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The effects of surficial deposit–drainage combinations on spatial variations of fire cycles in the boreal forest of eastern Canada

Nicolas Mansuy[A,E], *Sylvie Gauthier*[B], *André Robitaille*[C] *and Yves Bergeron*[D]

[A]Centre for Forest Research, Université du Québec à Montréal, C.P. 8888, Succ. Centre-ville, Montréal, QC, H3C 3P8, Canada.
[B]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du PEPS, PO Box 10380, Stn Sainte-Foy, Québec, QC, G1V 4C7, Canada.
[C]Ministère des Ressources naturelles et de la Faune du Québec, Direction des inventaires forestiers, 880 chemin Sainte-Foy, 5e étage, Québec, QC, G1S 4X4, Canada.
[D]Chaire industrielle en aménagement forestier durable (NSERC-UQAT-UQAM), Université du Québec en Abitibi-Témiscamingue, 445 boulevard de l'Université, Rouyn-Noranda, QC, J9X 5E4, Canada.
[E]Corresponding author. Email: nicolas.mansuy@rncan-nrcan.gc.ca

Abstract. Spatial variations in the fire cycle of a large territory (190 000 km^2) located in the boreal forest of eastern Canada were assessed using random sampling points. Our main objective was to determine if regions characterised by a large proportion of dry surficial deposit–drainage (SDD) burn more frequently than regions with a smaller proportion. Through a regionalisation of the landscape units, we analysed the effects of SDD on spatial variations of the fire cycle. A discriminant analysis involving the SDD and other physical variables (precipitation, temperature, aridity index, water bodies, elevation and slope) made it possible to identify a combination of variables characterising each region. A considerable variation in fire cycle was observed among the different SDD types (from 144 to 425 years) and between regions (from 90 to 715 years). Through the discriminant analysis, this study suggests that a combination of possible climatic top-down (precipitation $R^2 = 0.727$, aridity index $R^2 = 0.663$ and temperature $R^2 = 0.574$) and bottom-up factors (xeric undifferentiated till $R^2 = 0.819$ and humid undifferentiated till $R^2 = 0.691$) could explain this variation at the regional scale. Implications of those results for forest protection against fire and regional development are briefly discussed.

Additional keywords: climate, discriminant analyses, disturbance regime, drying potential, random sampling, regional scale, regionalisation, top-down and bottom-up factors.

Introduction

Wildfire has been a dominant disturbance in Canadian forests since the last Ice Age, shaping boreal landscapes with a high intensity and stand-replacing fires (Stocks 1991; Kasischke and Stocks 2000). The fire regime, which is comprised of the fire cycle, size, intensity, seasonality, type and severity, affects the boreal forest through the interruption or termination of tree or stand life cycles. A growing number of studies have investigated the spatial and temporal variations in fire frequency in the boreal forest (Larsen 1996; Reed *et al.* 1998; Weir *et al.* 2000; Beaty and Taylor 2001; Bergeron *et al.* 2004*a*; Larjavaara *et al.* 2004; Wallenius *et al.* 2004). However, the origin of these variations remains uncertain and, to a great extent, debatable. The spatial variability generated by the fire regime results from both the stochasticity inherent to forest fire (Lertzman and Fall 1998) and an assortment of complex interactions between climate, vegetation composition, topography and also human activities (Van Wagner 1987; Johnson 1992; Flannigan and Wotton 2001; Heyerdahl *et al.* 2001; Kasischke *et al.* 2002; Lefort *et al.* 2003; Cyr *et al.* 2007; Syphard *et al.* 2008; Li *et al.* 2009). The ecological and climatic factors that control this spatial heterogeneity not only vary from one ecosystem to another, but they also vary depending on the scale (landscape, regional, local) considered. Certain factors that operate at a global scale, such as climate, are said to have top-down effects (Johnson 1992; Payette 1992). Factors that operate more locally (from stand to drainage basin scale), such as topography or aspect (Lertzman and Fall 1998; Taylor and Skinner 2003; Cyr *et al.* 2007), have bottom-up effects. It is understood that these two types of factors influence fire cycle: if the top-down factors are predominant, then the fire regime is expected to vary at the regional level; if the bottom-up effects are prevalent, large variations are expected at the local level (Heyerdahl *et al.* 2001).

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Table 1. Classification of surficial deposit–drainage (SDD) combinations based on their texture, stoniness, thickness, morphology, drainage and their associated soil drying potential

Texture is defined in terms of size distribution of primary particles <2 mm. From the smallest to largest particles: C, clay (0.25–4 μm); Si, silt (4–63 μm); Sa, sand (63–2000 μm). The sequence of letters in the column indicates the importance of each element in the combination. Stoniness is defined in terms of size of the particles >2 mm. From the smallest to the largest particles: G, gravel (2–5 mm); P, pebble (75–250 mm); S, stone (250–600 mm); B, boulder (>600 mm). Thickness is the average thickness (m) of the deposit from the bedrock. Morphology is the general shape of the deposit observed in the field. Drainage classes: X, xeric; M, mesic; H, hydric; L, lateral. Drying potential refers to the speed at which water drains from the soil, and the potential availability of surface water for fuel types. A high drying potential is indicated by (+), whereas a low drying potential is represented by (−). The driest SDD are shown in bold. Code summarises the quality of the stoniness and texture: VAVC, very abundant, very coarse; AC, abundant, coarse; ROC, rock; MAC, moderately abundant, coarse; MAM, moderately abundant, moderate; MM, moderate, moderate; ORG, organic. The last letter refers to drainage classes when necessary. % pt represents the proportion of SDD represented by the random points

Surficial deposit combination	Description							% study area	
	Texture	Stoniness	Thickness	Morphology	Drainage	Drying potential	Code	% area	% pt
Juxtaglacial and disintegration moraine	**Sa**	**GPB**	**~10 m**	**Knob-and-kettle**	**X**	**+++++**	**VAVCx**	**6.7**	**7.2**
Juxtaglacial and disintegration moraine	**Sa**	**GPB**	**~10 m**	**Knob-and-kettle**	**M**	**++++**	**VAVCm**	**2.5**	**2.4**
Ablation till >1 m and rogen moraine	**SaSi**	**GB**	**1−5 m**	**Hummocky**	**X**	**+++**	**AC**	**3.1**	**3.6**
Bedrock >50%	**Null/SaSiC**	**Rock**	**0.25 m**	**Steep-sided/concave**	**X**	++ or −	**ROC**	**2.8**	**2.9**
Outwash	**SaSi**	**G**	**~10 m**	**Relatively flat**	**X**	**+**	**MAC**	**2.3**	**2.2**
Undifferentiated till between 25 cm and 1 m	SaSiC	SPG	0.25−1 m	Wavy	X	−	MAMx	7.0	5.5
Undifferentiated till between 25 cm and 1 m	SaSiC	SPG	0.25−1 m	Wavy	M	−	MAMm	14.2	13.9
Undifferentiated till >1 m	SaSiC	SPGB	5−10 m	Wavy	M	− −	MMm	34.8	38.1
Undifferentiated till >1 m	SaSiC	SPGB	5−10 m	Wavy	L	− − −	MMl	1.8	2.0
Undifferentiated till >1 m	SaSiC	SPGB	5−10 m	Wavy	H	− − − −	MMh	8.2	7.0
Organic >40 cm	Organic	Null	1−2 m	Wavy	H	− − − − −	ORG	12.4	11.0
Total								95.8	95.8

Fire cycle is defined as the time necessary to burn an area equivalent to the study area (Johnson and Gutsell 1994). The current fire cycle in the boreal forest of Quebec can vary from as short as 100 years to as long as 500 years, depending on the region studied (Bergeron *et al.* 2001, 2006; Lesieur *et al.* 2002; Lefort *et al.* 2004; Lauzon *et al.* 2007). This variation in fire cycle has been mainly explained by a top-down effect based on a west–east gradient: the climatic influences are more continental in the centre of the province, whereas in the east the climate is more humid, influenced by the rising air masses moving west to east, or north-west to south-east (Girardin 2009). Within these regions, some bottom-up effects of aspect and surficial deposits on fire cycle have been observed. In the North Shore region, Cyr *et al.* (2007) found that position on the slope was related to fire cycle since hilltops and upperslopes were subject to a lower fire cycle. In the Abitibi region, Bergeron *et al.* (2004*b*) found that fire cycle was lower on organic deposits than on fine- and coarse-textured deposits. Indeed, the effects of surficial deposit on fire cycle variations are often assumed but are barely clear in the literature. As surficial deposits play a key role in understanding the distribution and growth of vegetation (Robitaille and Allard 2007), more attention to their effect on fire cycle is required.

Surficial deposits are defined as sediments or materials that accumulated or were emplaced after component particles were transported by ice, water, wind, or gravity (Fullerton *et al.* 2003). The composition of surficial deposits affects the water flow content in the soil and also the moisture content of the litter and other fine fuels, as well as the vegetation. Dry forest fuels and winds are major contributors to large stand-destroying fires (Flannigan and Wotton 2001) and the drying of forest fuels results from drought periods of 3 days or more, associated with less than 1.5 mm of total precipitation (Flannigan and Harrington 1988). Dry surficial deposits characterised by excessive stoniness and sandy texture can accelerate the evacuation of water in the soil and diminish the quantity of water not only at the soil surface, but also in the vegetation. The originality of this paper is based on a classification of surficial deposit–drainage (SDD), combinations grouped in terms of their texture, stoniness, thickness and morphology, to illustrate their drying potential (Table 1). It is expected that the driest SDD combinations could promote conditions favourable to drying of the soil, fine fuels and vegetation, ultimately making the latter more easy to ignite and propagate fire.

Consequently, in this study, we analysed the effects of environmental characteristics, notably surficial deposits and their drainage, on spatial variations in fire cycle at the regional scale in the northern boreal forest of Quebec between 1940 and 2006. Our main hypothesis predicts that regions with a larger proportion of dry SDD should burn more often, leading to a shorter fire cycle than regions with a smaller proportion of dry SDD. The objectives of the present article are: (1) to estimate the fire cycles of the different SDD for the whole study area; (2) to conduct a regionalisation to analyse whether differences observed between SDD in the fire cycles were greater, smaller, or non-existent for the different regions of the study area; and (3) to determine the combination of climatic and physical factors that can explain spatial variations in the fire cycle, using a discriminant analysis. The study area, which is particularly

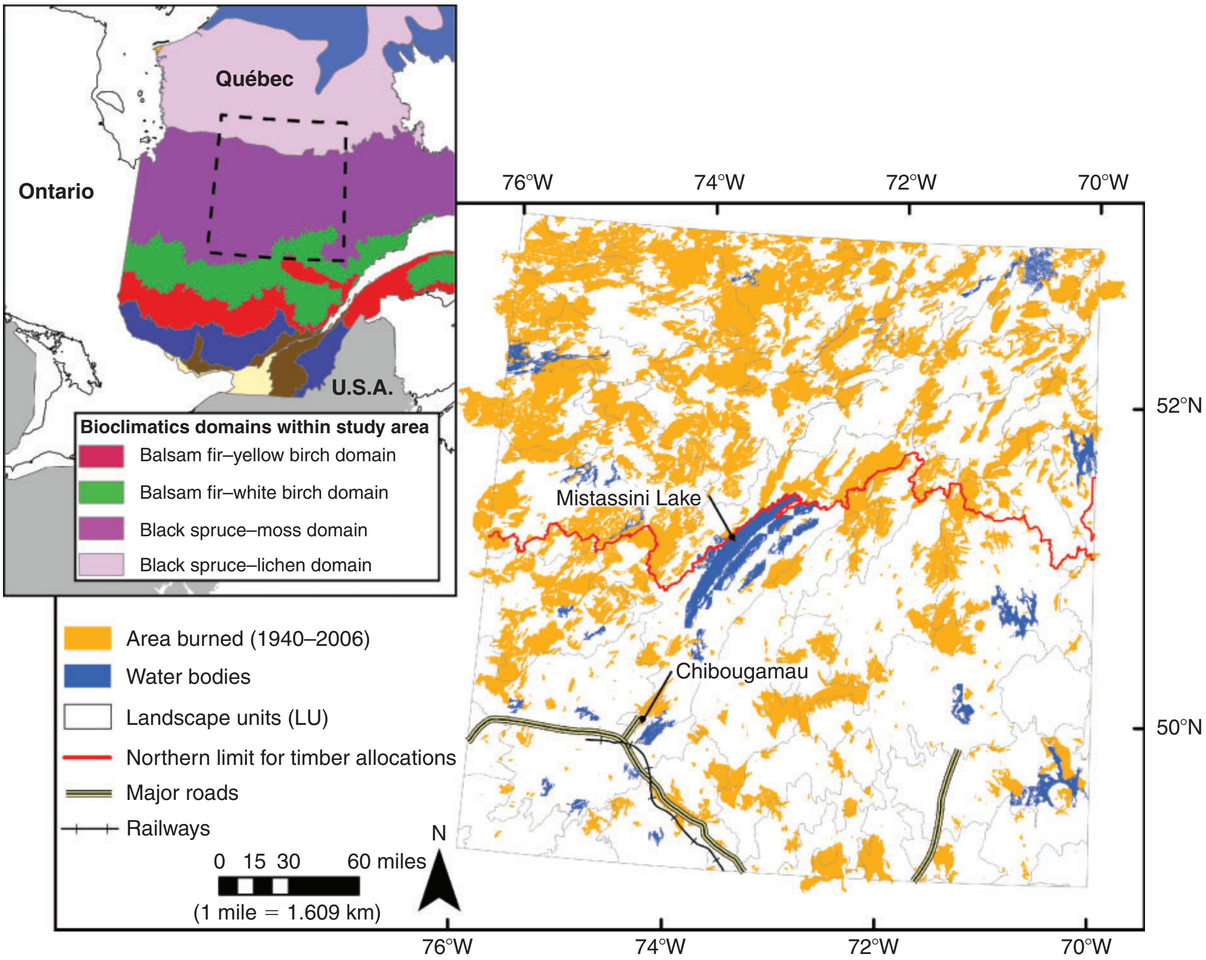


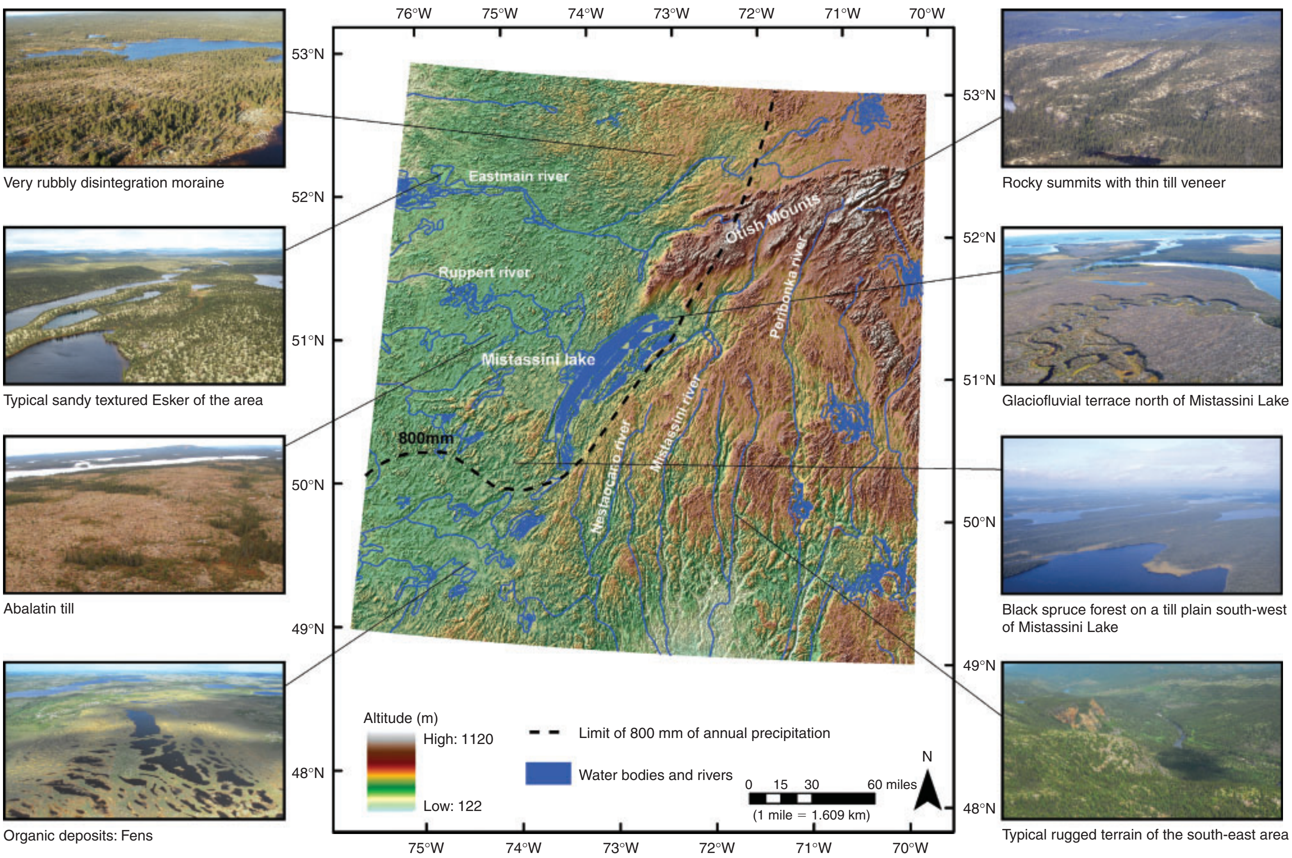
Fig. 1. Location of the study area within the main bioclimatic domain. The enlarged square refers to the study area subdivided into landscape units (defined as the portion of territory characterised by a recurrent arrangement of the main permanent environmental and vegetation factors). The northern limit for timber allocation also refers to the fire protection limit (intensive in the south, extensive in the north).

isolated and almost inaccessible by road, has only been described recently by the ministère des Ressources naturelles et de la Faune du Québec (MRNFQ). The current inventories are intended to address the lack of information regarding the forest vegetation, landscape characteristics and fire regime of this region. A better understanding of the factors responsible for changes in fire cycle can facilitate the protection of forests against fire. In addition, knowledge of broad-scale fire variations appears essential for delimiting natural forest regions in which sustainable forest management should take fire activity into account.

Study area

The study area encompasses a vast territory of roughly 190 000 km^2 between 70–76°W and 49–53°N (Fig. 1). The whole territory belongs to the Canadian Shield (Precambrian rock formation). The description of the study area is based on the natural elements that shape the landscape (i.e. hydrographic basins and relief). The hydrography, which covers 15% of the study area, is dominated by Lake Mistassini, the largest natural lake in Quebec (233 500 ha). Located north and west of Lake Mistassini, respectively, are the Eastmain and Rupert Rivers that flow in the direction of James Bay (Fig. 2). To the east of Lake Mistassini, flowing towards the south in the direction of Lac Saint-Jean and the St Lawrence River, there are also some rivers (the Mistassini, Peribonka and Nestaocano Rivers, to name a few; Fig. 2). The territory, which is mostly within the black spruce-feather moss bioclimatic domain, can be subdivided into five distinct parts (Figs 1, 2). The summary description that follows is predominantly adapted from the final report on the northern limit for timber allocation (MNRF 2000) and from Robitaille and Saucier (1998).

The first zone spreads out westward and north-west of Lake Mistassini, and consists of undulating hillocks with an average altitude of 350 m. The surface deposits are mainly composed of stony- and sandy-textured glacial deposits, which explain the abundance of xeric areas, particularly north of 52°N (the north-west corner of Fig. 2; photos 1, 2 and 3). Mean annual temperature ranges from −1.5° to 1.9°C, and mean annual precipitation varies between 680 and 800 mm.



The pictures are numbered from 1 to 8 from the top left corner to bottom right corner (photo credit: André Robitaille)

Fig. 2. Landform of the study area showing the location of some surficial deposits and water bodies that shape the landscape (photo credit: André Robitaille).

Extending from the first region, south of 50°N, the second zone consists of slightly undulating plains with a mean altitude of 350 m. Located between the Geer moraines and drumlins are depressions generally occupied by peat bogs, covering 20% of the surface area, with little forest cover (Fig. 2; photo 4). Mean annual temperature of this region ranges from −2.5° to 0°C and mean annual precipitation varies between 800 and 1000 mm.

The third zone is located north-east of Lake Mistassini and consists of high hilly territory (Mounts Techigami and Otish, Fig. 2; photo 5). Mean altitude ranges roughly between 700 and 750 m, with a peak at 1135 m. The surficial deposits are principally composed of till and various moraines with rocky outcrops that occupy ∼30% of the zone. Mean annual temperature varies from −6.0° to −1.5°C and mean annual precipitation varies between 800 and 950 mm.

The fourth zone is located east of Lake Mistassini and south of Mount Otish. This territory is slighty hilly, with a mean altitude of roughly 250 m, characterised by hillocks and a few hills covered by thick undifferentiated till. Mean annual temperature is ∼−1.5°C and mean annual precipitation is roughly 900 mm.

The fifth (and last) zone extends south from the fourth region. It consists of a very hilly terrain with a mean altitude of 600 m. The narrow and deep valleys (400 m deep), oriented north–south, cut across the plateau and are characterised by rocky escarpments (Fig. 2; photo 8). Thick undifferentiated till characterises the flat surfaces and the valley bottoms, whereas thin till covers the steep slopes and the rocky outcrops on the summits. Mean annual temperature is ∼−1.5°C and mean annual precipitation is ∼900 mm. Towards the south and east of this region, mean precipitation exceeds 1000 mm. It is located in the balsam fir-white birch bioclimatic domain.

With few roads or railways, the whole study area is relatively inaccessible and little affected by human activities. The largest city of the territory is Chibougamau with 30 000 inhabitants (Fig. 1). The northern limit for timber allocation divides the territory around 51°N. South of this limit, the forest is under management licences and intensive fire protection by the fire agency (Société de protection contre les incendies de forêts, SOPFEU, 'intensive' implying that all fires are fought). North of the allocation limit the forest is unmanaged (Fig. 1) and fire fighting is restricted to fires that put human infrastructures at risk (power lines, mines, natives communities). Indeed, human activities have had a relatively mild influence on the fire cycle across the territory as most of the area burned during very dry periods, when the SOPFEU efficiency is reduced by harsh fire behaviour (Lefort *et al.* 2003; Bergeron *et al.* 2004*b*; Gauthier *et al.* 2005). Therefore, spatial variations in fire cycle observed throughout the study area are mostly under climatic and biophysical control.

Materials and methods

SDD data

The surficial deposit and drainage data were gathered from two main sources. South of the limit of timber allocation (Fig. 1), spatial data were obtained from the third forest inventory (Létourneau *et al.* 2009). North of that limit, spatial data were obtained through the mapping of the Program d'inventaire écoforestier nordique (Létourneau *et al.* 2008). In both cases, the inventory program aims at describing the vegetation and the physical set-up of the forest, including surficial deposits.

During the last ice retreat, which ended ~6000 years ago in central Quebec-Labrador, various geomorphic agents, such as ice and meltwater from glaciers, have greatly contributed to the development of different types of surficial deposits (Robitaille and Allard 2007). In our study area, located in the heart of Quebec, the landforms are mainly composed of materials put in place by the direct action of glacier ice (till, moraines, etc.). Other materials were deposited by the meltwater running off glacier ice or filling a glacial lake (fluviaglacial, glaciolacustrine deposits). Among the deposits that have no glacial origin, we note the abundance of organic deposits and rocky outcrop. All of the deposit categories are easily distinguished from one another by their morphological–sedimentological characteristics, but can also be grouped based on their capacity to retain surface water. The surficial deposits and their drainage were assessed by photo interpretation at the scale of 1 : 40 000 by the geomorphologists team of the MRNFQ. The morphology of the different types of deposits made it possible to determine the drainage (xeric, mesic, hydric and lateral).

In order to illustrate their drying potential and their capacity to dry forest fuel, the surficial deposits of the territory were grouped into SDD combinations based on the following criteria: (1) texture (i.e. thin fraction of the deposit <2 mm) concerns the relative proportions of sand silt and clay; (2) stoniness refers to the size and proportion of the particles from the larger fraction >2 mm (i.e. gravel, pebble, stone, boulder); and (3) thickness of the deposits and their morphology were also considered as both can affect water retention.

The combinations of SDD used in this study are presented in Table 1, ranking from the driest to the most humid. The logic of our classification is briefly described below whereas the composition, description and the coding of the combinations are presented in Appendix 1. To create the combinations of SDD, we first distinguished the sandy textured deposits (Sa to SaSi; Table 1) from those containing a proportion of clay (SaSiC; Table 1). The presence of clay is critical because even if it is present only in a small proportion (~3% in till in the Canadian Shield of the province of Québec; Robitaille and Allard 2007), it plays a cohesive role of matrix elements, which can hold more water at the soil surface. Therefore, the undifferentiated tills that have a sandy-silty-clay texture were separated from the other deposits. They were then subdivided according to their thickness (25 cm to 1 m and >1 m) and according to the drainage class (Table 1).

Then, to distinguish combinations where the texture is mainly sandy-silty, we also considered the stoniness and morphology. Those criteria were used for the combination made up of juxtaglacial deposits and disintegration moraine, and for the combination of ablation till and Rogen moraines (Table 1). The first one is drier than the second because of a very abundant stoniness and very coarse texture. In addition, its knob-and-kettle morphology could promote faster evacuation of water. Finally, ablation till is less dry than its predecessors because it has a smoother morphology coupled with less stoniness and a finer texture (Table 1).

The combination of rocky outcrops (mainly composed of crystalline rocks with low permeability) can be covered with a layer of organic deposits or very thin till veneer (<25 cm) (Table 1). As it is often located on rugged terrain, the drainage is usually xeric. The last combination is composed of organic deposits (peatland) that exceed 40 cm in thickness (Table 1).

Landscape units data

The landscape units (LU) are one of the elements in the hierarchical ecological classification system developed by the MNRFQ (Saucier *et al.* 1998). The study area is subdivided into 48 LU defined as the portion of territory characterised by a recurrent arrangement of environmental (type of relief, average altitude, nature and proportion of the main surficial deposits, hydrography) and vegetation factors (nature and distribution of species). Several variables describing the climate and physical environment (precipitation, temperature, aridity index, elevation, slope, water bodies) have been compiled for each LU. The data on physical variables were obtained from Robitaille and Saucier (1998), who have extensively described the LU of southern Quebec. For the description of the northern units (north of 51°N), we referred to the final report on the northern limit of the commercial forest in Quebec (MNRF 2000) and to Proulx *et al.* (1987).

Fire data

In order to estimate fire cycle for the 1940–2006 period, we used the provincial fire spatial database provided by the MRNFQ. Within the study area, 1094 fires occurred between 1940 and 2006, with fire size ranging from 5 to 225 918 ha with an average of 5442 ha ± 15 101 (s.d.). Large fires (>50 000 ha) are responsible for burning over 65% of the study area; representing less than 13% of the total number of fires that occurred between 1940 and 2006 (Fig. 1). Most of these fires were classified with an exact ignition date by the SOPFEU. For remotely located fires, for which the perimeter was obtained using remote sensing (accounting for 30% of the fires), the fire dates are approximations subsequently integrated into classes of 5 years. For these fires, the middle value of each class was considered as their fire date. This database was included in ArcGis 9.2 (ESRI Inc., Redlands, CA, USA) with the following attributes: location, size and date. Without knowledge of the exact fire cause and taking the remoteness of the study area and the near absence of human settlements in the study area into account (roads, railways or towns; Fig. 2), the cause of fire was not considered in our analysis.

Random sampling

The study area covers 190 000 km^2, thus representing a considerable body of data. A random sampling of the entire study area (ArcGis 9.2) was performed using 30 000 randomly positioned points (excluding polygons defined as water and island). This number was considered sufficient to take into account the size of fires since each point represents ~6 km^2. The fire cycle estimate from a sample of points requires at least between 0.16 and 0.20% of total possible samples for a given territory (Li 2003). In our case, the smaller data cells are represented by the forest polygons (average size of 16 ha), ~1.2 million of which cover the whole territory. Therefore, a random sample of 30 000 points is sufficient because it represents ~4% of all possible samples. As LU size ranges from 93 500 to 1 427 400 ha (average size of 400 000 ha ± 297 900), it is not an obstacle for a reliable estimate of the CDF since each LU contains an average of 600 random points with 67 years of fire data for each point.

For each sampling point, we recorded three types of information:

1. The type of SDD extracted from the SDD polygons.
2. All possible fire dates from the MNRFQ fire spatial database; this made it possible to consider reburning over the study period. Therefore, a random point could have between 0 and 4 fire dates between 1940 and 2006.
3. The landscape unit, with its associated physical variables.

Estimations of fire cycle with the burn rate

Several methods can be used to estimate fire cycle (Johnson and Van Wagner 1985; Johnson and Gutsell 1994). The mean area burned per year (burn rate), similar to the percent annual area burned (PAAB), gives an accurate estimation of the fire cycle (Stocks *et al.* 2003). We estimated the burn rate using the points obtained from the random sampling (burned point ÷ total points per year). We then calculated the inverse of the mean burn rate to estimate the fire cycle. We also computed the standard error and used it to calculate the confidence interval. The percentage of burned points was first calculated to assess the fire cycle of the whole study area between 1940 and 2006 for each type of SDD, for each region defined by the regionalisation (see below), and finally for each type of SDD within each region.

Regionalisation and comparison of fire cycle based on survival analysis

Survival analysis is a class of statistical methods used for studying the occurrence and timing of events (Allison 1995), here the fire. Although they are not indispensable for estimating fire cycle, survival analyses make it possible to consider the entire survival distribution jointly with censored data (~60% of our data). The random points located inside a fire polygon were considered non-censored data because the fire date was known. Conversely, the points located outside any fire polygon were regarded as censored data since they did not burn between 1940 and 2006. Without knowledge of the exact fire dates, we assumed that these areas burned before 1940. The censored points that have no fire date are tagged with the date 1939, or a time since fire of 68 years. The LIFEREG procedure (v9.2; SAS Institute Inc., Cary, NC, USA; Allison 1995) computes and compares the survival distributions for the entire study period (1940–2006) rather than for a single value (mean fire cycle). This procedure was therefore used to compare the fire cycle among the different SDD and the regions identified below. Significantly different ($\alpha = 0.01$) elements were identified by a superscript letter for each SDD (Table 2) and for each region (Table 3).

In order to produce a regionalisation of the LU, we used an iterative process for comparing the estimated survival distribution based on Chi-square values and their probabilities. The LU with the lowest fire cycle values were grouped with the LU having the highest probability of not being different from the former (threshold >0.600). This process was repeated by taking the next non-grouped LU with the lowest fire cycle.

Table 2. Fire cycle of each surficial deposit–drainage (SDD) type for the whole study area (1940–2006)

The SDD combinations are classified from the shortest to the longest fire cycle. The driest deposits are shown in bold, the more humid are shown in italic (see soil drying potential in Table 1). The letter refers to the codes in Table 2 and Appendix 1. Fire cycle estimate from the burn rate with confidence interval (95% CI). Different letters indicate significantly different combinations

SDD	Burn rate	Fire cycle (years) (95% CI)
VAVCm	**0.69**	**144 (96–288)**^{A}
AC	**0.68**	**146 (100–273)**^{A}
VAVCx	**0.64**	**157 (109–282)**^{A}
ROC	**0.59**	**171 (116–323)**^{AB}
MAC	**0.58**	**173 (118–327)**^{AB}
MMm	*0.56*	*178 (123–322)*^{AB}
MAMm	*0.47*	*213 (150–368)*^{B}
MML	*0.41*	*246 (168–460)*^{BC}
ORG	*0.36*	*279 (184–568)*^{C}
MMh	*0.34*	*290 (203–510)*^{C}
MAMx	*0.24*	*425 (269–1017)*^{C}
Study area	0.49	201 (140–354)

Table 3. Fire cycle for each region defined from the regionalisation (1940–2006)

See Fig. 4 for the location of the regions. Fire cycle estimate from the burn rate with confidence interval (95%). Different letters indicate significantly different combinations

Region	Area (km^2)	Burn rate	Fire cycle (years) (95% CI)
A	18 525	1.11	90 (57–208)^{A}
B	35 157	0.78	129 (86–257)^{B}
C1	4265	0.67	149 (86–555)^{C}
C	42 468	0.48	205 (128–502)^{C}
D1	6492	0.42	237 (136–929)^{CD}
D	14 291	0.37	269 (150–1343)^{CD}
E	11 522	0.28	356 (164–∞)^{DE}
F	10 430	0.23	433 (200–∞)^{EF}
G1	15 043	0.16	634 (335–5890)^{F}
G	13 509	0.14	715 (353–∞)^{F}

Explaining spatial variation in fire cycle at the regional scale

To measure the impact of the SDD type on spatial variation in the fire cycle, we tested whether the number of observed burned

Table 4. (*a*) Mean fire cycle for each type of surficial deposit–drainage (SDD) in each region from the regionalisation; (*b*) χ_P^2 components for each type of SDD in each region

See Fig. 4 for the location of the regions. The driest SDD are shown in bold and the most humid SDD are shown in italic. Absolute χ_P^2 values higher than $\sqrt{(dll\chi^2[1,\alpha])(n_{cells})^{-1}}$ are indicated in grey. They are identified by boxes in which the number of observed burned points is significantly ($P < 0.001$) greater (light grey) or lower (dark grey) than the expected number of points. For (*a*) and (*b*): NA statistic not computed because the deposit is absent or occupies less than 1% of the region

SDD	Regions									
	A	B	C1	C	D1	D	E	F	G1	G
(*a*) Mean fire cycle (years)										
VAVCx	**92**	**117**	**151**	**163**	**180**	**232**	**231**	**335**	**704**	**774**
VAVCm	**82**	**127**	**134**	**172**	NA	**348**	**257**	**335**	NA	NA
AC	**90**	**121**	**295**	**176**	**211**	**217**	**208**	NA	NA	NA
ROC	**85**	**117**	**115**	**233**	**120**	**356**	NA	**683**	**376**	**287**
MAC	**82**	**157**	**241**	**168**	NA	**176**	**237**	**316**	**498**	**350**
MAMx	NA	*130*	NA	*277*	NA	*357*	*280*	*378*	*719*	*506*
MAMm	*83*	*119*	*150*	*269*	*219*	*318*	*427*	*466*	*818*	*463*
MMm	*94*	*124*	*142*	*192*	*283*	*238*	*325*	*416*	*590*	*594*
MML	*83*	*118*	*134*	*247*	*316*	*268*	*1407*	*616*	*5293*	NA
MMh	*97*	*132*	*101*	*323*	*214*	*326*	*560*	*385*	*611*	*1031*
ORG	*95*	*183*	*168*	*259*	*1173*	*254*	*504*	*452*	*597*	*1007*
Fire cycle region	90	129	149	205	237	269	356	433	634	715
(*b*) χ_P^2 components										
VAVCx	**−0.52**	**3.00**	**−0.37**	**8.39**	**10.92**	**3.19**	**12.08**	**4.49**	**−1.16**	**−1.78**
VAVCm	**1.95**	**0.17**	**1.41**	**2.12**	NA	**−2.42**	**4.86**	**3.34**	NA	NA
AC	**0.06**	**1.32**	**−10.28**	**5.12**	**4.08**	**5.05**	**10.12**	NA	NA	NA
ROC	**1.18**	**1.82**	**5.88**	**−1.31**	**23.18**	**−4.22**	NA	**−9.49**	**13.68**	**18.08**
MAC	**1.43**	**−2.51**	**−7.26**	**3.74**	NA	**7.06**	**8.79**	**4.94**	**5.01**	**15.83**
MAMx	NA	*−0.15*	NA	*−4.16*	NA	*−8.03*	*7.21*	*5.50*	*−3.24*	*7.50*
MAMm	*3.49*	*2.46*	*−1.10*	*−6.85*	*2.65*	*−6.59*	*−5.46*	*−4.90*	*−9.17*	*15.45*
MMm	*−2.54*	*2.66*	*2.17*	*4.46*	*−11.09*	*7.63*	*7.96*	*1.10*	*7.16*	*10.75*
MML	*0.93*	*1.31*	*1.00*	*−2.16*	*−6.23*	*0.03*	*−8.08*	*−5.23*	*−16.43*	NA
MMh	*−1.34*	*−0.54*	*8.46*	*−9.40*	*2.21*	*−5.07*	*−13.28*	*2.14*	*2.18*	*−12.89*
ORG	*−1.33*	*−10.67*	*−2.99*	*−7.29*	*−14.45*	*1.94*	*−10.47*	*−1.34*	*2.34*	*−16.46*

points was significantly different from the total number of points by SDD using Pearson's Chi-square component $\chi_P^2 = (\mathrm{O}-\mathrm{E})/\sqrt{\mathrm{E}}$ (where O is the percentage of burned points by SDD for each region and E is the percentage of points by SDD for each region). Significant differences above a threshold value ($\sqrt{(dll\chi^2[1,\alpha])(n_{cells})^{-1}}, \alpha = 0.001$ (Legendre and Legendre 1998)) indicate a tendency to burn more than expected for positive values, or to burn less than expected for negative values.

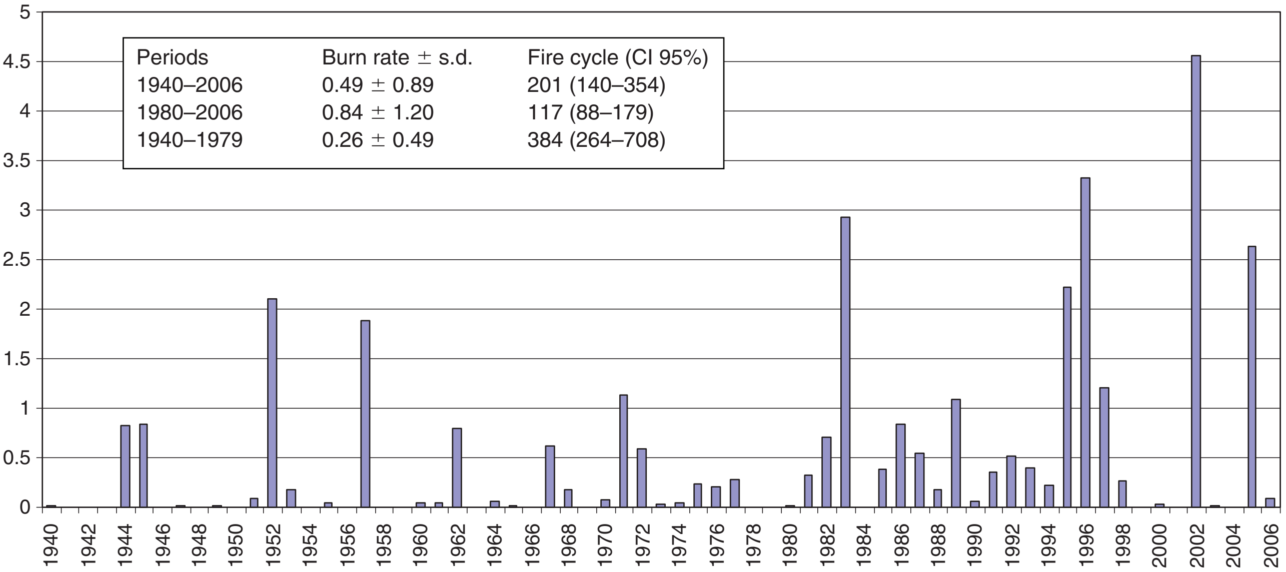
We then performed a discriminant analysis to identify which combinations of variables were the most powerful to distinguish the different regions. Discriminant function analysis was used to determine which variables could discriminate between two or more occurring groups. In our case, the groups corresponded to the LU within each region created from the regionalisation. Several variables describing each LU in terms of climate and physical environment (precipitation, temperature, aridity index, elevation, slope, water bodies), in addition to the 11 SDD, were used to generate the discriminant functions (Table 4). The analysis was first performed with Proc StepDisc (SAS Institute Inc.) to identify variables that are relevant for further analysis and those which are not. These variables were subsequently submitted to a Proc Discrim (SAS Institute Inc.) to estimate the classification success of the set of variables.

Results

SDD fire cycle at the broad scale

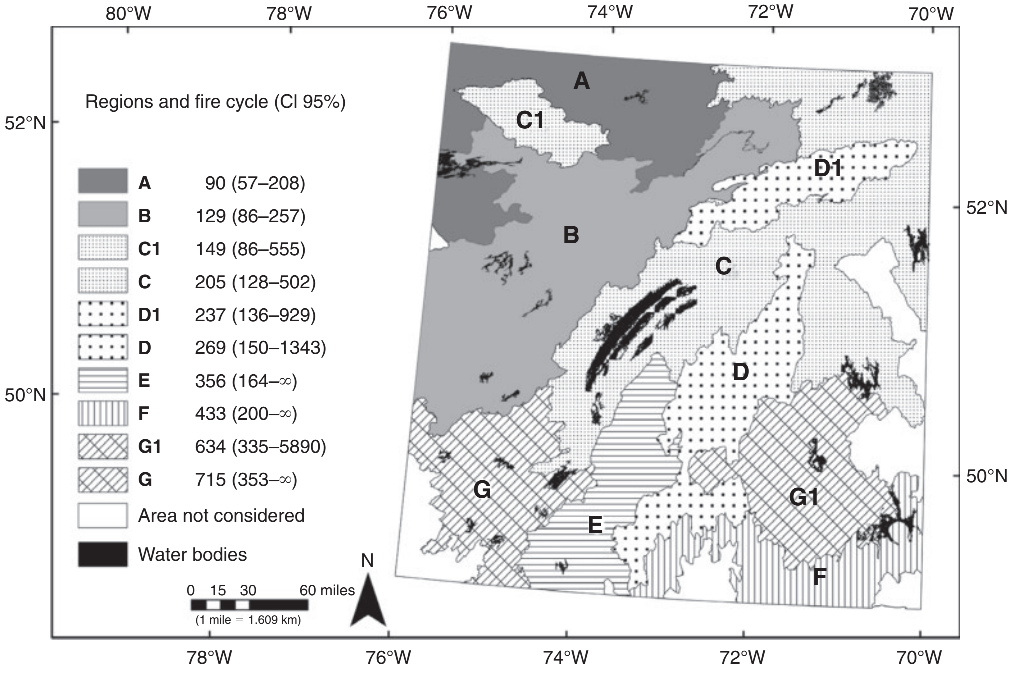
Based on data from the MNRFQ, fires consumed roughly 33% of the total study area (Fig. 3) between 1940 and 2006 (i.e. ~60 000 km^2). The study area was strongly affected by fire with an average of 0.49% of the area burned each year (fire cycle = 201 years) between 1940 and 2006. Large fire years, such as 2002 with more than 4.5% of the study area burned and 1996 with 3%, are easily distinguishable (Fig. 3). More than 20% of the territory has burned since the 1980s, with 0.89% of the territory burned annually between 1980 and 2006 (fire cycle = 117 years) compared with 0.26% between 1940 and 1979 (fire cycle = 385 years). However, it is difficult to assume there was a real change in the fire regime given the relatively short study period (67 years).

Within the whole study area the fire cycle for each SDD varies from 144 to 425 years (Table 2). The fire cycle of the driest deposits varies between 144 and 173 years whereas for the wettest deposits it varies between 178 and 425 years, suggesting a gradual increase in fire cycle values with increasing moisture. Overall, the driest SDD distinguished themselves significantly from the most humid (a and ab *v.* bc and c; Table 2). Specifically, the fire cycle for the driest deposits



Periods	Burn rate ± s.d.	Fire cycle (CI 95%)
1940–2006	0.49 ± 0.89	201 (140–354)
1980–2006	0.84 ± 1.20	117 (88–179)
1940–1979	0.26 ± 0.49	384 (264–708)

Fig. 3. Percentage of annual area burned and fire cycle estimated with randomised points for the whole study area between 1940 and 2006 and for different periods.



Regions and fire cycle (CI 95%)

▨	A	90 (57–208)
▨	B	129 (86–257)
▨	C1	149 (86–555)
▨	C	205 (128–502)
▨	D1	237 (136–929)
▨	D	269 (150–1343)
▨	E	356 (164–∞)
▨	F	433 (200–∞)
▨	G1	634 (335–5890)
▨	G	715 (353–∞)
☐	Area not considered	
■	Water bodies	

Fig. 4. Regionalisation of the study area into contiguous regions. The isolated LU (white portion) located on study area boundaries were excluded from the regionalisation. The fire cycle for each region was estimated from the burn rate with a confidence interval (95%). Although we are confident about the fire cycles for the regions with the current contours, fire cycles are subject to change according to future contours (data concerning LU limits are still being acquired).

nearly follows the same order as the drying potential presented in Table 1. The juxtaglacial and disintegration moraines (VAVCm and VAVCx) along with ablation (AC) till form a significantly distinct group (a), with the shortest fire cycle corresponding to the driest combinations. The rock (ROC), outwash (MAC) and thick till with mesic drainage (MMm) distinguish themselves from the first three deposits but always with a fire cycle <200 years (ab). We point out here that thick till with mesic drainage burns like a dry deposit (178 years) despite a predicted low drying potential (Table 1). Thin till with mesic drainage (MAMm) forms a class by itself (b), with a fire cycle of 213 years. Thick lateral till also forms a unique class (bc) with a fire cycle of 246 years. Organic deposits, thick hydric till and thin xeric till (c) are not significantly different from each other but they are significantly different from all other deposits due to their longer fire cycle (279–425 years).

Table 5. Discriminant analysis performed with 36 landscape units (LU) regrouped in 10 regions: (*a*) strongest discriminant variables; (*b*) less discriminant variables; (*c*) discrim procedure (SAS)

Variables are: PPT, mean annual precipitation (mm); TEMP, mean annual temperature (°C); SLOPE, mean slope (%); AI, aridity index determines the aridity degree of a region (to calculate the index we used the following formula, $AI = P/(T + 10)$, where P is total annual precipitation and T is mean annual temperature); ELEV, mean elevation (m); WATER, main water bodies (% area); see Table 1 for the surficial deposit–drainage (SDD) codes. The driest SDD are shown in bold and the most humid SDD are shown in italic. 'Proc Discrim' is the matrix of confusion regarding the classification of LU in each region versus those suggested by the discriminant analysis is available in Appendix 2

Stepdisc		Variables	Partial R^2	F value	Pr > F	Wilks' Lambda	Pr < Lambda
(*a*)	1	MAMx	*0.819*	*13.100*	*<0.0001*	*0.181*	*<0.0001*
	2	PPT	0.727	6.520	0.000	0.002	<0.0001
	3	AI	0.663	5.470	0.000	0.061	<0.0001
	4	MMh	*0.691*	*5.950*	*0.000*	*0.019*	*<0.0001*
	5	TEMP	0.574	3.440	0.008	0.008	<0.0001
(*b*)	6	MAMm	0.388	1.480	0.218		
	7	ELEV	0.365	1.340	0.276		
	8	ORG	*0.243*	*0.750*	*0.662*		
	9	MML	*0.239*	*0.730*	*0.676*		
	10	SLOPE	0.228	0.690	0.710		
	11	AC	**0.206**	**0.600**	**0.779**		
	12	MMm	0.205	0.600	0.780		
	13	VAVCm	**0.197**	**0.570**	**0.806**		
	14	WATER	0.158	0.440	0.900		
	15	ROC	**0.135**	**0.360**	**0.940**		
	16	VAVCx	**0.102**	**0.260**	**0.978**		
	17	MAC	**0.097**	**0.250**	**0.981**		
		Variable combinations	Error count estimates				
(*c*)	Proc Discrim	1–2–3–4-5			0.312		

However, thin till xeric burns less than might be assumed considering its moderate drying potential (Table 1).

Our first hypothesis is already partially supported because the drier SDD (in bold in Table 2) all have inferior fire cycles than the mean of the territory and they are also shorter than those of the more humid SDD (in italic in Table 2).These results demonstrate a certain effect of deposits the fire cycle. However, these analyses do not take into consideration the variations in climatic and physical factors characterising the large study area of 190 000 km^2.

Fire cycle for the different regions

Some LU that were located on the edge of our study area were removed from this analysis as their burned area was not representative of the entire LU. For the most part, the LU with similar survival distributions that were grouped together were spatially contiguous, although there were three exceptions (Fig. 3; Table 3). In these cases, the distant portions were distinguished in further analysis (C1, D1 and G1), although they were not significantly different.

The fire cycle increases progressively from 90 years in region A in the north-west to more than 715 years in the south-eastern region G1, but also from north to south in region G (fire cycle = 634 years). In the north-west of the study area, despite their geographical proximity, regions A, B and C1 are significantly different (Table 3). Region C1 is an enclave between regions A and B and it differs significantly due to a slightly longer fire cycle (i.e. 149 years against less than 100 years for region A and 129 years for region B). Region C, with a fire cycle of 205 years spreading from the middle of the territory to its north-eastern end, differs significantly from regions A and B but not from region C1. The D1 region is surrounded by region C, but its fire cycle is longer (237 *v.* 205 years). Regions D1 and D do not differ based on their fire cycle. Towards the south, region E has a slightly longer fire cycle than regions D and D1. However, region F distinguishes itself from region D but not from region E. Regions G1 (635 years) and G (715 years) are not significantly different from each other nor from region E, but they differ from the other regions due to their long fire cycle.

SDD fire cycle within each region

Within each region, the SDD usually has a fire cycle value close to the one estimated for the observed region (Table 4*a*). At first glance, regardless of the region, fire cycle differences between SDD appear smaller when observed at the regional level (Table 4*a*) than when observed a broader scale (Table 2). The regions clearly seem to influence the SDD's fires cycle. In the regions that burn often (A, B), the differences in fire cycle length of the SDD, whether dry or humid, xeric or mesic, is minimal. For example, humid SDD, which have a fire cycle longer than 200 years throughout the whole study area (Table 2), all have a fire cycle shorter than 100 years in region A (Table 4*a*). Similarly, the driest SDD, which have a fire cycle varying between 144 and 173 years (Table 2), generally have a shorter fire cycle in regions A and B (Table 4*a*). With an increase in the fire cycle region, we observed more significant effects of SDD (Table 4*a*). For instance, VAVCm, which has the shortest fire cycle in region A with 92 years, burns in 774 years in region G. Similarly,

Table 6. Mean values for precipitation, temperature, elevation, slope, aridity index, water bodies and all surficial deposit–drainage (SDD) combinations for the 10 regions

See Fig. 4 for the location of the regions. *n*, number of landscape units per region. See Table 5 for the description of physical variables. See Table 1 and Appendix 1 for the description of SDD. The strongest discriminant variables from Table 5*a* are shown in bold

	Regions									
	A	B	C1	C	D1	D	E	F	G1	G
n	5	7	1	10	1	2	2	4	2	2
Physical variables										
PPT (mm)	**700**	**821**	**700**	**925**	**1000**	**900**	**900**	**1063**	**1125**	**950**
TEMP (°C)	**−1**	**−1**	**−1**	**−2**	**−4**	**−1**	**−1**	**−1**	**−1**	**−1**
SLOPE (%)	7	5	7	7	15	8	4	10	9	4
AI	**78**	**97**	**78**	**120**	**138**	**100**	**100**	**112**	**125**	**100**
ELEV (m)	500	430	500	521	800	496	433	387	472	412
WATER (% area)	0.12	0.14	0.17	0.15	0.08	0.08	0.11	0.09	0.12	0.10
SDD (% area)										
VAVCx	0.06	0.09	0.03	0.10	0.12	0.04	0.04	0.03	0.04	0.04
VAVCm	0.03	0.02	0.02	0.01	0.00	0.01	0.01	0.02	0.01	0.02
AC	0.05	0.05	0.04	0.12	0.11	0.04	0.02	0.00	0.00	0.00
ROC	0.08	0.02	0.04	0.01	0.06	0.03	0.00	0.05	0.03	0.01
MAC	0.03	0.02	0.03	0.02	0.01	0.02	0.02	0.02	0.03	0.02
Sum of driest SDD	0.25	0.21	0.16	0.26	0.29	0.13	0.10	0.12	0.10	0.09
MAMx	**0.00**	**0.01**	**0.00**	**0.02**	**0.00**	**0.10**	**0.05**	**0.19**	**0.14**	**0.06**
MAMm	0.19	0.07	0.19	0.07	0.10	0.17	0.14	0.30	0.21	0.11
MMm	0.40	0.51	0.54	0.45	0.44	0.31	0.36	0.22	0.36	0.30
MML	0.01	0.02	0.01	0.02	0.06	0.02	0.01	0.03	0.03	0.01
MMh	**0.03**	**0.05**	**0.03**	**0.06**	**0.04**	**0.07**	**0.14**	**0.04**	**0.07**	**0.15**
ORG	0.08	0.12	0.05	0.09	0.03	0.10	0.14	0.05	0.05	0.24
Sum of most humid SDD	0.71	0.77	0.82	0.70	0.68	0.78	0.84	0.83	0.85	0.87

the organic deposits that burn in 95 years in region A burn in 1007 years in region G.

Regions A and B show effectively little intrazonal differences among SDD since none of their values are significant except for the organic deposits in region B (Table 4*b*). Starting with region C, SDD fire cycle values are often significantly different from the expected values. This pattern appears to be amplified in regions G1 and G. We also note a greater number of negative values (dark grey) at the bottom of Table 4*b*, corresponding to the most humid SDD; conversely, more positive values (light grey) are found at the top of Table 4, corresponding to the driest SDD. This confirms that the driest SDD (in bold) have a tendency to burn more than the more humid deposits (in italic), as shown in Table 2. In fact, this is true for VAVCx and VAVCm, which have a significantly higher probability of burning than expected. In contrast, organic deposits (ORG) and thin till with lateral drainage (MMl) have a lower probability of burning than expected in five and four regions, respectively (Table 4*b*). The other SDD burn more or less depending on the region considered. For instance, thin till with xeric drainage (MAMx), which was tagged as the SDD with the longest fire cycle (Table 2), burns significantly more than expected in regions E, F and G whereas it burns less than expected in regions C and D.

Explaining spatial variations in fire cycle

First, the Stepdisc procedure was used to highlight descriptors with the highest discriminant powers (Table 5*a*). Thin till with xeric drainage is the strongest descriptor ($R^2 = 0.81$), followed by precipitation ($R^2 = 0.727$), thick till with hydric drainage ($R^2 = 0.69$), aridity index ($R^2 = 0.66$) and temperature ($R^2 = 0.57$). Results indicate a significant relationship mainly between climatic variables (precipitation, temperature and aridity index), SDD types and our regionalisation based on fire cycle. The remaining variables (Table 5*b*) do not show any strong effects. The Discrim functions showed a classification error of 0.31, which means that ~70% of the LU are correctly classified (Table 5*c*). Indeed, the 30% classification error can be explained by the fact that some LU, although classified in one region, have fire cycles that are similar to the range characterised by another region, for example LU was classified in region A, instead of B (Appendix B).

The best classification descriptors presented in bold characters in Table 6 are discussed for each region. Regions A, B and C1 are the driest regions within the study area, with mean annual rainfall varying between 700 and 821 mm and an aridity index <100, the lowest of the study area. These three regions have hillocks terrain with an average altitude of ~500 m. They have a relatively high proportion of dry SDD (between 21 and 26%), except for C1 (16%), when compared with the other regions (Table 6). These dry SDD are composed of juxtaglacial and disintegration moraines containing a high proportion of boulders, stones and pebbles forming soils with a low potential for retaining water. In addition, region A differs from the others based on its higher proportion of outcrops (8%). Regions A, B and C1 also have in common the rear absence of MAMx (0 to 0.2%) and a low proportion of MMh that occupies between 3 and 6% of those areas. Region C is different from the previous regions with higher rainfall (925 mm) and a higher aridity index (120). Region C also has a relatively high proportion of dry SDD (26%), with the highest proportion of ablation till (AC) in the whole study area.

In region D1, precipitation increases further to reach 1000 mm, but temperatures reach the minimum observed in the entire study area (−4°C), thereby increasing the aridity index. Its high terrain, with Otish Mount reaching 1100 m, clearly distinguishes it from other regions. In addition, D1 has the highest proportion of dry SDD (29%) appearing at the summit (Fig. 3; photo 5), of which 6% is composed of rock and 12% of ablation till.

Regions D, E, F, G1 and G share a lower proportion of dry SDD than the preceding regions. Regions D and E, which are contiguous, form a homogeneous geographical entity with similar precipitation (900 mm) and temperatures (−1°C). Both regions D and E are characterised by deep valleys (~400 m) lined with thick mesic or hydric till. Dry SDD, which are poorly represented (10–12%), outcrop on steep slopes or at the summit (Fig. 3; photo 8). Region E differs from region D, with a greater proportion of thick hydric till (14%) and a lower proportion of thin xeric till (5 *v.* 10%).

Region F, which belongs to the balsam fir-white birch moss domain, shows a succession of hills and slopes oriented north–south, with an average rainfall of 1063 mm. Thin xeric till (MAMx) occupies the peaks and the most rugged areas (19%). North of region F, region G1 has the highest precipitation in the study area (1125 mm) and thick humid till (MMh) occupies 15% of the region. The driest SDD occupies 10% of the area whereas thick till occupies more than 50% and thin xeric till (MAMX) is more abundant than in any other region (14%).

In region G, precipitation is less important than in region G1 (950 mm). Region G is clearly different from the other regions with vast expanses of peatland that occupy 24% of the area and the lowest proportion of the driest deposits (9%). Thick hydric till (MMh) occupies 15% of the area, with 6% of MAMx.

Discussion

Influence of interregional climate variations on fire cycle

The short time period for investigation (1940–2006) does not allow a proper diagnosis of temporal variation in fire cycle to be made. However, we can highlight that important fire years occurred between the 1980s and 1990s. These large fire years were equally reported in the territory of Waswanipi, located west of our study area (Le Goff *et al.* 2007), in the Abitibi region (Bergeron *et al.* 2004*a*), in the centre of the province (Bergeron *et al.* 2001), and also in other regions of the Canadian boreal forest (Skinner *et al.* 1999; Gillett *et al.* 2004). The dataset is sufficient to establish significant spatial variations in the fire cycle of this northern region, which is still poorly understood. Interregional variations in fire cycle have been brought to light in the boreal forest of North America (Heinselman 1973; Johnson and Larsen 1991; Larsen 1996; Bergeron *et al.* 2006). Gauthier *et al.* (2001) suggested that an increase in fire cycle length from the west towards the east in eastern Canada was largely the result of a precipitation gradient, explained by a continental influence in the centre of the province and maritime climate in the North Shore (Cyr *et al.* 2007) and Gaspésie regions (Lauzon *et al.* 2007). The similar pattern observed at a large scale in this study area suggests the same phenomenon. The spatial organisation of the regions clearly suggests a strong influence of the climate at the broad scale. Precisely, our study area is encompassed by a north-west–south-east precipitation gradient. Precipitation increases rapidly from the west (region A with 700 mm) towards the east (region G1 with 1125 mm). In summer, during the fire season, this difference is accentuated as the area north-west of Lake Mistassini is characterised by less than 100 mm of monthly precipitation (in July and August); whereas in the south, precipitation reaches up to 125 and 135 mm in the extreme south-east (Proulx *et al.* 1987). This diagonal climatic gradient, which is clearly showing an 800-mm isohyet of annual rainfall, contributes to the top-down effects on fire cycle variations observed in this region. It is reasonable to stipulate that the large concentration of annual area burned in the north-west of the study area, more specifically in regions A and B, is under climatic control. Based on other studies, the large annual area burned is connected to high pressure systems in the upper atmosphere, specifically at the level of 500 hPa, which would create ideal dry conditions for triggering fire (Skinner *et al.* 1999). The lightning activity associated with increased convective activity (creating thunderstorms) during the breakdown of these positive tropospheric anomalies (Nash and Johnson 1996; Girardin 2009) results in lightning fires. Skinner *et al.* (2006) further documented the influence of previous winter sea surface temperatures of the Atlantic and Pacific Oceans on summer fire weather in the different forested regions across Canada. In particular, they highlighted the role of the Pacific Decadal Oscillation (PDO; Mantua *et al.* 1997) in creating a dipolar climatic control over the Quebec forest: the PDO would negatively affect fire activity in southern Quebec and positively affect the activity in northern Quebec (Skinner *et al.* 2006). Le Goff *et al.* (2007, 2008) also found a positive correlation between changes in decadal stand-age distribution in the Fire Triangle Area (south-west of Lake Mistassini) and changes in PDO phases.

The extension of our analyses over a longer time period could certainly confirm the trend of short mean fire cycle (201 years) or high burn rate (0.49) observed for the whole study area since it is commonly accepted that this part of the Quebec province experienced the largest area burned between 1959 and 1997 (Stocks *et al.* 2003). In addition, this paper shows a particularly high fire risk for regions A and B, which experienced the shortest fire cycles (<130 years) or highest burn rates (0.78 to 1.1) recorded in Quebec between 1940 and 2006. These results confirm and complete the work of Lefort *et al.* (2004) who found similar trends south of the 52°N in our study area. Indeed, regions A and B burn more frequently than the Taiga Shield East ecozone (burn rate = 0.24) and the Boreal Shield East ecozone (burn rate = 0.14) that surround the study area (table 1 in Stocks *et al.* 2003). The 50 000 km^2 area covered by regions A and B could then represent one of the shortest fire cycles (or higher burn rates) observed in eastern Canada for the current period.

Top-down–bottom-up effects on fire cycle

The significant differences observed between the SDD's fire cycles within the whole territory suggest that shorter fire cycles are associated with the driest SDD, whereas longer ones are associated with the more humid SDD. Contrary to the results of

Lesieur *et al.* (2002) and Lecomte and Bergeron (2005), our results may suggest an influence of SDD on fire cycle length. The consideration of their drying potential, something that has never been investigated in previous studies, seems to highlight their effects on fuel and, consequently, the potential to ignite and propagate fire. This is particularly obvious for the combination of juxtaglacial and disintegration moraines with xeric or mesic drainage and also with ablation till. These very dry deposits are made up of various types of very coarse materials coupled with a sandy texture that retains little water in the soil. In addition, their morphology displays a knob and basin topography that could accentuate drainage, thereby offering a dry substrate contributing to provision of dry fuel. This brings us to the same conclusion as Harden *et al.* (2001) who suggested that well-drained soils are more susceptible to short fire intervals than poorly drained soils. Conversely, organic deposits and thick till with lateral drainage definitely tend to burn less, no matter which region is considered (Table 4*b*; last line). This suggests that the peatlands in our territory, often localised in depressions, have a constant water supply and are therefore very difficult to dry, even during summer drought. In this context, there is low probability that organic deposits might constitute a flammable fuel capable of igniting and propagating fire in our study area. Nevertheless, it is true that under some special dry conditions coupled with a low watertable, peatlands can burn (Turetsky *et al.* 2004). But in our case, the long fire cycle observed in the G region seems linked to the high proportion of peatlands (24%). Between these two extremes, SDD that are intermediate as far as the soil drying potential is concerned have the potential to include large amounts of ground fuels and their fire cycle seems strongly influenced by factors other than their intrinsic characteristics. Indeed, SDD alone cannot explain the extent of fire cycle variations.

As many studies suggest (Turner *et al.* 1994; Lertzman and Fall 1998; Heyerdahl *et al.* 2001; Taylor and Skinner 2003; Mermoz *et al.* 2005), fire cycle is influenced by top-down factors (climate) and is associated with a combination of bottom-up factors (SDD, slope, topography and vegetation). The large area burned observed in regions A and B over the entire study period confirms that the combination of climate and physical variables (low precipitation, relatively flat topography, abundance of very dry SDD) enforced by the western winds created extreme conditions for fuels to dry, increasing their flammability. In this context of 'super dry region', the conjunction of these factors is sufficient to overwhelm the potential differences that more humid SDD could make (Gedalof *et al.* 2005). That is why our results indicate clearly that the SDD (dry or humid) did not differ in their fire cycle in regions A and B (except organic deposits). Conversely, in a particularly humid region with considerable summer rainfall coupled with the wide extent of humid deposits with very low drying potential, the different physical characteristics of SDD are well expressed, as in regions E, F and G. But even in those regions where climate is less conducive to fire (fire cycle >300 years), the driest SDD in the landscape seems to have a stronger probability of burning.

Although we can concede that the difference in fire cycle between regions C1 and A (149 *v.* 90 years) could simply result from a random variability in burned areas (one major fire in region A that would not have affected the other region, for example), our results could suggest a direct effect of SDD at the local scale. In fact, region C1 differs from region A by a lower proportion of dry SDD (16 *v.* 25%) whereas humid SDD types (82 *v.* 70%) are more important. It suggests that a high proportion of humid SDD could create conditions that are less prone to fire propagation, even in a regional context that is particularly dry.

Many studies have highlighted the effect of topography on fire cycle variations (Heyerdahl *et al.* 2001; Mermoz *et al.* 2005). The elevated topography corresponding to the Otish Mounts in region D1, in an otherwise relatively flat environment, might cause a natural break in the fuel and result in a longer fire cycle, although paradoxically the region includes 29% of dry SDD. Topography is thought to have more influence on fire severity than on fire cycle (Kushla and Ripple 1998; Broncano and Retana 2004). However, topography can also enhance precipitation and make the region more humid and therefore less prone to fire even with a higher dry SDD proportion, as is the case in region D1. Although we have not analysed the landscape position of the SDD, we recognise that together with the topography it can affect fire cycle, regardless of the drying potential. In our territory and at the regional scale, topography is of primary importance in determining the location of surficial deposits. The valley bottoms are lined with thick hydric till or mesic drainage whereas the steep slopes and summits are generally drier because they are covered with thin till or outcrops with excessive drainage. Similarly, we did not find any effect of slope on fire cycle variations, probably due the inadequate scale used (LU mean slope). However, the topography analysis requires a finer scale than the one used here to detect the effects of slope and aspect on water storage in SDD and their effect on fuel drying and, ultimately, on fire cycle length.

Conclusion

The amplitude of interregional variations in fire cycle observed in the area is considerable. The combined effect of climate and SDD appears to effectively control spatial variations in fire cycle. Moreover, in some instances, we have shown that their joint effect can somehow be synergistic when a high proportion of dry deposits accentuates the drought within a region with low precipitation. Conversely, a high proportion of humid SDD could decrease fire risk. These first analyses at the regional scale involving the potential of SDD for soil drying show a trend that could also be refined by studies at the local scale. Extending the fire database as far back in time as possible could prove that this heterogeneity is permanent as it appears to be strongly linked to the physical environment.

Our results have potential implications. First, our capabilities to predict such variations in fire cycle and to know the factors responsible for this heterogeneity are useful for fire management (Hirsch *et al.* 2001). For example, in the case of a prolonged drought period during which most fires occur, regions where the drying factors are additive (low precipitation + high proportion of dry SDD) would be more prone to fire ignition and would have a higher probability of having large wildfires (which could quickly become uncontrollable thereafter depending on the fuel) than areas with a more relatively humid environment (higher precipitation + low proportion of dry SDD + high proportion of organic deposits). This knowledge could help to set deployment and suppression objectives. Understanding the factors responsible for changes in fire cycle, also taking into account the scale at which they interact, could help optimising the protection of forests against fire in a cost-effective manner so that forest-related resources can be managed sustainably and continue to benefit all communities. Second, the regionalisation described in this paper, based on the fire cycle, could complement the ecological classification and boundaries of the forest management units established by the MRNQF. The large variability in climate, physical factors and fire cycle in this part of the province of Quebec makes it essential to develop management strategies that are flexible and adapted to the current and future fire activity of these different regions.

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Appendix 1. Percent area of the different surficial deposit types that are composed of the surficial deposit–drainage (SDD) combinations with their summarised description

Surficial deposit type codes (e.g. 1AB) refer to the cartographic codes commonly used for the province of Quebec in the surficial deposits classification system (Robitaille and Saucier 1996). The SDD code summarises the quality of the stoniness and the texture: VAVC, very abundant, very coarse; AC, abundant, coarse; ROC, rock; MAC, moderately abundant, coarse; MAM, moderately abundant, moderate; MM, moderate, moderate; ORG, organic

Surficial deposit type	% area	SDD codes	Description
1AB: Boulder field	0.09%	VAVC	Combination consists of disintegration moraine and juxtaglacial deposits. Although from different origins, the deposits comprised in this group have a very coarse and abundant stoniness (stones and boulders) and sandy texture. These deposits are generally thick (> 10 m) and have an elongated morphology with ridges (Esker) or exposed (Kame) or knob-and-kettle (disintegration moraines). Depending on the proportion of gravel, pebbles and stone blocks, the drainage varies from mesic to xeric. Therefore these deposits have been classified in two SDD types. These combinations have the highest drying potential of the study area because the particle size is very coarse and the morphology can possibly accelerate the evacuation of the water.
1AD: Washed till	0.08%		
1BF2A: Juxtaglacial front moraine	0.04%		
1BG: De Geer moraine	0.08%		
1BP: Disintegration moraine	5.01%		
2A: Juxtaglacial	4.15%		
2AE: Esker	0.54%		
2AK: Kame	0.02%		
2AT: Kame Terrace	0.02%		
1B: Deposits with specific morphology	0.01%	AC	Ablation tills and Rogen moraines are generally composed of loose or somewhat compacted material with an abundant stoniness. Gravel and boulders are abundant and the texture is sandy-silty and somewhat coarse. Thickness varies from 1 to 10 m (for the Rogen moraines, with a hummocky morphology). Even if the drainage is mostly xeric this combination is less dry than the previous one because it is usually based on a compacted base till which can retain some water.
1BA: Ablation till > 1 m	2.59%		
1BC: Rogen moraine	1.37%		
1BN: Ground moraine	0.01%		
M1A: Thin till <25 cm	0.08%	ROC	Rock outcrops can be covered with a thin layer of organic deposits or a very thin till veneer on the peaks and on the convex surfaces. Drainage is generally excessive and the drying potential is high to medium, depending on the presence of the organic or thin till layer.
R: Outcrop > 50%	1.83%		
R1A: Outcrop between 25 and 50%	1.36%		
2B: Proglacial	0.01%	MAC	This combination consists essentially of outwash characterised by a moderately abundant stoniness (sand and gravel) and a sandy to sandy-silty texture. The thickness can reach ten of meters with a generally flat topography. The drainage is mostly xeric and the drying potential is medium to high.
2BD: Fluvioglacial	0.02%		
2BE: Outwash	2.99%		
4GS: Glacio-lacustrine <25 cm	0.68%		
4P: Beach	0.01%		
5S: Marine shallow water facies	0.14%		
5SY: Marine deep water facies	0.01%		
9S: Stabilised dunes	0.10%		
1AR: Undifferentiated thin till (25 cm to 1 m)	19.53%	MAM	The undifferentiated tills are characterised by a texture with variable proportions of sand, silt, and also clay. Their thickness varies from 25cm to several meters, with a wavy morphology. Therefore they were first subdivided into 2 classes based on their thickness. (1) The thin Till (0.25 to 1 m) or MAM have a drainage class from xeric to mesic and they are usually located on the upper slopes. (2) The thick till (> 1 m) or MM located on the flat to concave surfaces with drainage ranging from mesic to hydric and seepage. The drying potential of the thin till is greater than the thick till that tends to retain more water.
1A: Undifferentiated thick till > 1 m	44.42%	MM	
1BD: Drumlins and drumlinoids	3.59%		
1BF: End moraine	0.02%		
1BT: Mound of till debris	0.01%		
7BR: Rippled ombrotrophic	0.23%	ORG	The last combination, the more humid, is composed of organic deposits (peatlands). Since the last ice retreat, the flat, poorly drained areas were gradually covered with organic deposits because of the slow decomposition of organic matter that characterises this boreal area. In our study area the thickness of peatlands can reach 1–2 m. The deposit is saturated with water and drying potential is extremely low.
7BS: Structured ombrotrophic	1.04%		
7BU: Uniform ombrotrophic	1.50%		
7E: Thick organic > 1 m	5.91%		
7FS: Structured minerotrophic	0.18%		
7FU: Uniform minerotrophic	0.01%		
7T: Thin organic (40 cm and more)	2.27%		
Total	100.00%		

Appendix 2. Confusion matrix

The shaded cells represent the correct classification

		Suggested classification										
		A	B	C1	C	D1	D	E	F	G1	G	Total
Actual classification	A	3	0	2	0	0	0	0	0	0	0	5
		60	0	40	0	0	0	0	0	0	0	100
	B	2	3	0	2	0	0	0	0	0	0	7
		28.57	42.86	0	28.57	0	0	0	0	0	0	100
	C1	0	0	1	0	0	0	0	0	0	0	1
		0	0	100	0	0	0	0	0	0	0	100
	C	0	2	0	8	0	0	0	0	0	0	10
		0	0	0	80	0	0	0	0	0	0	100
	D1	0	0	0	0	1	0	0	0	0	0	1
		0	0	0	0	100	0	0	0	0	0	100
	D	0	0	0	0	0	1	0	1	0	0	2
		0	0	0	0	0	50	0	50	0	0	100
	E	0	1	0	0	0	0	1	0	0	0	2
		0	50	0	0	0	0	50	0	0	0	100
	F	0	0	0	0	0	1	0	3	0	0	4
		0	0	0	0	0	25	0	75	0	0	100
	G1	0	0	0	0	0	0	0	0	2	0	2
		0	0	0	0	0	0	0	0	100	0	100
	G	0	0	0	0	0	0	1	0	0	1	2
		0	0	0	0	0	0	50	0	0	50	100
	Total	5	6	3	10	1	2	2	4	2	1	36
	%	13.89	16.67	8.33	27.78	2.78	5.56	5.56	11.11	5.56	2.78	100
	Rate	0.40	0.57	0.00	0.20	0.00	0.50	0.50	0.25	0.00	0.50	0.29