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# Using paleoecology to improve reference conditions for ecosystem-based management in western spruce-moss subdomain of Québec

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ABSTRACT

Ecosystem based management in Québec is framed by reference conditions defining percentage of old-growth forest (> 100-years-old) and forest composition characterizing pre-industrial forest landscapes. In the western spruce-moss bioclimatic subdomain (154 184 km$^2$) a fire cycle estimated at 150 years was used to target that 49% of the landscape has to be composed of old-growth forest. Yet, this target was developed using past (19th–20th C.) climate and vegetation data and assume that environment and ecosystem processes are homogeneous for the entire western spruce-moss bioclimatic subdomain. The wide spatial and narrow temporal windows limit the application of reference conditions under ongoing climate change.

Our aim was to classify current vegetation heterogeneity of the western spruce-moss subdomain into homogeneous zones and to study the long-term history of fire and vegetation within these zones. This approach will help to refine forest management targets that are based upon short-term records by providing a long-term perspective that is needed for the forests to be managed within their natural range of variability. Modern forest inventories data were used along with climate, physical variables, and natural and human disturbances to study the current vegetation-environment interactions among the western spruce-moss subdomain. We also used 18 published sedimentary pollen and charcoal series to reconstruct Holocene vegetation and Fire Return Intervals (FRI).

Contemporary data revealed 4 zones with homogeneous interactions between vegetation and environment. Pollen analysis revealed three long-term vegetation paths: early successional species dominance, late to early species transition and late successional species dominance. These suggest that modern forest composition results from Holocene trajectories occurring within each zone. Holocene mean FRI (mFRI) ranged from 222 to 258 years across the subdomain, resulting in old-growth forests ranging between 64% and 68%, depending upon the zone.

Paleoecological and contemporary results support that to make forest management more sustainable, current landscape heterogeneity that arises from millennial forest composition trajectories and fire cycle dynamics should be taken into account by down-scaling the previously established reference conditions.

## 1. Introduction

Conservation and sustainable management of ecosystems is a major concern for stakeholders and policy makers thus leading to the establishment of reference conditions used as guidelines for ecosystem restoration (Kuuluvainen, 2009, Pollock et al., 2012), conservation, and management (Goebel et al., 2005). In the province of Québec, these reference conditions consist of an average fire cycle and associated percent of old-growth forest (> 100-years-old) at the spatial scale of vegetation subdomains (average area of 77 587 km$^2$, Boucher et al., 2011). Old-growth forest stands, mostly composed of late successional species, shelter high biodiversity and, therefore, are valuable for conservation of vascular plants (Gauthier et al., 2000), non-vascular plants (Fenton et al., 2005), and animals (Drapeau et al., 2009). These

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reference conditions are used by forest managers as a scientific framework for measuring and bridging the gap between natural and managed forest landscapes, the main goal of which is maintaining these forests within their natural range of variability according to the pre-industrial period (19th–20th C.).

In Québec, the western spruce-moss subdomain is one of the largest subdomains (154 184 km$^2$) located in the northwestern portion of Québec's commercial forests (Saucier et al., 2009). Its reference conditions have been established from inventory data covering the 19th–20th centuries and showed that pre-industrial landscapes prior to the advent of industrial forestry were composed of 89% resinous species, 9% mixed stands, and 2% broadleaf stands (Boucher et al., 2011). A 150-year fire cycle for the last 200–300 years was estimated for this subdomain using dendrochronology (Bergeron et al., 2001) and the resulting percentage of old-growth forests was ~49% (Boucher et al., 2011). Old-growth forests are mostly composed of late successional species such as balsam fir (*Abies balsamea* [L.] Miller) and black spruce (*Picea mariana* [Mill.] BSP). The latter species can also be considered as early successional (Gagnon and Morin, 2001). Conversely, early-successional forest stands are composed of jack pine (*Pinus banksiana* Lambert), black spruce, trembling aspen (*Populus tremuloides* Michaux), and paper birch (*Betula papyrifera* Marshall) that eventually transit into black spruce forests in lowlands and flat topography zones, and black spruce stands mixed with balsam fir in uplands (Cogbill, 1985, Saucier et al., 2009). In this subdomain, vegetation composition and fire regime are highly spatially heterogeneous. Indeed, vegetation distribution within the region is driven by topography, coupled with climate, soil conditions and disturbance regimes (Palik et al., 2000, Grondin et al., 2014). As the main disturbance, fire interacts with age-class distribution of the stands (Bergeron, 2000), which in turn influences the percentage of old-growth forests (Cyr et al., 2005). Fire effects also display high spatial heterogeneity in southern Québec and at vegetation subdomain scales (Bergeron et al., 2004, Gauthier et al., 2015). Interestingly, mixed and coniferous zones of western Québec are characterized by different fire regimes and contrasting vegetation trajectories that were established after the retreat of the last glaciers, and persisted during the Holocene (Carcaillet et al., 2010, Blarquez and Aleman, 2015). For this subdomain, there is therefore a need to increase the resolution of landscape analyses and their associated millennial trajectories to ascertain whether the short time period that is currently used to define reference conditions is sufficient to cover the natural variability of these forest ecosystems (Landres et al., 1999).

Indeed, reference conditions are based upon data that date back to the Little Ice Age (1600–1850 CE), when climate was cooler and drier, and fire frequency was higher than what is currently observed (Bergeron and Archambault, 1993). This type of climate differs from the forecasted one since the predicted future climate of Québec is likely to be characterized by higher temperature and higher precipitation (IPCC, 2013). However, the increase in precipitation would not necessarily offset the increase in temperature, thereby leading to potentially higher fire activity (Girardin and Mudelsee, 2008). As wildfire frequency and intensity are major drivers of forest dynamics, a modification of fire regimes can deeply modify forest composition and dynamics for example by favoring the establishment of post fire early successional species (Cogbill, 1985). Thus, the choice of baseline data that are used to define management targets is critical and should provide information regarding the state of the targeted ecosystem, regardless of whether it is currently stable or transient (Gillson and Marchant, 2014). There is then a need for a higher temporal coverage of the above-mentioned reference conditions. Long-term information regarding ecosystem dynamics, therefore, can inform ecosystem range of variability according to past climate and fire regime changes (Dearing and Zolitschka, 1999). Thus, paleoecology represents an important source of data and methodological approaches for providing multi-millennial information on ecosystem functioning and improving guidelines for biodiversity conservation and management (Willis et al., 2010).

Here we used pollen analysis for long-term vegetation reconstructions in order to bring insights regarding post-glacial vegetation dynamics (Carcaillet et al., 2010) and to reconstruct regional vegetation trajectories that are followed by forests (Jamrichová et al., 2017). Charred particles that are contained in lake sediments and peatlands cores were used to reconstruct the Holocene Fire Return Interval (FRI) (Ali et al., 2012) and to calculate the long-term dynamics of old-growth forests within the landscape (Cyr et al., 2009).

We hypothesize that regional differentiation of vegetation in time and space would occur within the western spruce-moss subdomain under the multi-scalar influence of the environment, climate, and disturbances regimes. These regional differences would result from ecological legacies that have persisted after the retreat of Lake Barlow-Ojibway (i.e., ~8000 cal. years BP in the area; by convention, the present is 1950 CE). If long-term vegetation and fire dynamics explain current landscape heterogeneity, then this data will help to redefine current forest management targets that would comply with ecosystem-based management principles and objectives (Cyr et al., 2009, Bergeron and Fenton, 2012). Therefore, to inform forest managers regarding the long-term dynamics of ecosystems, the Holocene history of boreal forest ecosystems should be reconstructed. In particular, our aims are to (1) highlight and describe current landscape heterogeneity in the western spruce-moss bioclimatic subdomain forest of Québec, (2) to define and classify Holocene vegetation trajectories that have led to current vegetation heterogeneity, (3) to reconstruct FRIs to identify homogeneous fire regimes and analyze their consequences on vegetation distribution and finally (4) estimate the range of variability of the percentage of old growth forest for redefining reference conditions based on Holocene variability.

## 2. Material and methods

### 2.1. Study area

The western spruce-moss subdomain covers 154 184 km$^2$ of Québec, extending from 70°W to 80°W and from 48°N to 52°N (Fig. 1). This territory ranges from mixedwood boreal forest in the south to the spruce-lichen subdomain in the north (Saucier et al., 2009), which corresponds to the northwestern portion of Québec's commercial forests. Climate is characterized by low annual temperatures that range from −5 °C to 3 °C, with a clear North-South gradient. Total precipitation exhibits an East-West gradient, i.e., from 1300 mm to 600 mm, which is linked to increasing distance from the Atlantic Ocean (Grondin et al., 2007a). Elevation ranges from 15 m a.s.l. (above sea level) with a flat topography in the West to 630 m a.s.l. with a hilly topography in the East. The northwestmost region is dominated by organic deposits that diminish eastward. The Clay Belt is located in the southwest part of the study area and is characterized by a layer of clay left by the pro-glacial Lake Barlow-Ojibway. The central and eastern parts of the study area are dominated by till. Wildfires are abundant in the northern part of the study area and are less abundant elsewhere, particularly in the western part dominated by peatlands (Gauthier et al., 2015).

### 2.2. Contemporary zonation of the ecological districts

All modern data that are used were provided by the *Ministère des Forêts, de la Faune et des Parcs* (Ministry of Forests, Wildlife and Parks) of Québec and are defined at the district scale (Grondin et al., 2007a). Photo-interpretation of 1:60 000 scale surficial deposits and the analysis of 1:50 000 scale physiography on topographic maps permitted delineation of ecological districts (Robitaille, 1988). The study area is composed of 440 ecological districts, which have a mean surface of 300 km$^2$, and that have been characterized with respect to their current vegetation, climate, physical environment, and natural and human