot c) computed with the *treenetproc* R package (Haeni et al. 2020; Knüsel et al. 2021)

species-specific allometry (e.g., sapwood area), transpiration estimates can be derived at the forest stand level (Oishi et al. 2008; Link et al. 2014; Matheny et al. 2014; Renner et al. 2016; Hassler et al. 2018). Two different measuring techniques are also deployed for continuously monitoring stem radius changes, namely, dendrometers mounted with tangential pulling force (DRL26C) and dendrometers

mounted with radial pressing force (DC3), thus reducing potential weaknesses of each specific technique to infer tree growth and hydraulics at a subdaily resolution (Fig. 16.6). Processing of the recorded stem radius changes is useful to empirically disentangle: (i) irreversible changes (expansion) in the stem radius as a result of tree growth and (ii) reversible stem radius changes due to water use, i.e., subdaily variations and seasonal variation in stem water storage (King et al. 2013; Zweifel et al. 2016; Pappas et al. 2018; Haeni et al. 2020; Knüsel et al. 2021). These observations, along with concurrent sap flow measurements and established theoretical models (Mencuccini et al. 2013, 2016; Chan et al. 2016), can be used to provide process-based partitioning of hydraulic-, osmotic- and growth-driven stem fluctuations, complementing the aforementioned empirical approach for processing dendrometer data. In addition, 30 motion-sensing time-lapse cameras (Wingscapes BirdCam Pro; Ebsco Industries, Birghminham, AL) are also deployed at the sites to monitor leaf phenology from bud break in the spring to leaf senescence in the fall, taking images at various times during the day throughout the year. The cameras are installed 30 cm from the soil surface at an angle varying from 45° to 70° to monitor canopies of various heights covering understory and overstory species. Tree reproduction is monitored at the scale of the whole forest domain by an automated pollen counter and particle analyzer (RapidE, Plair SA) that identifies pollen grains at the species level in real time during the whole pollination season.

16.4.3 Campaign-Based Data Collection

Continuous measurements with automated methods are accompanied by field surveys and observational campaigns throughout the growing season. To date, this includes surveys for detailed monitoring of forest stand demography and aboveground tree biomass. To upscale tissue- and tree-level ecophysiological observations to the forest stand, which is the spatial scale at which policy- and decision-making is typically made, we need detailed characterization of forest stand demography and species-specific allometric characteristics (Waring and Landsberg 2011). Thus, at SBL, several circular subplots were established, and tree species and their stem diameter at breast height (1.3 m above the ground surface; DBH [cm]) were recorded (for trees with DBH \geq 5.0 cm) and used to estimate site- and species-level stem density and basal area (Table 16.1).

In addition, during the summer 2020 field campaign, more than 350 tree cores were collected with a “biomass-oriented” design (Babst et al. 2014; Pappas et al. 2020a). The analysis of these tree cores will permit: (1) detailed characterization of species-specific sapwood allometry, a key parameter for quantitative estimates of tree- and forest-level water use and transpiration, and (2) reconstruction of forest stand’s aboveground biomass increments to assess temporal variability in tree growth and the strength of the forest carbon sink (Babst et al. 2014; Pappas et al. 2020a). Moreover, when annual tree growth and biomass allocation patterns are combined with sub-annual (i.e., seasonal, daily, hourly) information on tree growth

from the stem dendrometers, then the temporal spectrum of variability in growth can be characterized from hourly to decadal time scales. Such cross-scale characterization of species-specific growth patterns can provide novel insights into species responses to environmental change and, ultimately, offer a quantitative understanding of species-specific resilience (Pappas et al. 2020b).

16.5 Outlook

The resulting knowledge from this pan-Canadian *Smartforests* network, which is designed to encompass a broad range of forests and climates in Canada, will pave the way for the development of innovative adaptation strategies to ensure sustainable forest management and will enhance our understanding of ecosystem functioning. Within the context of sustainable forest management, identifying how these forests change with and respond to climate fluctuations will support development of strategies to preserve economic and non-economic ecosystem services. The *Smartforests* network and the integration of site-specific measurements with larger-scale remote sensing products and model outputs will serve to identify early warning signals of forest responses to either subtle changes in climate or extreme events. In doing so, forest managers will be able to react quickly to develop adaptation strategies. Moreover, research across the *Smartforests* network will provide quantitative insights into the terrestrial biogeochemical cycles that will lead to constrained estimates of the strength of the forest carbon sink across Canada. Such constraints are necessary for Canada-wide estimates of forest carbon budgets and for guiding policy-making on climate change mitigation strategies. The collected observations across the *Smartforests* network will also contribute substantially to existing global networks of forest monitoring plots, including sap flow observations (SAPFLUXNET; Poyatos et al. 2020) and plant functional traits (TRY; Kattge et al. 2020), where Canadian forests are currently underrepresented.

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