

Fifty-year spatiotemporal analysis of landscape changes in the Mont Saint-Hilaire UNESCO Biosphere Reserve (Quebec, Canada)

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Abstract Diachronic analysis with a GIS-based classification of land-use changes based on aerial photographs, orthophotos, topographic maps, geotechnical reports, urban plans, and using landscape metrics has permitted insight into the driving forces responsible for landscape fragmentation in the Mont Saint-Hilaire (MSH) Biosphere Reserve over the period 1958–2015. Although the occurrence of exogenous factors, such as extreme weather and fires, can have a significant influence on the fragmentation of the territory in time and space, the accelerated development of the built environment (+470%) is nevertheless found to be primarily responsible for landscape fragmentation and the loss of areas formerly occupied by orchards, agriculture, and woodlands. The landscape metrics used corroborate these results, with a simplification of the shape of polygons, and once again reveal the difficulties of harmonizing different land uses. MSH has become somewhat of a forest island in a sea of residential development and

agriculture. To counter this isolation of fragmented habitat components, forest corridors have been proposed and developed for the Biosphere Reserve and particularly for the core area. Two corridors, to the north and south, are used to connect the protected area and other wooded areas at the regional scale, in order to promote genetic exchange between populations of various species. In that regard, the forest buffer zone around the hill continues to play a key role and has great ecological value for species and ecological preservation and conservation. However, appropriate management and landscape preservation actions should recognize and focus on landscape composition and the associated geographical configuration.

Keywords Landscape fragmentation · Biosphere reserve · Mont Saint-Hilaire

Introduction

The United Nations Educational, Scientific and Cultural Organization (UNESCO) launched the Man and the Biosphere Programme (MAB) in 1970, with the creation of several biosphere reserves (BRs) worldwide (UNESCO 1996). The recent UNESCO MAB strategy for the period 2015–2025 aims to promote the following four strategic objectives for the 669 BRs located in 120 countries: (i) conserve biodiversity, restore and enhance ecosystem services, and foster the sustainable use of natural resources; (ii) contribute to building sustainable, healthy, and equitable societies, economies, and thriving

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human settlements; (iii) facilitate sustainability science and education for sustainable development; and (iv) support mitigation and adaptation to climate change and other aspects of global environmental change (UNESCO 2016). Knowing that sustainable development is based on the triptych of environment-economy-society, the environment component nonetheless comprises all of the necessary base conditions—in terms of carrying capacity, constraints, hazards, natural resources, etc.—within which economic and social systems subsequently evolve. In that regard, it is important to note that a BR differs from other protected areas, such as national parks, wilderness areas, and wildlife refuges. Indeed, BRs represent a unique and very flexible form of protected area, based on their own system of governance to ensure that community concerns are taken into account by land managers and adaptable to local circumstances (Batisse 1982; Price 2002; Ishwaran et al. 2008; Schliep and Stoll-Kleemann 2010).

BRs have three interrelated and mutually reinforcing functions, namely (i) the conservation of landscapes, ecosystems, species, and genetic variation; (ii) economic, human, and cultural development; and (iii) to provide logistical support for research, monitoring, and environmental education (UNESCO 2000). The central area is usually dedicated to ecosystem conservation, while the surrounding area is a buffer zone, used to mitigate the impacts of human activity in the third area. This buffer zone is used for training and education, environmental monitoring, and scientific research. The third, or transition, area is dedicated to collaboration between various stakeholders in the area, toward implementing practices and policies that enable sustainable economic, social, cultural, and environmental development (UNESCO 2000). Since UNESCO designated many BRs a few decades ago, such as the Mont Saint-Hilaire (MSH) BR in 1978 (CNMSH 2011; McGill University 2017), and with recent and ongoing global environmental changes, which affect the variability of natural systems (i.e., climate change, frequency of extreme events) as well as the vulnerability of human populations (i.e., infrastructure, socio-demographic dimensions), it appears quite relevant to question the spatiotemporal evolution of these BRs over the last decades, particularly with regard to landscape changes rather than focusing solely on management effectiveness of the protected area (i.e., Reed and Egunyu 2013).

Landscape quantification represents a notable current issue for BRs, particularly because of the important

influence of landscape on the quality of human life and because of the active role of landscape as a resource for economic activities (Déjeant-Pons 2006; di Giulio et al. 2009). Landscape is then considered to be strongly linked to human activity (e.g., Jeager et al. 2007). Appropriate management and landscape preservation actions should recognize and focus on landscape composition and the associated geographical configuration (Bodesmo et al. 2012). These actions should, at the same time, prioritize the identification of the landscape segments that are critical for species preservation or for ecological processes, thereby providing more effective management plans (Collinge 1996; Lindenmayer et al. 2012; Rudnik et al. 2012). For this reason, landscape fragmentation analysis, which represents a very useful quantitative ecological tool because it measures the organization of landscape elements in both space and time (Leitão and Ahern 2002), plays a major role. Fragmentation is usually described as a process by which, at the landscape scale, ecosystems are broken down into smaller parcels with significant ecological consequences, such as habitat loss, and decreases in population and biodiversity (Wilcox and Murphy 1985; Fahrig 2003; Fisher and Lindenmayer 2007). Human disturbances (e.g., agriculture, forestry, housing development) and, to a lesser extent, natural disturbances (e.g., fires, strong winds, insect epidemics) are the main causes of fragmentation and change in the natural environment (Gardner et al. 1987; van Dorp and Opdam 1987; Forman 1995). Therefore, many related indices have been developed to quantitatively measure changes in the landscape (Moser et al. 2002; Li and Wu 2004; Kim and Pauleit 2005; Uuemaa et al. 2009). Likewise, many software packages such as FRAGSTATS and Patch Analyst have emerged (e.g., McGarigal et al. 2002), enabling a better understanding of a given area in terms of its species richness, ecosystem services, human activities, and landscape structure (Uuemaa et al. 2013; Pătru-Stuparu et al. 2015). Indeed, the quantification of spatial heterogeneity appears mandatory for a better understanding of the relationship between fragmentation processes and the resulting landscape pattern (Turner 1990).

In the province of Quebec in eastern Canada, the significant increase in home prices in the main urban areas, such as Montreal, over the past decades has led people to settle increasingly in suburban areas (Vachon 2011). Like most large urban areas of the world, the metropolitan area of Montreal has seen its population

increase over the past decades and the potential spatial expansion seems limitless, except for areas constrained by natural limitations (i.e., bounded by sea or mountain ranges) and/or high-frequency and high-intensity hazards. According to United Nations (UN) Habitat (2010), urban sprawl has become a global problem, because it contradicts sustainable development. Indeed, the overdevelopment of space leads to the loss of farmland and natural ecosystems and therefore to the extinction of and threat to many plant and animal species (Fahrig 2003; Fortin et al. 2008; Krauss et al. 2010). From a socio-economic point of view, urban expansion also leads to significant energy costs in terms of construction and maintenance of infrastructure, also increasing transport costs and causing severe landscape fragmentation (Norman et al. 2006; Jaeger et al. 2007; van der Ree et al. 2011; Freudenberger et al. 2013). Located 30 km east of the metropolitan area of Montreal, with a population of approximately 3.5 million people, the BR of MSH represents an interesting case study through which to analyze the effectiveness of careful development planning, which is intended to respect the principles of sustainable development and as such to prevent, or at least mitigate, exposure to natural hazards and use conflicts in a region, while also preserving ecosystems. Therefore, this study will focus on how landscape changes are reflected in planning. What forces drove these changes?

In this regard, a geographic and multiscale approach in time and space, combining biophysical components and processes of human development in the area, appears relevant, especially in the context of a UNESCO BR. The objectives of this paper are threefold: (i) to characterize the process of suburbanization at the scale of the MSH municipality since the mid-twentieth century; (ii) to produce a high-resolution spatiotemporal analysis of the patterns and processes of landscape fragmentation using a geographic information system (GIS) and landscape metrics; and (iii) to quantify the land-use changes in time and space for the period 1958–2015.

Materials and methods

Study area

The municipality of MSH is located 30 km east of Montreal, in the periurban area of the Richelieu River valley (Fig. 1), occupying 44.29 km², with a population

of 18,813 inhabitants (City of Mont Saint-Hilaire 2016), resulting in an average density of 425 inhabitants/km². It is bordered to the west by the Richelieu River and to the east by the MSH hill (Gilbert and Foland 1986; Currie 1989; Brisebois and Brun 1994). The maximum elevation of the hill is 375 m above the surrounding plain (414 m asl) (Feininger and Goodacre 1995), and it covers an area of approximately 10 km². However, the core area and the buffer zone of the BR are approximately 5 and 6 km², respectively, whereas the transition zone is 44 km², which is the smallest BR in Canada (Reed and Egunyu, 2013).

Geologically, there are more than 340 types of minerals, corresponding to approximately 10% of all known minerals, 40 of which are unique in the world (McGill University 2017; Centre de la Nature du Mont Saint-Hilaire (CNMSH) 2011). The maple-hickory precolonial forest, which has never been exploited commercially, represents one of the few areas of biodiversity conservation associated with this complex ecosystem. Over 600 species of vascular plants have been recorded on the hill. Furthermore, the Dieppe Cliffs is a refuge for peregrine falcons and many other animal (i.e., 200 bird and 30 mammal species) and plant species threatened or vulnerable in Quebec (Millien 2003; Planning committee of the perimeter of the mountain 2004a; McGill University 2017).

Census data and spatiotemporal analysis of the built environment

Data for the period 1961–2016 from Statistics Canada, Montreal Metropolitan Community (MMC), and the Municipality of MSH were used to characterize the socio-demographic evolution of the population over the past decades in the study area. Statistical data provide information on the quantitative fluctuations of the population overall, but do not provide relevant information on its spatial distribution and evolution within a given area, which is crucial knowledge in developing a prospective vision of the landscape (Burel and Baudry 1999; Forman and Godron 1986). The spatial extent and evolution of different residential areas have, therefore, been determined from an analysis of multitemporal aerial photos from 1958, 1966, 1972, 1977, 1984, and 1994. A series of orthophotos from 2007 and 2015 from the MMC database was also used, in combination with several maps (Table 1).

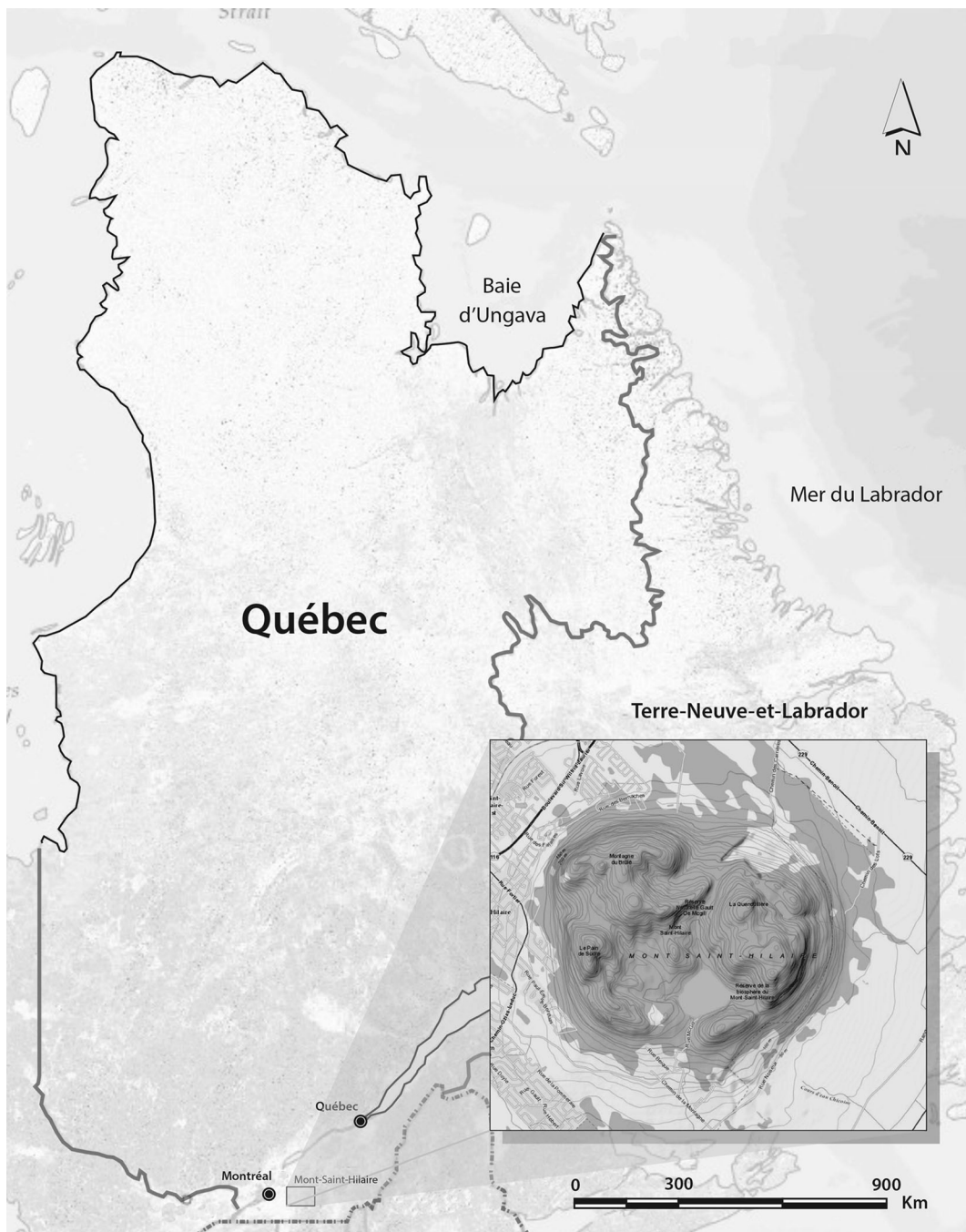


Fig. 1 Location of the Mont Saint-Hilaire Biosphere Reserve (midpoint: 45° 32' N; 73° 09' W)

Calculation of landscape fragmentation indices

The diachronic landscape fragmentation analysis for the period 1958–2015 focused on the total area of MSH (44.29 km²). Listed land use was divided into six classes: (1) agriculture; (2) woodlands; (3) orchards; (4) the

core area and the buffer zone of the MSH Biosphere Reserve; (5) residential area (suburban); and (6) other (including unknown) uses (Table 2). A land-use map was created based on the polygons that were delineated from scanned aerial photographs from the years 1958, 1966, 1972, 1977, 1984, and 1994, which were first

Table 1 Aerial photographs, orthophotos, and maps used in this study

Year	Flight	Reference number	Scale	Source
Aerial photographs				
1958	A16289	197-199	1:32,000	Energy, Mines and Resources Canada. Ottawa: NAPL Reproduction Center
1966	Q66213	49-52	1:40,000	Ministère des terres et forêts, Service de la photogrammétrie et de la Cartographie. Photo-cartothèque provinciale, Québec
1972	Q72804	212-214	1:25,000	Ministère des terres et forêts, Service de la photogrammétrie et de la Cartographie. Photo-cartothèque provinciale, Québec
1977	Q77894	120-123	1:40,000	Ministère des terres et forêts, Service de la photogrammétrie et de la Cartographie. Photo-cartothèque provinciale, Québec
1984	Q84819	31-33	1:40,000	Ministère de l'Énergie et des Ressources, Service de la cartographie, Québec
1994	Q94500	146-148	1:40,000	Ministère de l'Énergie et des Ressources, Service de la cartographie, Québec
2007–2015	328 5042-5048 330 5044-5048 332 5042-5048 334 5042-5046		Orthophotos	Montreal Metropolitan Community (MMC)
Maps				
1952	31H11	Unknown	1:50,000	Department of National Defence Army Survey and Establishment, Canada
1971	31h/11b	UTM NAD 1927	1:25,000	Energy, Mines and Resources Canada

orthorectified and georeferenced. High-resolution orthophotos from 2007 and 2015 were also used. The digitization of polygons for each class was conducted at the scale of 1:5000, with a nonautomated (i.e., manual) classification performed so as to reduce the risk of misinterpretation. Scanning and polygon area calculations were carried out using QGIS 2.0 software. All maps were then compared, and the nature of changes underway within each land-use category was measured for different time periods.

Although several landscape metrics exist (e.g., Lausch and Herzog 2002), three distinct but complementary indices have been used here, given their particular relevance. Namely, the shape index (SI), the mean shape index (MSI), and the average weighted shape

index (AWSI). The SI (Eq. 1) provides information on the level of anthropogenic intervention in an area and is calculated as follows:

$$SI_i = \frac{p_i}{2 \sqrt{\pi \times a_i}} \tag{1}$$

where *p* and *a* are the perimeter and area of the polygon, respectively. Taking the square root in the denominator ensures that the calculation is independent of the absolute spatial scale (Comber et al. 2003). The resulting SI value is equal to 1 if the polygon is perfectly circular, and increasing values result as the shape of the polygon becomes more irregular (Forman and Godron 1986; Moser et al. 2002).

Table 2 Description of the land cover classes used in this study

Class	Description
Agriculture	Cropland or fallow, and associated houses and farm buildings
Woodlands	All wooded areas not within or connected to MSH, and covering an area larger than 1 ha
Orchards	Space dedicated to the cultivation of fruit trees
MSH Biosphere Reserve	The woody core area and buffer zone of MSH
Suburban	Residential areas, including some businesses and industrial activity
Other	Wastelands, quarries, and gravel pits, and areas where use is impossible to determine

The MSI provides the average SI for all polygons, divided by the number of polygons for a given class (NP) (McGarigal and Marks 1994). The MSI (Eq. 2) is determined by the following:

$$MSI = \frac{\sum_{i=1}^m SI_i}{NP} \quad (2)$$

Finally, the AWSI was also calculated to minimize the weight given to anthropogenic polygons with a large perimeter and a small area (Moser et al. 2002). Likewise, this index provides a more realistic picture of the SI, by giving more weight to polygons with a larger area (McGarigal and Marks 1994; Kim and Pauleit 2005), which are more representative of a class that contains only a few polygons (McGarigal and Marks 1994). The AWSI (Eq. 3) is calculated as follows:

$$AWSI = \frac{\sum_{i=1}^m SI_i \times a_i}{\sum_{i=1}^m a_i} \quad (3)$$

Identification and delineation of restricted areas

From the 2007 and 2015 orthophotos, coupled with data from the National Topographic Data Base (NTDB), a digital elevation model was constructed using ArcMap 9.3 software. This allowed the accurate estimation of the distance between housing developments near the talus and the buffer zone of the MSH Biosphere Reserve. The analysis of rockfall hazards was achieved by integrating GIS coordinates of the security perimeter previously delimited and reported in Tanguay (2003).

Results

Human development of the area and spatial expansion of the built environment

The statistics reveal sustained population growth over the past 57 years (1958–2015), corresponding to an increase of 470%. The number of inhabitants increased from 4007 in 1961 to over 18,813 in 2015. The decade from 1971 to 1981 is associated with the highest growth rate, of ~75%. This population growth is further reflected in an increased population density of the area, rising from 90 inhabitants/km² in 1961 to more than 425 inhabitants/km² in 2015 (City of Mont Saint-Hilaire

2016). Note that in just 5 years, from 2001 to 2006, nearly 800 new private homes were constructed in the area, testifying to the increased suburbanization of the MSH foothills. From the 44.29 km² corresponding to the municipality of MSH, 12.8 km² are suburban, and this area is already over 87% developed (~11.14 km²). However, some natural constraints (i.e., steep slopes, landslide hazards) represent a little more than 1 km² of the land that remains available. Figure 2 shows the evolution of suburbanization for the following periods: before 1958, 1959–1965, 1966–1971, 1972–1976, 1977–1983, 1984–1993, 1994–2007, and 2007–2015.

Before 1958, residential development was mostly concentrated near the Richelieu River and on the south side of MSH. Between 1958 and 1966, three additional residential areas were developed, two of these located closer to the hill. Subsequently, from 1967 to 1971, already existing residential areas were expanded and a new development to the southwest of MSH took place. The red area in Fig. 2 corresponds to the years 1972 to 1976. This period marks the beginning of rapid population growth. Indeed, among others, the development of neighborhoods located much closer to the western and northwestern flanks of the hill are notable. The period 1977 to 1983 was associated with increased growth in the suburban areas around some existing neighborhoods. Note the residential construction on the southwest side of the hill, within 500 m of the buffer zone, and the further development of this area between 1984 and 1993. Finally, between 1994 and 2015, residential development occurred mainly on the northwest side of MSH, near areas with steep slopes and rockfall hazards.

Landscape fragmentation and fine-scale analysis of land-use changes

Between 1961 and 1993, forest cover was greatly fragmented, and the total forested area decreased by ~75% at the regional scale (Centre de la Nature du Mont Saint-Hilaire (CNMSH) 2010), corresponding to 18% in the study area (Millien 2003). The main causes of deforestation were residential development and expanding agricultural area (Planning committee of the perimeter of the mountain 2004b; Centre de la Nature du Mont Saint-Hilaire (CNMSH) 2010). For MSH, forest covering the piedmont and the perimeter has important value, since it acts as a buffer between suburban development and the central conservation

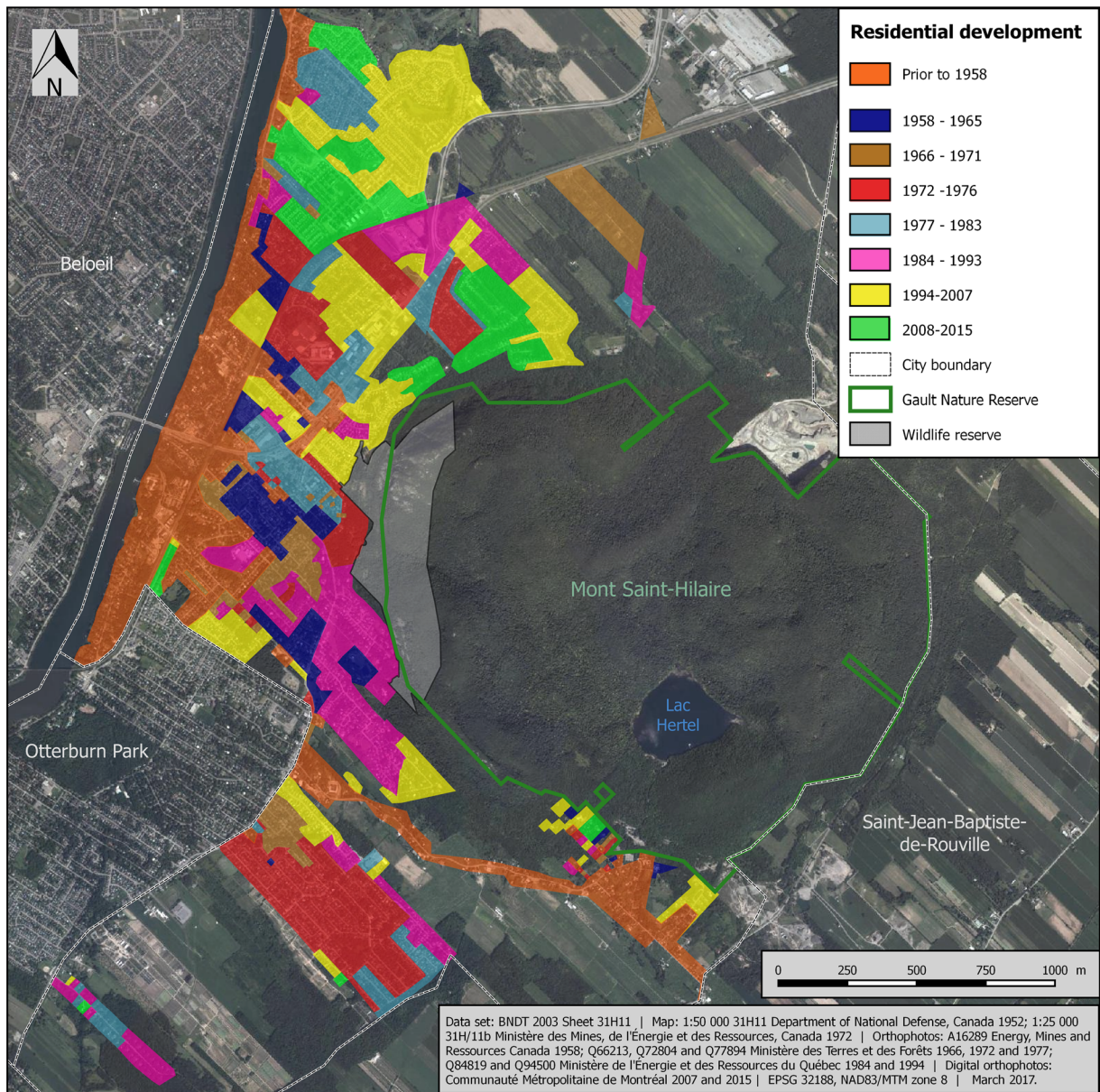


Fig. 2 Spatiotemporal evolution of the MSH suburbanization for the period 1958–2015

area of the BR. In 2009, forest cover occupied 18.12 km², or over 40% of the area (Montreal Metropolitan Community (MMC) 2011). Of that, 10 km² are protected, since they are located on the McGill University Gault Nature Reserve, a provincial legislation that was implemented following the first periodic review of the BR in 1997 (Reed and Eguny 2013). Another 6 km² of unprotected wooded area occupy the MSH piedmont. In total, the central conservation area and the partially unprotected buffer

zone contain more than 88% of the wooded area of the municipality.

At a finer scale, the diachronic analysis of landscape fragmentation for the period 1958–2015 allowed a better understanding of the land-use changes in time and space through use of the shape indices (SI, MSI, AWSI) described in the “Materials and methods” section above. Figure 3 and Table 3 summarize the situation in 1958 and in 2015, as well as the cumulative changes that took place between these years.

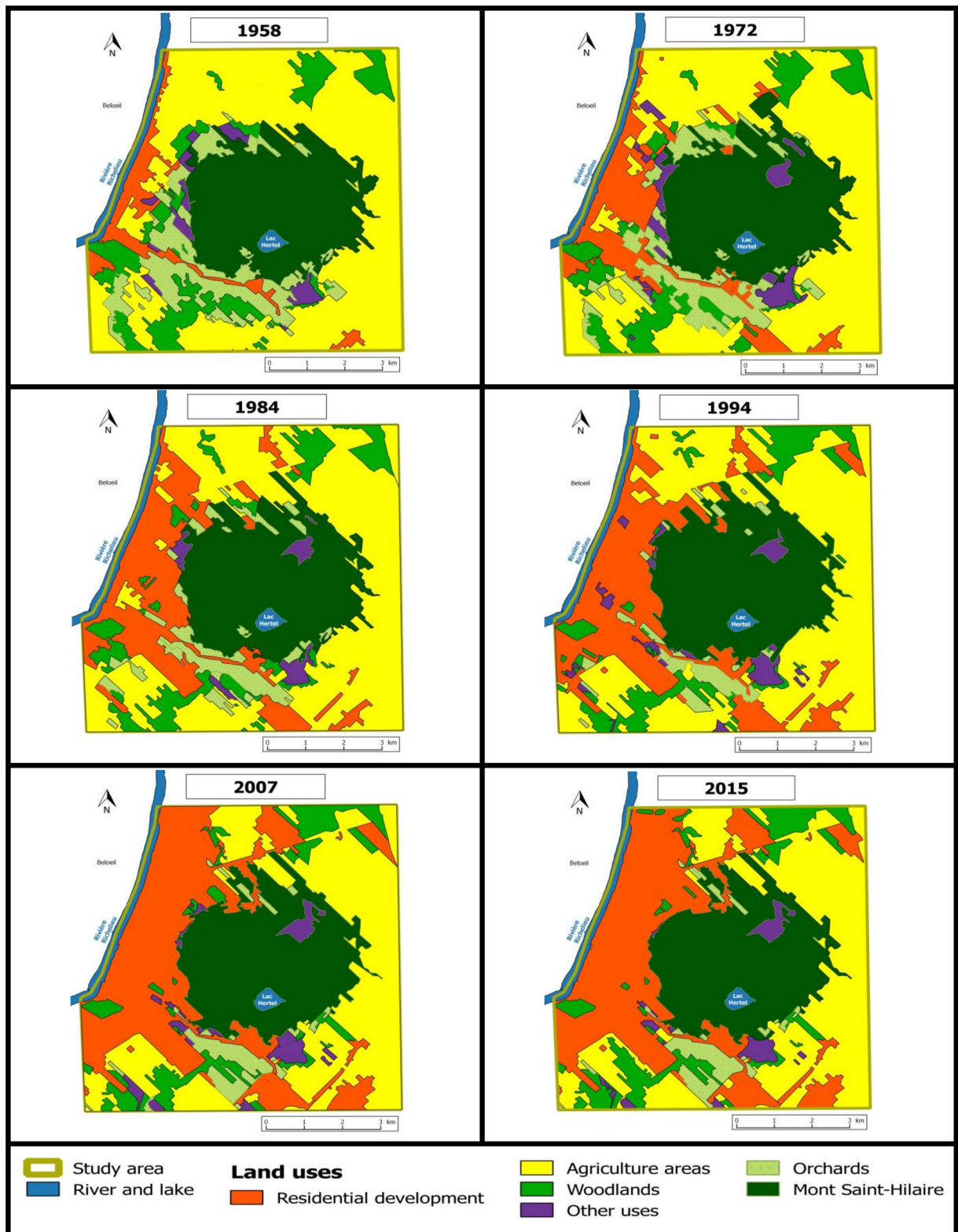


Fig. 3 Spatiotemporal evolution of land-use changes for the period 1958–2015

Table 3 Land-use characteristics for 1958 and 2015, and the overall change from 1958 to 2015 (italicized for each land-use class)

Land-use class	Year	Proportion (%)	Polygons (N)	Area (km ²)	Perimeter ^a (km ²)	SI	MSI	AWSI
Agriculture	1958	45.79	8	29.55	3.69	17.55	2.19	3.44
	2015	31.37	19	20.24	1.07	22.78	1.90	2.73
	<i>Change</i>	<i>-14.42</i>	<i>11</i>	<i>-9.31</i>	<i>-2.62</i>	<i>5.23</i>	<i>-0.29</i>	<i>-0.71</i>
Woodlands	1958	11.06	20	7.14	0.36	38.49	1.92	2.52
	2015	8.77	27	5.66	0.21	48.27	1.66	2.61
	<i>Change</i>	<i>-2.29</i>	<i>7</i>	<i>-1.48</i>	<i>-0.15</i>	<i>9.78</i>	<i>-0.26</i>	<i>0.09</i>
Orchards	1958	10.80	26	6.97	0.27	46.11	1.77	2.72
	2015	3.60	19	2.32	0.12	28.54	1.50	1.92
	<i>Change</i>	<i>-7.20</i>	<i>-7</i>	<i>-4.65</i>	<i>-0.15</i>	<i>-17.57</i>	<i>-0.27</i>	<i>-0.80</i>
MSH Biosphere Reserve	1958	24.86	1	16.04	16.04	2.87	2.87	2.87
	2015	24.33	1	15.70	15.70	2.39	2.39	2.39
	<i>Change</i>	<i>-0.53</i>	<i>0</i>	<i>-0.34</i>	<i>-0.34</i>	<i>-0.48</i>	<i>-0.48</i>	<i>-0.48</i>
Suburban	1958	5.27	4	3.40	0.85	10.52	2.63	5.01
	2015	29.75	11	19.20	1.75	25.74	1.84	3.70
	<i>Change</i>	<i>24.48</i>	<i>7</i>	<i>15.80</i>	<i>0.90</i>	<i>15.22</i>	<i>-0.79</i>	<i>-1.31</i>
Other uses	1958	2.23	9	1.44	0.16	16.02	1.78	1.84
	2015	2.29	14	1.48	0.11	30.83	1.71	1.75
	<i>Change</i>	<i>0.06</i>	<i>5</i>	<i>0.04</i>	<i>-0.05</i>	<i>14.81</i>	<i>-0.07</i>	<i>-0.09</i>

^aThe average perimeter of polygons

Agricultural area Overall, for the period from 1958 to 2015, agricultural land in the study area has been fragmented (Fig. 3), as evidenced by the increased number of polygons (+137%, from 8 to 19) and the coinciding decrease in the total area dedicated to agriculture (-14.42%, corresponding to -9.31 km²), which together have significantly reduced the average polygon size (-71%, from 3.69 to 1.07 km²) (Table 3). The average perimeter of agricultural polygons, like the MSI (-0.29) and AWSI (-0.71), also declined due to the stronger presence of the suburban sector over time, which can be found surrounding all agricultural areas.

Woodlands Woodlands are characterized by increased fragmentation over time (Fig. 3), with a greater number of polygons in 2015 compared to 1958 (+35%; from 20 to 27), and a slight decrease in their total spatial extent across the study area (-1.48 km², corresponding to -20.73%) (Table 3). This decrease in wooded area seems to have been quite consistent across the following periods: 1958–1972 (-12.61%), 1972–1984 (-9.46%), and 1984–1994 (-9.20%), and finally stabilizes thereafter. A substantial decrease (-42%) in the average polygon size was also observed. More than 2 km² of

land that was forested in 1958 were occupied by residential developments since 2015. The MSI (-0.26) and AWSI (0.09) also decreased over this period.

Orchards Orchards are the only land-use class for which the number of polygons (from 26 to 19), their average size (-56%), the total area (from 6.97 to 2.32 km²; -66.72%), and the MSI (-0.27) and AWSI (-0.80) all decreased over the 1958 to 2015 period (Fig. 3; Table 3). The most substantial loss in total area occurred between 1984 and 1994 (-44.53%). However, this was followed by a small increase (+11.01%) from 1994 to 2007.

Mont Saint-Hilaire Biosphere Reserve The perimeter and the total hill area (zones 1 and 2) decreased slightly over the study period. The shrinking process, however, did not occur uniformly in time or across the entire polygon. A very slight decrease (-2.12%) was recorded for the period 1994 to 2015. Given that MSH is characterized by a single polygon, there is a corresponding decrease (-0.48) in each of the indices calculated over the entire period considered (Table 3). At a finer scale, three notable changes can be observed (Fig. 3): (1) an expansion on the west side, which

is associated with the transformation of a wasteland to a woodland in a former gravel pit; (2) a perforation of nearly 1 km² associated with gravel exploitation on the north side of the hill; this exploitation does not appear on the 1958 map because it was not yet operational at that time; and (3) aggregation, since the thin woody band, which previously separated the two agricultural areas on the north side, disappeared, and the two agricultural polygons merged. In total, more than half a square kilometer of the land that was a buffer zone in 1958 was used for residential development in 2015.

Suburbanization Essentially comprised of residential developments, the suburban areas experienced a substantial increase in the number of polygons (+7, from 4 to 11). With the creation of new districts, the area dedicated to residential housing (3.40 km² in 1958 to 19.20 km² in 2015) greatly expanded (15.80 km²; +464.71%). The diachronic analysis revealed a large increase over the period 1958–1972 (+106.47%), compared to the 1984–1994 period (+23.32%) (Fig. 3). The average polygon size also increased from 0.85 to 1.75 km². The MSI (−0.79) and AWSI (−1.31) both decreased between 1958 and 2015, given the anthropogenic impact on the area (Table 3).

Other land uses There is an increase in the number of polygons (+55.56%, 9 to 14), but this does not correspond to a significant increase in the total area (+2.78%; see Table 3) of the land uses other than agriculture, woodlands, orchards, the BR, and suburban area. This spatial expansion is mainly related to the increase in mineral exploitation on the northeast and southwest sides of MSH (Fig. 3). The average polygon size remained quite constant (−0.05 km²). In contrast, a large fluctuation is noted for the periods 1958–1972 (+65.28%) and 1972–1984 (−50.42%), as well as from 1984 to 1994 (+44.52%). The MSI and AWSI decreased slightly (−0.07 and −0.09, respectively) over the whole period considered (Table 3).

Restricted areas and natural hazards

Several homes on the MSH piedmont are located near steep slopes and scree slopes, which can be hazardous. Indeed, the western and northern slopes of MSH include a steep talus from which potential rockfalls represent a threat to several homes. Located between 110 and 190 m asl, these slopes are generally at the base of rocky cliffs

with a height of 10–20 m. The Dieppe Cliffs on the western side of MSH are more imposing, however. Part of the rocky escarpment (~70°) was exploded in 1981 to minimize potential collapses and the fall of large boulders (Tanguay 1991). The distance from the top, at 367 m asl, and the first homes, at 80 m asl, is 425 m, with an average inclination of 34°.

Over the past 30 years, several scientific and geotechnical reports were published regarding rockfall hazards and potential mitigation solutions (Udd 1979; Peckover 1980; Durville 1980; Sinh et al. 1980a, b; Ballivy 1990; Tanguay 1990, 1991, 1997; Tanguay 2003). Most of these concluded that there is a potential rockfall hazard, which remains difficult to evaluate in terms of timing, frequency, and magnitude. Durville (1980) noted two zones particularly vulnerable to hazards, and, in the following decade, a trench was dug to protect future residences located at the foot of the Dieppe Cliffs (on the des Falaises, de la Grotte, and des Fées streets) from rockfalls (Tanguay 1997). At the time, only one house was located in the hazardous zone, along Cardinal Street. Less than 20 years later, two new residences were built (in 1988 and 1994), and the security perimeter was enlarged (City of Mont Saint-Hilaire 2016). A total of six houses are now located within the perimeter, although, according to Tanguay (2003), “it is not possible to guarantee the security of this sector without achieving stabilization works.”

Discussion

Patterns and processes of landscape fragmentation

The considerable population growth that has taken place since the late 1950s has favored the expansion and increased density of the built environment (Montreal Metropolitan Community (MMC) 2011). This trend, coupled with the attractiveness of MSH, likely because of its natural environment (i.e., the Biosphere Reserve), suggests that the pressure for residential development will be even greater in the coming years, as assumed in estimates made for the short and medium terms. This recent suburbanization is already problematic with regard to the location of some houses in the rockfall hazard zone. Despite scientific reports published in the early 1980s (e.g., Durville 1980), the town of MSH has nonetheless proceeded to residential development near the scree slopes. The area already dedicated to

residential housing is already developed over more than 90%, so the development of new neighborhoods located much closer to the western and northwestern flanks of MSH is not surprising. The latter is located at the boundary of the conservation area (zone 1) and has therefore been built at the expense of the forest and the buffer zone (zone 2), once again making residential development one of the main causes of deforestation and fragmentation of natural landscape (Millien 2003; Planning committee of the perimeter of the mountain 2004b; Centre de la Nature du Mont Saint-Hilaire (CNMSH) 2010). The forest buffer zone around MSH continues to play a key role, however, and has great ecological value for preservation and conservation.

The spatiotemporal analysis of landscape fragmentation clearly shows a significant reduction in natural environments (MSH, woodlands, etc.), as the built environment (suburban) increases. This is associated with a simplification of the shape of polygons, mostly related to the increase in suburban areas. Indeed, the new developments or intensive human activities are characterized by well-defined plots with regular straight edges (Forman and Godron 1986; Krummel et al. 1987; Kim and Pauleit 2005). In contrast, plots having undergone less anthropogenic influence generally have more complex shapes (Turner 1990; Moser et al. 2002). For all land-use classes studied, there was a decrease in both MSI and AWSI indices between 1958 and 2015. Referring to the classification of Bogaert and Salvador-Van Eysenrode (2004) concerning landscape fragmentation, four main types of transformation have occurred in the study area: (1) fragmentation; (2) creation; (3) shrinking; and (4) removal.

The fragmentation mainly concerns agricultural areas and woodlands. In fact, nearly 90% of the loss of agricultural land coincided with suburban development. Creation is exclusively associated with suburbanization and the class referred to as “other uses,” corresponding to the development of residential neighborhoods and changes in land use, such as uncultivated areas. In that regard, the strong variations recorded over shorter periods in this land cover class might be explained by the fact that some farmland and orchards have been abandoned and left uncultivated, becoming woody areas after several years. The shrinking process is mainly associated with the BR and its buffer zone (zone 2) rather than the central conservation area (zone 1). As recorded in Table 3, the sharp increase in the suburbanization of MSH may explain the decrease (−0.48) in the

SI metric. Finally, removal was only found to affect orchards. Relatively speaking, the loss of orchard area is the largest for all land-use classes analyzed. Indeed, of the 4.65 km² lost, approximately 67% was occupied by suburban development in 2015. However, because of their sensitivity to climate, orchards, and consequently the land area devoted to them, may experience drastic interannual decrease. For example, the loss of 29% of the land area devoted to orchards between 1972 and 1984 appears to be related to the occurrence of unseasonally cold episodes. At that time, 15% of Quebec’s apple trees died, and many others suffered injury, resulting in a drastic drop in apple production in 1981 (Rousselle 1983; Lease et al. 2009). Similar periods of extreme freezing in spring or autumn were also recorded between 1984 and 1994, corresponding to a loss of 45% of the associated spatial extent. The occurrence of exogenous factors, such as extreme weather and fires, can therefore have a significant influence on the fragmentation of the territory in time and space.

Prospective vision for the Mont Saint-Hilaire UNESCO Biosphere Reserve

MacArthur and Wilson’s (1967) theory of island biogeography has as its central tenet to take into account the size and spatial distance between habitat fragments (i.e., islands) as an explanatory factor of biodiversity (Burel and Baudry 1999; Ricklefs and Miller 2005). Applied to continental biodiversity (Blondel 1979; Drouin 1995), landscape ecology aims to address the interrelationships between space and ongoing ecological processes (Turner et al. 1989; Turner 2005), while providing a better understanding of the human influence on the structure, organization, and functioning of ecosystems in space and time (Wiens and Milne 1989; Zha et al. 2008). Although its size could be variable, the term “landscape” in ecology is generally defined as a heterogeneous space with land plots of various biotic and abiotic characteristics (Turner 2005). This heterogeneity can be natural; related to geology, surficial deposits, or microclimate; and/or related to anthropogenic activities, such as agriculture, deforestation, and housing development (Burel and Baudry 1999; Forman and Godron 1986). Landscape fragmentation is a parcelling process that results in habitat loss and reduced populations and biodiversity in the short, medium, and long terms (Wilcox and Murphy 1985; Tilman et al. 1994; Fisher and Lindenmayer 2007). For this reason, the landscape

fragmentation analysis is very important for the preservation of biological diversity and for the management of ecosystems and the environment under specified policies (Hu et al. 2008; Bodesmo et al. 2012) intended to build harmonious human-environment relationships and promote sustainable landscape management.

MSH has become somewhat of a forest island in the center of a sea of a residential development and agriculture (Millien 2003). To counter the isolation of fragmented habitat components, forest corridors have been proposed and developed for the MSH Biosphere Reserve and particularly for the core area (zone 1) (Nature-Action 2010). Two corridors, to the north and south, are used to connect the protected area (zones 1 and 2) and other wooded areas at the regional scale, in order to promote genetic exchange between populations of various species (Bonnin 2008). Therefore, these corridors not only are places of passage for animals but also consolidate the surrounding natural areas and promote the maintenance of existing populations and the recruitment of new species (Planning committee of the perimeter of the mountain, 2004b; Bonnin 2008; Centre de la Nature du Mont Saint-Hilaire (CNMSH) 2010). Although this initiative is part of the development objectives of the BR cooperation area, the deforestation of the footslope has become a major issue (e.g., of forest corridors; Nature-Action 2010), as has the growing popularity of MSH for recreational activities. However, it is estimated that a minimum of 30% of the forest cover is necessary to ensure the health and sustainability of biodiversity (Planning committee of the perimeter of the mountain 2004a).

Conclusions

Sustainable land use is a difficult concept to implement, given the impossibility of fully harmonizing collective and individual needs. In the context of the MSH BR, the central area (zone 1) is dedicated to ecosystem preservation and conservation. The second zone, surrounding the first, is a buffer zone that aims to mitigate the impacts of human activity to zone 1. However, rapid population growth in recent decades has caused unprecedented residential development, thereby accentuating the fragmentation of the landscape. This buffer zone should normally enable and promote genetic exchange by providing wildlife corridors adapted to reach more peripheral areas. These corridors exist, but they too are

experiencing increasing fragmentation resulting from the growing suburbanization since the 1980s, which has also increased human exposure and vulnerability to natural hazards, as evidenced by the six residences located in the rockfall hazard zone.

Spatiotemporal analysis for the period 1958–2015, using aerial photographs and orthophotos, allowed the mechanisms underlying the increased landscape fragmentation to be determined. Although some exogenous factors, such as fires and extreme weather, can have an impact on land use, the accelerated development of the built environment is nevertheless found to be primarily responsible for landscape fragmentation and changes in land use in the study area. The landscape metrics used corroborate these results and once again reveal the difficulties of harmonizing different land uses, as well as the lack of consideration with respect to natural hazards (i.e., despite the Law on Civil Protection established in 2001) and the UNESCO Biosphere Reserve status. In this regard, sustainable development appears to be an interesting avenue for municipalities and larger cities, but, in reality, the practicalities of implementing the concept remain quite challenging.

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