Contemporary Issues in Québec's Temperate Forest — Part 1: Profile of the Forests

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ABSTRACT

We propose a series of papers presenting the main issues for Québec's temperate forest arising from the multiplicity of rapid environmental and socioeconomic changes. This first paper presents a brief profile of Québec's forests to establish a basis for the reflections presented in the remaining papers. Compilations show that the area dominated by deciduous species typical of the Northern temperate zone accounts for 8.8% of the province's total forest, and that these species are also found mixed with coniferous species on 4.9% of the territory. The disturbances affecting these forests are generally more partial than severe. The most abundant species include shade-tolerant hardwoods such as sugar maple (*Acer saccharum* Marsh., 152.4 Mm^3), red maple (*Acer rubrum* L., 141.5 Mm^3), yellow birch (*Betula alleghaniensis* Britt., 135.6 Mm^3) and American beech (*Fagus grandifolia* Ehrh., 27.5 Mm^3). A demographic analysis shows that populations of the first 3 species have declined slightly in recent decades, whereas the American beech has tended to proliferate. Sugar maple and American beech are likely to become more abundant toward the northern boundary of their range, possibly due to climate change. However, beech bark disease may hinder the progression of the American beech in Québec.

Keywords: deciduous forest, mixed forest, forest map, forest condition, forest disturbances

RÉSUMÉ

Nous proposons une série d'articles qui présentent les principaux enjeux pour la forêt tempérée du Québec face aux changements environnementaux et socio-économiques multiples et rapides. Ce premier article brosse un portrait sommaire de la forêt québécoise afin d'établir les fondements de la réflexion présentée dans les suivants. Les compilations révèlent que la forêt dominée par les essences feuillues typiques de la zone tempérée nordique représente 8,8 % du territoire forestier de la province, et que ces essences se trouvent aussi en mélange avec des essences résineuses sur 4,9 % du territoire. Les perturbations que subissent ces forêts sont plus souvent partielles que sévères. Les essences les plus abondantes incluent les essences feuillues tolérantes à l'ombre comme l'érable à sucre (*Acer saccharum* Marsh., 152,4 Mm^3), l'érable rouge (*Acer rubrum* L., 141,5 Mm^3), le bouleau jaune (*Betula alleghaniensis* Britt., 135,6 Mm^3) et le hêtre à grandes feuilles (*Fagus grandifolia* Ehrh., 27,5 Mm^3). L'analyse de leur démographie révèle chez les trois premières un léger déclin au cours des dernières décennies; en revanche, le hêtre à grandes feuilles tend à proliférer. Par ailleurs, l'abondance de l'érable à sucre et du hêtre à grandes feuilles devrait augmenter à la limite nord de leur aire de répartition, possiblement en raison des changements climatiques. La maladie corticale du hêtre pourrait toutefois freiner la progression du hêtre à grandes feuilles au Québec.

Mots clés: forêt mixte, forêt décidue, carte forestière, état de la forêt, perturbations forestières

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Introduction

Forests are currently subjected to a multiplicity of rapid changes including: climate change and its impacts on the main abiotic (fire, drought wind, snow and ice) and biotic (insects and pathogens) agents of disturbance; biological invasions including those caused by global trade; increased air pollution caused by sulphur and nitrogen oxides, volatile organic compounds, carbon monoxide and fine particles among others; variations in the populations of certain forest-dwelling herbivores; intensification of forestry operations and the fight against wildfires and insect infestations; and land use changes. All these changes can have significant impacts for the status and functioning of forest ecosystems (Trumbore *et al.* 2015; Seidl *et al.* 2017; Janowiak *et al.* 2018; Danneyrolles *et al.* 2019; Reed *et al.* 2021; Coughlin *et al.* 2023; Williams *et al.* 2023; Cui *et al.* 2024).

Given the impacts that these changes have already had for sustainable forest management, and those yet to come, adaptation strategies are needed. However, because of lack of knowledge and uncertainty surrounding the future of the forests in an ever-changing environment, the task of preparing these strategies is challenging and concerns not only ecological factors but also social, political and economic aspects (Himes *et al.* 2023).

To help forest managers as they address these challenges, we propose a series of papers setting out the issues we feel are important for Québec's temperate forest. We have targeted this particular sector of the forest because its dynamics and disturbance regime differ from those of the boreal forest. Although our analysis is limited to Québec's forest due to the province-specific content and sources of the data used, it is nevertheless also relevant to forests of the same type in other Canadian provinces and in the northeastern American states (Fig. 1).

This first paper presents a brief profile of the composition, age structure and disturbance regime of Québec's forests. Its main aim is to lay the foundations for the reflections presented in the other papers, which will consider the forest and land management issues raised by contemporary environmental changes (biological invasions, climate change and air pollution) and socioeconomic changes. The last paper in the series will review the main documented impacts of silvicultural treatments for Québec's temperate forest and will identify the potential and limitations of silvicultural actions.

When this series of papers is considered collectively, we believe readers will find all the basic elements they need to understand the contemporary issues arising from global changes in these types of forests, and to prepare adaptation strategies designed to ensure that these forest ecosystems are managed in a sustainable way.

Methodology

To lay the foundations for reflections on the issues facing Québec's temperate forest as a result of contemporary global changes, we produced brief profiles of the composition, age structure and disturbance footprint in the province's forests under management, using the ecoforest map and the results of inventories carried out by the Ministère des Ressources naturelles et des Forêts (MRNF). In addition, we examined recent changes to the forest canopy and the demography of the main deciduous species found in the northern temperate zone. This profile complements those produced for Québec's forest under management (MRNF 2009b) and for the province's deciduous and mixed forest (Boulet 2015; Boulet and Pin 2015).

The ecoforest map serves as the primary source of information for forest management in Québec (MRNF 2009a; MFFP 2015, 2020a). Over the past 50 years, the entire territory has been analyzed every decade or so from black-and-white or infrared photographs (scale: ~1:15000). Polygons with common characteristics regarding forest attributes (composition, density, age, height), soil parent material, soil drainage, land slope, historical disturbances and ecological type are delineated and characterized. Water bodies, farmland, unproductive land, roads and other non-forested areas, are also delineated. Photo-interpretation follows standard protocols and is verified using a network of checkpoints that photo-interpreters visit to validate information. Stand characteristics, such as stem density, basal area, and wood volume by species, are estimated for each polygon of the ecoforest map based on compilations of forest inventory data conducted every decade. These inventories consist of a land-based survey of the forest from tens of thousands circular sample plots each covering an area of 400 m^2 (MFFP 2016a, 2022a, 2022b), as compilation methods have evolved over time (MFFP 2017).

Composition, age structure and tree size

We compiled the forest area under management using the original ecoforest map from the forest inventory of southern Québec (downloaded version of March 8, 2022, MFFP 2022c). The map was produced almost in its entirety by photo-interpretation of the area using aerial photographs taken between 2002 and 2017. Using information on canopy type (Deciduous [D], mixed [M] and coniferous [C]) and stand species groupings, we categorized each polygon of the ecoforest map into one of seven canopy subtypes (Table 1): deciduous canopy dominated by tolerant deciduous species (D-TD), deciduous canopy dominated by intolerant deciduous species (D-ID), deciduous canopy dominated by non-commercial deciduous species (D-NcD), mixed canopy dominated by tolerant deciduous species (M-TD), mixed canopy dominated by intolerant deciduous species (M-ID), mixed canopy dominated by conifers (M-C) and lastly, coniferous canopy (C).

A list of 46 exploitable commercial species identified in Québec is shown in Table 2, with their common and scientific names, their 3-character species code used for forest inventories in Québec, the category used in this paper for each species, and the forest zone with which they are typically associated. Shade-intolerant deciduous species (ID) include paper birch, grey birch and *Populus* spp., i.e., mainly species typical of the boreal zone. Shade-tolerant deciduous species (TD) include sugar maple, red maple, yellow birch, American beech, northern red oak and basswood. These deciduous species, typical of the northern temperate zone, are not all shade-tolerant but have been grouped under this heading in Québec's forest inventories (MRNF 2009a; MFFP 2015, 2020a). Despite the confusion surrounding the shade tolerance of some species, we used the terms "tolerant deciduous" (TD) and "intolerant deciduous" (ID) in the compilations to refer to these deciduous species groups because they reflect current practice. Most coniferous species (C) are typical of the boreal zone, but some, like the eastern white pine or eastern hemlock, are more typical of the northern temperate zone than of the boreal zone. We also included productive forest areas with undetermined canopy type (REGEN, height < 7 m), as well as unproductive forest areas (UFA: alder groves and bare land) and forest areas used for non-forestry purposes (FAUNFP).

In addition, we compiled stand age structures for these canopy subtypes, also using the ecoforest map. Age class covers both stand structure and the age of the trees in the stands (MFFP 2015). Stand structure is referred to as regular (even-aged) if the trees are all in the same age class, and irregular or storied (uneven-aged) if the trees are in different age classes. We considered only the age class of the upper story of layered stands. Age class is usually undetermined (IND) for stands measuring ≤ 2 metres in height. Using this information, we established the following general age classes: 10 = 0–20 years; 30 = 21–40 years; 50 = 41–60 years; 70 = 61–80 years; 90 = 81–100 years; 120 = 101 years and over; YI = young uneven-aged or irregular stand (origin ≤ 80 years); OI = uneven-aged or irregular old-growth stand (origin > 80 years).

We compiled the total gross merchantable volume (in Mm^3) for the province and the average gross merchantable volume per stem (in $dm^3 \cdot stem^{-1}$), by species and by canopy subtype, using the results of the inventories associated with the original

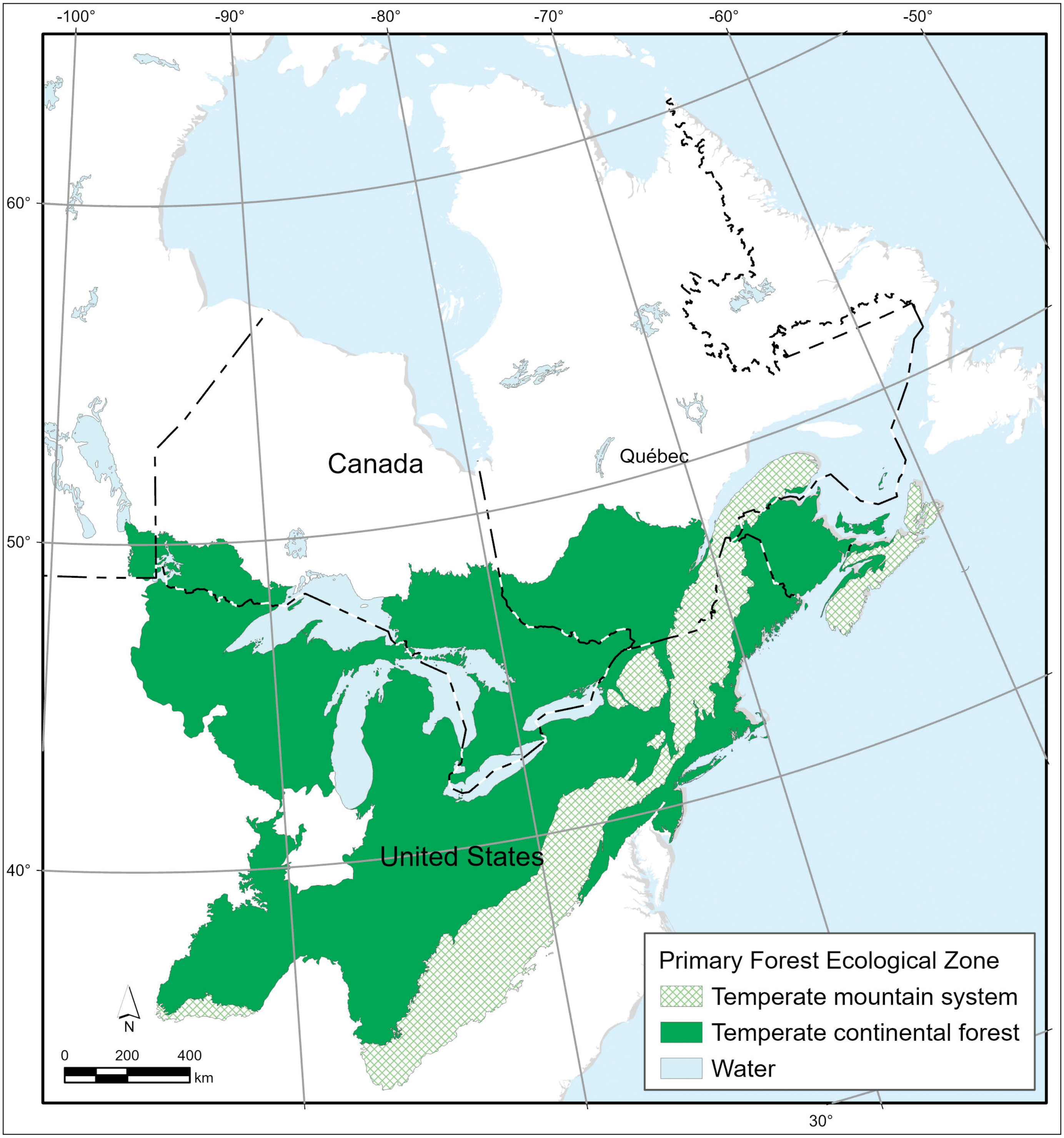

Fig. 1. Temperate continental forest and temperate mountain systems ecological zones in North America, as defined by the Food and Agriculture Organization of the United Nations (FAO 2022). Digital vector data [1:10,000,000].

ecoforest map (MFFP 2022c). This component of the profile is therefore based in part on the stand-based methodology compilations produced from the forest inventory of southern Québec (MFFP 2017), which took the form of a land-based survey of the forest from roughly 100,000 circular sample plots each with an area of 400 m^2 (MFFP 2022b).

To obtain a more detailed profile of stands with a significant percentage of temperate zone deciduous species, we subdivided the D-TD and M-TD canopy subtypes into 15 broad species groups based on the percentage of sugar maple (SM), yellow birch (YB), other TD species, ID species and, lastly, non-commercial deciduous species (NcD) that the photo-interpreter identified in the stand. We created an additional group for tolerant deciduous and coniferous plantations invaded by other species groups and subsequently classified in the M-TD canopy subtype.

Disturbance regimes

We also used the original ecoforest map to compute the proportion of productive forest land by natural disturbance or human intervention, as well as the canopy subtype. This approach does not allow for consideration of disturbances affecting areas smaller than the minimum mapping area, or unlisted past disturbances that cannot be identified by photo-interpretation. A natural disturbance or human intervention was classified as “initiating” if it removed more than 75% of the stand’s basal area, and as “partial” if it removed between 25% and 75%. Using Oliver and Larson’s (1996) terminology, an initiating disturbance or intervention is deemed major because it leads to stand replacement, whereas a partial disturbance is deemed minor because it leaves most of the trees standing. Frequent non-serious disturbances, such as those caused by the death of a standing tree (e.g., Seymour *et al.* 2002), are not noted on the map.

With regard to initiating disturbances and interventions, we grouped all types of cuts under the heading of clearcuts. We added the very small number of polygons initiated by ice storm to the “undetermined” group. Other initiating disturbances included burn, plantation, severe infestation, total windthrow, agricultural wildland and total dieback.

For partial disturbances and interventions, we grouped all types of cuts under the heading of partial cuts, and planting, enrichment and fill planting were all grouped under the heading of enrichment. Other partial disturbances or interventions include mild infestations, precommercial thinning, partial windthrow, partial dieback, partial burn and partial ice storm damage.

Recent changes to the forest canopy

We characterized recent changes to the forest by canopy type, using data from the tessellate forest information system known as SIFORT (MFFP 2022d). SIFORT is derived from systematic sampling of past ecoforest maps using polygons measuring 15 seconds of latitude by 15 seconds of longitude, over an average area of roughly 14 hectares. The information assigned to each polygon (tesserla) created is that from past ecoforest maps (canopy type, species grouping, age class, etc.) from the centroid of the tesserla. Using this database, we characterized changes to the forest by type of canopy, from the first ecoforest map (prepared from aerial photographs taken from 1950 to 1978) to the fourth ecoforest map (prepared from aerial photographs taken from 2000 to 2015). Canopy type is the basic criterion of forest stratification, and, unlike species groupings, its classification had not changed since the first inventory (Pelletier *et al.* 2007). We also considered changes to the size of unproductive forests and forest areas not used for forestry.

Demographics of the main temperate deciduous species

We prepared a demographic profile of the four main tolerant deciduous species (sugar maple, red maple, yellow birch and American beech) for each bioclimatic subdomain in Québec’s ecological classification system (MFFP 2020b). To do this, we compiled the diameter distributions showing the average number of living stems per hectare for each 2-cm diameter class using temporary sample plot data from the second (1981–1994) and fourth (2001–2018) ecoforest inventories carried out in southern Québec (MFFP 2022a, 2022b). The first forest inventory (1970–1983) carried out in Québec has not been published due to methodological differences. The databases include measurements taken in almost 100,000 sample plots during

Table 1. Categorization of the area according to canopy subtype, canopy type and terrain category.

Canopy subtype	Definition
Deciduous canopy dominated by tolerant deciduous species (D-TD)	Deciduous species make up more than 75% of the basal area of the stand, and more than 50% of the deciduous portion is made up of tolerant deciduous species.
Deciduous canopy dominated by intolerant deciduous species (D-ID)	Deciduous species make up more than 75% of the basal area of the stand, and more than 50% of the deciduous portion is made up of intolerant deciduous species.
Deciduous canopy dominated by non-commercial deciduous species (D-NcD)	Deciduous species make up more than 75% of the stand’s basal area, and more than 50% of the deciduous portion is made up of non-commercial deciduous species.
Mixed canopy dominated by tolerant deciduous species (M-TD)	Coniferous species make up 25% to 50% of the basal area of the stand, and more than 50% of the deciduous portion is made up of tolerant deciduous species.
Mixed canopy dominated by intolerant deciduous species (M-ID)	Coniferous species make up 25% to 50% of the basal area of the stand, and more than 50% of the deciduous portion is made up of intolerant deciduous species.
Mixed canopy dominated by conifers (M-C)	Coniferous species make up 50% to 75% of the basal area of the stand.
Coniferous canopy (C)	Coniferous species make up more than 75% of the basal area of the stand.
Regeneration (REGEN)	Stand less than 7 m high with an indeterminate canopy type.
Unproductive forest area	Alder groves and bare land.
Forest area used for non-forestry purposes	Non-forested land (urban area or area devoted to industrial, mining, agricultural, tourist or resort activities, etc.).

Table 2. List of commercially exploitable tree species in Québec.

Category*	Species	Scientific name	Code†	Ecological zone‡
Intolerant deciduous species	Paper birch	*Betula papyrifera*	BOP	Boreal
	Grey birch	*Betula populifolia*	BOG	Boreal
	Eastern cottonwood	*Populus deltoides*	PED	Temperate
	Large-toothed aspen	*Populus grandidentata*	PEG	Temperate
	Balsam poplar	*Populus balsamifera*	PEB	Boreal
	Trembling aspen	*Populus tremuloides*	PET	Boreal
	Hybrid poplars	*Populus sp.*	PEH	N. A.
Tolerant deciduous species	Yellow birch	*Betula alleghaniensis*	BOJ	Temperate
	Bitternut hickory	*Carya cordiformis*	CAC	Temperate
	Shagbark hickory	*Carya ovata*	CAF	Temperate
	Black cherry	*Prunus serotina*	CET	Temperate
	Bur oak	*Quercus macrocarpa*	CHG	Temperate
	Swamp white oak	*Quercus bicolor*	CHE	Temperate
	White oak	*Quercus alba*	CHB	Temperate
	Northern red oak	*Quercus rubra*	CHR	Temperate
	Sugar maple	*Acer saccharum*	ERS	Temperate
	Silver maple	*Acer saccharinum*	ERA	Temperate
	Black maple	*Acer nigrum*	ERN	Temperate
	Red maple	*Acer rubrum*	ERR	Temperate
	White ash	*Fraxinus americana*	FRA	Temperate
	Red ash	*Fraxinus pennsylvanica*	FRP	Temperate
	Black ash	*Fraxinus nigra*	FRN	Temperate
	American beech	*Fagus grandifolia*	HEG	Temperate
	Butternut	*Juglans cinerea*	NOC	Temperate
	White elm	*Ulmus americana*	ORA	Temperate
	Rock elm	*Ulmus thomasii*	ORT	Temperate
	Slippery elm	*Ulmus rubra*	ORR	Temperate
	Eastern hop-hornbeam	*Ostrya virginiana*	OSV	Temperate
	Basswood	*Tilia americana*	TIL	Temperate
Conifers	White spruce	*Picea glauca*	EPB	Boreal
	Norway spruce	*Picea abies*	EPO	N. A.
	Black spruce	*Picea mariana*	EPN	Boreal
	Red spruce	*Picea rubens*	EPR	Temperate
	European larch	*Larix decidua*	MEU	N. A.
	Hybrid larch	*Larix sp.*	MEH	N. A.
	Japanese larch	*Larix leptolepis*	MEJ	N. A.
	Tamarack	*Larix laricina*	MEL	Boreal
	Eastern white pine	*Pinus strobus*	PIB	Temperate
	Pitch pine	*Pinus rigida*	PID	Temperate
	Pin gris	*Pinus banksiana*	PIG	Boreal
	Red pine	*Pinus resinosa*	PIR	Temperate
	Scots pine	*Pinus sylvestris*	PIS	N. A.
	Eastern hemlock	*Tsuga canadensis*	PRU	Temperate
	Balsam fir	*Abies balsamea*	SAB	Boreal
	Eastern white cedar	*Thuja occidentalis*	THO	Temperate

* Tree species category used for forest inventories in Québec.
† Code used to designate species for forest inventories in Québec.
‡ Ecological zone of distribution of the species (temperate or boreal for native species, not applicable [N. A.] for exotic species).

each measurement campaign, for a total of more than 215,000 plots compiled in the two campaigns used for the analysis. We compiled data on saplings (stems with a diameter of 2 to 8 cm, measured at a height of 1.3 m, inventoried in a 40 m² subplot) and on merchantable stems (stems with a diameter [measured at a height of 1.3 m] ≥ 9.1 cm, inventoried in a 400 m² plot).

For each species, we calculated the average number of stems per hectare per diameter class, for each subdomain in Québec's ecological classification system, considering only the system's regional landscape unit as the sampling stratum (Fig. 2). This type of *a posteriori* stratification is similar to that produced by a stratified sampling plan (MFFP 2016a). The compilation was produced in the R environment (R Core Team 2024) using the survey package, version 4.0 (Lumley 2004), with the regional landscape unit area as a correction factor for the final population. In the case of diameter classes and species not identified in a given sample plot, we used a null value in our compilations. For information purposes, a regional landscape unit tends to be fairly homogeneous in terms of relief, altitude, geomorphology, hydrography and vegetation (MFFP 2021). Québec has 364 regional landscape units covering an average area of roughly 4000 km².

For a tree population, analysis of the number of trees in successive diameter classes of equal widths has long been used as a method to describe population dynamics (De Liocourt 1898, 1900; Picard and Gasparotto 2016). Liocourt's law states that, for a given tree population, the number of trees in successive diameter classes of equal width forms a decreasing geometric series, with a fairly constant ratio between successive classes. So-called "sustainable" (i.e., balanced) classes are those where the geometrics are stabilized through a balance of recruitment, growth and mortality (Manion and Griffin 2001; Rubin *et al.* 2006; Cale *et al.* 2014). On a graph, the logarithmic conversion of the number of trees per diameter class produces a straight line (Leak 2002). When a plateau forms in the centre of the curve, this is known as a rotated sigmoid (Leak 2002). The concept of balance in Liocourt's law, developed originally for large-scale analysis of fir forests in France, has been used by numerous researchers to study tree population stability across various spatial scales ranging from landscapes to subcontinents (Manion and Griffin 2001; Garnas *et al.* 2011).

Data handling and production of figures

Most of the analyses were carried out in the R environment (R Core Team 2024), using packages *dplyr* for data handling (Wickham *et al.* 2023), *sf* for vectorized spatial data handling (Pebesma 2018; Pebesma and Bivand 2023), *raster* for rasterized spatial data handling (Hijmans 2023), as well as *ggplot2* and *cowplot* for production of the figures (Wickham 2016; Wilke 2024). The maps were produced using QGIS (version 3.4).

Results and discussion

Forest stands

Québec is located at the junction of the northern temperate vegetation zone and the boreal zone (Fig. 2). TD species therefore dominate the landscape in the south of the province (Fig. 3), where these species are at the northern limit of their range. Further north, they gradually give way to ID and C species, which are better adapted to the colder temperatures of the boreal zone. C species dominate in the boreal zone but are still plentiful further in the south of the province, in the northern

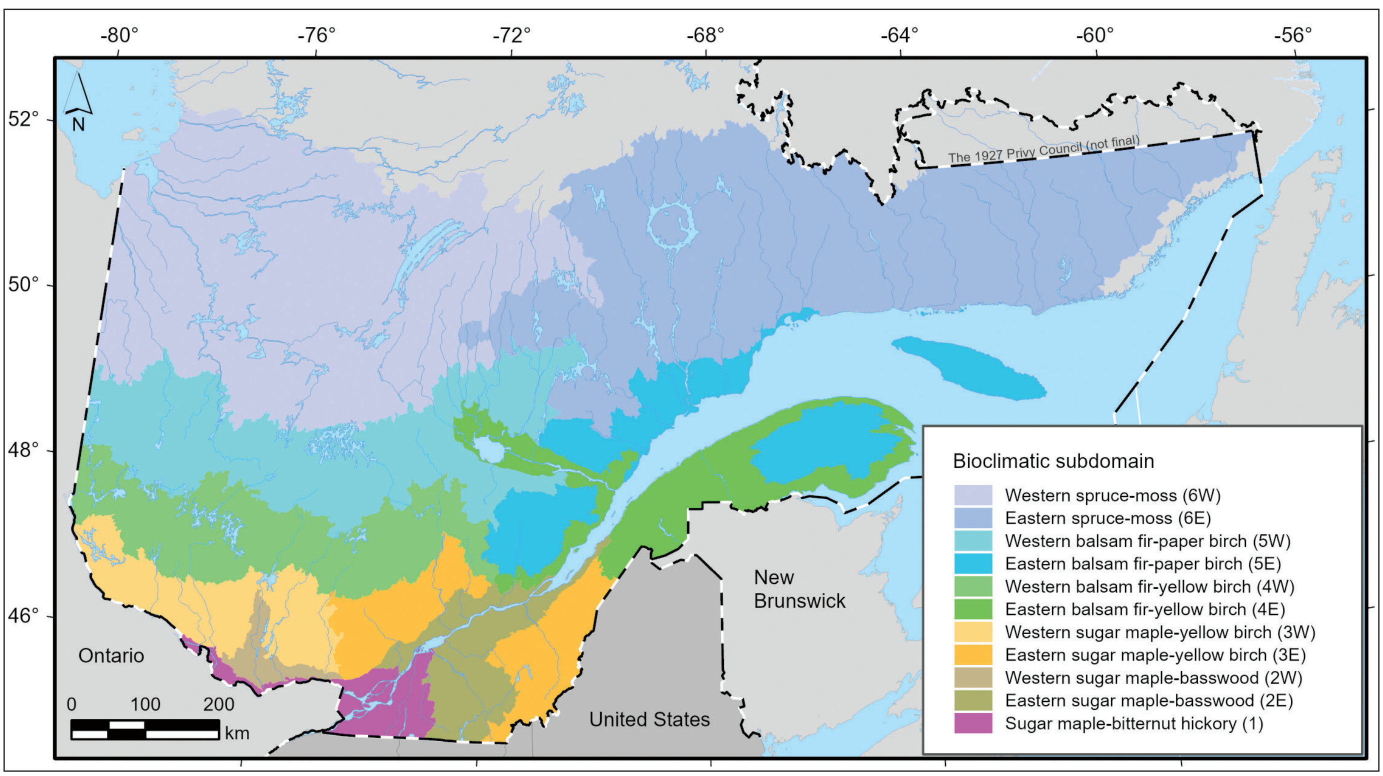

Fig. 2. Bioclimatic subdomains defined according to Québec's ecological classification system. Domains are defined according to the dominant vegetation type at the final stage of succession on mesic sites, while subdivisions into western and eastern subdomains are based on differences in precipitation regimes and natural disturbances that result in appreciable differences in vegetation cover (MFFP 2021). Domains 1 to 4 are part of the northern temperate vegetation zone, while domains 5 and 6 are part of the boreal zone.

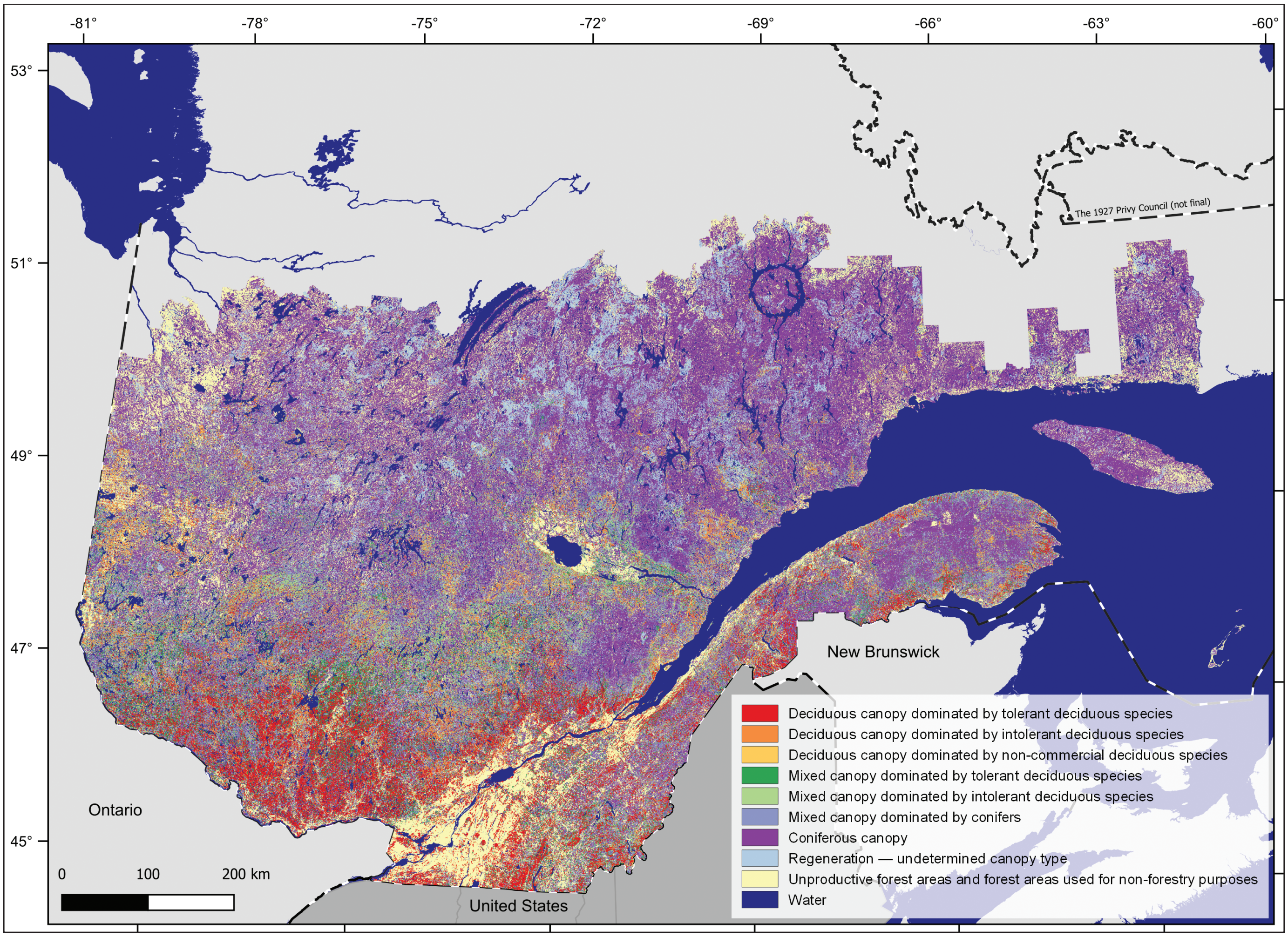

Fig. 3. Contemporary areas occupied in Québec, by canopy subtype or land category. Data source: Original ecoforest map of Québec.

temperate zone. Some isolated stands dominated by TD species can also be found in the northern portion of the boreal zone. The forest mosaic is therefore influenced to a large extent by the temperature gradient in southern Québec, and also by site characteristics and past disturbances, both of which have influenced the present-day distribution of species across the region.

At the provincial level, the D, M and C canopy types account respectively for 15.3%, 25.1% and 50.0% of all productive forests, and 9.6% of the productive forest is currently undergoing regeneration (Table 3). Of the D-type canopies, the D-TD subtype accounts for 8.8% of the province's total forest, and the D-ID subtype for 5.9% of the forest.

The D-TD canopy subtype is composed mostly of sugar maple stands (54.2%), yellow birch stands (11.6%) and stands dominated by other TD species (Table 4). Sugar maple and yellow birch also occur abundantly in the M-TD subtype, which accounts for 4.9% of the province's productive forest (Table 3). In this subtype, 9.4% are mixed stands dominated by sugar maple, 33.2% are mixed stands dominated by yellow birch, and 57.4% are mixed stands dominated by other TD species (Table 5).

Of the 10 broad species groups dominated by sugar maple (23 012 km²), so-called pure sugar maple stands (i.e., with less than 25% of other species) are clearly in a minority, accounting for just 17% of the group, or 3900 km² (Tables 4 and 5). This percentage, although small, may also have been enhanced by anthropic disturbances in the 19th and 20th centuries (e.g., Brisson and Bouchard 2003). At the time, numerous maple stand companion species were targeted for harvesting (e.g., white pine and oak for shipbuilding, hemlock for tanneries), while sugar maple trees were kept standing for maple syrup production in privately owned forests. There was also very little interest in processing sugar maple into lumber before the 1960s (Boulet 2015).

Species abundance and tree size

The 20 most abundant species account for 99% of the province's gross merchantable volume, estimated at 3257.7 Mm³ (Table 6). Of these, the seven most abundant coniferous species account for nearly 70% of the total gross merchantable volume, all species combined, while each of the groups composed of seven tolerant deciduous and the four most abundant intolerant deciduous species account for roughly 15% (Table 6). In order, the nine most abundant species are black spruce (986 Mm³), balsam fir (723 Mm³), paper birch (246 Mm³), trembling aspen (212 Mm³), white spruce (199 Mm³), sugar maple (153 Mm³), red maple (142 Mm³), yellow birch (136 Mm³) and jack pine (120 Mm³); together, they account for 90% of the total gross merchantable volume. American beech (27.5 Mm³), red oak (20.5 Mm³), black ash (8.8 Mm³) and American basswood (8.2 Mm³) are the other four tolerant deciduous species classified among the most

Table 3. Contemporary forest area in southern Québec, by canopy subtype and land category.

Land category	Canopy subtype*	Area × 000 km²	Area %
Productive forest area	Deciduous canopy dominated by tolerant deciduous species (D-TD)	38.6	8.8
	Deciduous canopy dominated by intolerant deciduous species (D-ID)	26.0	5.9
	Deciduous canopy dominated by non-commercial deciduous species (D-NcD)	2.6	0.6
	Mixed canopy dominated by tolerant deciduous species (M-TD)	21.6	4.9
	Mixed canopy dominated by intolerant deciduous species (M-ID)	35.5	8.1
	Mixed canopy dominated by conifers (M-C)	53.1	12.1
	Coniferous canopy (C)	219.5	50.0
	Regeneration — undetermined canopy type (REGEN)	42.3	9.6
	Total	**439.2**	**100.0**
Unproductive forest area		55.3	–
FAUNFP		32.4	–

* Data source: Original ecoforest map. The composition is therefore determined by photo-interpretation. Shade-intolerant deciduous (ID) species include paper birch, grey birch and *Populus* sp.; shade-tolerant deciduous species (TD) include sugar maple, red maple, yellow birch, American beech, northern red oak and basswood. FAUNFP = forest area used for non-forestry purposes.

Table 4. Contemporary area occupied by the D-TD canopy subtype (deciduous canopy dominated by tolerant deciduous species), according to the stand species grouping. Deciduous species make up more than 75% of the basal area of these stands, and more than 50% of the deciduous portion is made up of tolerant deciduous species. The composition is grouped according to the proportion (more than 50% or more than 25%) of the species or group of species in the deciduous portion of the stand.

Stand species grouping	Proportion >50%	Proportion >25%	Area × 000 km²	Area %
Sugar maple	SM	SM	3.9	10.0
Sugar maple with yellow birch	SM	YB	5.1	13.3
Sugar maple with tolerant deciduous species	SM	TD	10.2	26.3
Sugar maple with intolerant deciduous species	SM	ID	1.8	4.6
Sugar maple with non-commercial deciduous species	SM	NcD	0.01	0.03
Yellow birch	YB	YB	0.9	2.4
Yellow birch with sugar maple	YB	SM	1.8	4.6
Yellow birch with tolerant deciduous species	YB	TD	1.0	2.7
Yellow birch with intolerant deciduous species	YB	ID	0.7	1.9
Yellow birch with non-commercial deciduous species	YBJ	NcD	0.002	0.005
Tolerant deciduous species	TD	TD	5.9	15.2
Tolerant deciduous species with sugar maple	TD	SM	1.8	4.8
Tolerant deciduous species with yellow birch	TD	YB	1.1	2.8
Tolerant deciduous species with intolerant deciduous species	TD	ID	3.3	8.5
Tolerant deciduous species with non-commercial deciduous species	TD	NcD	1.1	2.9
Total — deciduous canopy dominated by tolerant deciduous species			**38.6**	**100.0**

Note: SM = sugar maple; YB = yellow birch; TD = shade-tolerant deciduous species other than sugar maple and yellow birch; ID = shade-intolerant deciduous species (paper birch, grey birch and *Populus* sp.); NcD = non-commercial deciduous species. The combination of maples (code ER) is included with sugar maple (code ERS), and red maple (code EO) as well as indeterminate deciduous species (code FX) are included among the tolerant deciduous species.

abundant, but they are much less abundant than the maples and yellow birch. White pine, which used to be an important symbol of forestry operations in Eastern Canada (e.g., Thompson *et al.* 2006), now accounts for just 49.7 Mm³, or nearly half the volume of cedar (91.1 Mm³), but still more than red spruce (35.0 Mm³), tamarack (22.6 Mm³) and hemlock (18.2 Mm³).

This profile of gross merchantable volumes by species does not take into consideration the sometimes-significant differences between species in terms of volumes lost to decay or non-use (e.g., merchantable branches). The net volume of typical coniferous species in the boreal zone is generally between 4% and 6% less than the gross merchantable volume, compared to between 20% and 30% less for tolerant deciduous species typical of the northern temperate zone (BMMB 2022). Jack pine (9th, with 120 Mm³) would probably have ranked just above sugar maple (6th, with 153 Mm³) if net volumes had been calculated instead of gross volumes.

Table 5. Contemporary area occupied by the M-TD canopy subtype (mixed canopy dominated by tolerant deciduous species), according to the stand species grouping. Coniferous species make up 25% to 50% of the basal area of the stand, and more than 50% of the deciduous portion is made up of tolerant deciduous species. The composition is grouped according to the proportion (more than 50% or more than 25%) of the species or group of species in the deciduous portion of the stand.

	Proportion		Area	
Stand species grouping	**>50%**	**>25%**	**× 000 km²**	**%**
Sugar maple with conifers	SM	SM	0.1	0.3
Sugar maple with yellow birch and conifers	SM	YB	0.8	3.9
Sugar maple with tolerant deciduous and conifers	SM	TD	0.6	2.9
Sugar maple with intolerant deciduous and conifers	SM	ID	0.5	2.4
Sugar maple with non-commercial deciduous and conifers	SM	NcD	0.002	0.01
Yellow birch with conifers	YB	YB	1.7	7.8
Yellow birch with sugar maple and conifers	YB	SM	1.4	6.6
Yellow birch with tolerant deciduous and conifers	YB	TD	1.9	9.0
Yellow birch with intolerant deciduous and conifers	YB	ID	2.1	9.8
Yellow birch with non-commercial deciduous and conifers	YB	NcD	0.003	0.01
Tolerant deciduous species with conifers	TD	TD	5.0	23.2
Tolerant deciduous species with sugar maple and conifers	TD	SM	0.3	1.4
Tolerant deciduous species with yellow birch and conifers	TD	YB	1.1	5.1
Tolerant deciduous species with intolerant deciduous and conifers	TD	ID	3.6	16.8
Tolerant deciduous species with non-commercial deciduous and conifers	TD	NcD	1.5	6.8
Tolerant deciduous or coniferous plantation, overrun	TD	R	0.9	4.1
Total — mixed canopy dominated by tolerant deciduous species			**21.6**	100.0

Note: SM = sugar maple; YB = yellow birch; TD = shade-tolerant deciduous species other than sugar maple and yellow birch; ID = shade-intolerant deciduous species (paper birch, grey birch and *Populus* sp.); NcD = non-commercial deciduous species. The combination of maples (code ER) is included with sugar maple (code ERS), and red maple (code EO) as well as indeterminate deciduous species (code FX) are included among the tolerant deciduous species.

Sugar maple dominates volumes in the D-TD canopy subtype, while yellow birch and red maple dominate the deciduous portion of the M-TD subtype (Table 6). The volumes of these two species decrease gradually in the M-C, M-ID and C subtypes. Conversely, the volume of coniferous species increases in these canopy subtypes. Nearly 13% of the total volume is found in the D-TD canopy subtype, even though it accounts for less than 9% of the total forest area.

Trees of all species have an average gross merchantable stem volume of 1 to 2.5 times more in the D-TD canopy subtype than in the C subtype (Table 7). For most species, the average gross merchantable stem volume decreases gradually from the northern temperate zone in the south to the boreal zone in the north. In order, the average gross merchantable stem volume decreases gradually in the D-TD (315 dm³), M-TD, M-C, M-ID, D-ID and C (153 dm³) canopy subtypes. In order, white pine (939 dm³), large-toothed aspen (536 dm³), red pine (457 dm³), American basswood (430 dm³) and eastern hemlock (371 dm³) are the species producing the largest trees. Although these species are not responsible for the largest total gross merchantable volumes (volume), they all have the ability to produce large trees (Burns and Honkala 1990). Their high average stem volumes perhaps reflect an over-representation of large-diameter stems in the diameter distribution due to the difficulty of recruiting smaller trees in the population. The scarcity of white pine, red oak and eastern hemlock, among other things due to past overharvesting, firefighting, white-tailed deer overpopulation or the presence of new pests, is already well documented (MFFP 2016b). Large-toothed aspen is highly shade-intolerant, and the prevalence of partial cuts among the dominant disturbances in the northern temperate zone may limit its recruitment. As for eastern hemlock populations, they are maintained mainly through post-harvest stump sprouts rather than regeneration via seedling crops (Crow 1990). Yellow birch regeneration difficulties may also partly explain why this species' average stem volume (281 dm³) is higher than those of the other three dominant species in the northern temperate zone, namely sugar maple (233 dm³), red maple (128 dm³) and American beech (222 dm³). Balsam fir (85 dm³), black spruce (103 dm³) and paper birch (109 dm³) are the species with the smallest trees on average. This is due among other things to their more boreal character and the fact that they often grow in places where rigorous climate conditions limit tree growth. The fact that balsam fir trees are smaller, on average, than black spruce trees is very probably due to stand age, since fir forests were damaged significantly by the last spruce budworm outbreak (Duchesne and Ouimet 2008). The average size of tolerant deciduous, intolerant deciduous and coniferous trees is very similar (from 200 to 223 dm³) and very close to the average for all trees, estimated at 211 dm³.

Disturbance regimes

In Québec, an initiating disturbance or intervention has been identified for roughly one third (36.1%) of the total productive forest (Table 8). For these stands whose origins are known,

Table 6. Contemporary total gross merchantable volume (Mm^3) of the 20 most abundant species on productive forest land in southern Québec, by canopy subtype.

	Total gross merchantable volume, by canopy subtype* (Mm^3)								
Species	**D-TD**	**D-ID**	**D-NcD**	**M-TD**	**M-ID**	**M-C**	**C**	**REGEN**	**Total**
ERS	128.5	6.1	0.025	10.0	2.3	4.1	1.5	0.016	152.5
ERR	55.9	14.2	0.107	24.7	14.4	22.5	9.6	0.021	141.5
BOJ	60.8	8.7	0.062	31.3	11.5	17.6	5.5	0.005	135.6
HEG	22.7	0.8	0.008	2.2	0.2	1.2	0.3	0.005	27.5
CHR	14.3	1.0	0.001	2.3	0.4	1.9	0.6	0.013	20.5
FRN	2.9	1.2	0.006	1.5	1.0	1.6	0.6	0.002	8.8
TIL	6.4	0.6	0.001	0.6	0.2	0.4	0.1	0.003	8.2
Total TD	291.4	32.6	0.210	72.6	30.0	49.3	18.4	0.065	494.6
BOP	17.5	52.4	0.108	13.4	62.4	52.3	47.8	0.010	245.9
PET	14.1	71.0	0.116	6.4	53.2	32.9	34.6	0.013	212.3
PEG	6.2	6.0	0.011	1.5	2.3	2.1	0.9	0.006	19.1
PEB	0.8	2.1	0.009	0.5	1.8	2.4	2.4	0.001	10.0
Total ID	38.6	131.5	0.245	21.8	119.7	89.7	85.8	0.030	487.4
EPN	1.0	14.9	0.118	1.9	31.4	64.8	871.8	0.013	986.0
SAB	32.0	38.3	0.297	33.6	74.4	139.7	404.6	0.017	722.9
EPB	10.8	13.6	0.081	10.0	24.7	39.0	100.5	0.008	198.6
PIG	0.2	3.0	0.029	0.3	6.9	11.0	98.7	0.004	120.2
THO	5.9	3.0	0.027	8.2	6.3	22.4	45.3	0.010	91.1
PIB	6.1	2.5	0.008	5.7	4.0	17.0	14.3	0.039	49.7
EPR	3.9	0.9	0.020	4.3	2.3	10.3	13.3	0.003	35.0
MEL	0.7	0.3	0.015	0.6	1.0	2.8	17.2	0.004	22.6
PRU	7.2	0.5	0.006	4.5	0.5	4.1	1.4	0.013	18.2
Total C	67.8	77.0	0.601	69.2	151.6	311.2	1567.0	0.110	2244.5
Others	11.4	2.4	0.039	2.8	1.3	3.7	9.5	0.012	31.2
Total overall	**409.3**	**243.6**	**1.095**	**166.4**	**302.6**	**453.8**	**1680.7**	**0.217**	**3257.7**

* Canopy subtype: D-TD = deciduous canopy dominated by tolerant deciduous species; D-ID = deciduous canopy dominated by intolerant deciduous species; D-NcD = deciduous canopy dominated by non-commercial deciduous species; M-TD = mixed canopy dominated by tolerant deciduous species; M-ID = mixed canopy dominated by intolerant deciduous species; M-C = mixed canopy dominated by conifers; C = coniferous canopy; REGEN = regeneration — undetermined canopy type. See Table 2 for species codification.

most are the result of human intervention (23.4%), such as clearcutting (18.2%), planting (4.6%) or wildland (0.6%). The remaining stands (12.6%) are the result of natural disturbances, including total burn (10.4%), severe insect outbreaks (1.5%), total windthrow (0.7%) and, to a much lesser extent, total dieback (0.03%). The large wildfires that occurred in 2023 (affecting 13 000 km², or nearly 2% of Québec's forests) are not included in this profile. They were, however, concentrated in the western boreal zone (BFEC 2023). The D-TD canopy subtype is characterized by a larger percentage of stands of indeterminate origin (87.5%) compared to the D-ID, M and C subtypes, of which 28.3% to 37.1% were initiated by severe disturbances (Table 8).

The above observations reveal a latitudinal gradient in the disturbance regime: severe disturbances leave a greater footprint in the boreal zone than in the northern temperate zone (Fig. 4). In addition, individual disturbances generally cover larger areas. Couillard *et al.* (2022) also reported these trends in an extensive study of fire regimes in Québec: the largest and most frequent fires were observed in the western portion of the boreal zone, whereas the smallest and least frequent were observed in the northern temperate zone, especially the eastern portion. These authors estimated that the fire cycle was between 540 and 840 years in most of Québec's northern temperate zone, but around 300 years in the extreme western portion of the zone in Québec, i.e., the hottest and driest portion that contains more pine and red oak trees, which are better adapted to fires. Prior to this, Drever *et al.* (2006) estimated the large fire cycle to be nearly 500 years (area > 200 ha) in Témiscamingue, in the extreme western portion of Québec. The cycle was shorter (230 years) in white pine forest sites and longer (920 years) in sugar maple sites. Forests dominated by tolerant deciduous species in northeastern North America generally undergo few major or severe disturbances such as wildfires or windthrow over areas of several hectares (e.g., Frelich and Lorimer 1991; Seymour *et al.* 2002). Consequently,

Table 7. Contemporary average gross merchantable volume per stem (in $dm^3 \cdot stem^{-1}$) of the 20 most abundant species on productive forest land in southern Québec, by canopy subtype. Values in bold correspond to groups containing a volume of at least 1 Mm^3.

	Average gross merchantable volume per stem, by canopy subtype* ($dm^3 \cdot stem^{-1}$)								
Species	**F-FT**	**F-FI**	**F-NC**	**M-FT**	**M-FI**	**M-R**	**R**	**REGEN**	**Average**
ERS	**306**	**171**	168	**246**	**183**	**199**	**193**	235	**233**
ERR	**214**	**105**	83	**166**	**101**	**116**	**89**	129	**128**
BOJ	**332**	**263**	180	**321**	**269**	**276**	**233**	265	**281**
HEG	**229**	140	173	**257**	170	**226**	253	172	**222**
CHR	**592**	**316**	296	**449**	277	**302**	234	281	**457**
FRN	**224**	**130**	76	**145**	**127**	**117**	87	91	**150**
TIL	**500**	285	180	372	288	428	259	233	**430**
Average TD	**312**	**178**	137	**247**	**178**	**196**	**154**	**202**	**223**
BOP	**217**	**124**	84	**168**	**113**	**110**	**84**	163	**109**
PET	**521**	**333**	167	**462**	**315**	**288**	**236**	359	**298**
PEG	**636**	**444**	279	**608**	**561**	**543**	331	421	**536**
PEB	326	**293**	175	265	**281**	**246**	**244**	309	**265**
Average ID	**409**	**264**	147	**344**	246	228	156	309	223
EPN	**131**	**120**	67	**153**	**124**	**120**	**93**	114	**103**
SAB	**101**	**92**	78	**107**	**90**	**92**	**78**	72	**85**
EPB	**274**	**238**	166	**313**	**265**	**259**	**199**	192	**233**
PIG	327	**327**	134	308	**312**	**271**	**159**	335	**199**
THO	**315**	**190**	167	**280**	**219**	**215**	**202**	284	**234**
PIB	**1149**	**821**	693	**1168**	**929**	**994**	**761**	641	**939**
EPR	**239**	172	150	**223**	**201**	**203**	**177**	116	**202**
MEL	346	172	146	320	**204**	**224**	**159**	214	**176**
PRU	**425**	269	267	**308**	238	**343**	**394**	288	**371**
Average C	**323**	**217**	154	**319**	235	249	149	252	200
Other	**206**	**253**	145	**200**	**228**	**249**	**222**	**223**	**221**
Average overall	**315**	**221**	**148**	**286**	**225**	**232**	**153**	**242**	**211**

* Canopy subtype: D-TD = deciduous canopy dominated by tolerant deciduous species; D-ID = deciduous canopy dominated by intolerant deciduous species; D-NcD = deciduous canopy dominated by non-commercial deciduous species; M-TD = mixed canopy dominated by tolerant deciduous species; M-ID = mixed canopy dominated by intolerant deciduous species; M-C = mixed canopy dominated by conifers; C = coniferous canopy; REGEN = regeneration — undetermined canopy type. See Table 2 for species codification.

the natural conditions in these forests are rarely conducive to regeneration of shade-intolerant species.

The D-NcD canopy subtype, although relatively scarce, is usually generated by clearcutting (59.1%) or wildland (17.3%, Table 8). Most regenerating stands with undetermined species groups are also the product of human intervention (64.6%, including clearcutting [56.5%], wildland [4.1%] and planting [4.0%]). In cases involving natural disturbances (35.4%), the most common kinds are total burns (29.6%), followed by total windthrow (3.8%), severe outbreaks (1.9%) and dieback (0.1%).

Forests are also affected by partial disturbances and interventions. In Québec as a whole, partial disturbances or interventions affect roughly one fifth (20.6%) of the total productive forest (Table 9). In most cases where partial disturbances or interventions are known to have occurred, human intervention was the most common type (11.2%), including partial cuts (7.3%), precommercial thinning (3.7%) and enrichment planting (0.2%). The remainder (9.4%) were natural disturbances, namely less severe outbreaks (5.2%), partial windthrow (3.1%), partial dieback (0.7%) or partial burn (0.4%).

The partial disturbance/intervention footprint is greatest in the D-TD and M-TD canopy subtypes; nearly one third of these forests (31.5% to 37.6%) appear to have been disturbed in recent years (Table 9). In these stands, partial cutting is by far the main type of disturbance/intervention (23.4% to 34.9%). Minor outbreaks rank second (1.7% to 5.8%) and are also the main partial disturbance observed in M-ID and M-C canopy subtypes (8.9% to 11.7%), ahead of partial cuts (7.9% to 8.2%). C type stands, for their part, were mostly disturbed by partial windthrow (5.6%) and minor outbreaks (4.8%), with a similar percentage (5.6%) undergoing precommercial thinning. The spruce budworm (*Choristoneura fumiferana* Clemens) is by far the most common defoliator of coniferous species in Québec, and the forest tent caterpillar (*Malacosoma disstria* Hübner) is the most common defoliator of deciduous species (MRNF 2023). Given that the D-NcD canopy subtype and regenerating

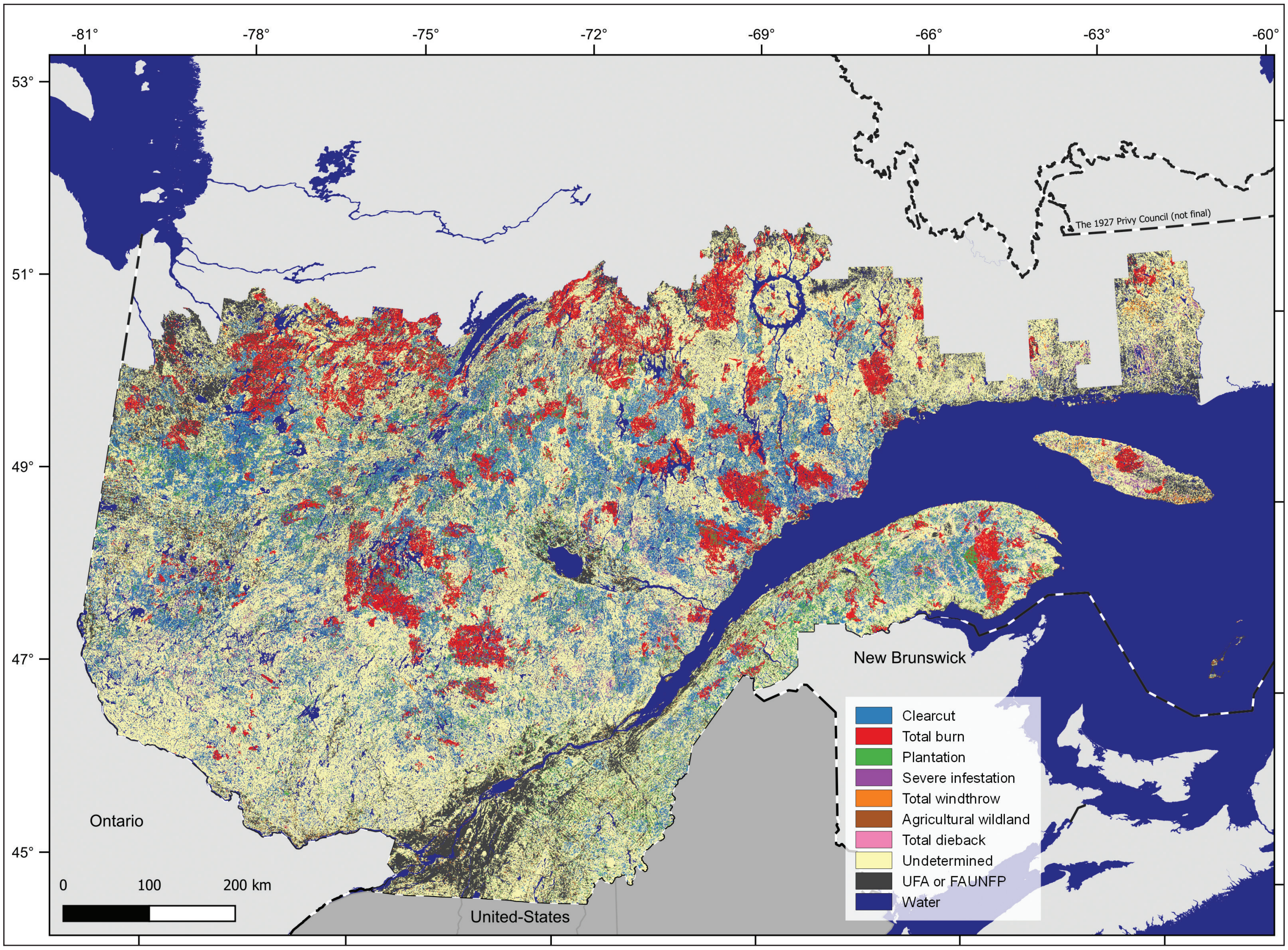

Fig 4. Contemporary footprint of initiating disturbances and interventions in southern Québec. Note: The major forest fires of 2023 (13 000 km²) are not shown; they were primarily located in the northwestern quadrant of southern Québec. Data source: Original ecoforest map. UFA = unproductive forest areas; FAUNFP = forest area used for non-forestry purposes.

Table 8. Contemporary proportion of productive forest land in southern Québec, by initiating disturbance or intervention and canopy subtype.

Canopy subtype	Area (× 000 km²)	Initiating disturbance or intervention (%)*							
		CC	P	AW	TB	TW	SI	TD	UND
Deciduous canopy dominated by tolerant deciduous species (D-TD)	38.6	9.5	0.2	0.6	2.0	0.1	0.2	<0.1	87.5
Deciduous canopy dominated by intolerant deciduous species (D-ID)	26.0	15.1	0.2	0.1	18.1	0.1	0.4	<0.1	65.9
Deciduous canopy dominated by non-commercial deciduous species (D-NcD)	2.6	59.1	3.6	17.3	6.4	1.5	7.9	0.3	4.0
Mixed canopy dominated by tolerant deciduous species (M-TD)	21.6	18.6	4.5	0.7	2.4	0.3	2.0	<0.1	71.5
Mixed canopy dominated by intolerant deciduous species (M-ID)	35.5	14.1	1.4	<0.1	10.9	0.2	1.7	<0.1	71.7
Mixed canopy dominated by conifers (M-C)	53.1	20.1	5.5	0.2	7.5	0.5	3.3	<0.1	62.9
Coniferous canopy (C)	219.5	12.5	6.3	<0.1	8.8	0.4	1.1	<0.1	70.8
Regeneration — undetermined canopy type (REGEN)	42.3	56.5	4.0	4.1	29.6	3.8	1.9	0.1	<0.1
Total of productive forest land	–	**18.2**	**4.6**	**0.6**	**10.4**	**0.7**	**1.5**	**0.03**	**63.9**

* Data source: Original ecoforest map. All types of cuts were grouped under the heading of clearcuts (CC). Initiating natural disturbances and human interventions (including plantations and restocking, grouped under the abbreviation [P]) are defined as events that remove more than 75% of a stand's basal area or that contributed to the establishment of the current stand (e.g., plantation). AW = agricultural wildland; TB = total burn; TW = total windthrow; SI = severe infestation; TD = total dieback; UND = undetermined initiating perturbation or intervention. Only the most recent disturbance or intervention for each ecoforest polygon is considered.

Table 9. Contemporary proportion of productive forest land in southern Québec, by partial disturbance or intervention and canopy subtype.

Canopy subtype	Partial disturbance or intervention (%)*								
	PC	PCT	ENR	MI	PW	PD	PB	PID	UND
Deciduous canopy dominated by tolerant deciduous species (D-TD)	34.9	0.6	0.2	1.7	0.2	0.1	<0.1	0.1	62.4
Deciduous canopy dominated by intolerant deciduous species (D-ID)	10.0	1.7	0.1	5.1	1.1	1.4	0.1	0.1	80.5
Deciduous canopy dominated by non-commercial deciduous species (D-NcD)	0.2	1.8	0.3	0.0	<0.1	<0.0	<0.1	<0.1	97.6
Mixed canopy dominated by tolerant deciduous species (M-TD)	23.4	1.5	0.4	5.8	0.2	0.1	<0.1	0.1	68.5
Mixed canopy dominated by intolerant deciduous species (M-ID)	8.2	1.2	<0.1	11.7	1.3	1.0	0.1	<0.1	76.4
Mixed canopy dominated by conifers (M-C)	7.9	3.3	0.2	8.9	1.3	0.6	0.2	<0.1	77.8
Coniferous canopy (C)	1.7	5.6	0.2	4.8	5.6	0.9	0.8	<0.1	80.5
Regeneration — undetermined canopy type (REGEN)	0.1	1.6	1.0	<0.1	<0.1	<0.1	<0.1	<0.1	97.3
Total of productive forest land	**7.3**	**3.7**	**0.2**	**5.2**	**3.1**	**0.7**	**0.4**	**<0.1**	**79.4**

* Data source: Original ecoforest map. All types of cuts were grouped under the heading of partial cuts (PC). Partial disturbances and interventions encompass natural phenomena and cuts that remove 25% to 75% of the stand's basal area. They also include silvicultural operations aimed at improving stand structure, such as precommercial thinning (PCT), and artificial regeneration treatments like enrichment (ENR). MI = mild infestation; PW = partial windthrow; PD = partial dieback; PB = partial burn; PID = partial ice storm damage; UND = undetermined partial perturbation or intervention. Only the most recent disturbance or intervention for each ecoforest polygon is considered.

stands are mostly created by major disturbances, there are very few traces of partial disturbances in these forests. Where such traces exist, precommercial thinning is the main partial intervention applied (1.6% to 1.8%).

The importance of partial disturbance/intervention type by canopy type follows a latitudinal gradient of the disturbance regime, with a stronger partial disturbance footprint in the northern temperate forest than in the boreal zone (Fig. 5). Partial cuts are more prevalent in the temperate zone located in the south of the province, while minor outbreaks predominate in the temperate/boreal transitional zone, precommercial thinning in the southern portion of the boreal zone and partial windthrow in the northern portion of the boreal zone (Fig. 5).

Although harvesting based on a diameter limit was preferred in the past (Boulet 2015; Boulet and Pin 2015), partial cuts are now preferred in D-TD and M-TD stands in order to create small openings that further limit the dominant natural disturbance regime and foster regeneration in the form of shade-tolerant or semi shade-tolerant species (MRN 2013). According to the literature review by Seymour *et al.* (2002), small openings resulting from tree death are formed more frequently (50 to 200 years) in these types of stands, but they tend to be small and more minor. Tree death occurs either when a tree or small group of trees reach maturity, or when a combination of factors causes tree vigour to decline (McCarthy 2001). It generally follows a drop in growth, crown dieback or progressive rot (Barden 1980; Houston 1981). Climate factors such as winter/spring freeze/thaw sequences, droughts or heatwaves may also play a role (Allen *et al.* 2010; Peng *et al.* 2011). Wind gusts may kill one or more standalone trees (Guillemette *et al.* 2017). Lack of light and nutritional deficits (Bal *et al.* 2015) may also adversely affect tree vigour and increase the risk of mortality. Disturbances caused by insects, diseases or animals (Edgar and Westfall 2022), as well as damage from neighbouring fallen trees (Barden 1980), can also have a similar effect. Partial damages caused by ice storms are rarely seen in D-TD or M-TD stands (0.1%, Table 9). Ice damages trees but does not necessarily cause immediate extensive mortality (Deschênes *et al.* 2019). Increased mortality following severe ice storms occurs over several years; some species, such as American beech and eastern hop-hornbeam (ironwood), are more susceptible while others, like the eastern hemlock and sugar maple, are less affected.

Age structure

The latitudinal gradient of the disturbance regime impacts stand age structure (Table 10). Nearly half (49.1%) the D-TD subtype is composed of old-growth irregular, uneven-aged stands, and nearly one third (30.3%) of young irregular, uneven-aged stands. Only 20.6% of the D-TD subtype is composed of regular or storied stands, most of which (13.9%) are young stands under 40 years of age. The M-TD subtype is also composed mostly of irregular or uneven-aged stands (63.4%). Only about one third (36.6%) of the total M-TD subtype is composed of regular or storied stands, most of which (29.1%) are young stands under 40 years of age. Conversely, the D-ID and M-ID subtypes are mainly regular or storied. This predominance is more marked in the D-ID subtype (87.3%) than in the M-ID subtype (73.2%). In both cases, the 30, 50 and 70-year age classes each account for roughly 20% of the total area, while the 10- and 90-year age classes are somewhat less abundant. C and M-C forests are also mostly regular or storied. Dominance of regular or storied structures is greater in the C cover type (77.5%) than in the M-C subtype (66.3%). Lastly, the D-NcD subtype is composed almost exclusively of young regular stands in the 0-20-year age class (79.7%) or the 21-40-year age class (18.8%).

Contemporary changes to the forest canopy

Analysis of changes to the area occupied by each canopy subtype since the first ecoforest map shows that the regenerating forest (for which the canopy subtype cannot be established) has declined considerably in size since the end of the last century. Based on the first ecoforest map interpreted from aerial photographs from the 1950s to 1978, nearly 21% of the productive forest area was at the regeneration stage, compared to 10% in the most recent characterization from photograph years 2000 to 2015 (Table 11). This means that more than 45,000 km^2 of

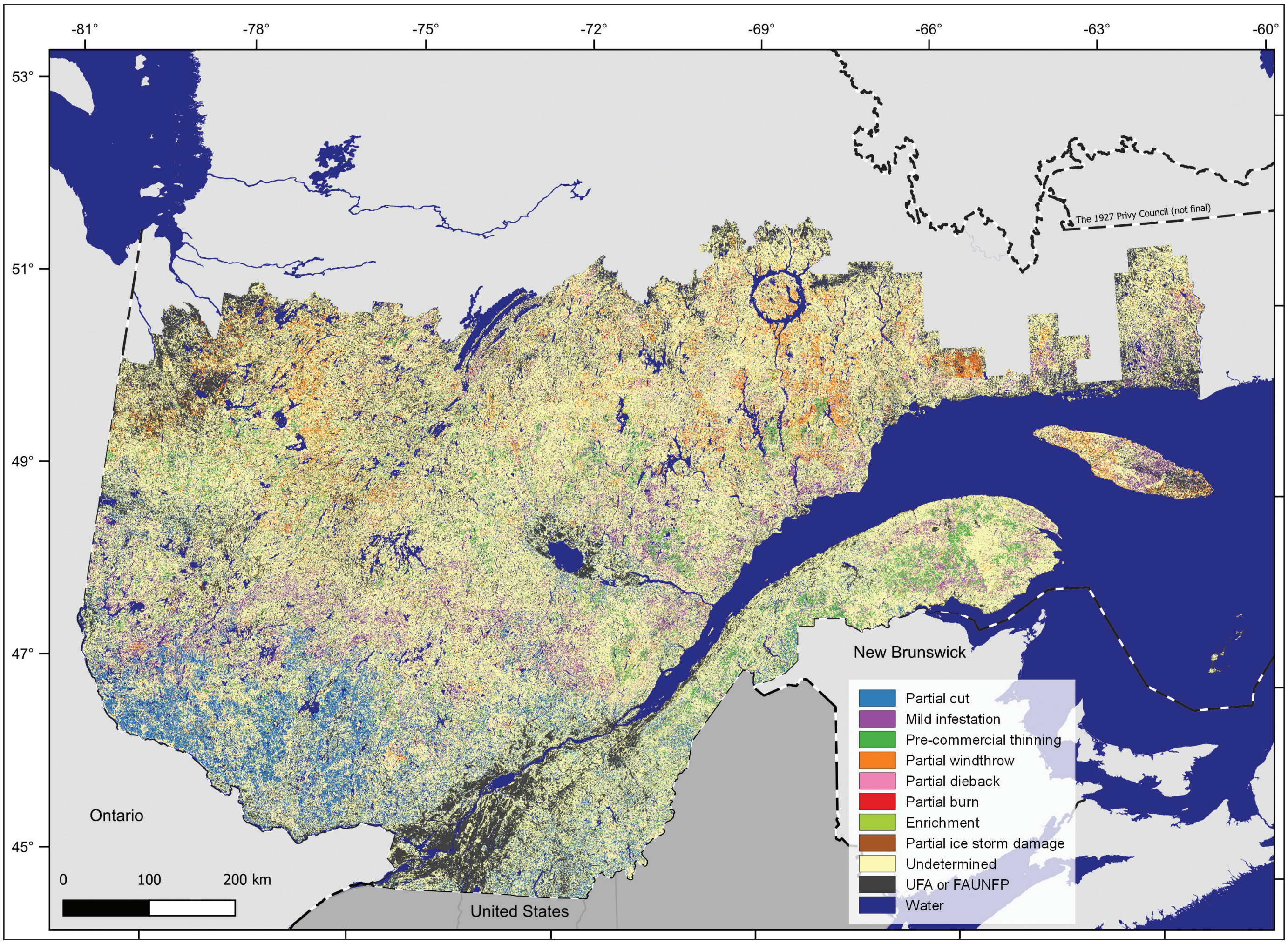

Fig. 5. Contemporary footprint of partial disturbances and interventions in southern Québec. Note: Data source: Original ecoforest map. UFA = unproductive forest areas; FAUNFP = forest area used for non-forestry purposes.

Table 10. Contemporary proportion of productive forest land in southern Québec, by age synthesis class and canopy subtype.

	Proportion by age synthesis class (%)*								
Canopy subtype	**10**	**30**	**50**	**70**	**90**	**120**	**YU**	**OU**	**UND**
Deciduous canopy dominated by tolerant deciduous species (D-TD)	8.5	5.3	3.7	1.4	1.5	0.1	30.3	49.1	<0.1
Deciduous canopy dominated by intolerant deciduous species (D-ID)	7.6	19.6	20.7	25.5	13.0	0.9	8.2	4.5	<0.1
Deciduous canopy dominated by non-commercial deciduous species (D-NcD)	79.7	18.8	0.4	0.1	<0.1	<0.1	0.9	0.1	<0.1
Mixed canopy dominated by tolerant deciduous species (M-TD)	21.6	7.5	4.4	2.1	0.9	0.1	24.7	38.7	<0.1
Mixed canopy dominated by intolerant deciduous species (M-ID)	4.1	20.8	19.2	19.6	8.2	1.3	17.2	9.6	<0.1
Mixed canopy dominated by conifers (M-C)	12.6	22.7	13.8	10.1	5.0	2.2	18.9	14.8	<0.1
Coniferous canopy (C)	6.1	15.4	9.8	12.8	9.5	24.0	4.5	17.8	0.3
Regeneration — undetermined canopy type (REGEN)	23.3	5.5	0.4	<0.1	<0.1	<0.1	<0.1	<0.1	70.8
Total productive forest lands	**9.9**	**14.8**	**9.9**	**10.9**	**6.9**	**12.4**	**10.3**	**17.9**	**7.0**

* Data source: Original ecoforest map. Only the age class of the upper story of layered stands was considered. The age class is generally undetermined (UND) for stands measuring 0 to 2 metres in height. 10 = 0–20 years; 30 = 21–40 years; 50 = 41–60 years; 70 = 61–80 years; 90 = 81–100 years; 120 = 101 years and more; YU = young uneven-aged stand or of irregular structure (origin ≤ 80 years); OU = old uneven-aged stand or of irregular structure (origin > 80 years).

Table 11. Evolution of the areas of southern Québec, by canopy type or land category and the years of aerial photography.

Canopy type	Area (1950–1978) × 000 km²	%	Area (1964–1993) × 000 km²	%	Area (1983–2001) × 000 km²	%	Area (2000–2015) × 000 km²	%
Deciduous canopy	51.6	12.3	63.8	15.6	61.3	14.9	62.1	14.9
Mixed canopy	80.0	19.1	81.5	19.9	93.4	22.8	119.3	28.6
Coniferous canopy	199.2	47.7	182.4	44.5	173.5	42.3	193.8	46.5
Regeneration — undetermined canopy type	87.2	20.9	82.6	20.1	82.2	20.0	41.7	10.0
Productive forest land — Total	**418.0**	**100.0**	**410.3**	**100.0**	**410.4**	**100.0**	**417.0**	**100.0**
Unproductive forest land	40.7	–	51.3	–	49.5	–	41.8	–
Forest areas used for non-forestry purposes	36.1	–	33.2	–	33.9	–	32.5	–
Water bodies	49.0	–	49.0	–	50.0	–	52.5	–
Total area monitored	**543.8**	–	**543.8**	–	**543.8**	–	**543.8**	–

Data source: Tessellate forest information system, original data. Coniferous species make up more than 75% of the basal area of coniferous stands, between 25% to 50% of the basal area of mixed stands and less than 25% of the basal area of deciduous stands.

forest have regenerated since the end of the last century. These forests appear to have regenerated as the M canopy type; the area occupied by this type increased from 19.2% to 28.6%, or by roughly 40,000 km², during the same period. The area occupied by the D canopy type also increased, but to a lesser extent: there were roughly 10,000 km² more of this canopy type in 2000–2015 (62,100 km², 14.9%), than in 1950–1978 (51,600 km², 12.3%). Conversely, the area occupied by the C canopy type decreased by roughly 5000 km² during the period in question, or by 1.2% at the provincial level. The area occupied by unproductive forests and bodies of water increased by roughly 1100 km² and 3500 km², respectively, while that occupied by non-forest land decreased by roughly 3600 km². Afforestation of former agricultural wildland and flooding of land to create hydroelectricity reservoirs are the kinds of land use changes that might have caused these variations. These trends are consistent with the increase in living biomass in the boreal and temperate forest that has been observed globally in the last three decades, while the tropical forest biomass declined during the same period (Pan *et al.* 2024).

Demography of the main tolerant deciduous species

Figure 6 shows the diameter distribution of the main TD species (sugar maple, red maple, yellow birch and American beech) in each bioclimatic domain in Québec's ecological classification system (Fig. 2; MFFP 2020b). The demographic profile shows that red maple is more abundant, performs best (shallower slope) and attains greater diameters in the south of the province than in the north, and that it is all but absent from the spruce forest (which explains why domain 6 is excluded from Fig. 6). Red maple is also significantly more abundant in the eastern maple-basswood subdomain (2E) than in the western equivalent (2W).

The latitudinal and longitudinal gradients are less obvious for sugar maple, which is slightly less abundant in the fir-yellow birch domain (4) than in the maple domains (1 to 3), although the dynamics are fairly similar across the regions. However, it is much less abundant than red maple in the fir-paper birch domain (5). The non-linear relationship for these two maple species suggests a certain level of population instability. Divergence from the straight line is more significant in the case of sugar maple. The lower frequency of small-diameter stems (roughly 10–18 cm) suggests that stem recruitment was insufficient over a given period to maintain a balanced population. However, contemporary recruitment of stems at the 2-cm class diameter threshold appears to be sufficient to form an eventual straight line with the intermediate diameter classes. In several regions, the relation-initiating ordinate is similar to a straight-line ordinate that characterized the larger-diameter stem population (e.g., 20 cm and over). The convex form in the small diameter classes suggests that sugar maple recruitment has increased significantly in recent years in the fir-paper birch domain (subdomains 5E and 5W). In this case, the value of the relation-initiating ordinate is significantly higher than the ordinate of a straight line representing the larger diameter classes. We can therefore expect increased abundance in these more northern areas.

This type of relation, showing increased recruitment, is especially significant for American beech in the western fir-yellow birch subdomain (4W). The American beech diameter relations show contemporary recruitment far in excess of the rate that previously maintained the current population, across all regions in which the species is present. This species is therefore likely to become more abundant in the subdomains in which it is present, including the 4W subdomain in which it is currently less abundant. However, beech bark disease may have a considerable impact on American beech population dynamics in Québec. The disease, which causes tree death shortly after infection, has progressed very quickly westwards in the province during the last decade (MFFP 2020c). Future forest inventory compilations will document that impact. In terms of distribution, the American beech is extremely rare in the fir-paper birch domain, while red maple and sugar maple are able to grow there.

Analysis suggests that the yellow birch population is fairly stable, despite the slightly rotated sigmoid curve observed in some subdomains. The species dynamic (represented by the diameter relation slope) also varies by bioclimatic subdomain. The species has a basic mortality rate (and hence a slope) that is slightly shallower in the maple-yellow birch and fir-yellow birch domains, in which it also achieves larger diameters than in the fir-paper birch, maple-basswood and maple-bitternut hickory domains.

Overall, the analysis produces a convex form of diameter relation in the smaller diameter classes for deciduous species typical of the northern temperate zone. The curve is often accentuated in domains situated at the northern limit of the species' range, where they are less abundant. These demographic relations suggest that these species will become more important north of their contemporary range, especially in the case of sugar maple in the fir-paper birch domain (5) and American beech in the western fir-yellow birch subdomain (4W).

Demographic changes to tree populations are spread over a long period ranging from decades to hundreds of years, depending on species longevity. In the shorter term, changes occur first for small trees whose abundance depends on population recruitment rates. These young trees will then form the population based on growth rates and stem mortality. Diameter distribution curves therefore illustrate the outcome of these population dynamics over time, and certain inferences can be drawn concerning population status and dynamics. Analysis of contemporary demographic changes provides a shorter-term additional view of population dynamics.

Figure 7 presents the variation in the number of trees per 2-cm diameter class for the main TD species in each bioclimatic domain in Québec's ecological classification system, for the period comprised between the second (1981–1993) and fourth (2003–2018) forest inventories of southern Québec (MFFP 2020b). Among other things, the profile shows that in just 20 years, the number of sugar maple, red maple and yellow birch saplings (diameter < 10 cm) declined in the maple subdomains and increased slightly in the western fir-paper birch subdomain (5W). Conversely, the presence of American beech increased significantly in the western maple-basswood subdomain (2W) and in the western maple-yellow birch domain (3W). The relative variation for beech is one of the most important contemporary variations, given that this is not the most abundant species in these regions' forest canopy. The increase in the presence and abundance of American beech in maple forests is already well documented in northeastern North America (Duchesne and Ouimet 2009; Bose *et al.* 2017; DRF 2017). However, beech bark disease may hinder the species' progression in the future (MFFP 2020c).

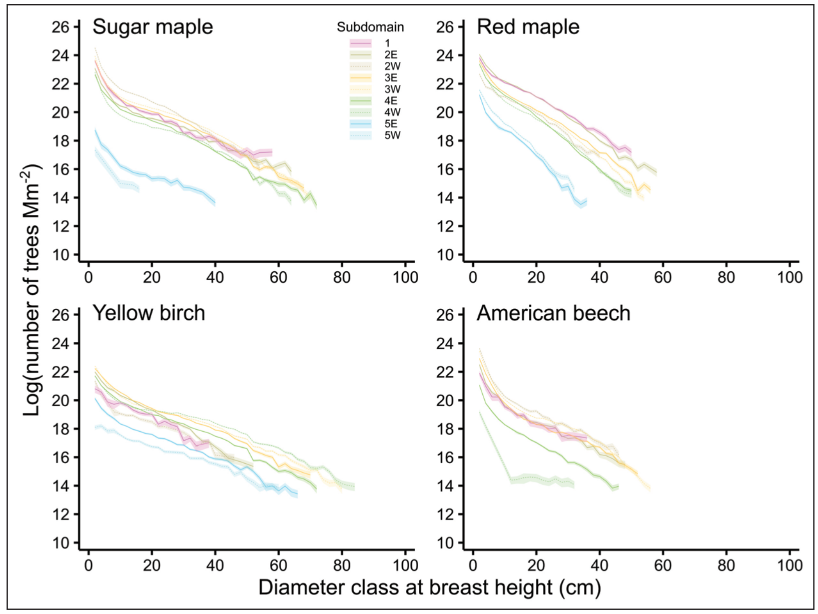

Fig. 6. Diameter distributions (number of trees per 2 cm diameter class at breast height) of the main tolerant deciduous species (sugar maple, red maple, yellow birch, and American beech) as part of the fourth forest inventory of southern Québec (2003–2018), for each of the bioclimatic subdomains of Québec's ecological classification system. The shaded areas represent an interval of ± 1 standard error from the mean. Only averages compiled from at least 10 sample plots are shown. Bioclimatic domains: 1 = Sugar maple-bitternut hickory; 2 = Sugar maple-basswood; 3 = Sugar maple-yellow birch; 4 = Balsam fir-yellow birch; 5 = Balsam fir-paper birch; 6 = Spruce-moss. The letters E and W respectively distinguish the Eastern and Western bioclimatic subdomains.

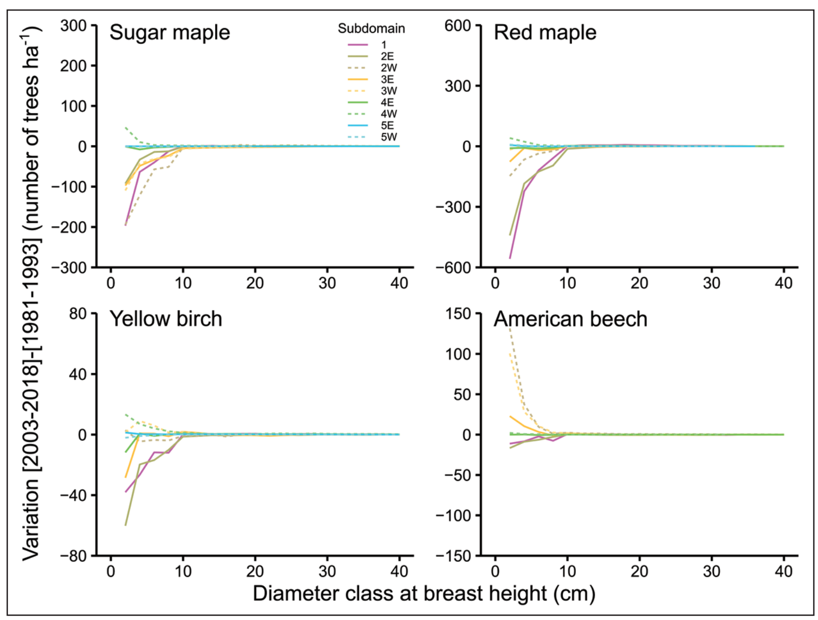

Fig. 7. Variation in the number of trees of the main tolerant deciduous species between the second (1981–1993) and the fourth (2003–2018) forest inventories of southern Québec, by 2 cm diameter class (measured at breast height, i.e., 1.3 m), for each bioclimatic subdomain of Québec's ecological classification system. Bioclimatic domains: 1 = Sugar maple-bitternut hickory; 2 = Sugar maple-basswood; 3 = Sugar maple-yellow birch; 4 = Balsam fir-yellow birch; 5 = Balsam fir-paper birch; 6 = Spruce-moss. The letters E and W respectively distinguish the Eastern and Western bioclimatic subdomains.

Conclusion

Although occupying a much smaller area of the province than the C canopy type (219 500 km²), the D-TD canopy subtype nevertheless occupies roughly 38 600 km², in addition to another 21 600 km² in the M-TD canopy subtype. These forests are also located closer to inhabited areas and infrastructure, making them more easily accessible for vacation use, development and exploitation. Sugar maple, red maple and yellow birch are the three main TD species typically found in Québec's northern temperate zone, but they are mixed with dozens of other species in this area of transition toward the boreal zone.

The origins of D-TD canopy subtype stands are usually not known because, unlike forests in the boreal zone, there have been very few initiating disturbances. However, stands of this type tend to have undergone numerous partial disturbances, mostly of human origin, such as partial cutting. In addition, isolated dead trees or small groups of dead trees are not mapped. There are some local and regional disparities in the northern temperate zone, due mainly to site quality and disturbance history, but they have not been considered in this analysis.

This analysis of contemporary changes to the forest canopy shows that the forest has regenerated in recent decades throughout the province. Most of the regeneration has been as M stands and, to a lesser extent, D stands. Conversely, the area occupied by the C canopy type has decreased slightly since the end of the last century.

Variations in the diameter distributions of the main tolerant deciduous species show a slight decrease in sugar maple, red maple and yellow birch populations and an increase in American beech populations in recent decades. Although a decline in the occurrence and abundance of sugar maple to the benefit of the American beech has been documented in northeastern North America in recent years, the demographic profile clearly shows that sugar maple is still abundant across all diameter classes (2 cm and over, measured 1.3 m above the ground) and that, accordingly, population maintenance does not appear to be threatened at this time. The sugar maple population shows some signs of imbalance, with a shortage of small merchantable trees (roughly 10 to 18 cm in diameter), but this imbalance may eventually be countered by an abundance of smaller stems. In addition, the compilations show that these two species are likely to become more abundant toward the northern limit of their range, possibly due to climate change. However, beech bark disease may hinder the progression of the American beech. Despite these observations, drawn from the demographic profile of these species at bioclimatic subdomain level, sugar maple regeneration problems and proliferation of the American beech may nevertheless occur either locally or regionally.

This profile and the ensuing observations lay the foundations for a reflection on the main contemporary issues in Québec's temperate forest. These issues, relating mainly to global changes and forest management, are presented in more detail in the remainder of this series.

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References

Allen, C.D., A.K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D.D. Breshears *et al.* 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259(4): 660–684. https://doi.org/10.1016/j.foreco.2009.09.001

Bal, T.L., A.J. Storer, M.F. Jurgensen, P.V. Doskey and M.C. Amacher. 2015. Nutrient stress predisposes and contributes to sugar maple dieback across its northern range: A review. Forestry 88(1): 64–83. https://doi.org/10.1093/forestry/cpu051

Barden, L.S. 1980. Tree replacement in a cove hardwood forest of the Southern Appalachians. Oikos 35(1): 16–19. https://doi.org/10.2307/3544722

BFEC. 2023. [Bureau du Forestier en chef]. Feux de forêt de l'été 2023. Gouvernement du Québec, Bureau du Forestier en chef. Communiqué de presse du 29 novembre 2023. https://www.quebec.ca/nouvelles/actualites/details/feux-de-foret-de-lete-2023-52494

BMMB. 2022. [Bureau de mise en marché des bois]. Modèle d'évaluation de rentabilité des investissements sylvicoles (MÉRIS). Gouvernement du Québec, ministère des Ressources naturelles et des Forêts, Bureau de mise en marché des bois. https://bmmb.gouv.qc.ca/media/29260/meris.zip

Bose, A.K., A. Weiskittel and R.G. Wagner. 2017. A three decade assessment of climate-associated changes in forest composition across the north-eastern USA. J. Appl. Ecol. 54(6): 1592–1604. https://doi.org/10.1111/1365-2664.12917

Boulet, B. 2015. Le portrait de la forêt feuillue et mixte à feuillus durs au Québec — Survol historique. Document d'information. Gouvernement du Québec, Bureau du forestier en chef. 67 p. + 5 annexes. https://forestierenchef.gouv.qc.ca/wp-content/uploads/Portrait-de-la-foret-feuillue_Boulet_Bilan1.pdf

Boulet, B. and D. Pin. 2015. Le portrait de la forêt feuillue et mixte à feuillus durs au Québec — Les perturbations et leur effet sur la dynamique forestière. Document d'information. Gouvernement du Québec, Bureau du forestier en chef. 31 p. https://forestierenchef.gouv.qc.ca/wp-content/uploads/Perturbation_Pin_Bilan2008-2013.pdf

Brisson, J. and A. Bouchard. 2003. In the past two centuries, human activities have caused major changes in the tree species composition of southern Québec, Canada. Ecoscience 10(2): 236–246. https://doi.org/10.1080/11956860.2003.11682771

Burns, R.M. and B.H. Honkala (eds.). 1990. Silvics of North America: 1. Conifers; 2. Hardwoods. USDA For. Serv., Agri. Hand. 654. 877 p. Washington, DC. https://www.srs.fs.usda.gov/pubs/misc/ag_654/table_of_contents.htm

Cale, J.A., S.A. Teale, J.L. West, L.I. Zhang, D.R. Castello, P. Devlin and J.D. Castello. 2014. A quantitative index of forest structural sustainability. Forests 5(7): 1618–1634. https://doi.org/10.3390/f5071618

Couillard, P.-L., M. Bouchard, J. Laflamme and F. Hébert. 2022. Zonage des régimes de feux du Québec méridional. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière. Mémoire de recherche forestière nº 189. 23 p. https://mffp.gouv.qc.ca/documents/forets/recherche/MRF189.pdf

Coughlin, J., C. Clark, L. Pardo, R. Sabo and J. Ash. 2023. Sensitive tree species remain at risk despite improved air quality benefits to US forests. Nature Sustainability 6: 1607–1619. https://doI.org/10.1038/s41893-023-01203-8

Crow, T.R. 1990. *Tilia Americana* L. In Burns, R.M. and B.H. Honkala (eds.), Silvics of North America: 2. Hardwoods. USDA For. Serv., Agric. Hand. 654. Washington, DC. https://www.srs.fs.usda.gov/pubs/misc/ag_654/volume_2/tilia/americana.htm

Cui, J., M. Zheng, Z. Bian, N. Pan, H. Tian, X. Zhang, Z. Qiu, J. Xu and B. Gu. 2024. Elevated CO_2 levels promote both carbon and nitrogen cycling in global forests. Nat. Clim. Change 14: 511–517. https://doi.org/10.1038/s41558-024-01973-9

Danneyrolles, V., S. Dupuis, G. Fortin, M. Leroyer, A. de Römer, R. Terrail, M. Vellend, Y. Boucher, J. Laflamme *et al.* 2019. Stronger influence of anthropogenic disturbance than climate change on century-scale compositional changes in northern forests. Nature Commun. 10(1): 1265. https://doi.org/10.1038/s41467-019-09265-z

De Liocourt, F. 1898. De l'aménagement des sapinières. Bulletin de la Société Forestière Franche-Comté et Belfort 6: 396–409.

De Liocourt, F. 1900. Sapinières — Manuscrit conservé à l'École nationale du génie rural, des eaux et des forêts. Nancy.

Deschênes, É., M.H. Brice and J. Brisson. 2019. Long-term impact of a major ice storm on tree mortality in an old-growth forest. For. Ecol. Manage. 448: 386–394. https://doi.org/10.1016/j.foreco.2019.06.018

Drever, C.R., C. Messier, Y. Bergeron and F. Doyon. 2006. Fire and canopy species composition in the Great Lakes-St. Lawrence forest of Témiscamingue, Québec. For. Ecol. Manage. 231(1-3): 27–37. http://doi.org/10.1016/j.foreco.2006.04.039

DRF. 2017. [Direction de la recherche forestière]. Expansion du hêtre à grandes feuilles et déclin de l'érable à sucre au Québec : portrait de la situation, défis et pistes de solution. Avis scientifique du comité chargé d'étudier l'écologie et la sylviculture des peuplements contenant du hêtre et de l'érable. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction de la recherche forestière. Avis scientifique, 146 p. https://mffp.gouv.qc.ca/documents/forets/connaissances/recherche/AvisScientHEG-ERS.pdf

Duchesne, L. and R. Ouimet. 2008. Population dynamics of tree species in southern Quebec, Canada: 1970–2005. For. Ecol. Manage. 255(7): 3001–3012. https://doi.org/10.1016/j.foreco.2008.02.008

Duchesne, L. and R. Ouimet. 2009. Present-day expansion of American beech in northeastern hardwood forest: Does soil base status matter? Can. J. For. Res. 39(12): 2273–2282. https://doi.org/10.1139/X09-172

Edgar, C.B. and J.A. Westfall. 2022. Timing and extent of forest disturbance in the Laurentian mixed forest. Front. For. Glob. Change 5: 963796. https://doi.org/10.3389/ffgc.2022.963796

FAO. 2022. [Organisation des Nations Unies pour l'alimentation et l'agriculture]. Forêts d'Amérique du Nord, édition 2.0. Données numériques vectorielles [1:10,000,000] [on line]. Commission de Coopération environmentale (CCE), Commission des forêts pour l'Amérique du Nord (CFAN). http://www.cec.org/fr/atlas-environnemental-de-lamerique-du-nord/forets-damerique-du-nord-2022/ (accessed 15 July 2022).

Frelich, L.E. and C.G. Lorimer. 1991. Natural disturbance regimes in hemlock-hardwood forests of the Upper Great Lakes region. Ecol. Monogr. 61(2): 145–164. https://doi.org/10.2307/1943005

Garnas, J.R., M.P. Ayres, A.M. Liebhold and C. Evans. 2011. Subcontinental impacts of an invasive tree disease on forest structure and dynamics. J. Ecol. 99(2): 532–541. https://doi.org/10.1111/j.1365-2745.2010.01791.x

Guillemette, F., M.-M. Gauthier and R. Ouimet. 2017. Partitioning risks of tree mortality by modes of death in managed and unmanaged northern hardwoods and mixedwoods. For. Chron. 93(3): 246–258. https://doi.org/10.5558/tfc2017-033

Hijmans, R.J. 2023. *raster*: Geographic data analysis and modeling. R package version 3.6-26 [on line]. https://cran.r-project.org/package=raster

Himes, A., J. Bauhus, S. Adhikari, S.K. Barik, H. Brown, A. Brunner, P.J. Burton, L. Coll, A.W. D'Amato *et al.* 2023. Forestry in the face of global change: Results of a global survey of professionals. Curr. For. Rep. 9: 473–489. https://doi.org/10.1007/s40725-023-00205-1

Houston, D.R. 1981. Stress triggered tree diseases: The diebacks and declines. USDA For. Serv., Northeastern For. Exp. Sta., nº NE-INF81-41-. Broomall, PA. 36 p. https://www.nrs.fs.usda.gov/pubs/inf/ne_inf_41_81.pdf

Janowiak, M.K., A.W. D'Amato, C.W. Swanston, L. Iverson, F.R. Thompson III, W.D. Dijak, S. Matthews, M.P. Peters, A. Prasad *et al.* 2018. New England and Northern New York forest ecosystem vulnerability assessment and synthesis: A report from the New England climate change response framework project. USDA For. Ser., North. Res. Sta., Gen. Tech. Repo. NRF-173, Newtown Square, PA. 234 p. https://doi.org/10.2737/nrs-gtr-173

Leak, W.B. 2002. Origin of sigmoid diameter distributions. USDA For. Serv., North. Res. Sta., Res. Pap. NE-718. Newtown Square, PA. 10 p. https://doi.org/10.2737/NE-RP-718

Lumley, T. 2004. Analysis of complex survey samples. J. Stat. Soft. 9(8): 1–19. https://doi.org/10.18637/jss.v009.i08

Manion, P.D. and D.H. Griffin. 2001. Large landscape scale analysis of tree death in the Adirondack Park, New York. For. Sci. 47(4): 542–549. https://doi.org/10.1093/forestscience/47.4.542

McCarthy, J. 2001. Gap dynamics of forest trees: A review with particular attention to boreal forests. Environ. Rev. 9(1): 1–59. https://doi.org/10.1139/er-9-1-1

MFFP. 2015. [Ministère des Forêts, de la Faune et des Parcs] Norme de stratification écoforestière — Quatrième inventaire du Québec méridional. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Dir. inv. for. https://mffp.gouv.qc.ca/documents/forets/inventaire/norme-stratification.pdf

MFFP. 2016a. [Ministère des Forêts, de la Faune et des Parcs]. Norme d'inventaire écoforestier, Placettes-échantillons temporaires, édition 2016. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction des inventaires forestiers. 172 p. https://mffp.gouv.qc.ca/documents/forets/inventaire/Norme-PET.pdf

MFFP. 2016b. [Ministère des Forêts, de la Faune et des Parcs]. Intégration des enjeux écologiques dans les plans d'aménagement forestier intégré de 2018-2023, Cahier 4.1 — Enjeux liés à la composition végétale. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction de l'aménagement et de l'environnement forestiers. 86 p. https://cdn-contenu.quebec.ca/cdn-contenu/forets/documents/gestion/CH_4_1_Composition_vegetale_MRNF.pdf

MFFP. 2017. [Ministère des Forêts, de la Faune et des Parcs]. Méthodologie des compilations forestières du 4e inventaire écoforestier du Québec méridional. Cas particulier des estimations k-NN. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction des inventaires forestiers. 36 p. https://mffp.gouv.qc.ca/documents/forets/inventaire/methodologie-compilations-forestieres-4e-inventaire-ecoforestier-qc-meridional.pdf

MFFP. 2020a. [Ministère des Forêts, de la Faune et des Parcs]. Cartographie du 5e inventaire écoforestier du Québec méridional — Méthodes et données associées, 3e édition. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction des inventaires forestiers. https://mffp.gouv.qc.ca/documents/forets/inventaire/carto_5E_methodes_donnees.pdf

MFFP. 2020b. [Ministère des Forêts, de la Faune et des Parcs]. Classification écologique du territoire québécois. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction des inventaires forestiers [on line]. https://www.donneesquebec.ca/recherche/fr/dataset/systeme-hierarchique-de-classification-ecologique-du-territoire

MFFP. 2020c. [Ministère des Forêts, de la Faune et des Parcs]. Évolution de la maladie corticale du hêtre au Québec en 2019, Québec, Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction de la protection des forêts, 14 p. https://mffp.gouv.qc.ca/documents/forets/Evolution-maladie-corticale_2019.pdf

MFFP. 2021. [Ministère des Forêts, de la Faune et des Parcs]. Classification écologique du territoire québécois. Gouvernement du Québec, ministère des Forêts, de la Faune et des Parcs, Direction des inventaires forestiers. 11 p. https://mffp.gouv.qc.ca/documents/forets/inventaire/classification_ecologique_territoire_quebecois.pdf

MFFP. 2022a. [Ministère des Forêts, de la Faune et des Parcs]. Placettes-échantillons temporaires du deuxième inventaire [on line]. Partenariat Données Québec. https://www.donneesquebec.ca/recherche/dataset/placettes-echantillons-temporaires-2e-inventaire-1980-1993 (accessed 15 July 2022).

MFFP. 2022b. [Ministère des Forêts, de la Faune et des Parcs]. Placettes-échantillons temporaires du quatrième inventaire [on line]. Partenariat Données Québec. https://www.donneesquebec.ca/recherche/dataset/placettes-echantillons-temporaires-4e-inventaire-2004-a-aujourd-hui (accessed 15 July 2022).

MFFP. 2022c. [Ministère des Forêts, de la Faune et des Parcs]. Carte écoforestière originale de l'inventaire écoforestier du Québec méridional [on line]. Partenariat Données Québec. https://www.donneesquebec.ca/recherche/dataset/resultats-d-inventaire-et-carte-ecoforestiere (accessed 14 July 2022).

MFFP. 2022d. [Ministère des Forêts, de la Faune et des Parcs]. Système d'information forestière par tesselle (SIFORT) [on line]. Partenariat Données Québec. https://www.donneesquebec.ca/recherche/dataset/systeme-d-information-forestiere-par-tesselle-sifort (accessed 14 July 2022).

MRN. 2013. [Ministère des Ressources naturelles]. Le guide sylvicole du Québec, Tome 2. Les concepts et l'application de la sylviculture, collective work under the supervision of C. Larouche, F. Guillemette, P. Raymond and J.-P. Saucier, Les Publications du Québec, 744 p.

MRNF. 2009a. [Ministère des Ressources naturelles et de la Faune]. Normes de cartographie écoforestière — troisième inventaire écoforestier. Gouvernement du Québec, ministère des Ressources naturelles et de la Faune, Direction des inventaires forestiers. https://mffp.gouv.qc.ca/documents/forets/inventaire/norme-cartographie-ecoforestiere.pdf

MRNF. 2009b. [Ministère des Ressources naturelles et de la Faune]. Le portrait de l'évolution de la forêt publique sous aménagement du Québec méridional des années 1970 aux années 2000. Gouvernement du Québec, ministère des Ressources naturelles et de la Faune, Forêt Québec, Direction des inventaires forestiers et Direction de l'environnement et de la protection des forêts, 142 p. https://mffp.gouv.qc.ca/documents/forets/inventaire/evolution-foret-publique.pdf

MRNF. 2023. [Ministère des Ressources naturelles et des Forêts]. Insectes, maladies et feux dans les forêts du Québec en 2022. Gouvernement du Québec, ministère des Ressources naturelles et Forêts, Direction de la protection des forêts. 74 p. https://mffp.gouv.qc.ca/documents/forets/RA_2022_DPF.pdf

Oliver, C. D. and B.A. Larson. 1996. Forest stand dynamics, Update Edition. Yale School of the Environment Other Publications. 1. https://elischolar.library.yale.edu/fes_pubs/1

Pan, Y., R.A. Birdsey, O.L. Phillips, R.A. Houghton, J. Fang, P.E. Kauppi, H. Keith, W.A. Kurz, A. Ito *et al.* 2024. The enduring world forest carbon sink. Nature 631: 563–569. https://doi.org/10.1038/s41586-024-07602-x

Pebesma, E. 2018. Simple features for R: Standardized support for spatial vector data. The R Journal 10(1): 439–446. https://doi.org/10.32614/RJ-2018-009

Pebesma, E. and R. Bivand. 2023. Spatial data science: with applications in R. Chapman and Hall/CRC. https://doi.org/10.1201/9780429459016

Pelletier, G., Y. Dumont, and M. Bédard. 2007. SIFORT—Système d'Information FORestière par Tesselle, Manuel de l'usager. Gouvernement du Québec, ministère des Ressources naturelles et de la Faune. iii+125 p. https://diffusion.mffp.gouv.qc.ca/Diffusion/DonneeGratuite/Foret/DONNEES_FOR_ECO_SUD/SIFORT/1-Documentation/Manuel_usager_SIFORT_123.pdf

Peng, C., Z. Ma, X. Lei, Q. Zhu, H. Chen, W. Wang, S. Liu, W. Li, X. Fang *et al.* 2011. A drought-induced pervasive increase in tree mortality across Canada's boreal forests. Nat. Clim. Change 1: 467–471. https://doi.org/10.1038/nclimate1293

Picard, N. and D. Gasparotto. 2016. Liocourt's law for tree diameter distribution in forest stands. Annals For. Sci. 73: 751–755. https://doi.org/10.1007/s13595-016-0563-4

R Core Team, 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienne, Autriche [on line]. https://www.r-project.org/

Reed, S.P., A.A. Royo, A.T. Fotis, K.S. Knight, C.E. Flower and P.S. Curtis. 2021. The long-term impacts of deer herbivory in determining temperate forest stand and canopy structural complexity. J. Appl. Ecol. 59(3): 812–821. https://doi.org/10.1111/1365-2664.14095

Rubin, B., P. Manion and D. Faber-Langendoen. 2006. Diameter distributions and structural sustainability in forests. For. Ecol. Manage. 222(1–3): 427–438. https://doi.org/10.1016/j.foreco.2005.10.049

Seidl, R., D. Thom, M. Kautz, D. Martin-Benito, M. Peltoniemi, G. Vacchiano, J. Wild, D. Ascoli, M. Petr *et al.* 2017. Forest disturbances under climate change. Nature Clim Change 7: 395–402. https://doi.org/10.1038/nclimate3303

Seymour, R.S., A.S. White and P.G. DeMaynadier. 2002. Natural disturbance regimes in northeastern North America—evaluating silvicultural systems using natural scales and frequencies. For. Ecol. Manage. 155(1–3): 357–367. https://doi.org/10.1016/S0378-1127(01)00572-2

Thompson, I.D., J.H. Simard and R.D. Titman. 2006. Historical changes in white pine (*Pinus strobus* L.) density in Algonquin Park, Ontario, during the 19th century. Natural Areas Journal 26(1): 61–71. https://doi.org/10.3375/0885-8608(2006)26[61:HCIWPP]2.0.CO;2

Trumbore, S., P. Brando and H. Hartmann. 2015. Forest health and global change. Science 349(6250): 814-818. https://doi.org/10.1126/science.aac6759

Wickham, H. 2016. *ggplot2*: Elegant graphics for data analysis. Springer-Verlag, New York. 260 p. https://doi.org/10.1007/978-3-319-24277-4

Wickham H., R. François, L. Henry, K. Müller and D. Vaughan. 2023. *dplyr*: A Grammar of Data Manipulation. R package version 1.1.4. [on line]. https://CRAN.R-project.org/package=dplyr (accessed 20 October 2024).

Wilke, C.O. 2024. *cowplot*: Streamlined plot theme and plot annotations for "ggplot2". R package version 1.1.3. [on line]. https://cran.r-project.org/package=cowplot (accessed 20 October 2024).

Williams, G.M., M.D. Ginzel, Z. Ma, D.C. Adams, F. Campbell, G.M. Lovett, M.B. Pildain, K.F. Raffa, K.J.K. Gandhi *et al.* 2023. The global forest health crisis: A public-good social dilemma in need of international collective action. Annu. Rev. Phytopathol. 61: 377–401. https://doi.org/10.1146/annurev-phyto-021722-024626