Corridors, biodiversité, et services écologiques: un réseau écologique pour le maintien de la connectivité et une gestion résiliente aux changements climatiques dans l'Ouest des Basses-Terres du Saint-Laurent

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Project 554014

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Preface

This project arose from a request by the *Ministry of Sustainable Development, Environment, Wildlife and Parks* of the Quebec government to design a network of wildlife corridors that would permit the maintenance of biodiversity under climate change. This goal of this research project was therefore to identify and design an ecological network of forest habitats for the region surrounding Montreal that is resilient to future changes in land use and climate. The results of the final chapter identify the forest fragments that are key to sustaining the connectivity of the region now and into the future, as far as 2050. The team will produce many more results over the coming months, all of which will be made available freely available via the project's web page. We believe the methodology and results contained in this initial report provide a foundation for the conservation and management of ecological connectivity in the region over the coming century. We hope that our research will inform policy and conservation on the ground. We are particularly excited about the links between our results and the promising initiative to create a greenbelt around Montreal.

Acknowledgements

The authors would like to thank the entire *Montérégie Connection* research team of students, postdocs, and technicians for their contributions to the success of this project. The results we summarize here would not have been possible without all your efforts over the last two years. We would also like to thank the Ouranos team, in particular Travis Logan and Robert Siron for their support, and the science advisory committee for their feedback. We thank also our many partners that shared their data, expertise and time to make this project a success. We look forward to working with our partners to ensure these results are put to good use.

Ces travaux ont été réalisés dans le cadre d'un projet soutenu par la mesure 26 du Plan d'action sur les changements climatiques 2006–2012 du gouvernement du Québec. Les résultats et opinions présentés dans cette publication sont entièrement la responsabilité des auteurs et n'engagent pas Ouranos ni ses membres.

April 2013

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Chapter 1

Selecting focal species

1 Introduction

The study area encompasses many plants, vertebrates (217 birds, 56 mammals, 17 amphibians, 15 reptiles) and invertebrate species. It is very difficult to account for them all individually in the design of an ecological network. Several options exist to represent the range of life-histories and habitat needs of this local biodiversity. The first is based on habitat types as a surrogate for the communities they shelter (i.e. a coarse filter approach; Hunter 1991), the second uses focal species approach that represents the dimensions of life-history and demography characteristic of this diversity (Margules & Pressey 2000). The focal-species approach is challenging, because it is hard to represent biodiversity in its entirety with a small set of species and it commonly only accounts for well described organisms such as vertebrates (e.g. Lambeck 1997, Lindemayer et al. 2002). However, this approach also has the advantage of directly accounting for species-specific habitat preferences and dispersal abilities that are of primary importance when dealing with landscape connectivity (Didham et al. 2012). We therefore chose the focal-species approach, as a suitable abstraction to reduce the great diversity of plants and animals within our study area to operational entities (Opdam et al. 2008).

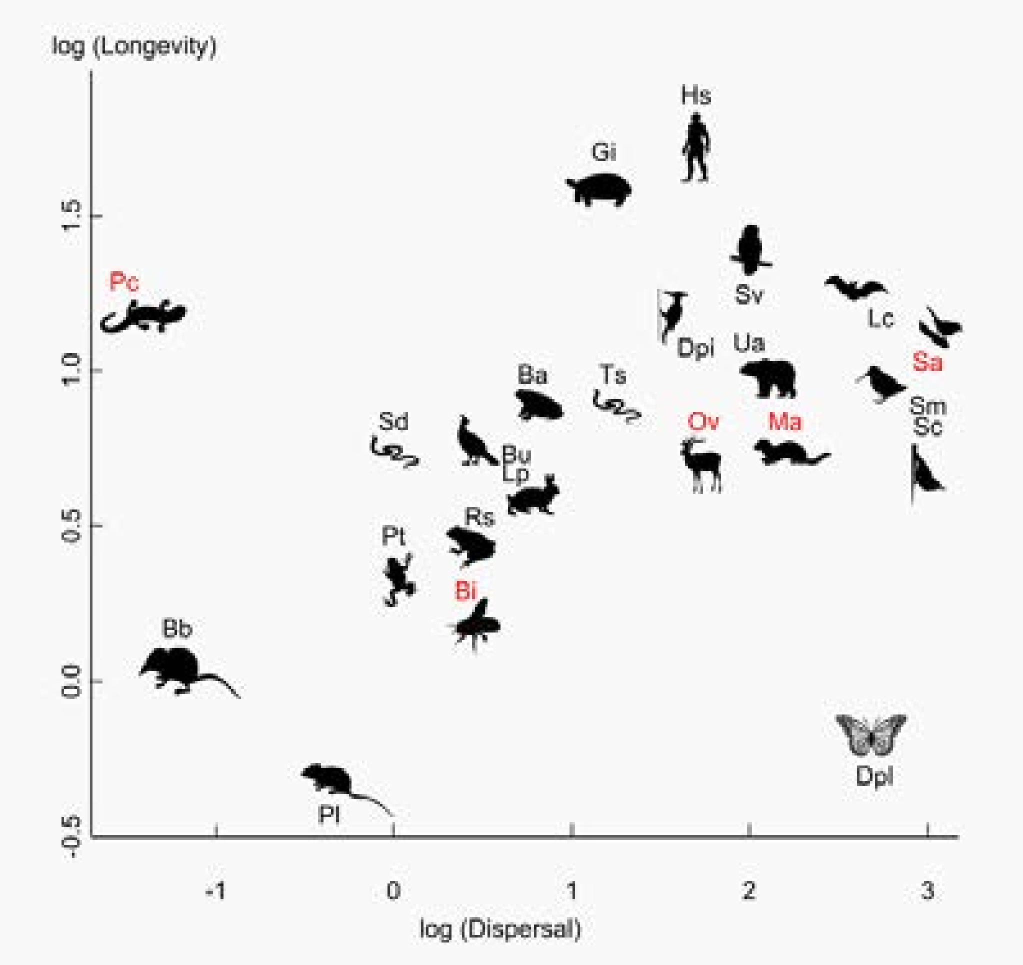


Figure 1-1: Selection of animal species (and their comparison with Homo sapiens Hs) and the subset of species presented in this report (in red) within a dispersal / longevity space. Pc = Plethodon cinereus, Bb = Blarina brevicauda, Pl = Peromyscus leucopus, Dpl = Danaus plexipus, Bi = Bombus impatiens, Pt = Pseudacris trisetaria, Rs = Rana sylvatica, Lp = Lepus americanus, Bu = Bonasa umbellus, Sd = Storeria dekayi, Ba = Bufo americanus, Ts = Thamnophis sirtalis, Dpi = Dryocopus pileatus, Ov = Odocoileus virginianus, Ma = Martes americana, Ua = Ursus traits (body size, longevity and fecundity).

We selected focal species of plants (x4), invertebrates (x2) and volant (x6) and non-volant (x13) vertebrates. We selected these species using multivariate ordination (principal components analysis) on a reduced number of key life history traits. The results of these analyses will be reported elsewhere.

For each species we obtained good data on distribution, habitat preferences, movement and climate preference. Chapter 3 describes how we quantified the habitat preferences of our five focal species, whilst Chapter 5 addresses how we estimated their climate niche and change in distribution.

The following sections provide relevant summary information about the ecology of our focal species.

2 Focal species

White-tailed deer (*Odocoileus virginianus*)

White-tailed deer are the most abundant species of large herbivore found in North America, and are found predominantly in the southern part of Canada (Canadian Biodiversity, 1999) but can reach as far north as Great Slave Lake in Northwest Territories (Canadian Geographic,2013). Adults can grow to 0.9 to 1.1 m and weigh 45 to 136 kg (males), 39 to 60 kg (females) (Ministry of Natural Resources, 2013) and live on average up to 6 years (Ministry of Natural Resources, 2013).

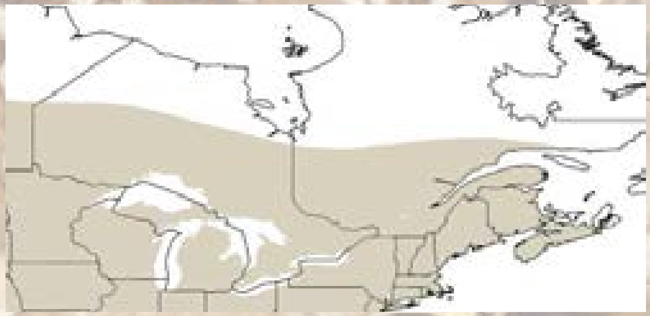
Diet: woody plants, grasses, herbs, and forbs, It also includes fiddleheads, mushrooms, and blueberries (Environment Canada, 1990).
Annual life cycle:

Spring: Birth of offspreing from late March to early August, most fawns are born during the last week of May or the first week of June. Diet is mostly comprised of grasses, clovers and shoots (Ministry of Natural Resources, 2013).

Summer: Mainly consists of foraging to gain mass for the winter, they can eat up to 4 kg of green plant material each day (shoots, tips and buds of plants, flowers).

Fall: This period is also known as “the rut” (Ministry of Natural Resources, 2013) or the breeding season, which typically takes place during the last three weeks of November, although some fawns and yearlings breed in December and, rarely, into January (Environment Canada, 1990).

Winter: They move into winter deer yards, which are concentrated areas where there is a relative abundance of food and shelter. White-tailed deer prefer young conifer habitat during the winter, particularly when snow deepens and temperatures drop, because they provide cover from falling snow and help to moderate extreme temperatures (Ministry of Natural Resources, 2013).



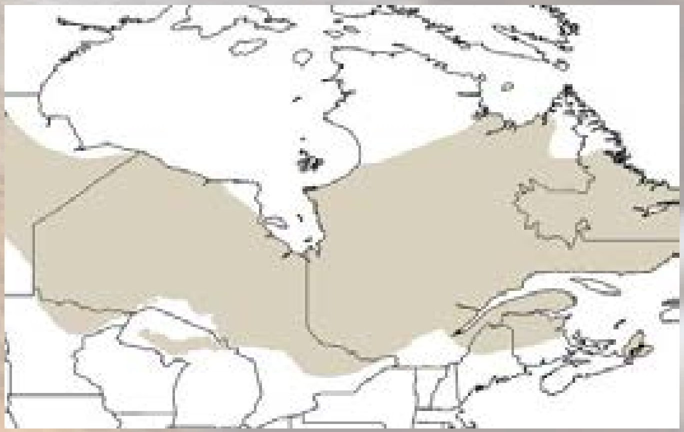
Distribution map of *Odocoileus virginianus*, (north eastern America)

Odocoileus virginianus photo credit: cotinis / Foter.com / CC BY-NC-SA

American Marten *(Martes americana)*

The marten also known as the Canadian or American sable (Canadian Musuem of Nature, 2013) is a small carnivorous predator, of the weasel family (Mustelidae) (Environment Canada, 1977) they range 0.5-0.7 m in length and weigh 0.5-1.4 kg (Stone, 2010). They have few natural enemies except for bobcats, lynx, and in some cases coyotes (Canadian Biodiversity, 1999). Considered to be a solitary animal spending most of its time in trees. They are found throughout Canada in canopy covered coniferous or mixed forests (Canadian Biodiversity, 1999; Stone, 2010). Martens are considered to be threatened in some parts of Canada (Newfoundland and Nova Scotia) (Parks Canada, 2009) because of trapping for the fur industry and forest harvesting, but nationally considered secure by Nature Serve.

Martens are quite active during the summer, and can spend up to 60% of their time foraging, but that number can drop to 16% during winter depending on prey availability and location (Stone, 2010). Martens mostly feed on red-backed voles, deer mice, field voles, varying hare, grouse, squirrels, and shrews. They are also known to take birds' eggs and amphibians and make extensive use of berries, especially raspberries and blueberries (Environment Canada, 1977). Breeding starts after one to two years and can last until 12 years during July or August and give birth the following March or April to a litter ranging from 1 to 5 kits (Stone, 2010) the average is 3 kits (Environment Canada, 1977). Kits are born in dens, in a hollow trees, branches, cavities or broken tops of live trees, snags, stumps, logs, woody debris piles or old squirrel's nests. (Stone, 2010; (Environment Canada, 1977) where they spend most of their time until June or July (Environment Canada, 1977). The mother and kits are together until late August or September, when they disperse. This is the only time when martens are together (Environment Canada, 1977).



Distribution map of *Martes americana*:, (north eastern America)

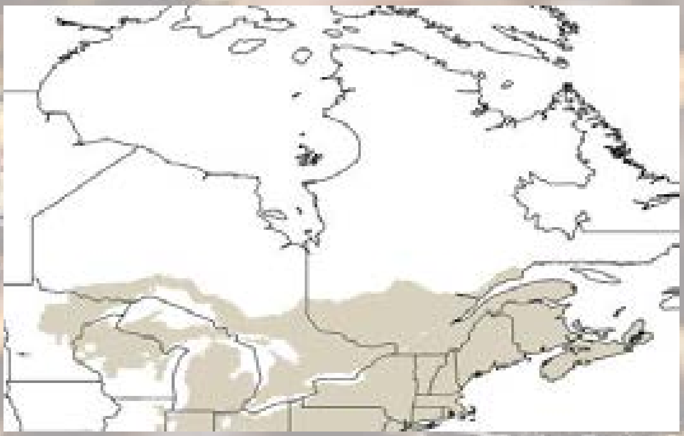
Martes americana: photo credit: Tatiana Gettelman / Foter.com / CC BY-NC-SA

Red-backed Salamander (Plethodon cinereus)

The red-back salamander is the only terrestrial salamander in Quebec. They live under the leaf litter or coarse woody debris of mature deciduous forests, (Bider & Matte, 1996) sometimes can be found in mixed or coniferous forest providing that they are cool and moist (CARCNET, 2012). The animals do not require moisture from bodies of water, rather they draw water from the moisture of the leaf litter to prevent them from desiccating (Bider & Matte, 1996). They are found in the eastern part of Canada in Ontario, Quebec and the maritime provinces. Because of their small home range, they are extremely territorial (CARCNET, 2012). Red backs have two different colour phases, one is black or dark grey with red (usually) or brownish orange but may also be yellow, pink or grey.

Breeding begins in the third year of the female and takes place every second fall, and in some circumstances as late as the following spring. Egss are laid either June or July in small clusters between 3-13 eggs on the ceiling of damp cavities in old rotting logs. The complete larval stage is carried out within the egg and when hatched the young are about 10mm in length and have small external gills that are later reabsorbed (CARCNET, 2012; Bider & Matte, 1996).

Adult Diet: ants, beetles, mites, spiders, springtails and small fly larvae, snails, millipedes, centipedes, moth larvae and isopods, earth worms, flies. Red back salamanders are pulse eaters, so they eat large amounts if environmental conditions are favourable (Howard, 2013).



Distribution map of *Martes americana*:, (north eastern America)

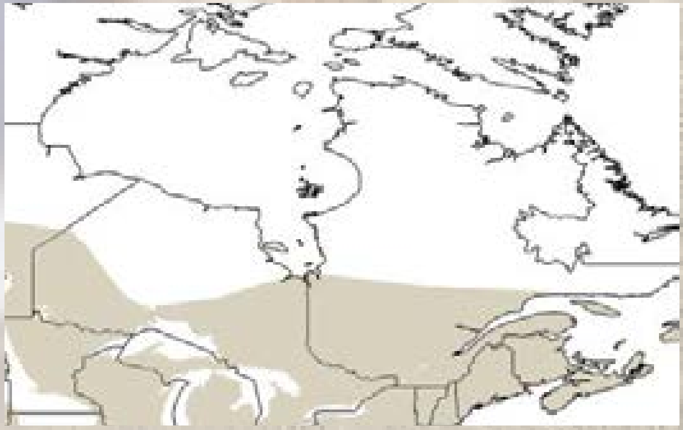
Plethodon cinereus - photo credit: DaveHuth / Foter.com / CC BY-NC

Ovenbird (*Seiurus aurocapilla*)

A small ground-nesting migratory songbird of the forest floor, the ovenbird is one of the most characteristic birds of the eastern forests (Loss et al.2012 ,Van Horn & Donovan 1994). The Ovenbird gets its name from its covered nest. The dome and side entrance make it resemble a Dutch oven. (Van Horn,& Donovan 1994). Ovenbirds are negatively affected by forest fragmentation and have become a model organism for understanding the effects of habitat fragmentation and forest harvest on songbirds. (Porneluzi, et al., 2011). Habitat fragmentation affects reproductive success by increasing the number of predators, brood parasitism by brown-headed cowbirds (Molothrus ater) and male courtship in small forest fragments (Hallworth, 2011). European earthworms, an invasive species in mixed sugar maple forests are causing the oven bird population to decline by eating the rich layer of leaf litter on the forest floor. This causes habitat destruction by removing thick leaf litter and replacing it with grasses and sedges making the ovenbird more visible and vulnerable to predators and reducing nesting sites. (Loss et al. 2012). Half of all adult Ovenbirds die each year during migration (Van Horn,& Donovan 1994)

Ovenbirds breed in mature deciduous or mixed forests in nests above ground on leaf-covered floors, or in a cluster of low plants or shrubs near an opening in the forest. The female builds the nest with dried grass, leaves, moss, and other vegetative matter. Female lays 3 to 6 white eggs with brown and grey markings (Bouglouan, 2013). Twelve days later the eggs hatch, and 8 days after hatching, the young leave the nest (Hallworth, 2011). This species may produce occasionally two broods per year (Bouglouan, 2013), but typically are only able to raise one successful nest in a season. Nesting on the forest floor comes with the risk of predation from squirrels, chipmunks, and other ground-dwelling nest predators (Hallworth, 2011).

Diet: Ovenbirds feed on insects, crickets, ants, caterpillars, aphids, moths and beetles. They also eat spiders, earthworms, slugs and snails (Bouglouan, 2013)



Distribution map of *Martes americana*:, (north eastern America)

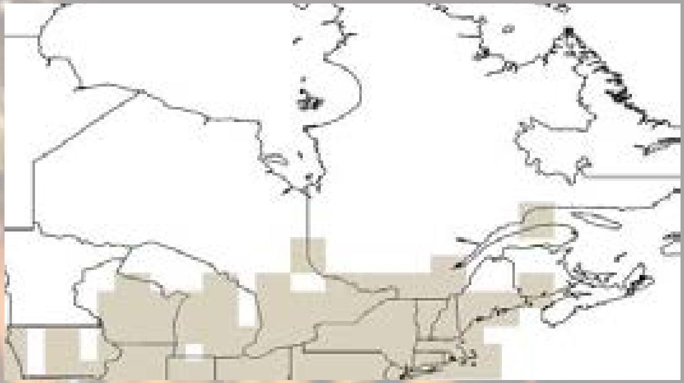
Seiurus aurocapilla photo credit: cotinis / Foter.com / CC BY-NC-SA

Common Eastern Bumble Bee (*Bombus impatiens*)

This is the most often encountered bumble bee across much of eastern North America. Bumble bees are generalist, they are characterized by expansive foraging ranges and are highly mobile organisms freely traversing forested, rural and suburban areas. (Balaban & Balaban, 2006). Bumble bees are active pollinators of commercial crops and are a common species in blossoming apple orchards across the Monteregie, Quebec.

Bumble bees are primitively social insects and usually nest in the ground of open fields and woods (Encyclopedia of Life, 2013), often making use of old rodent burrows. Unlike honey bee hives, their nests last for just one season The common eastern bumble bee has relatively large nests compared to other bumble bees, often containing 300 -500 workers (Encyclopedia of Life, 2013; Harvard Entomology, 2013). Fertilized queens hibernate during the winter and emerge in the spring to feed and then lay eggs in a suitable nest. Only the mated queens survive the winter, while all the males and workers die off. Common eastern bumble bees have a long active season, from March to November (Harvard Entomology, 2013).

Diet: only nectar and pollen and do not produce large amounts of honey. (Encyclopedia of Life, 2013)



Distribution map of *bombus impatiens*, (north eastern America)

Bombus impatiens- photo credit: e_monk / Foter.com / CC BY-NC-SA

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Chapter 2

A new landcover classification for the study region

1 Introduction

Our goal was the creation of an updated land cover classification and land cover map for the study extent. This was an essential input layer for the subsequent analyses of the spatial distribution of habitat of our focal species (Chapter 3), the land use change model (Chapter 4) and habitat connectivity analyses (Chapter 5).

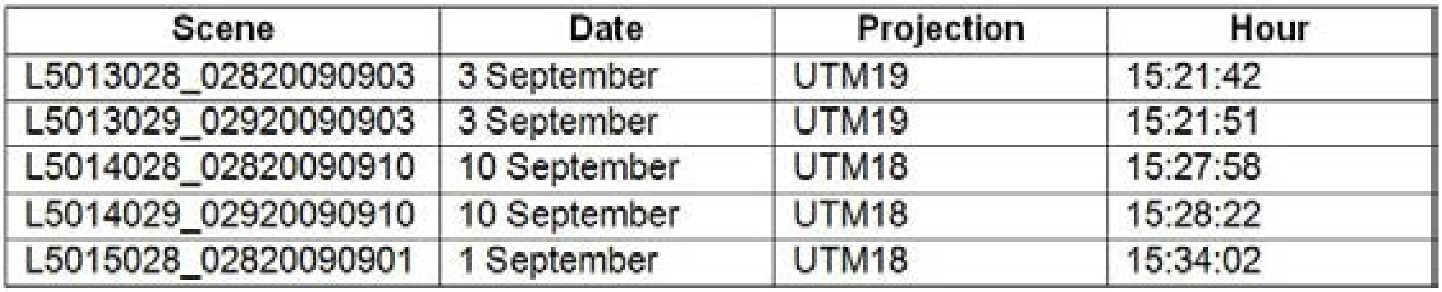
The new land cover classification presented here integrates information available in existing digital databases such as SIEF (Système d'information écoforestière) or BDTQ (Base de données topographiques du Québec), but also adds Landsat derived data.

2 Remote sensing image processing

We used the Landsat 5 TM (Thematic Mapper) scenes from 2009, produced by the U.S Geological Survey and acquired from Earth Explorer (http://earthexplorer.usgs.gov/), which had a very small area covered by clouds, as a source for the remote sensing data. To process and analyze the data we used IDRISI TAIGA Imaging Processing software acquired from Clark Labs (http://www.clarklabs.org).

Our study area is covered by five Landsat scenes (see table 1) that have seven spectral bands. The Ground Sampling Interval (pixel size) for bands 1 through 5 and 7 is 30 m, while for the thermal band (band 6) it is 120 m.

Table 1 Landsat scenes information



Scene	Date	Projection	Hour
L5013028_02820090903	3 September	UTM19	15:21:42
L5013029_02920090903	3 September	UTM19	15:21:51
L5014028_02820090910	10 September	UTM18	15:27:58
L5014029_02920090910	10 September	UTM18	15:28:22
L5015028_02820090901	1 September	UTM18	15:34:02

The scenes were processed to Standard Terrain Correction (Level 1T) to provide systematic radiometric and geometric accuracy (terrain corrected). UTM 19 scenes were re-projected to UTM 18 and all scenes were subjected to an atmospheric correction to remove the haze. Haze has a tendency to alter images, so in order to correct that we used the Cos(t) model (Chavez 1996) from IDRISI atmospheric module. After the atmospheric correction the images were mosaicked together using the average as an overlap method. Overlapping the average removed the clouds form the image and allowed for a smoother transition between images that had no cloud cover.

3 Classification of Landsat images

Every surface has a Spectral Response Pattern (SRP) allowing it to either reflect, absorb or transmit electromagnetic energy from one wavelength to another, in various degrees. We used supervised and unsupervised methods to classify land cover. Both techniques were tested and coupled with different classifiers, however the best results were obtained from the supervised method using the segmentation classification.

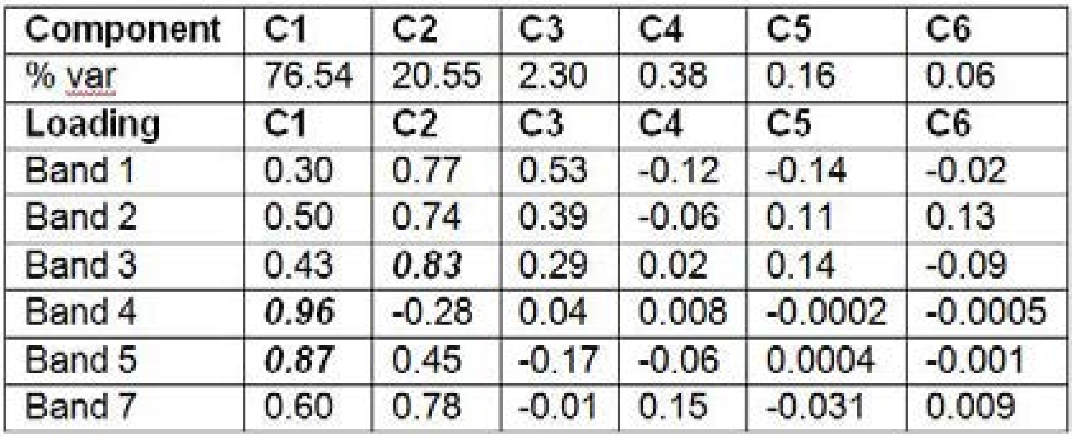
4 Methodology

Segmentation classification represents a hybrid methodology between pixel-based and segment-based classification. It contains three main parts:

- Image segmentation
- Create training sites using the segmentation result
- Segment classification

The first step was to look at the variability of the reflectance values in the original band set using the PCA (Principal Components Analysis) linear transformation technique. In our case (see table 2), the first two components shows the most variance (97%). Examining the loadings we can see the degree of correlation between the new components and the original bands. The correlation between component 1 and bands 4 (0.95) and 5 (0.86) are very high. Band 3 is highly correlated with component 2 (0.83). Therefore, bands 4, 5 and 3 capture most of the variability, and they were identified as the best combination for the composite image. This image was later used as a reference image for the segmentation classification (Jusoff et al. 1995; Grenier et al. 2007).

Table 2 Correlation between the bands



Component	C1	C2	C3	C4	C5	C6
% var	76.54	20.55	2.30	0.38	0.16	0.06
Loading	C1	C2	C3	C4	C5	C6
Band 1	0.30	0.77	0.53	-0.12	-0.14	-0.02
Band 2	0.50	0.74	0.39	-0.06	0.11	0.13
Band 3	0.43	***0.83***	0.29	0.02	0.14	-0.09
Band 4	***0.96***	-0.28	0.04	0.008	-0.0002	-0.0005
Band 5	***0.87***	0.45	-0.17	-0.06	0.0004	-0.001
Band 7	0.60	0.78	-0.01	0.15	-0.031	0.009

Segmentation is an object-based classification methodology which groups adjacent pixels into image segments with similar spectral signatures based on similarity threshold (Eastman 2012). This procedure identifies objects from a coarse to a fine scale, so multiple iterations were done to identify the best spatial scale to map the land cover classes within our study area (Grenier et al. 2007). To assess the similarity over the bands we applied a moving window of 3x3 pixels and outlined the segments using different threshold values for the tolerance. Similarity controls the level of homogeneity in the image so a larger threshold will result in a generalized segmentation result. In our case, for the pixel segmentation we set the similarity tolerance to 30 (see Figure 2-1). All bands were weighted according to the PCA variance. Bands 4 and 5 had a PCA variance of 0.3, band 3 was 0.2 and 0.066 for bands 1, 2 and 7.

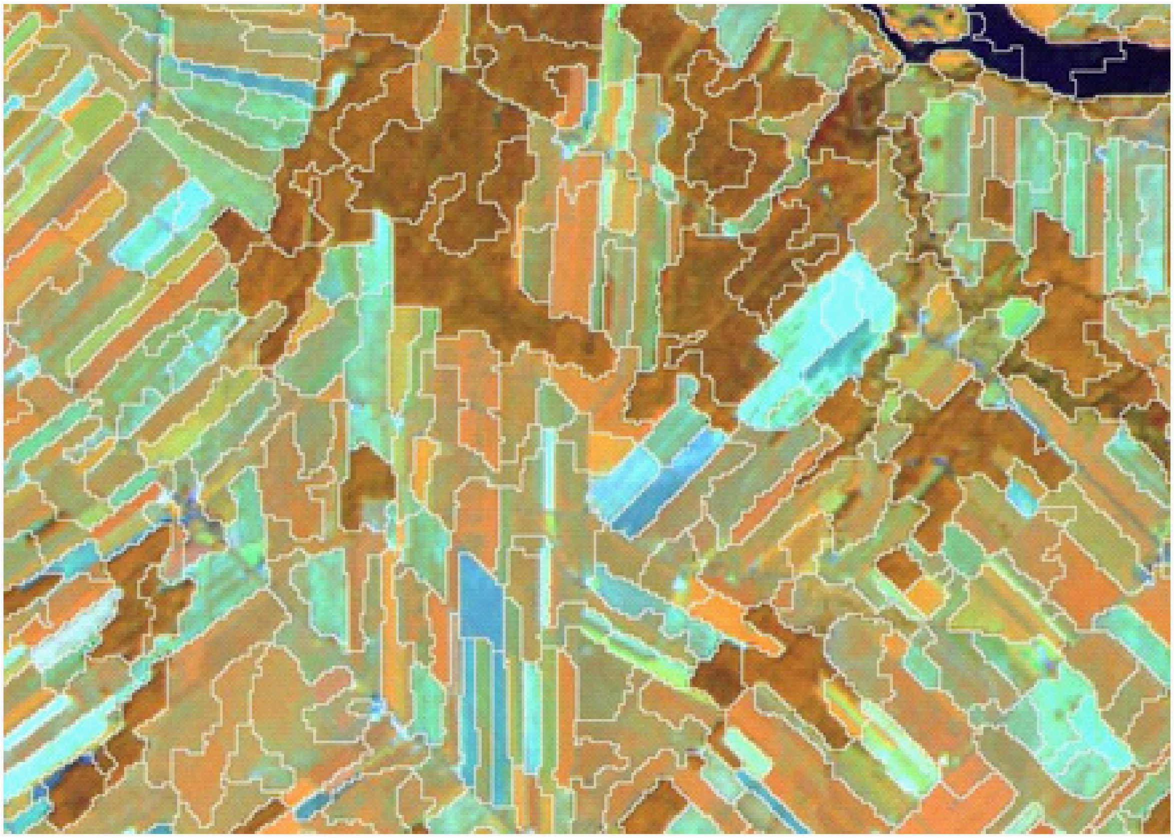


Figure 2-1: Segmentation of the pixels using the threshold 30 as level of generalization

Using the segmentation file as a reference image for sampling, the next step was to identify the training sites for each land cover category. To improve accuracy when picking training sites in our study area, we used ancillary data such as:

- Landsat image colour composite (e.g 4,5,3 or 5,3,4) to define different vegetation types and variations in moisture (2009);
- Eco-forestry data from SIEF (Système d'information écoforestière) database to identify the forest types (deciduous, conifers and mixed). Data was used from 2001, 2002, 2003, and in a small area of data from 2004 and 2008. Forest loss between 2004-2009 were included in shapefiles from GEOMONT to validate the training sites within the forest;
- BDTQ (Base de données topographiques du Québec) not-classified wetland data from 1998 to 2003 and 2008 for the island of Montréal and the surrounding area; ecoforestry data associated with wetlands from SIEF (wet barren area and flooded site), and more refined data provided by GEOMONT (2008) for the Montérégie. The latter contains different wetland categories such as treed or non-treed (marsh, fen, swamp or bog);
- Agricultural data from BDCA (Base de données des cultures assurées, 2009) that contains different types of crops;

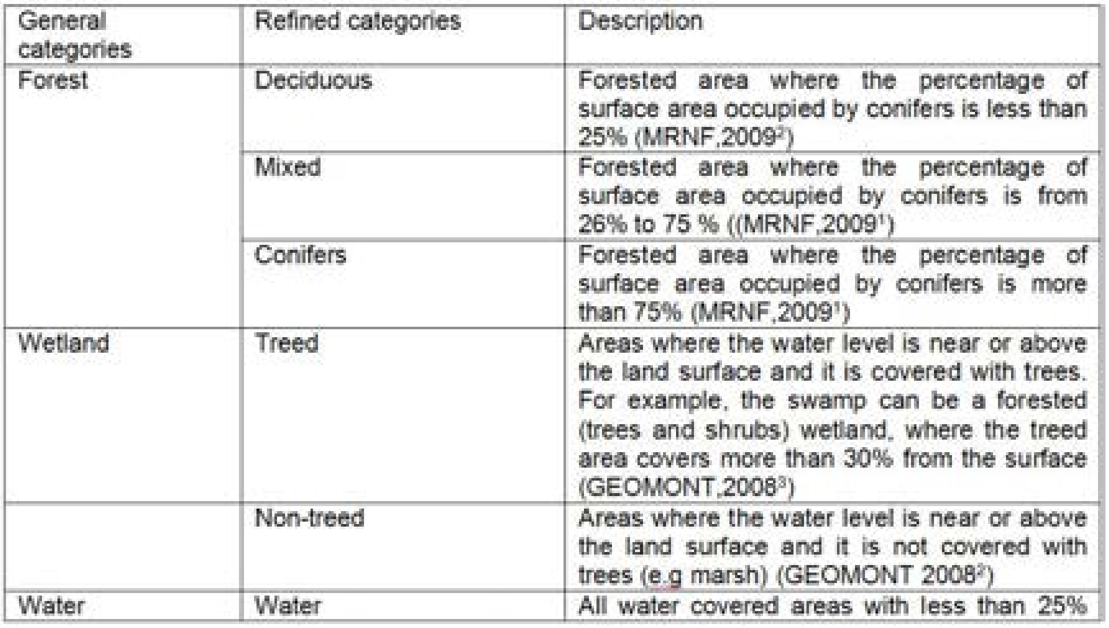
- Unsupervised classification using bands 4, 5 and 3, previously done that gives information about the main clusters that showed similar spectral response;
- EOSD (Earth Observation for Sustainable Development of Forests) database published by Canadian Forest Service in 2006, which represents land cover classifications useful in identifying different vegetation types. This classification of vegetation types used for the remote sensing images from Landsat7ETM+ and the unsupervised classification as a method;
- Orthophotos from 2009 provided by Géoboutique Québec (Ministère des Ressources naturelles et de la Faune). These images partly covered our study area, but they were very helpful in identifying and confirming most of the land-cover categories, given that they had a 30 cm pixel resolution.

Each cover type was represented by at least 10 training sites and we end up with 20 cover types that captured as much of the variability as possible. The different cover types are:

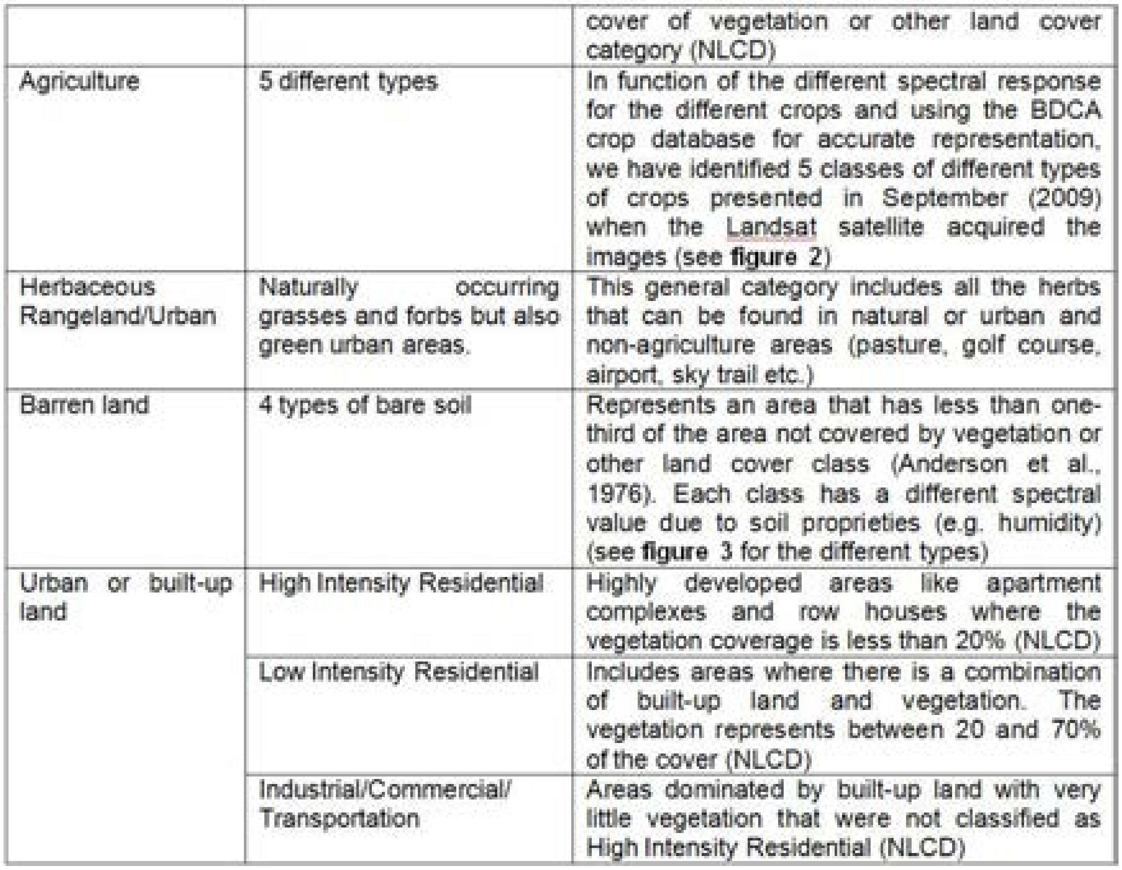
- Forest deciduous, mixed and conifers
- Wetland treed and non-treed
- Water
- Agriculture, 5 types of crops
- Grass
- Bare soil, 4 types of soils
- Developed areas with 3 classes: high-density and low-density residential, and industrial/commercial/transportation.

The land cover categories were based on the land cover classification framework for remote sensing data described by Anderson et al., (1976), and on the National Land Cover Dataset classification (NLCD). The NLCD uses a modified form of the USGS's Anderson Land Use and Land Cover Classification System. Depending on data resolution the classification can have multiple levels of categorization. Usually, Landsat data characteristics can be used to derive more general land cover categories, however it is not restricted to this general level because by combining with ancillary data we can obtain more refined categories.

Table 3 Description of the land cover categories



General categories	Refined categories	Description
Forest	Deciduous	Forested area where the percentage of surface area occupied by conifers is less than 25% (MRNF,2009[2])
	Mixed	Forested area where the percentage of surface area occupied by conifers is from 26% to 75 % ((MRNF,2009[1])
	Conifers	Forested area where the percentage of surface area occupied by conifers is more than 75% (MRNF,2009[1])
Wetland	Treed	Areas where the water level is near or above the land surface and it is covered with trees. For example, the swamp can be a forested (trees and shrubs) wetland, where the treed area covers more than 30% from the surface (GEOMONT,2008[3])
	Non-treed	Areas where the water level is near or above the land surface and it is not covered with trees (e.g marsh) (GEOMONT 2008[2])
Water	Water	All water covered areas with less than 25%



		cover of vegetation or other land cover category (NLCD)
Agriculture	5 different types	In function of the different spectral response for the different crops and using the BDCA crop database for accurate representation, we have identified 5 classes of different types of crops presented in September (2009) when the Landsat satellite acquired the images (see **figure** 2)
Herbaceous Rangeland/Urban	Naturally occurring grasses and forbs but also green urban areas.	This general category includes all the herbs that can be found in natural or urban and non-agriculture areas (pasture, golf course, airport, sky trail etc.)
Barren land	4 types of bare soil	Represents an area that has less than one-third of the area not covered by vegetation or other land cover class (Anderson et al., 1976). Each class has a different spectral value due to soil proprieties (e.g. humidity) (see **figure** 3 for the different types)
Urban or built-up land	High Intensity Residential	Highly developed areas like apartment complexes and row houses where the vegetation coverage is less than 20% (NLCD)
	Low Intensity Residential	Includes areas where there is a combination of built-up land and vegetation. The vegetation represents between 20 and 70% of the cover (NLCD)
	Industrial/Commercial/ Transportation	Areas dominated by built-up land with very little vegetation that were not classified as High Intensity Residential (NLCD)

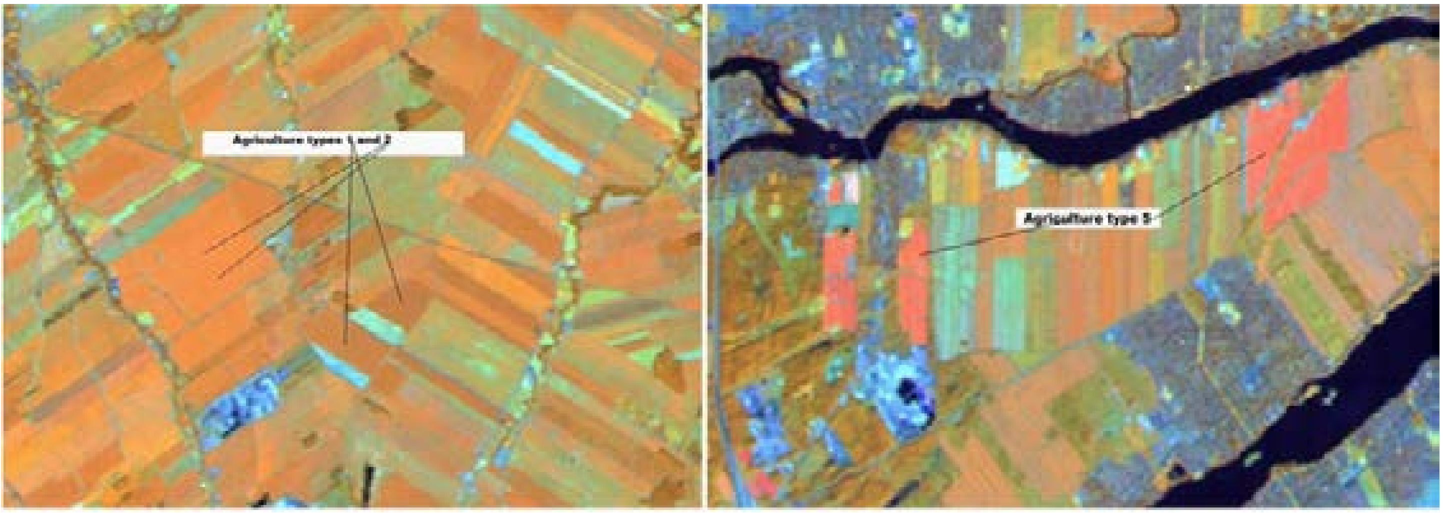


Figure 2-2: Types of agriculture using as reference the 453 band composition image

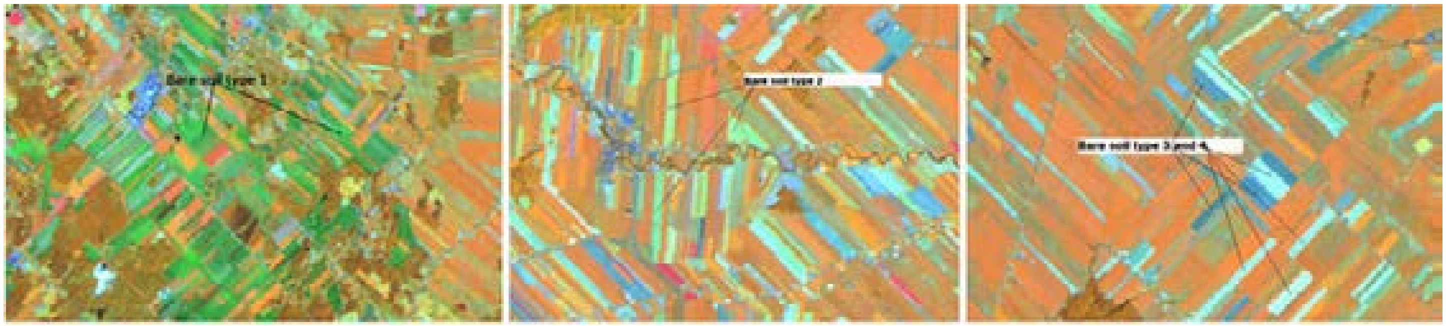


Figure 2-3: Types of bare land using as reference the 453 band composition image

Figure 2-4: Urban or built up areas on Montreal Island. Lilac color represents the low residential areas, as we can see in western part of Montreal Island, mauve represents the high residential areas and dark mauve are the industrial/commercial zones, such as the area around the airport.

The final step was to classify the segments using the SEGCLASS module in IDRISI that needed a segmentation image and a pixel classification reference image. In order create the reference image we used the segments identified as training sites from the segmentation module, and the Maximum Likelihood Classifier with equal prior probabilities for each spectral signature. The MLC estimates the pixel membership to one of the classes using the mean and variance/covariance data of the signature files. To smooth the resulting image we used a digital filtering (kernel) module with a filter size of 3x3 pixels that represented the mode of the 9 pixel values. The output was a less pixelated map..

To improve the image accuracy, we masked the regions that were misclassified as clouds, cloud shadows, plane traces, and shadows due to topography or tall buildings (e.g. downtown Montreal). Errors due to the spectral similarity of categories, were sometimes caused by the variability caught in the training site selection. Two different masks were used: one covering the main areas affected by topography and areas where there were errors due to spectral similarity between categories (e.g. agriculture versus forest, coniferous/wetland areas or shallow water/shadow of tall building). The other mask was used for cloud cover or shadows. For the first mask, we used the segments from the segmentation classification for the areas that needed correction, and for the second, we digitized the polygons that covered the problematic areas. All masked areas were updated with the SIEF land use categories, and reclassified to resemble the supervised classification categories.

5 Land classification map

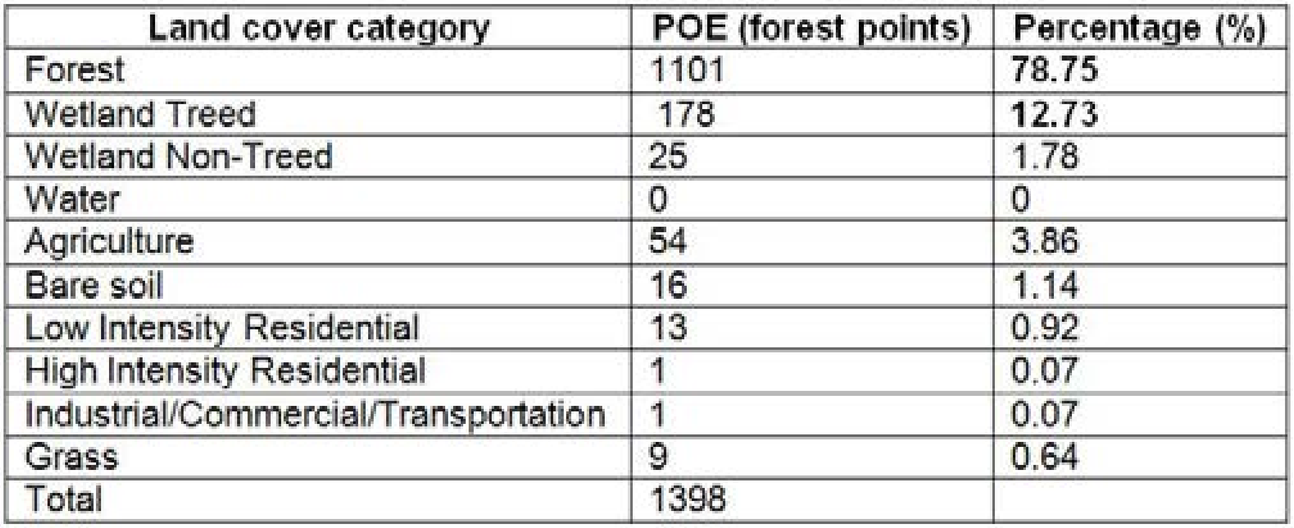
The final land classification map is shown in Figure 2-5, and is summarized by 10 general land cover categories that were the most representative for the study area. The area is dominated by agriculture in the St. Lawrence Central Lowlands (center of the map) and a forest dominated landscape in north-western, Laurentian mountains, and south-eastern, Appalachian mountains.

Agriculture (yellow on the map), bare soil (grey) and grass (light green) represented 42.16% of the study area, followed by the forested area (forest and wetland treed, fir green and dark olive on the map) covering 38.7% of the area, and urban areas (all shades of purple) covering 7.23%. By large urban areas, we refer to the urban agglomeration category from THE SIEF database WHICH was our main land-use map for our analysis. The urban category in our classification added more information such as parks, open areas, low and high residential or commercial areas that can be of great importance from a species perspective. Therefore, for our analysis, we used the latter urban category.

6 Validation

We used a cross-tabulation method that compares two types of data for validation. All 1398 POEs (Points d'Observation Écologique) presented in our study area were used in the validation process. These points were measured within a forest and contain information about the observed variables of the physical environment and vegetation (MRNF, 1994). As shown in the table 4 91.48 % of the points fell within the forest category from the Landsat derived land cover map.

Table 4 Forest point membership to a certain land use category



Land cover category	POE (forest points)	Percentage (%)
Forest	1101	78.75
Wetland Treed	178	12.73
Wetland Non-Treed	25	1.78
Water	0	0
Agriculture	54	3.86
Bare soil	16	1.14
Low Intensity Residential	13	0.92
High Intensity Residential	1	0.07
Industrial/Commercial/Transportation	1	0.07
Grass	9	0.64
Total	1398	

A second cross-tabulation method was done using as validation data the BDCA agriculture database (BDCA, 2009). We randomly extracted 639 points from all the agriculture polygons that together represented a range of different crops. As shown in table 5, most of the points (95.3%) fell within the agriculture, bare soil and grass categories.

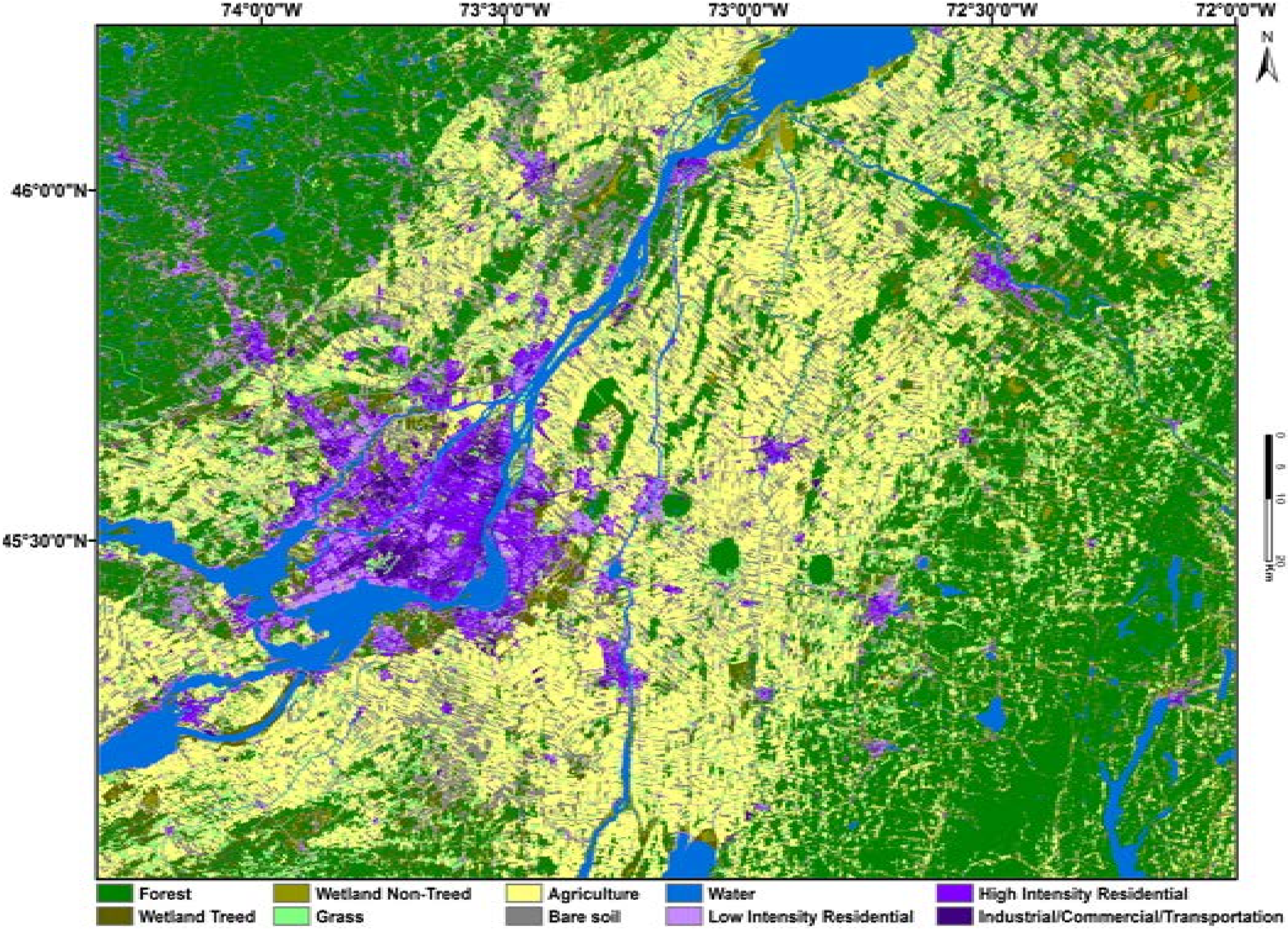
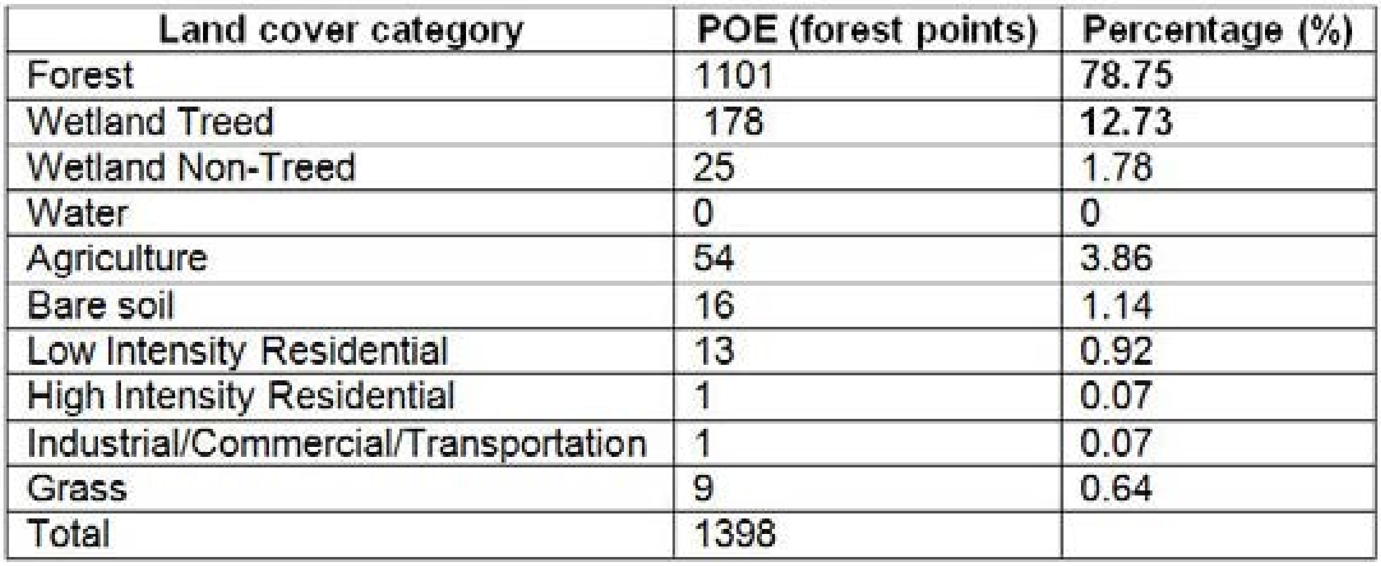


Figure 2-5: Land cover classification categories for the study extent

Table 5 Agriculture point membership to a certain land use category



Land cover category	POE (forest points)	Percentage (%)
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Low Intensity Residential	13	0.92
High Intensity Residential	1	0.07
Industrial/Commercial/Transportation	1	0.07
Grass	9	0.64
Total	1398	

7 Conclusion

Our Landsat derived land cover classification map is, to our knowledge, the most recent map for the study area. It served as the basis for all subsequent analysis described in this report.

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Chapter 3

Modeling habitat quality for the focal species

1 Introduction

Species live in particular ranges of environmental conditions and the fitness of individuals varies based on the local conditions (Chase and Leibold 2003). This relationship, between the fitness of individuals and their environment, can be modeled quantitatively and mapped across landscapes to predict the likelihood of occurrence of a species in any given location within its range (known as habitat suitability modeling; Rushton et al. 2004). For the purpose of broad-scale, conservation planning, habitat suitability models are implemented in GIS to determine suitability based on raster layers such as land cover, land use, elevation, and distance to roads. These spatial habitat models provide an assessment of habitat quality across the landscape of interest and are used to derive the patch and resistance layers needed for connectivity analyses (described in Chapter 7).

The main goal here was to set up a general modeling framework with which we could model habitat quality for each selected animal focal species (see Chapter 1). The generality of this framework allowed us to compare differences in habitat quality among species at a given point in time and also to quantify changes in habitat quality for a given species over time in response to land use change scenarios (see Chapter 5). We define here habitat quality as the capacity of a single pixel to sustain individuals of a species given its type of use, cover and surroundings. We used for this a classical approach relying on the attribution of habitat preference values for different types of land use and of landscape configuration based on an intensive literature review (e.g. Polasky et al. 2008). The connectivity analyses that are presented in the following chapters required the definition of habitat patches (this Chapter) and resistance surfaces (see Chapter 7) for each focal species. Habitat quality modeling and habitat patch delimitation are detailed in the next sections.

2 Assessing habitat quality and defining habitat patches for the focal species

2.1 Habitat quality models

2.1.1 Land cover effect and baseline habitat quality maps

We used SIEF data from the 3rd eco-forestry inventory as the land cover base map for the following work. In order to facilitate the identification of good quality habitat for a focal species, to get a good representation of the different types of land use/cover across the study area, and to remain consistent with the land use change modeling section (see Chapter 5), we considered eight different land use categories: (1) crop / agriculture, (2) built but non urban areas, (3) disturbed habitat 1 (predominantly tree nurseries, willow-brush, cleared land), (4) urban areas, (5) forest, (6) disturbed habitat 2 (predominantly golf courses, botanical gardens, campsites), (7) open water, (8) wetlands.

Crop (1), Forest (5) and urban areas (4) are the dominant land cover types within our study area (approximately 40%, 40% and 10% land cover). Within these three dominant types, we refined the cover information with: 1) for the forest, we used SIEF information on stand age, density and type (deciduous, mixed, and coniferous) differently weighted depending on species' preferences and having as a guide quality models made by the MRNF) for croplands, we used information from BDTQ, on the linear elements that occurred within the landscape (e.g. hedges and drainage ditches), 3) for the urban areas, we used information from our own land use classification, made using Landsat 2009 remote sensing images (see Chapter 2), in order to distinguish between high residential / commercial, low residential, forested (e.g. urban parks), open vegetated and water surfaces that were not well described in the SIEF land cover data. From this information we derived a baseline quality map relying on information about species-habitat compatibility (what land cover types are suitable habitat for the species).

We scaled habitat quality between 0-100 to depict species habitat requirements and preferences as follows: 0 = no use at all, < 30 avoided, 30 - 60 = occasional use for non-breeding, 60 - 80 = consistent use for breeding, 80 - 100 = best habitat for survival and breeding.

2.1.2 Landscape configuration and habitat quality modifiers

In order to account for landscape configuration and for the different linear elements (e.g. forest edges and roads) we used multiplicative modifiers between 0 and 1 to reduce the quality of some pixels that were for instance close to (or on) roads. We accounted for the following factors:

Edge effects: distance to forested area and distance to open non-forested areas (Data: SIEF)

Many species can be negatively or positively affected by edges at the interface between forest and open areas (Murcia 1995, Guay, S., 1994). For each pixel in the landscape, we calculated the Euclidean distance to both its nearest non-forested pixel (within the forest, Figure 3-1, left panel) and to its nearest forested pixel (outside the forest Figure 3-1, right panel) to account for this effect. We estimated critical distance threshold above which species would be positively (or negatively) by an edge. For instance Seiurus aurocapilla (ovenbird) and Sitta Canadensis (nuthatch) are interior species and were thus given a distance to non-forest threshold of 100 m (Van Horne 1990, Burke et al. 1998, Smith et al. 2011). In contrast, Scolopax minor (woodcock) preferentially uses forest edge for feeding (open areas within 200 m around the forest) and for breeding (350m from an opening, Hudgins et al. 1985).

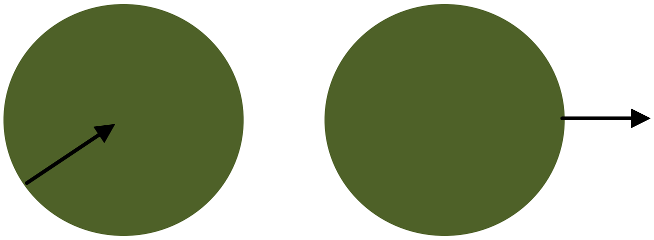

Figure 3-1: Edge effect within and outside the forest

Distance to roads (Data: Reseau routier national from geobase – 2007)

Habitat quality and other ecological factors are also affected by roads (Forman 1998). The main factors influencing the effects of roads are traffic density (number of vehicles per hour), the speed limit and the width of the road. In particular, a road might become a problem as soon as it is within the home range of an individual. Amphibians and reptiles that are slow moving animals have no car avoidance ability and are very sensitive to two lane roads with low to moderate traffic. Large and mid-size mammals are more affected by two lane high-speed roads (they are often excluded from bigger roads by fences). Birds and small mammals are more affected by wide and high-speed highways. Roads can have an impact on the behavior of some species at distance of several hundred meters.

We used complementary information in order to account for the numerous roads that were not present in the land cover map (classified in category (2) built but non urban areas). We made two categories of roads and further combined them by multiplication of their impacts.

Distance to major roads – We considered here the Euclidean distance to roads (calculated in the same fashion as distance to forest edge) with the labels: artere, autoroute, express, service, bretelle. To simplify and make both land cover rasters and roads feature lines compatible, we considered that these larger roads were 90 m wide after Figure 3-2, scheme (top panel). This encompassed on average: 2 x 3 traffic lanes of 3.5 m, plus 2 left-side lanes of 1 m, plus 2 emergency lanes of 3 m, plus at least 1.5 m of central material, so at least 30.5 m wide. There is also a deforested border of several meters on each side. We thus considered that 90 m around the road line was not habitable a.

Distance to minor roads – We considered here that these were only 30 m wide. This encompasses on average: 2 lanes of 3.5 m, plus 2 emergency lanes of 3 m, so at least 13 m wide. As the resolution of our maps is 30 m, we considered one pixel to be the width of the road, even if this is an overestimate. We can consider that the edge effect due to the road is included in this width for some small sensitive species (Figure 3-2, bottom panel).

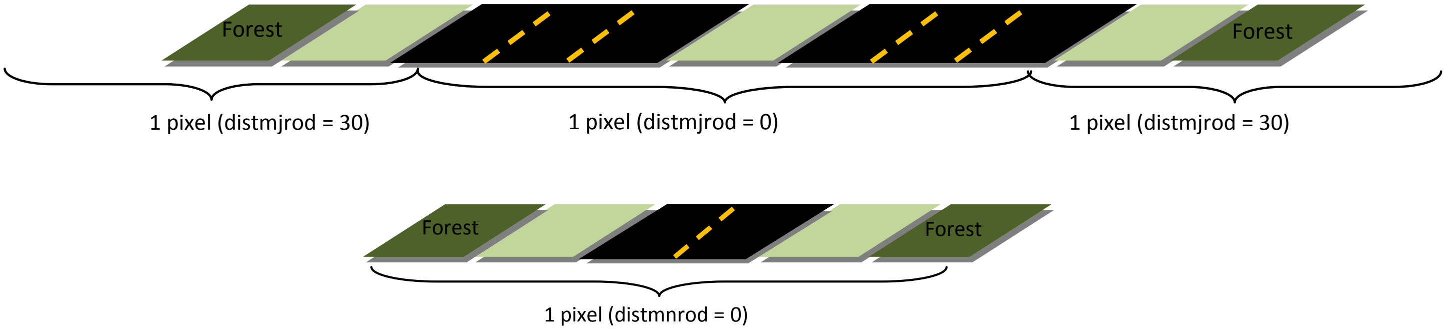

Figure 3-2: Simplification of major (top) and minor roads (bottom)

All habitat factors were combined to form a single habitat quality map, leading to a single habitat quality value for each pixel. Potential habitat was finally defined as all the pixels that had a quality above or equal to 60 (the value that we set as the threshold, see above).

2.1.3 Validation of habitat quality models

To ensure the quality of our models, we tested them either to other more refined quality models from MRNF or from local species occurrences data.

MRNF models:

For some of our focal species, the MRNF has already published refined habitat quality models that when compared with our models considered additional information like tree species grouping (e.g. balsam fir or sugar maple), tree height, forest disturbances (total windfall, severe disease, total burn, etc.) and interventions (clear cut, plantation, etc.), although they did not account for the external influences like (distance to road, water, etc.) . Our models thus aimed to be a simplification of those MRNF models that we could project into the future. We found that our models did a good job of capturing the main tendencies of habitat quality and at the same time they were more complex because they accounted for the external disturbances that can decrease the quality of habitat.

Species occurrence data:

For small mammals, we used data from the CDPNQ. For amphibians and reptiles, we used data from the AARQ. We did not use these data directly for model calibration due to the low accuracy of their geographical location (100 m order of magnitude) compared to the resolution of land use data (30 m). But we checked that most occurrences were close to a suitable area (i.e. with a quality over 60)

2.2 Patch delimitation

For the graph approach described in the next chapters (Chapter 5), we needed to define habitat patches, i.e. aggregated zones of good habitat that can support a population or at least a pair of individuals. Classically, patches are defined as sets of adjacent habitat cells (structural patches). However, patches are not fixed elements of the landscape, they are organized hierarchically within the landscape and different organisms perceive and react to these landscape features at different spatial scales and hierarchical levels. Thus they should be defined relative to the particular organisms under consideration (Turner 2001). It is even more important when dealing with multiple species that vary in their grain of perception (Baguette 2007). In this case, some alternative definition may be more appropriate in order to adjust the discrepancies between the map resolution (30 m) and the different ranges of species' perceptions (e.g. from few centimeters for the salamander to several hundreds of meters for a bear or a deer). For medium to large animals (e.g. marten, deer, Figure 3-3), we thus used the method proposed by Girvetz and Greco (2007) in order to smooth patch shape in accordance with the species' perception. This approach groups together several structural patches that may be used by the individuals as a single habitat patch as defined by their perception range and daily movements. This clustering also reduced potential habitat patch number, which was a major issue for small-bodied species. For the smallest species (e.g. salamander) and those sensitive to patch edge (e.g. ovenbird), we kept the classical definition of patches based on contiguity, but we averaged the habitat quality values with a 3 x 3 pixels window before applying the habitat quality threshold (60) in order to eliminate single cells that were surrounded by low quality habitat (to keep patch number within manageable limits).

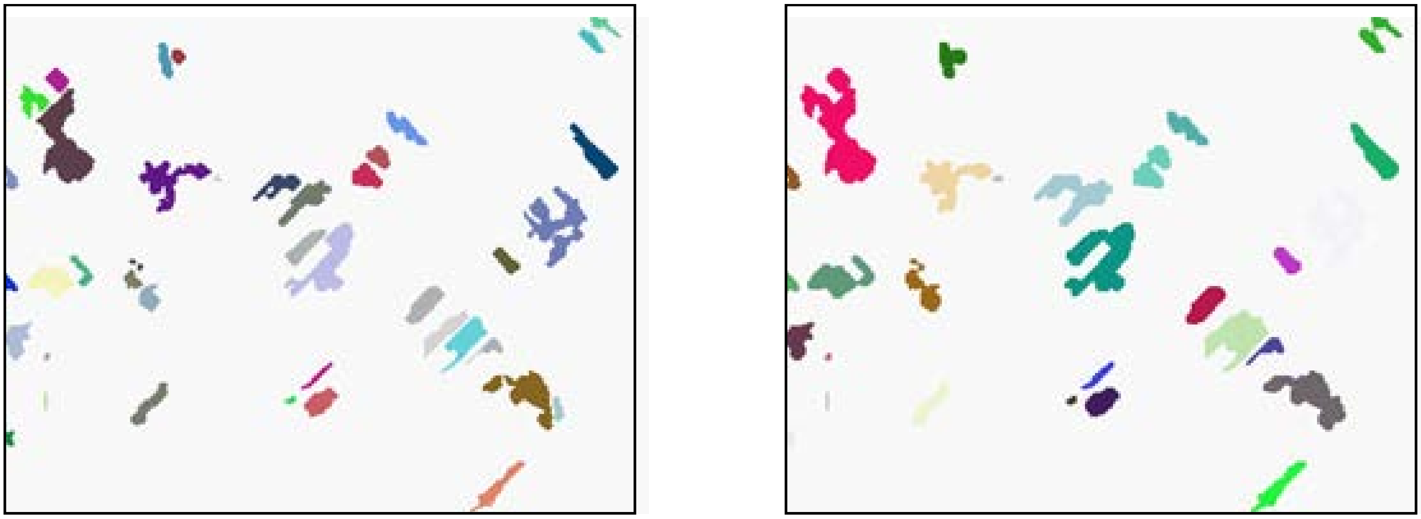

Figure 3-3: Illustration of the patch definition method for the marten for a zoom in the study area – Left: classical structural patches based on cell adjacency (12873 patches in the whole study area) – Right: Girvetz and Greco (2007) method (8871 patches in the whole study area). Unique colours represent unique patches based on the patch delineation.

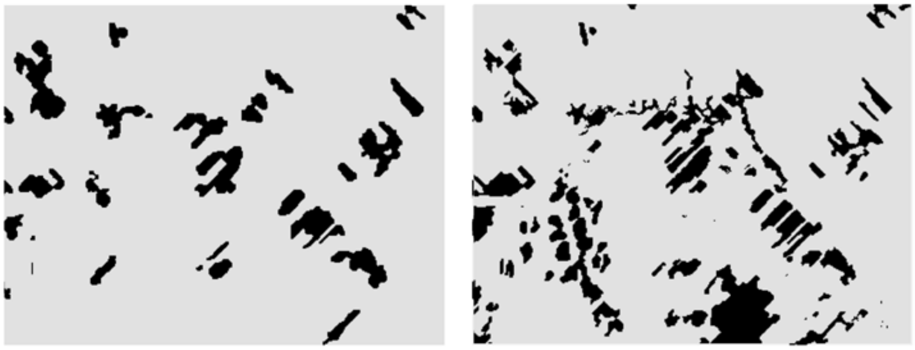

Figure 3-4: Illustration of the species-specific definitions of habitat and patches in the present – (left) marten, (right) ovenbird

We derived potential habitat maps for each focal species under current conditions (present land use from SIEF data). This led to the maps that are presented below (MAPS). We used the same models to project potential habitat into the future based on land use change scenario maps (see Chapter 5). Thanks to our general framework, we obtained comparable maps between species and for a single species over time (Figure 3-4). Habitat and patches were defined in a species-specific way in order to better account for species differences in terms of landscape and space use (Figure 3-5 -Figure 3-9).

Our approach is rooted in literature-based models and therefore can be vulnerable to high uncertainty, variability in the relationship between suitability and environment if the study was not conducted in our study region, and quantitative errors in habitat suitability scores derived from qualitative habitat suitability studies. However, the benefits of these literature-based models outweigh their weaknesses for conservation planning as they are simple and relatively fast to develop, they allow us to model the habitat quality for multiple species without collecting new field data, they are more reliable than expert-based models, and their sensitivity to specific parameters can be quantified.

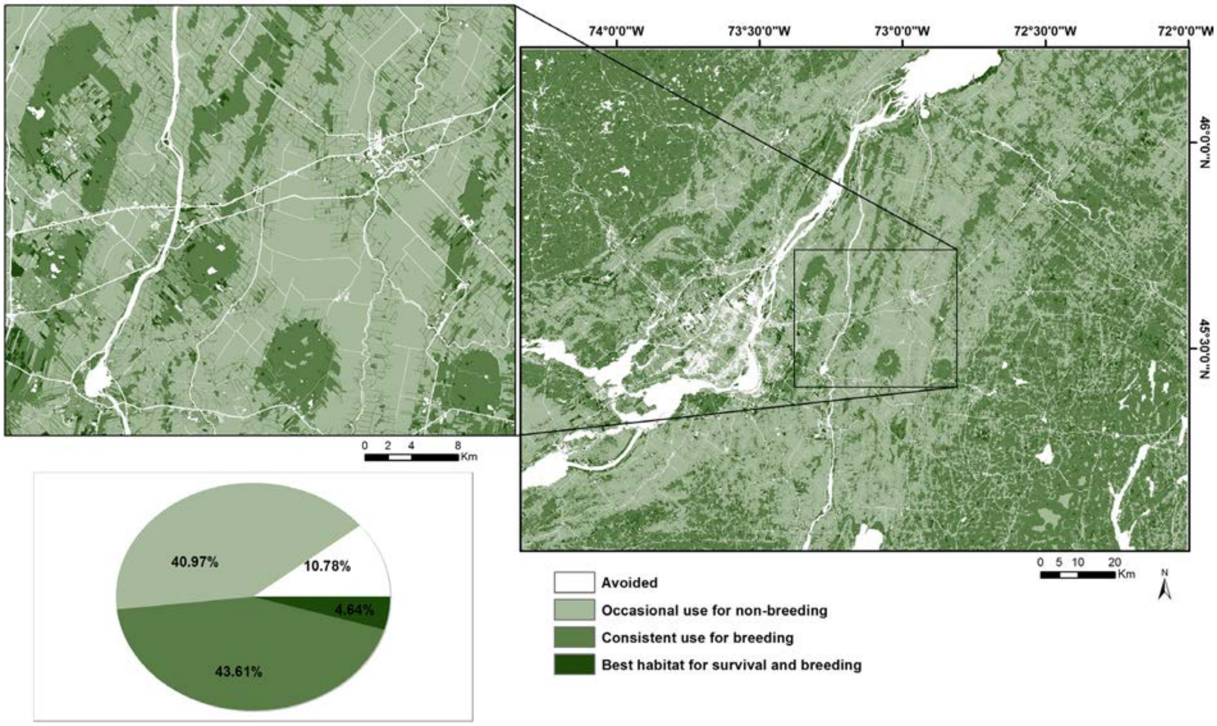

Figure 3-5: Maps of the spatial distribution of habitat for *Bombus impatiens*. Right, the distribution of habitat quality for 4 classes of habitat. The pie chart shows the relative proportion of habitat in each class across the entire study extent.

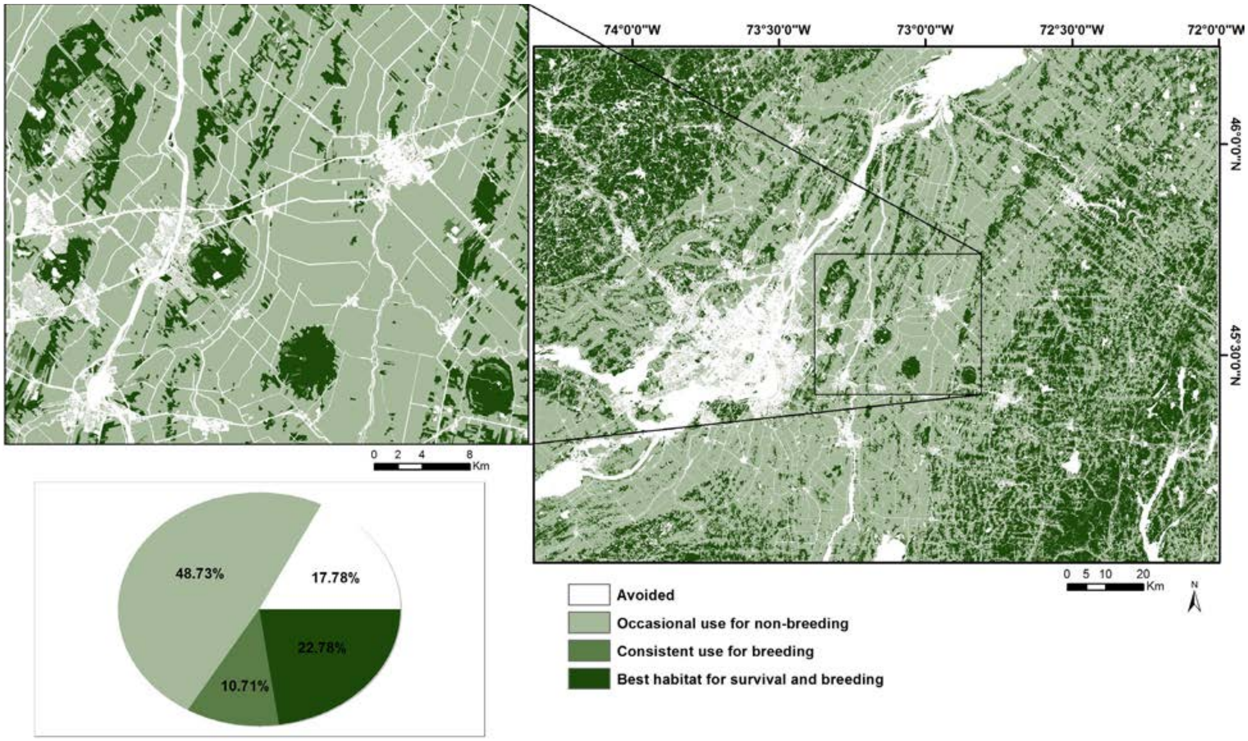

Figure 3-6: Maps of the spatial distribution of habitat for *Plethodon cinereus*. Right, the distribution of habitat quality for 4 classes of habitat. The pie chart shows the relative proportion of habitat in each class across the entire study extent.

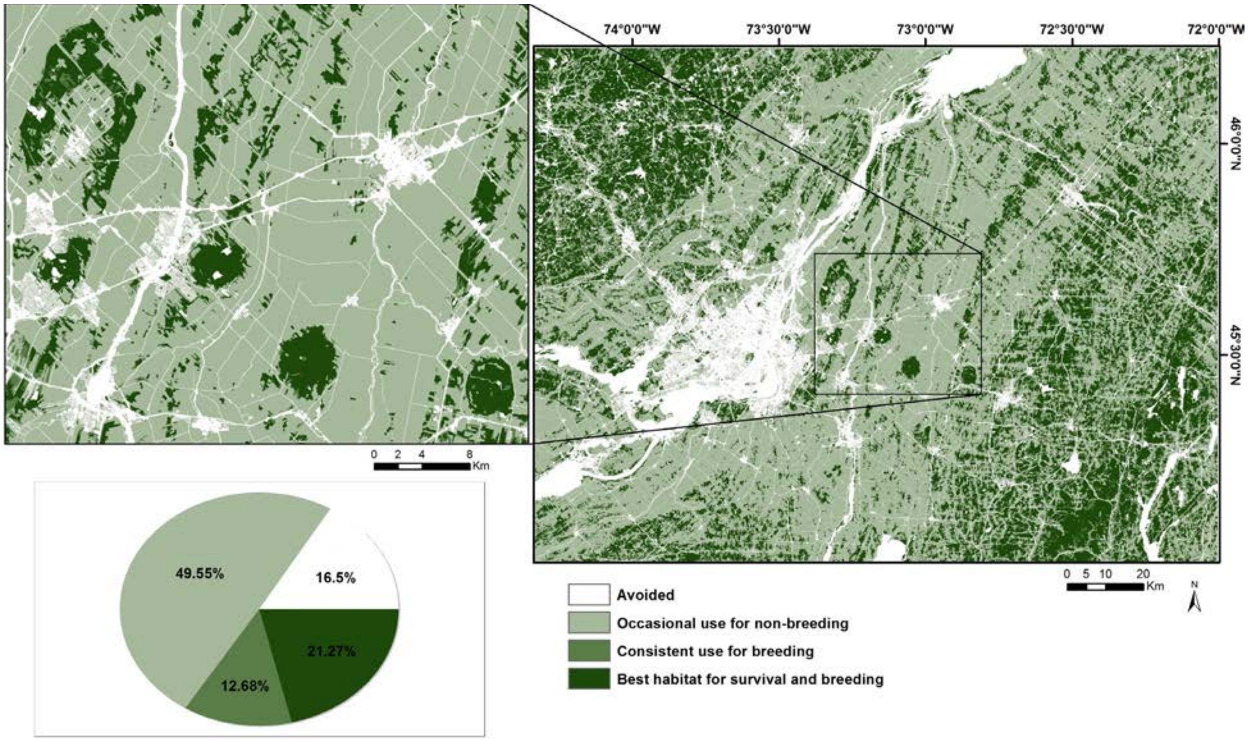

Figure 3-7: Maps of the spatial distribution of habitat for *Seiurus aurocapilla.* Right, the distribution of habitat quality for 4 classes of habitat. The pie chart shows the relative proportion of habitat in each class across the entire study extent.

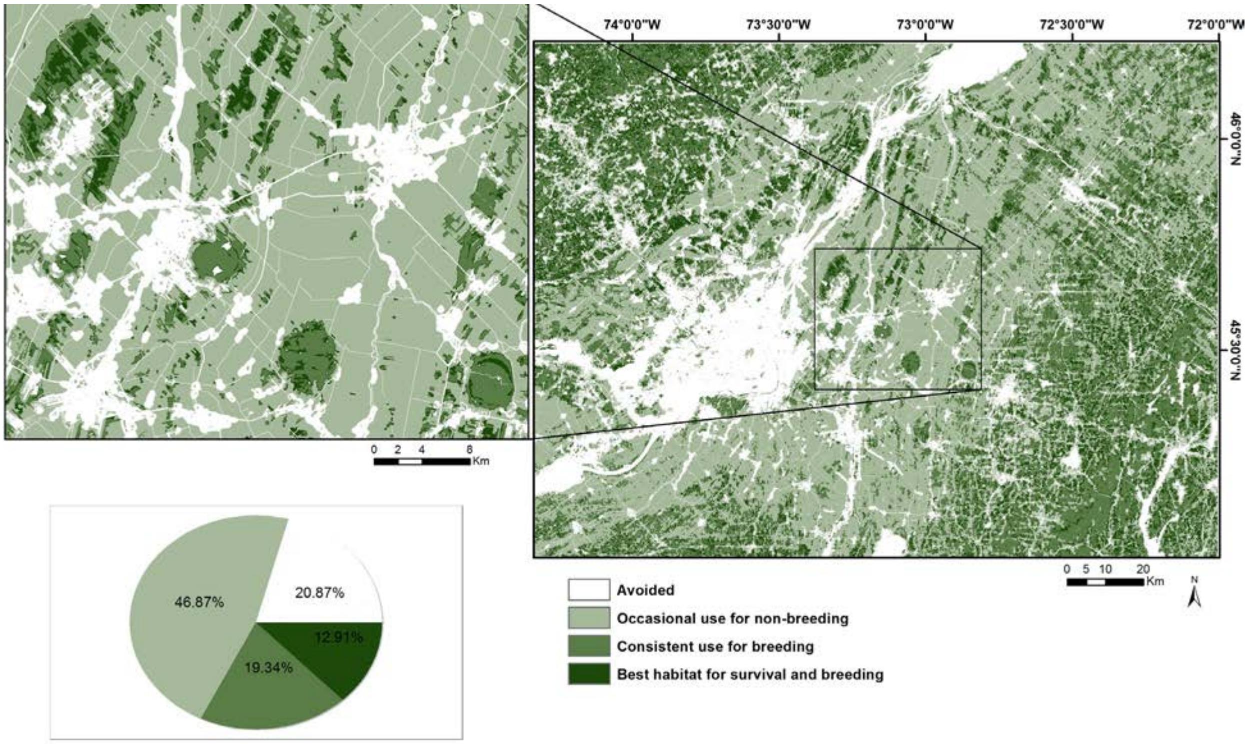

Figure 3-8: Maps of the spatial distribution of habitat for *Odocoileus virginianus*. Right, the distribution of habitat quality for 4 classes of habitat. The pie chart shows the relative proportion of habitat in each class across the entire study extent.

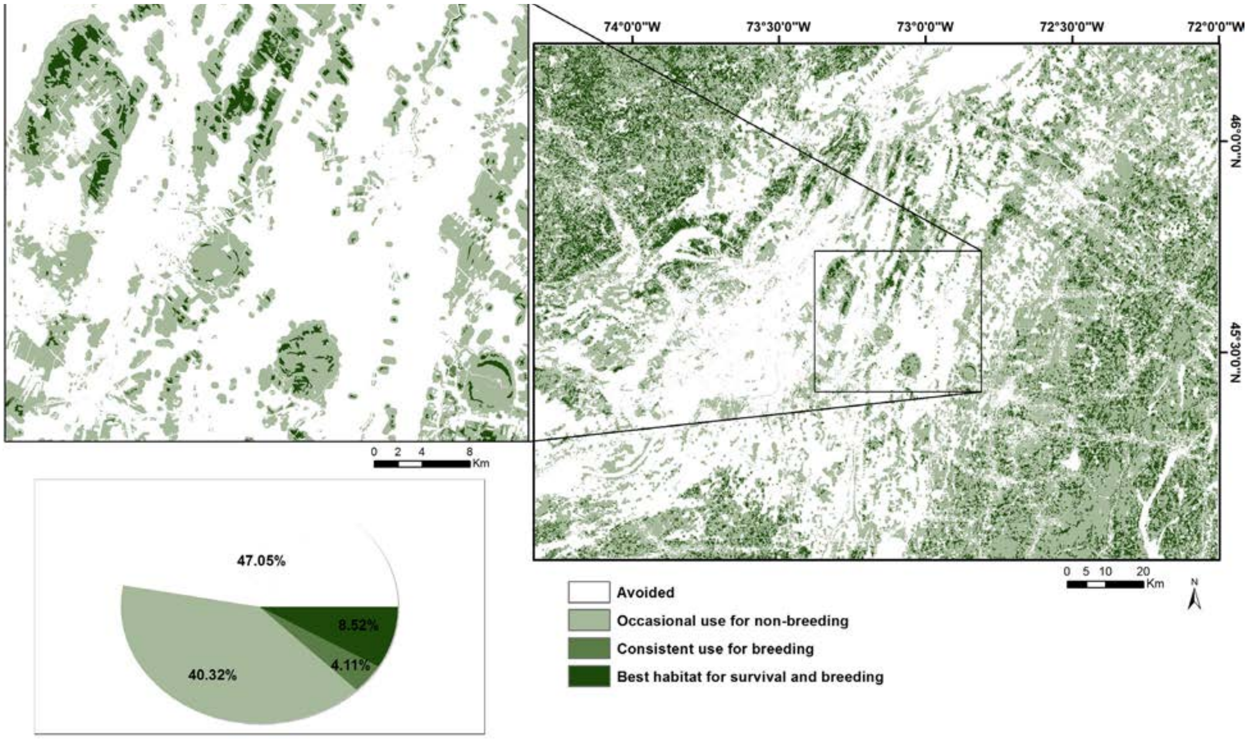

Figure 3-9: Maps of the spatial distribution of habitat for *Martes americana*. Right, the distribution of habitat quality for 4 classes of habitat. The pie chart shows the relative proportion of habitat in each class across the entire study extent.

4 Conclusion

To our knowledge these are the first high-resolution habitat quality maps for these five focal species for the study area. Our approach is rooted in literature-based models and therefore can be vulnerable to high uncertainty, such as variability in the relationship between suitability and environment if the study was not conducted in our study region. However, the benefits of these literature-based models outweigh their weaknesses for conservation planning as they are simple and relatively fast to develop, they allow us to model the habitat quality for multiple species without collecting new field data, and their sensitivity to specific habitat parameters can be quantified. These habitat quality layers served as inputs to the connectivity analyses (Chapter 6)

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Chapter 4

A land use change model to simulate land cover change from 2000 to 2050

1 Introduction

Land use and land cover changes are known to be one of the major drivers of biodiversity loss in terrestrial ecosystems (Sala et al. 2000). In general, these land use changes lead to natural habitat loss and increased habitat fragmentation over time. Habitat fragmentation typically results in the creation of many smaller patches of increasing isolation so that changing habitat configuration is a significant signature of land cover change. Current conservation efforts are focused on restoring connectivity, but a key challenge is anticipating future patterns of habitat loss and fragmentation. Good models of land use and land cover change are an essential part of planning for future habitat loss and restoration of landscape connectivity.

Land cover change involves different trajectories of change in space and time. For example, some areas in a region may be experiencing agricultural abandonment which is followed by natural reforestation versus agricultural intensification which leads to more deforestation. Predicting the trend, rate and timing of land use and land cover change is crucial for the evaluation of how the composition and configuration of habitat for different species will change over the coming decades.

Our study region possesses a central band of intensive agriculture running parallel to the St Lawrence River (St. Lawrence Central Lowlands) and is bounded to the northwest by the Laurentian Mountains and to the southeast by the foothills of the Appalachians (Figure 2-5 in Maria’s Chapter 2). The area is composed of a complex mosaic of land cover types dominated by the city of Montreal and agro-forest ecosystems inherited from past land use change initiated by European settlement. Changes in agricultural policy have brought about further land use change over recent decades (Bélanger and Grenier 2002). Today the central part of the study area is composed of highly fragmented woodlands, surrounded by a sea agricultural matrix. This remaining woodland is rich in biodiversity and harbors forest flora and fauna vulnerable to extirpation. Rapid growth of the region’s human population is resulting in urban spread and the development of new residential and commercial zones on the north and south shores of the St Lawrence. Similar trends in land use change are expected in the near future as the population size of the Greater Montreal Area is projected to increase by one million by 2030.

The main objectives of this chapter where to 1) develop a land use change model capable of providing plausible scenarios of change in the spatial distribution of land cover, and 2) simulate potential future land-cover change based on an evaluation of current land use patterns and their dynamics in the recent past.

2 Historical changes, current dynamics and future scenarios

2.1 Land use history in brief

Three hundred years ago, southern Quebec was mostly forested (Belanger et al. 2002). Intensive human settlement in the area started in the late 18th century (around 1820, Brisson et al. 2003), such that by 1888, the area was one of the most cultivated on the new continent, with forest lots kept for firewood found only on poor quality soils. During the 19th century, the need for agricultural land and for wood, led to intensive logging activity (Brisson et al. 2003). During the 20th century, the improvement of drainage conditions made it possible to cultivate new areas and led to the abandonment of the poorest soils and most remote and steepest areas. During this period forest area remained more or less constant. The late 20th and early 21st century has seen a new increase in deforestation with an increased demand for construction and agricultural land (Environment Canada 2010 Pan et al. 1999). The complex interaction between soil quality and drainage, topography and human activities have thus led to the current mosaic where clay plains are mainly cultivated, while forest fragments (often managed or disturbed) remain on glacial moraine deposits.

2.2 Current dynamics

Currently, our study area is dominated by agriculture and forest that cover respectively 40% (27% of the administrative Monteregie, 12% in the MRC Roussillon) and 41% of the area (from the SIEF land use map). Other land use types include built areas (10%, including urban and commercial areas) and open water (6.5%).

Urban areas

Urban sprawl is associated with a marked increase in population size and the growth of the recreation-housing market. The Greater Montreal Area (GMA) is the most populated area in Quebec with 3.9 million inhabitants, i.e. almost half of the Quebec population. The population size of the GMA is expected to grow by between 4 and 20 % over the period 2011-2031 (André et al. 2009). These trends also show some spatial heterogeneity with Laval, the Laurentians and Lanaudiere expected to see the greatest increases (Figure 4.1). A major issue with suburban sprawl is that it occurs on high quality soils that are permanently lost for agriculture (Jobin et al. 2010), this led the Quebec government in the 1980s to establish a plan for the protection of agricultural land through land zoning.

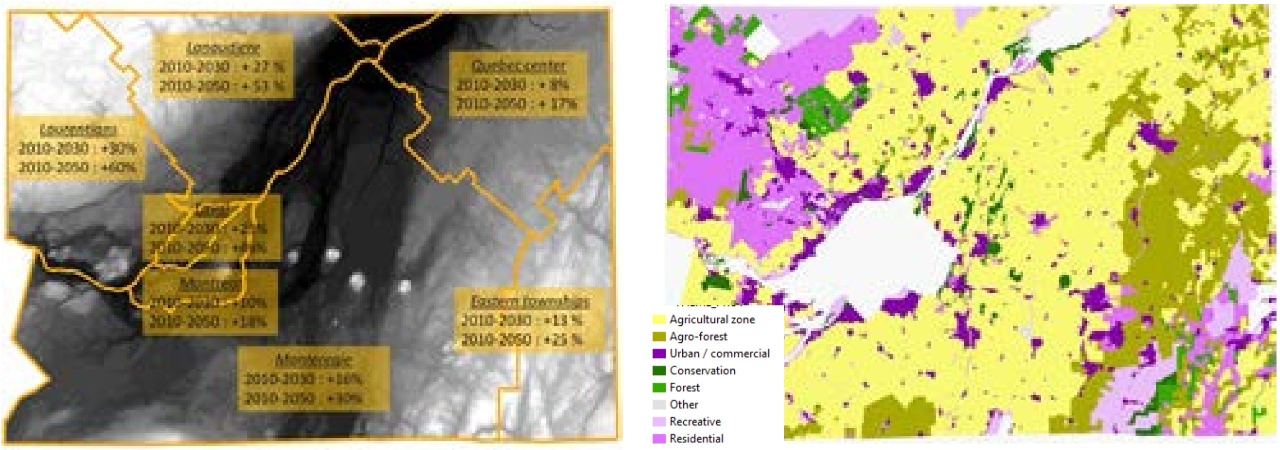


Figure 4.1: Demographic trends and land development zoning for the study area – (left) demography trends for the next 40 years and their spatial discrepancies – (right) land zoning in the study region from SIGAT.

Agriculture

One third of Quebec's agricultural production is located in the Montérégie (REF). In addition to favorable climate and soil, the region is in the vicinity of the Montreal and Quebec economic markets and well connected to others in North America. Agricultural production (1950-1970) in the past was dominated by diary farms and perennials crops (70% of Quebec apples produced in the Monteregie) and acericulture (Menard 2007). Current production (since 1970) is mainly annual crops (corn, soya, wheat, Menard 2007) and pork farms, which has lead to an increased demand in corn production for animal feed, and in acreage to spread manure (Jobin et al. 2010). Again, these tendencies are spatially heterogeneous with an intensification of agriculture on richer soils and the abandonment of the poorest soils (Rioux, Ruiz, Domont). The replacement of traditional dairy farms by annual crops (+44% of soy production between 1991 and 2001) has also led to a sharp decline in semi-natural grasslands (Jobin et al. 2010).

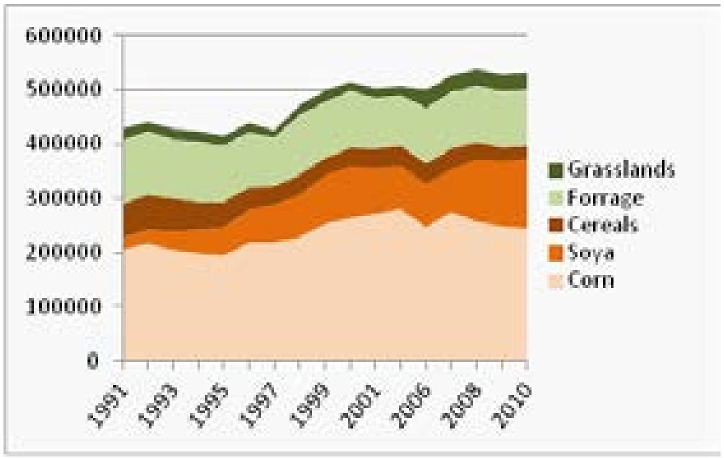


Figure 4.2 - Trends in surfaces used for agricultural production in the administrative Montérégie between 1991 and 2010 – Surface area in hectares.

Forest

The forest in the Montérégie is either deciduous (around 70% of the surface area) or mixed (20%). Forest loss has occurred in conjunction with the expansion of urban and agricultural land cover. Geomont reported a loss of 9000 ha in the Montérégie between 1999 and 2004 (Sokpoh 2010). In some of the regional county municipalities (RCM), less than 10% of former forested area remains; a value far below the threshold for forest integrity (Belanger et al. 1999). Belanger et al. (2002) reported that 31 RCMs out of the 59 within the St Lawrence valley are less than 50% forested. Some forest remnants are protected for their patrimonial value and high biodiversity (135 “Écosystèmes Forestiers Exceptionnels” in the Montérégie). A Quebec regulation now controls deforestation in agricultural areas in some of the MRCs of the region (Quebec 2013), but it is doubtful that this will be sufficient to reverse deforestation and improve forest connectivity.   Our land use model aims to explore the extent of forest loss over the next 50 years.

2.3 Future scenarios

We kept our approach as simple as possible in order facilitate our understanding of the potential interactions between land use and climate change scenarios. We developed our methodology around a single **“Business As Usual” scenario** of land use change that we compared to a scenario of no land use change over the period 2010-2050.

Urban areas

Based on current demographic trends, an average population increase of 18% is expected by 2030 and of 35% by 2050 (Fig. 4.1). We thus considered a 20 % increase in built areas (urban and commercial) by 2050 would be a reasonable business as usual scenario that might represent either a strong population increase accompanied by a densification of housing, or a less strong population increase accompanied by current trends in urban sprawl.

Agriculture

We conducted a simple linear extrapolation of recent past trends in land cover change (displayed on Fig. 4.2. When extrapolating from the 2000-2010 period, this leads to a potential increase of 12% in the area used for agricultural production by 2050. When we extrapolated from the 1990-2010 period, we observed a potential increase of 40% in the area used for agricultural production by 2050. We thus considered a reasonable intermediate "business as usual" scenario to be a 20 % increase in agricultural areas (excluding perennial crops such as apple orchards that are considered as fixed given their small surface area) by 2050.

For the remaining land uses, we assumed no change in surface area through to 2050. We also considered as a first simplification that there would be no new roads constructed over the period 2010-2050. We assumed that the four following categories of land cover could not become agriculture or new urban zones in the future: built but non-urban areas, urban areas, disturbed habitat (e.g., golf courses, botanical gardens, campsites, orchards) and open water.

3 Model description

We used a modified version of the CLUE model (Verburg and Overmars, 2009, t2.1). This model combines both: 1) a top-down approach, accounting for broad-scale socio-economic constraints by imposing the expected quantity of change over the study area (e.g. 10% increase in urban area) following broad economic and demographic scenarios; 2) a bottom-up approach accounting for local geomorphological, soil, and climatic local constraints on the spatial allocation of these changes. The first step was the scenario definition that we detailed in the previous section. The second step required the determination of the most plausible spatial allocation for the projected land cover changes.

We considered here the same eight land uses as described in Chapter 3: (1) crop / agriculture, (2) built but non urban areas, (3) disturbed habitat 1 (tree nursery, willow-brush, cleared land), (4) urban areas, (5) forest, (6) disturbed habitat 2 (golf course, botanical garden, campsites, orchards), (7) open water, (8) wetlands.

3.1 Identify areas with a high probability to become urban or cultivated

We used statistical models to locally relate the current occurrence of urban and agricultural land use to a set of explanatory physical and human variables (e.g. slope, altitude, distance to roads, soil types, and human density). This is an approach increasingly used in geography (e.g. Pontius et al. 2001), which relies on the assumption that the current spatial organization of land-use types across the study region reflects past processes of land-use change. This approach is very similar to that used in ecology to model species' distributions (see Chapter 6). Specifically, we used generalized linear models calibrated from random samples over the entire area, with the occurrence of urban or agriculture as response variables and physical factors as explanatory variable. We used a step AIC procedure in order to keep the most parsimonious models for each land use type, which we describe below.

Urban areas

Urban areas were mainly linked with the distance to roads (Fig. 4.3). The model was reasonably good with a good predictive power (AUC value of 0.8). In order to get a better balance between low and high probabilities, which is necessary for the following step of selecting the cells in the landscape that are not yet urbanized but could be in a near future, we rescaled the probabilities with a 8th root function (Figure 4.3).

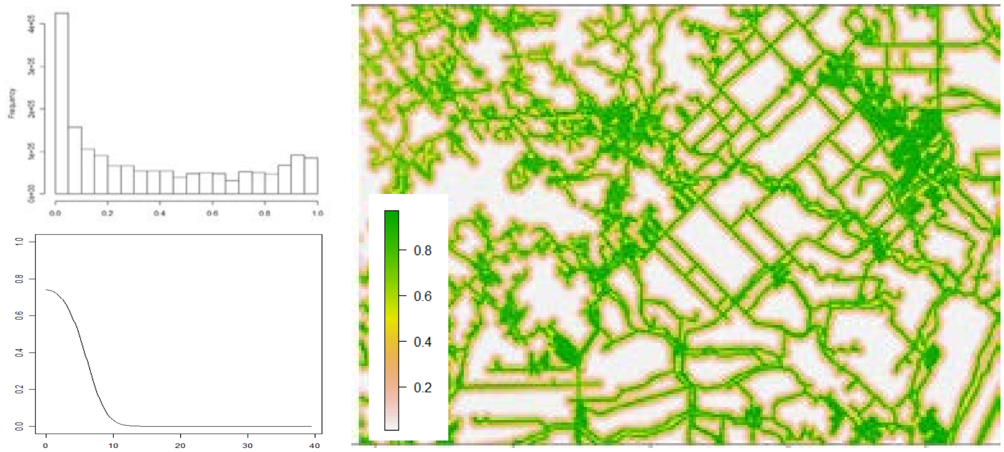


Figure 4.3– Probability of becoming urban – (top left) distribution of probability values after the transformation, (left bottom) relationship between probability to become urban and distance to roads, (right) probabilities of becoming urban with a zoom on the town of Joliette.

Cultivated areas

Cultivated areas were mainly linked with the altitude of the terrain (topography), soil drainage and distance to roads (Fig. 4.4). The model was very good with an AUC value of 0.9.

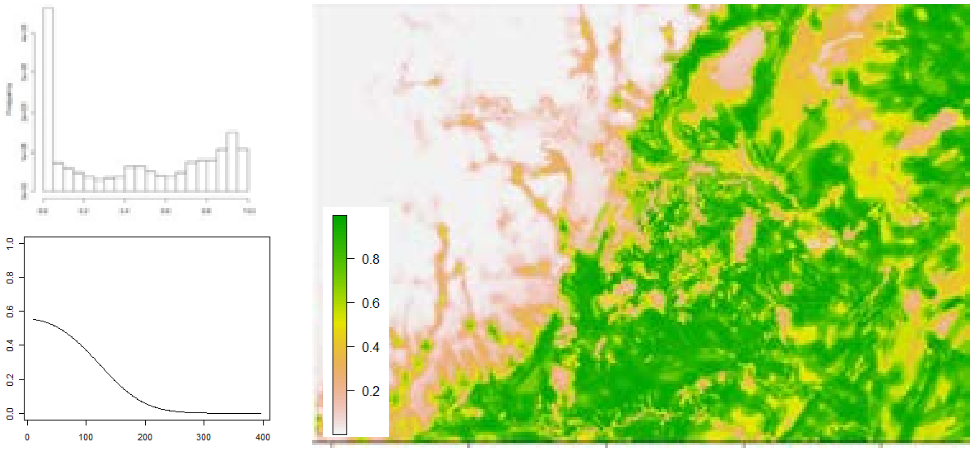


Figure 4.4 – Probability of becoming cultivated – (left top) distribution of probability values, (left bottom) relationship between probability to become cultivated and altitude, (right) probabilities of becoming agriculture with a zoom on the town of Joliette.

3.2 Accounting for land management and development processes

In order to select for the cells that could become urban or cultivated, while accounting for some land management rules, we:

- Set probabilities to 0 for cells that were already urban or cultivated (for probability to become cultivated only).
- Set probabilities to 0 for cells that were occupied by built but non urban areas (category 2), disturbed habitat (category 2: golf course, botanical garden, campsites, orchards) or open water (category 7).
- Set probabilities of becoming urban to 0 for cells that were within the agriculture zoning
- Set up probabilities of change to 0 for protected areas within the study area
- Set probabilities to 0 for cells that did not have any of their eight neighboring cells already occupied by urban or agriculture.

3.3 Running the model over time

At each time step, we defined the number of cells NU (respectively NA) that were expected to become urban (respectively agriculture) following the scenario described in 2.3.

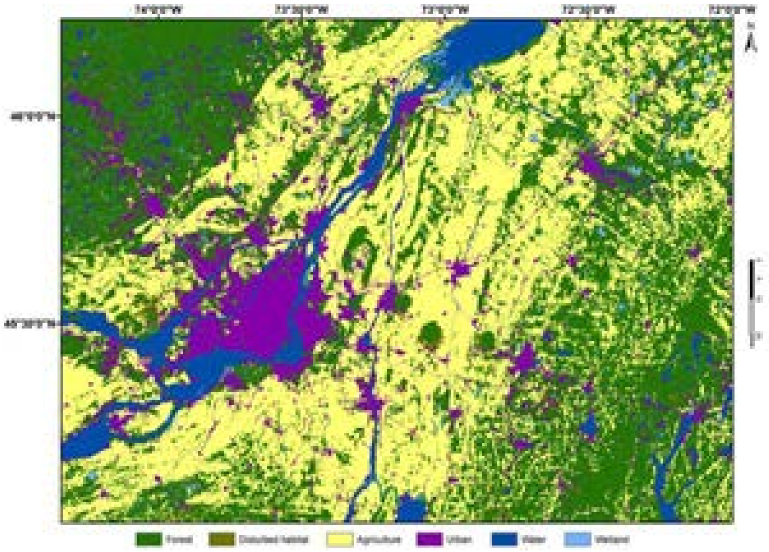
NU = 0.2 * initial number of urban cells /10

We then selected the 5 * NU (respectively 5 * NA) cells with the highest probability of becoming urban (respectively agriculture) and among these, we randomly drew NU cells (respectively NA). This procedure was used first to select the new urban cells, and for these cells, the probability was then set up to 0 before rerunning the procedure to select the new agriculture cells.

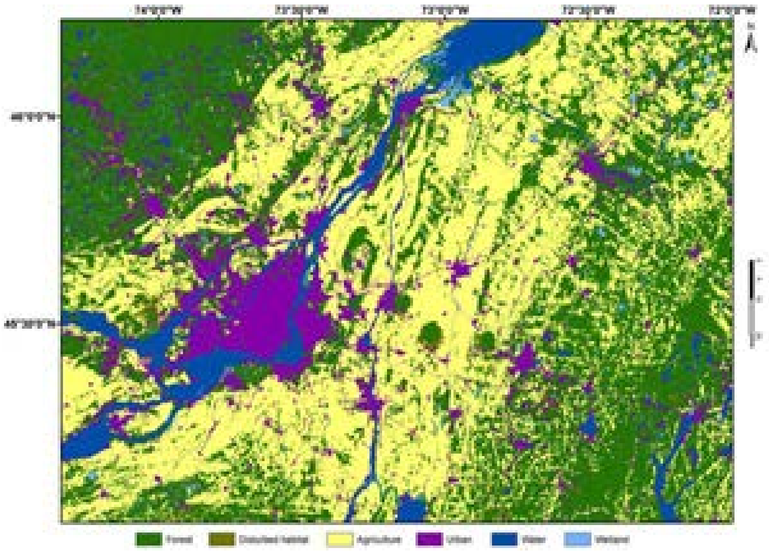
We then updated the land use map and reran the same procedure for urban and the agriculture for the ten time steps. In the next iteration the same probability maps were used, but we updated them by setting up probabilities of change to 0 for the new urban and agriculture areas.

4 Simulated maps for 2025 and 2050

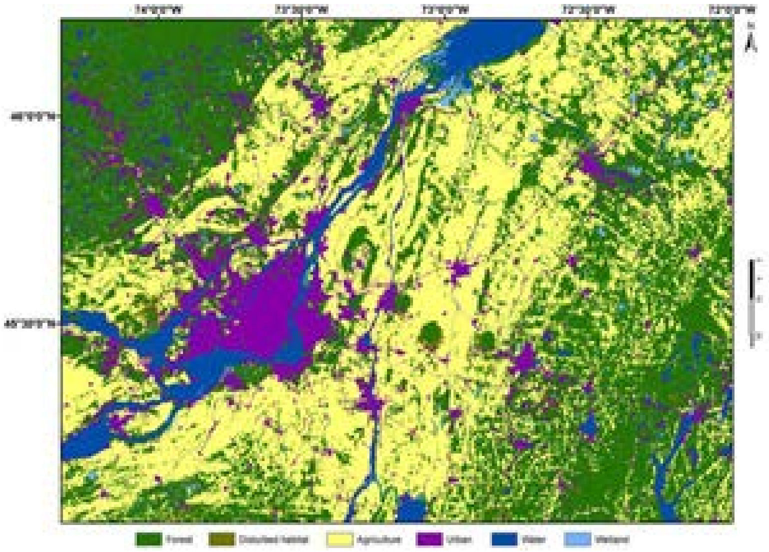
We ran the land use change model over the whole study area for the period 2000 (initial map of land use) to 2050 (horizon for future climate scenarios, see Chapter 6). In order to optimize the trade-off between computing time and the number of time steps, we chose to run ten five-year time steps. From this, we obtained the final map for 2050 shown in Figure 4-5. The land cover in the region in this project assuming business as usual is characterized by a number of features. First there is marked region of urban spread and development mainly to the northwest of Montreal in the region of the Laurentians. Second, as expected from the scenario we selected, there is a large loss of forested areas in the central agriculture zone characterized by the creation of many small forest fragments and the erosion of larger fragments. igure 4-6 a shows the marked increase in the number of fragments from 2000 to 2025, although this trend continues to 2050 the rate of increases slows markedly. Figure 4-5 b-d shows the dramatic increase in the frequency of the smallest fragment size class (<10ha) over time. In summary, the region is characterized by increasing levels of forest fragmentation over the next 40 years. One consequence of this is reduced habitat connectivity.



2000



2025



2050

Figure 4-5: Maps for 2000, 2025 and 2050 showing the change in land cover for the 6 land classes represented by the land use change model.

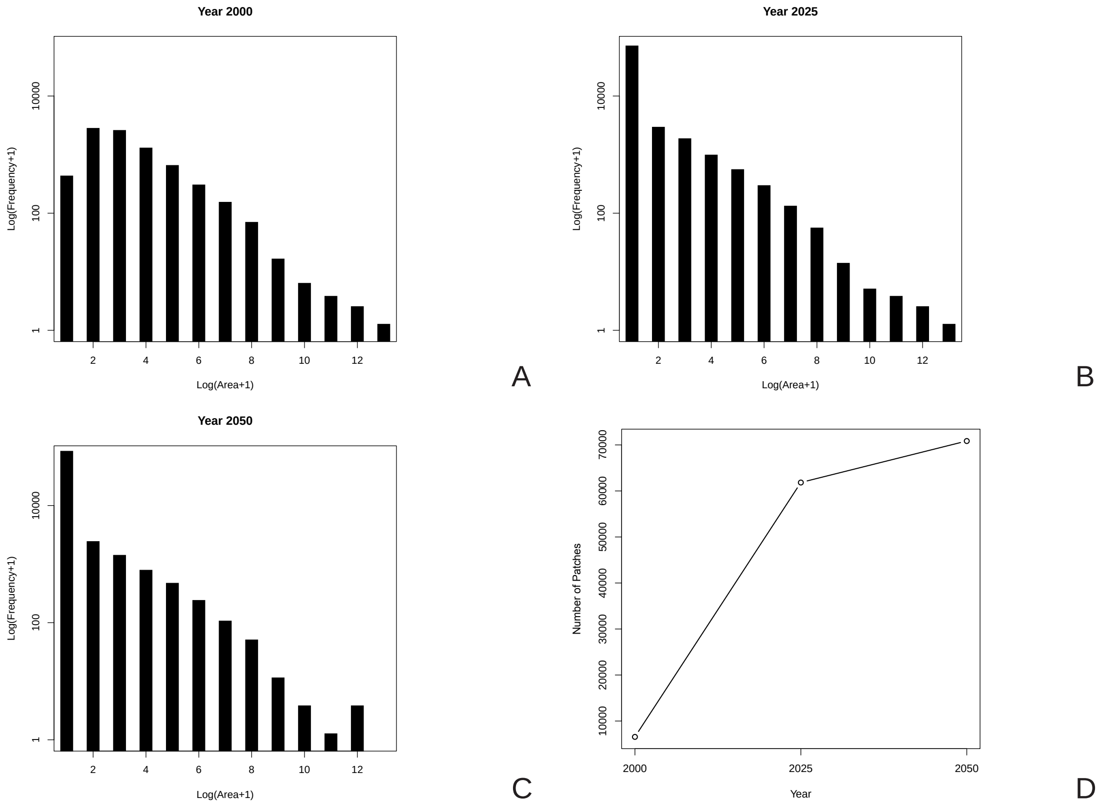


Figure 4.6 - Plots for a) 2000, b) 2025, and c) 2050 showing the change in the frequency distribution of habitat fragments of different sizes. We can see a marked increase in the smallest size class from 2000 to 2050. Plot d) shows the change in the number of forest fragments in the region from 2000 to 2050 as predicted the land use change model

4 Conclusion

We have built a new land use change model for this study region. Ongoing research will validate its assumptions and projections. The main limitation with our "business as usual" simulation is that it does not account yet for the policy regulation on deforestation in the Montérégie. Nonetheless, we believe this is a reasonable "Business As Usual" trajectory for the study area out to 2050. We used these land use maps from 2025 and 2050 to simulate potential future habitat for the study's focal species based on the modeling framework described in the Chapter 3.

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Chapter 5

Modeling the change in climate suitability to 2050

1 Introduction

One of the main objectives of this project was to account for climate change consequences in the design of a regional habitat network. This requires anticipating the changes in the geographic distributions of our focal species. We used the classical species distribution modeling approach (Guisan & Thuiller 2005) to model changes in the distribution of our focal species out to 2050.

Here we focused only on climate variables, as other environmental variables such as soil and vegetation structure are already included within the small scale habitat models detailed in the Chapter 3. Climatic suitability reflects the expected occurrence of a species at broad spatial scales and is thus complementary to the fine scale models in Chapter 3. We provide maps of the change in the distribution of our focal species in the study region for 2025 and 2050.

2 Climatic data

2.1 Initial data and future climate scenarios provided by OURANOS

Our baseline climate data were derived from monthly climatic surfaces of precipitation and temperature generated by McKenney et al. (2006) using the Hutchinson's thin plate splines (Hutchinson 2004) to interpolate observed climate normals from weather stations. We used averaged data derived for the period 1971-2005 at a resolution of 10 x 10 km for all Eastern North-America (Figure 5-1). We calibrated the models under current conditions over this large area in order to ensure we were properly delineating the full niche of the focal species. We included three variables that have been identified as key climatic variables with little correlation for our study area: mean annual temperature (MAT), mean annual precipitation (MAP) and useful precipitation (e.g. the ratio of the sum of June, July and August monthly precipitation to total annual precipitation; USP).

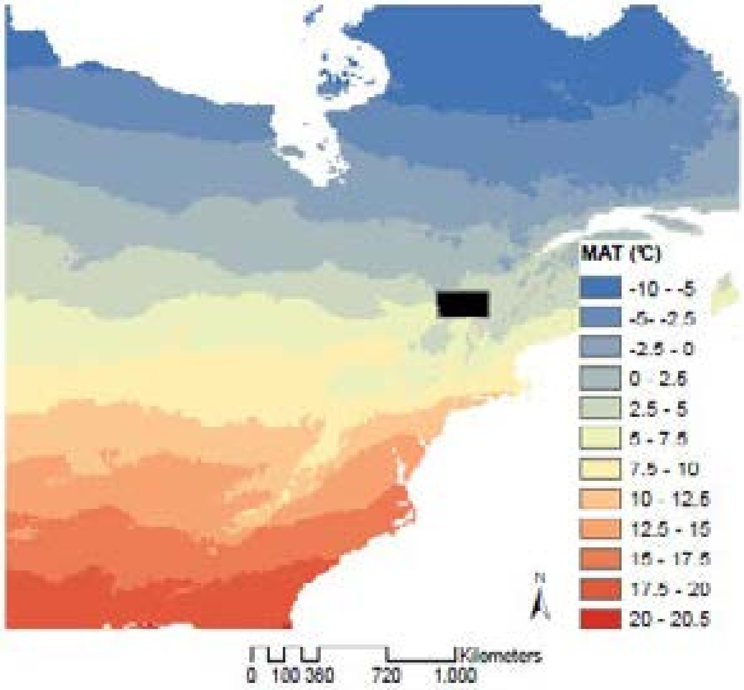
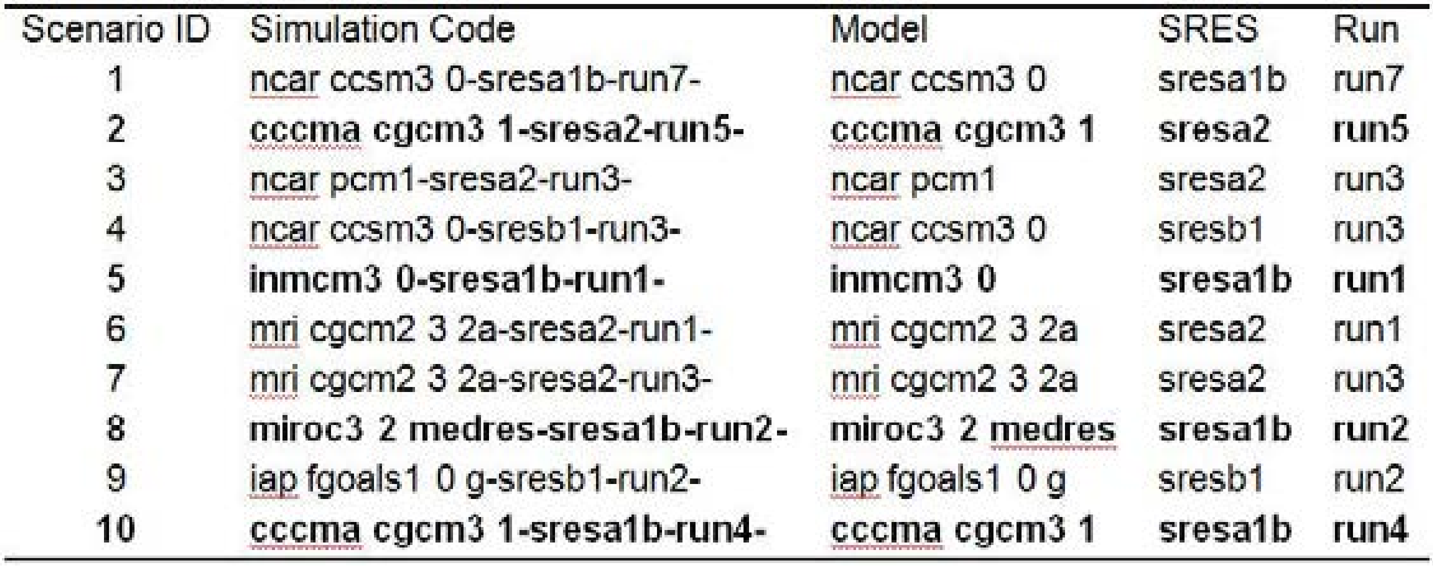


Figure 5-1: – Mean annual temperature for the period 1971-2005 over the calibration area. The black rectangle indicates our study area within the calibration zone.

We used ten climate change scenarios based on one of three projected future greenhouse gas emission scenarios (SRES families A1b, A2, B1; Nakicenovic et al., 2000) implemented in six air-ocean general circulation models and one regional climate model (Table 1). These ten scenarios have been selected with a k-means clustering approach to represent in our study area the variability (ca. 80% of the total variance) of 136 global simulations that were used for the Coupled Model Intercomparison Project (CMIP3) (Meehl et al. 2007). We used the future horizon 2050 for our analyses (average on 2041-2050 simulations).

Table 1. Climate scenario selection (10 groups): List of climate model simulations used in future climate scenario construction. In bold, the four scenarios we selected for our analyses.



Scenario ID	Simulation Code	Model	SRES	Run
1	ncar ccsm3 0-sresa1b-run7-	ncar ccsm3 0	sresa1b	run7
2	**cccma cgcm3 1-sresa2-run5-**	**cccma cgcm3 1**	**sresa2**	**run5**
3	ncar pcm1-sresa2-run3-	ncar pcm1	sresa2	run3
4	ncar ccsm3 0-sresb1-run3-	ncar ccsm3 0	sresb1	run3
5	**inmcm3 0-sresa1b-run1-**	**inmcm3 0**	**sresa1b**	**run1**
6	mri cgcm2 3 2a-sresa2-run1-	mri cgcm2 3 2a	sresa2	run1
7	mri cgcm2 3 2a-sresa2-run3-	mri cgcm2 3 2a	sresa2	run3
8	**miroc3 2 medres-sresa1b-run2-**	**miroc3 2 medres**	**sresa1b**	**run2**
9	iap fgoals1 0 g-sresb1-run2-	iap fgoals1 0 g	sresb1	run2
10	**cccma cgcm3 1-sresa1b-run4-**	**cccma cgcm3 1**	**sresa1b**	**run4**

2.1 Further scenarios exploration and selection

Given the large number of scenarios and outcomes produced by this project (land use change scenarios * climate change scenarios * species * network analyses), we decided to display our results for only the more extreme climate scenarios for our region (i.e., the most different from current conditions), based on the assumption that these would depict the more extreme responses within which all the potential responses should be included.

We used principal component analysis (Figure 5-2) to identify four scenarios (2, 5, 8 and 10 in Table 1) that best represent these extremes.

3 Species occurrence data

We used species distribution maps for the whole calibration area ,from three different sources, for each of the five selected focal species (see Chapter 1 and Table 2): 1) American Marten and the White-tailed deer we used Nature Serve (http://www.natureserve.org/getData/index.jsp, Patterson et al. 2007), 2) for the Red-backed Salamander the Red List http://www.iucnredlist.org/technical-documents/spatial-data) and 3) the for Common Eastern Bumblebee we used GBIF (http:\\data.gbif.org). After compiling data for all species distribution and climatic data over the calibration area, we randomly selected 10 000 points to be used for models calibration.

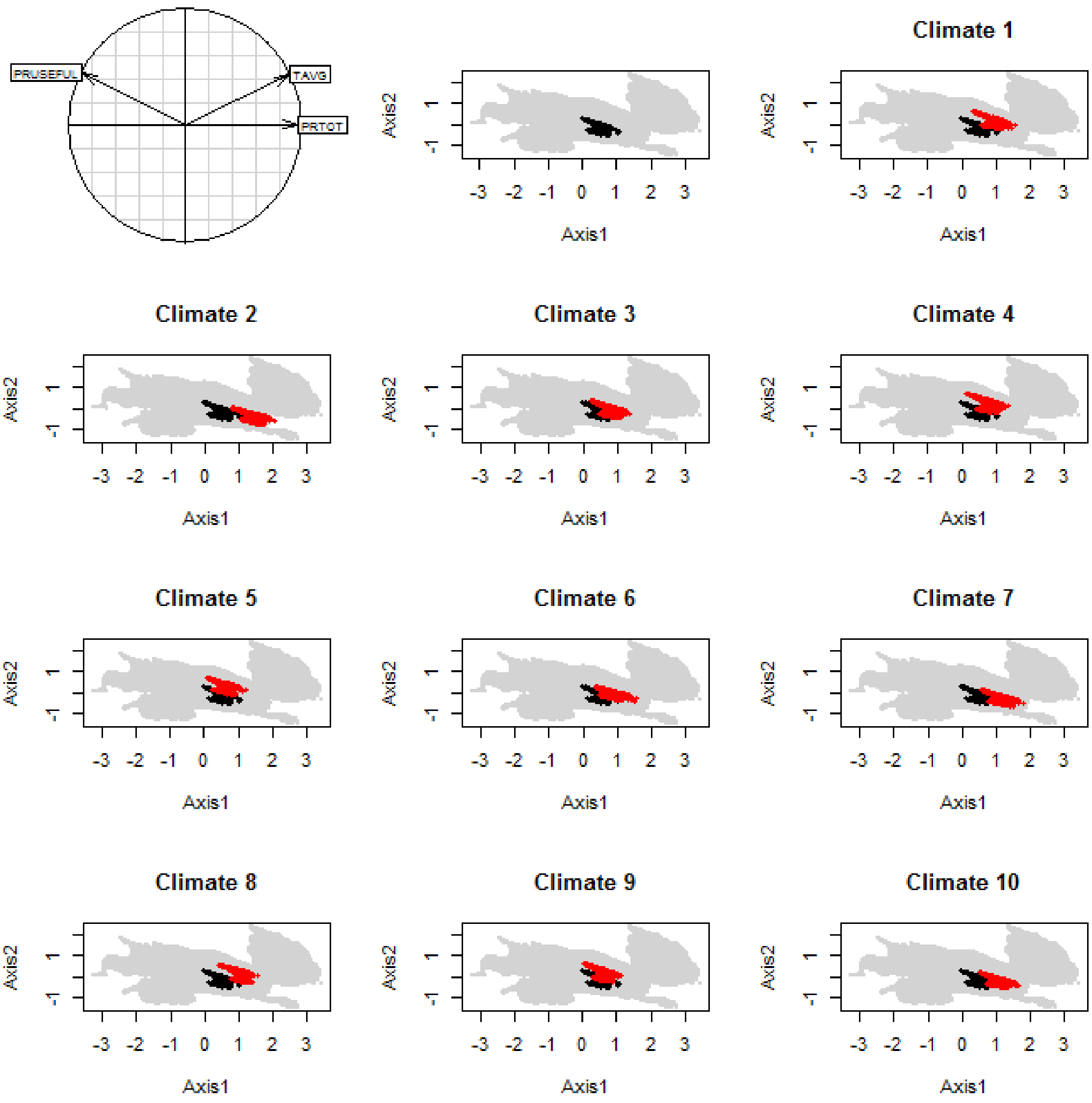


Figure 5-2: Representation of the ten preselected climatic scenarios along the first two axes of a Principal Component Analysis (first axis: 83% of variance and second axis: 13% of variance). Grey dots give the current climatic conditions over the whole Eastern North-America (Figure 1). Black dots give the current conditions in our study area. The red dots give the future conditions for the different scenarios.

4 Species distribution models for the focal species assuming unlimited dispersal

4.1 Modelling methods

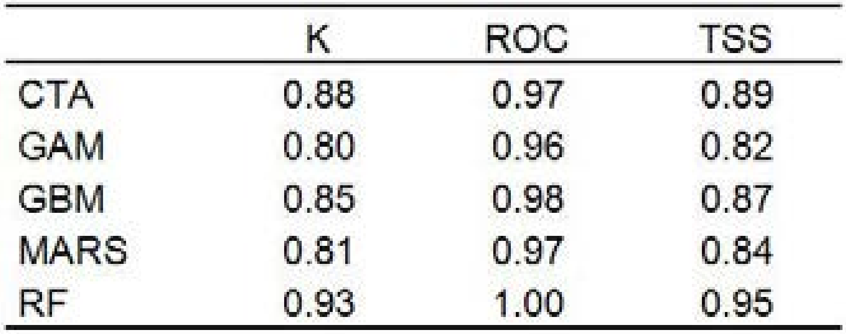
We used the BIOMOD package (Thuiller et al. 2009) under the R environment (R Development Core Team 2008) to implement species distribution models for our focal species. Preliminary tests allowed us to identify, among the nine models proposed within BIOMOD, the five models that generally had the highest predictive power (see section 4.2) for our five species. We thus used the five following models to account for variability: two regression methods (generalized additive models (GAM) and multivariate adaptive regression splines (MARS), one classification method (classification tree analysis, CTA) and two machine-learning methods (generalized boosted models, GBM, and random forest, RF). Models were calibrated using a calibration subset of 70% of the data and evaluated with the remaining 30%. In order to account for the variability arising from these random selections of calibration/evaluation subsets, we ran this procedure twenty times per model, which led to a total hundred different runs per species. Finally, we used a committee averaging procedure (Marmion et al. 2009; Thuiller et al. 2009) to synthesize the predictions from all these models. For each run. Binary transformation was carried out using the threshold that maximised the true skill statistics (TSS, Allouche et al. 2006). Binary predictions were then summed and divided by 100. This led to an overall suitability index ranging between 0 (meaning none of the hundred runs predicted the species to be present) and 1 (all runs predicted the species to be present).

4.1 Model evaluation

The models' ability to discriminate between occupied and non-occupied cells was assessed by calculating three different criteria: the area under the receiver operating characteristic (ROC) curve (AUC, Fielding & Bell 1997), the true skill statistics (TSS, Allouche et al. 2006) which is the sum of sensitivity and was shown to produce the most accurate predictions (Jimenez-Valverde & Lobo 2007) and Kappa (Cohen 1960). An approximate guide for classifying the accuracy of models using these metrics is (Swets, 1988): 0.90-1.00=excellent; 0.80-0.9=good; 0.70-0.80=fair; 0.60-0.70=poor; 0.50-0.60=fail. These metrics were calculated with the 30% remaining data not used for the calibration.

Our models were all good to very good, with an average value obtained for each type of model and each statistics presented in Table 2.

Table 2. Average values of the predictive power of the different models obtained across species for each evaluation measure. Abbreviations are given in the main text.



	K	ROC	TSS
CTA	0.88	0.97	0.89
GAM	0.80	0.96	0.82
GBM	0.85	0.98	0.87
MARS	0.81	0.97	0.84
RF	0.93	1.00	0.95

5 Predictions of changes over time in the climatic suitability of the focal species

Our study area is small and climatically very homogeneous compared to North America (Figure 5-1). It was thus expected that we could obtain three main types of response for the climatic suitability of the focal species within the area (Figure 5-3):

Case 1- The study area is climatically suitable in the present and will remain suitable in the future.
Case 2- The study area is climatically suitable in the present and will not remain suitable in the future.
Case 3- The study area is not climatically suitable in the present and will become suitable in the future.

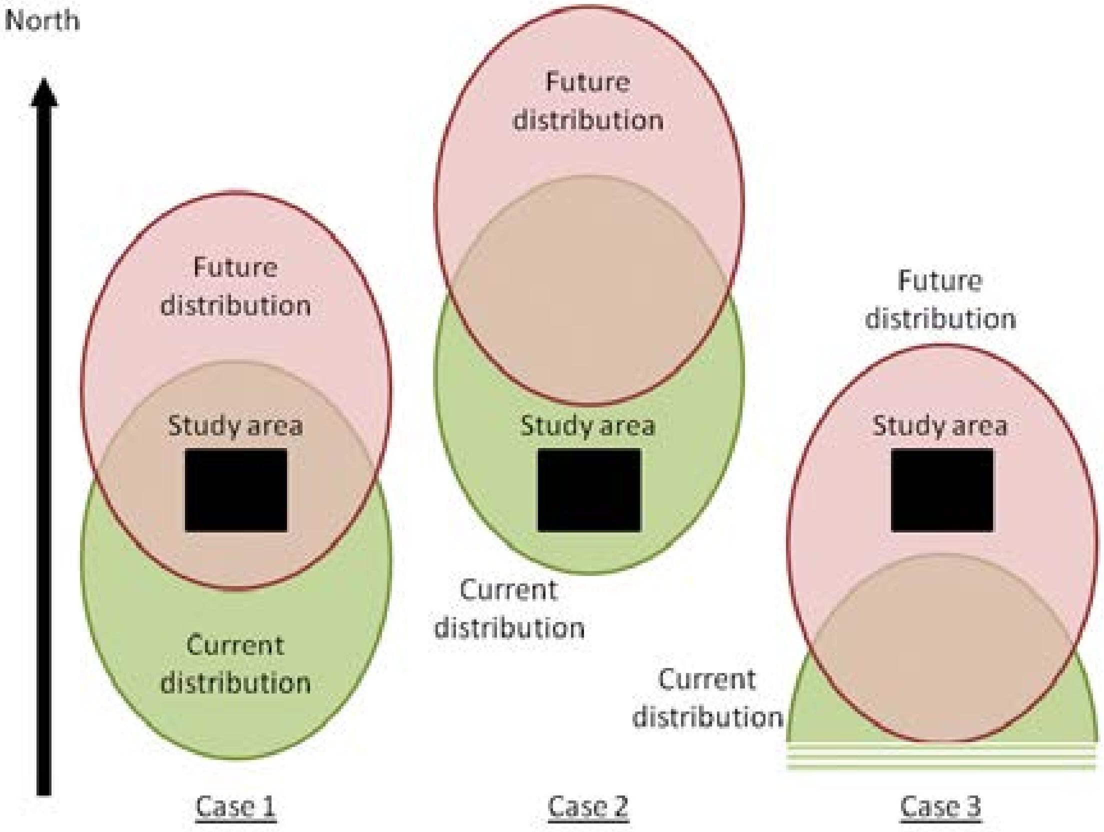


Figure 5-3: The three main types of response expected for the climatic suitability of the focal species within the area

As we selected focal species that were currently present in the study area, they were exclusively representing cases 1 or 2. Interestingly, all the scenarios did not necessarily lead to the same distribution shift for a given species. This is due to strong differences that exist between the potential future combinations of precipitation and temperature conditions, some of which do not have any analogue in the present (Figure 5-3). For instance for Sitta canadensis (not one of our focal species but used here for illustration) scenarios 5 and 8 lead to conditions in the study area that are outside of the species current climatic preferences, while scenarios 2 and 10 lead to conditions that remain within the climate space it currently experiences (Figure 5-4).

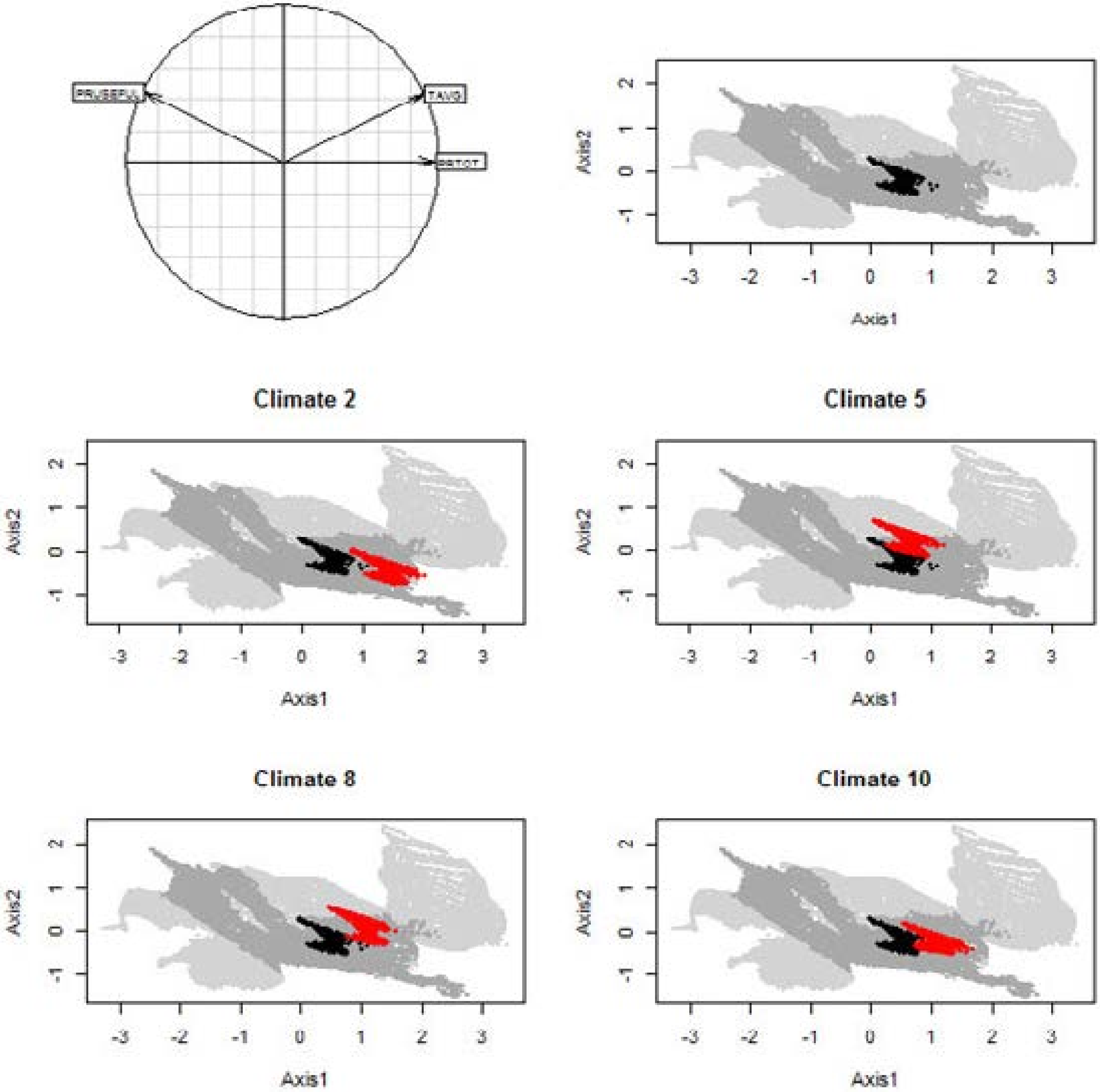
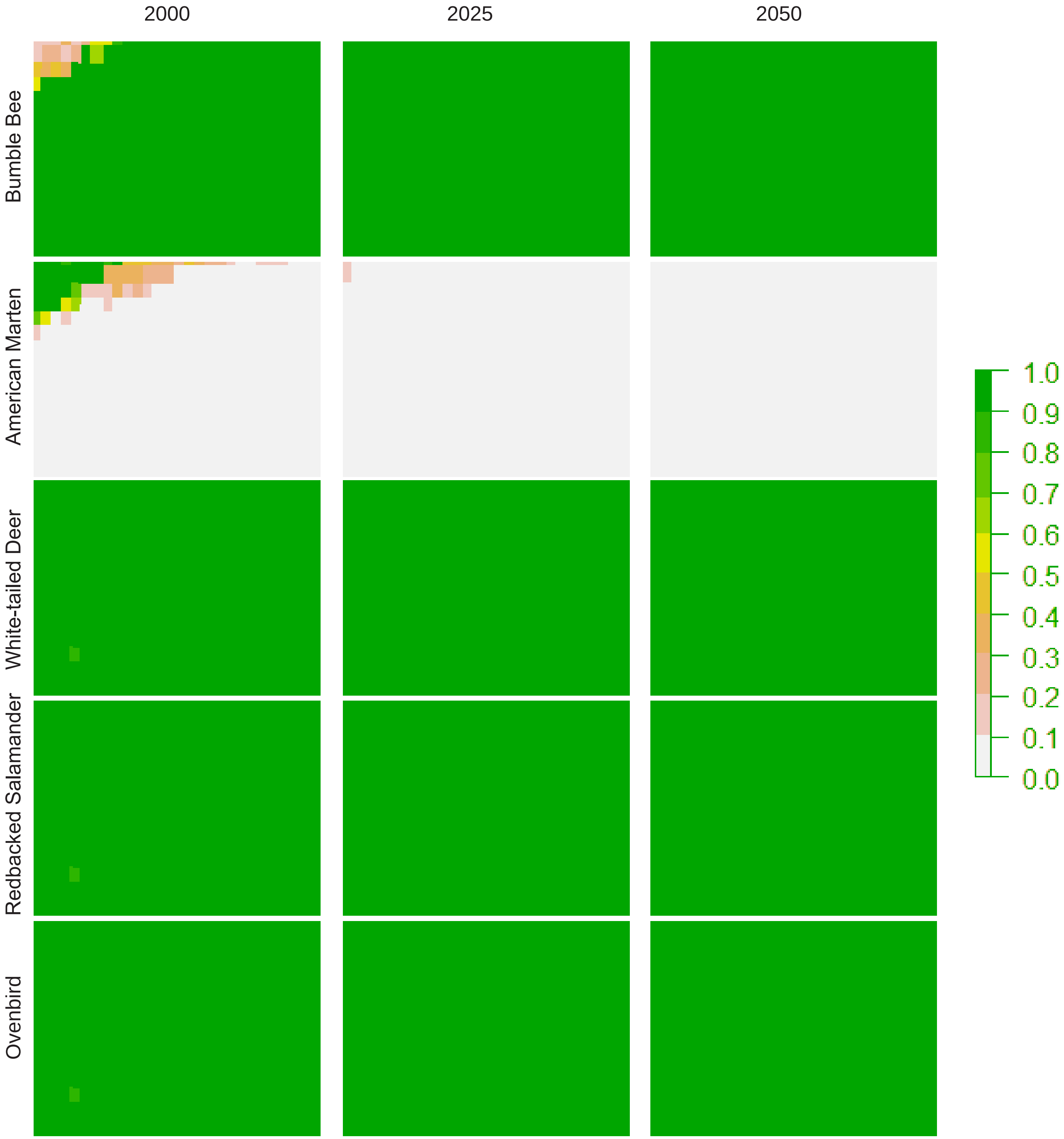


Figure 5-4:Representation of distribution of Sitta canadensis (Red-breasted Nuthatch) in the climatic space for the four most extreme scenarios along the first two axes of a Principal Component Analysis (see Fig. 2). Light grey dots give the current climatic conditions over the whole Eastern North-America. Dark grey dots give the distribution of the species within this climatic space. Black dots give the current conditions in our study area. The red dots give the future conditions for the different scenarios.

The change in climate suitability for each of our five focal species over the three time points (2000, 2025 and 2050) for only two contrasting climate scenarios is shown in Figure 5. Because the region is either climatically suitable or unsuitable over these time horizons the maps show little spatial heterogeneity in conditions.


2000
2025
2050
Bumble Bee
American Marten
White-tailed Deer
Redbacked Salamander
Ovenbird
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

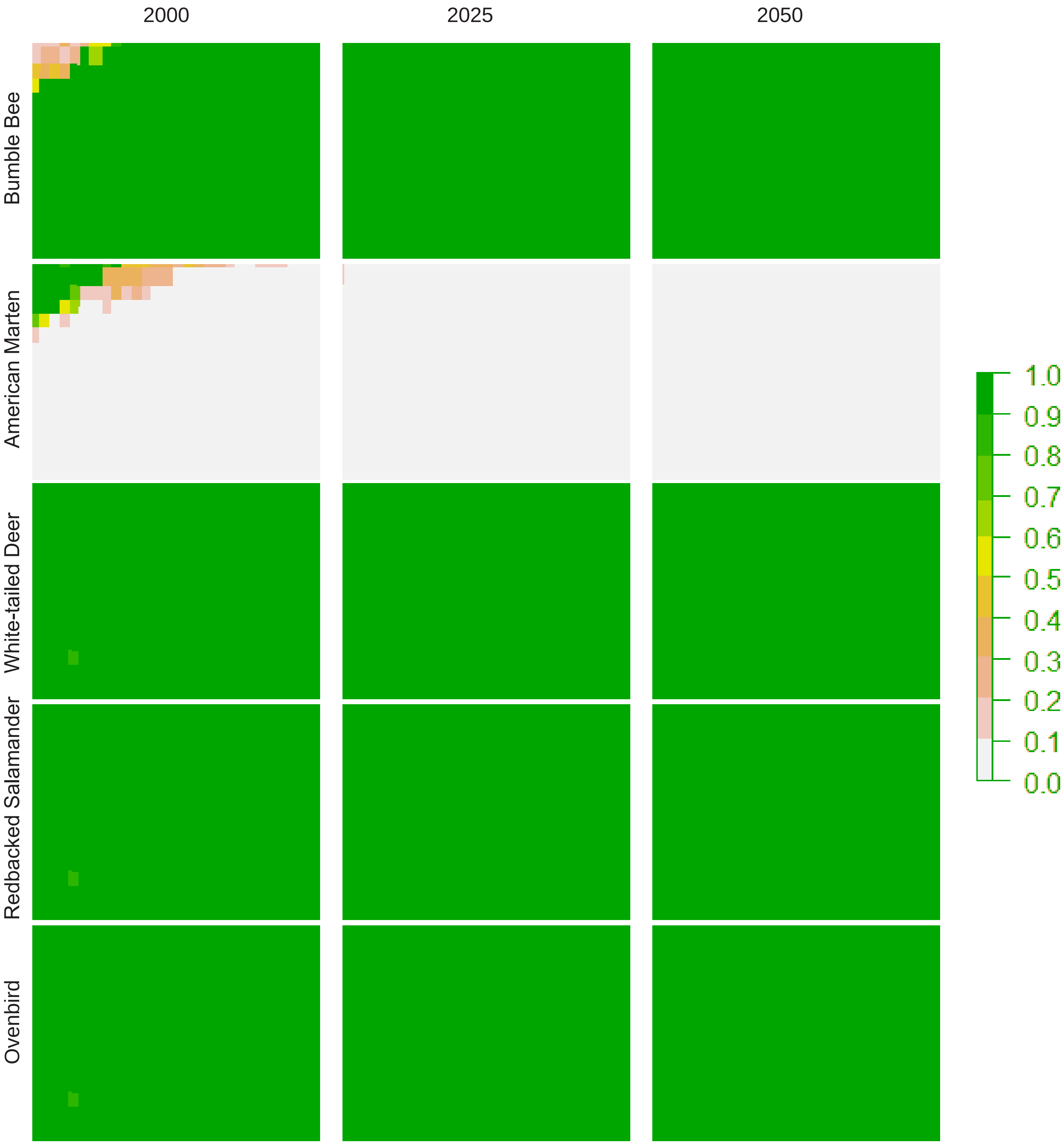


Figure 5-5: 30 maps of the study region for the change in climate suitability for each of our five focal species over the three time points (columns across the top from left to right: 2000, 2025 and 2050) for two contrasting climate change scenarios.

6 Conclusion

We generated statistically robust maps of the climate distribution of our focal species for the study region. Because of the relatively small scale of our study region and the fact that we used only two future time points, these maps reveal fairly simple patterns of change in niche suitability in space over time. Nonetheless these maps served as the basis for the connectivity and network prioritization analyses described in chapters 6 and 7.

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Chapter 6

Multi-scale connectivity for multiple species

1 Introduction

Conserving landscape connections has become an integral component of modern conservation plans (Crooks and Sanjayan 2006) as a means of countering the effects of habitat loss and fragmentation which are the dominant drivers of species extinctions (Sih et al. 2000). Connectivity across landscapes influences the viability of spatially structured populations with a variety of mechanisms over multiple spatial and temporal scales. Networks of connected habitat patches increase movements among otherwise isolated populations (Gonzalez et al. 1998) allowing for recolonizations of empty habitat patches (Clereau & Burel 1997), promoting an exchange of genetic material (Mech & Hallet 2001), and improving the probability of metapopulation persistence (Hanski 1999). Migration networks also provide important connectivity across the lifecycle of highly mobile species that rely on landscape connections to follow regular fluctuations in their resources (Milner-Gulland et al. 2011). Connectivity between current and future distributions driven by climatic change will be a crucial determinant of whether a species persists or become extinct over the long-term (Hannah 2011).

The literature expounding the importance of connectivity for these ecological processes is plentiful; however, the practice of maintaining, creating, and protecting connectivity is only beginning to operationalize the theory (Zetterberg et al. 2010). Advancements in the design of connected landscapes have either implicitly incorporated multiple scales of ecological processes or have explicitly focused on a single scale of interest such as population dynamic consequences (e.g., Urban et al. 2009), large-scale migration (e.g., Taylor and Norris 2010), or climate change (e.g., Phillips et al. 2008). Conservation network design involves multi-objective optimization problems where multiple ecological processes are protected within the same landscape. A synthesis of approaches to protect connectivity at multiple scales will be essential to mitigate the complex process of habitat fragmentation and loss in human-altered landscapes. Our approach is based on the design of multi-purpose habitat networks that can promote the persistence of metapopulations within the network but also allow for traversability of the network during either seasonal migrations or range shifts in response to climate-induced changes in habitat distribution.

One of the main challenges of designing connected networks of habitat is the need to maintain connectivity for multiple species simultaneously. Connectivity is a species-specific concept however that encapsulates the dispersal abilities of the species and its habitat preferences (Taylor et al. 1993). Hence, an ecological network designed to maintain biodiversity is composed of a superposition of species-specific habitat networks. For each species, their habitat network reflects the connectivity of the landscape from their unique perspective. This arises through the definition of species-specific nodes that incorporate information about the size, shape, and quality of patches as well as species-specific links that incorporate the movement abilities of the species and the permeability of the matrix surrounding habitat patches from the species' perspective (Urban et al. 2001). Due to this species-specific nature of habitat networks, most connectivity studies that employ network techniques focus on a single species. In this chapter, we apply a general framework to the five focal species (Chapter 1) to quantify the connectivity of the habitat at the scale of the study region.

The three eco-provinces within our study region (Figure 2-5, Chapter 2) allowed us to examine two types of connectivity in forested ecosystems for each of our focal species: 1) connectivity within the highly fragmented forest network of the St. Lawrence Central Lowlands and 2) traversability across the St. Lawrence Central Lowlands forest network between the Appalachian Mountains along the southern edge and the foothills of the Laurentian Mountains at the northern edge.

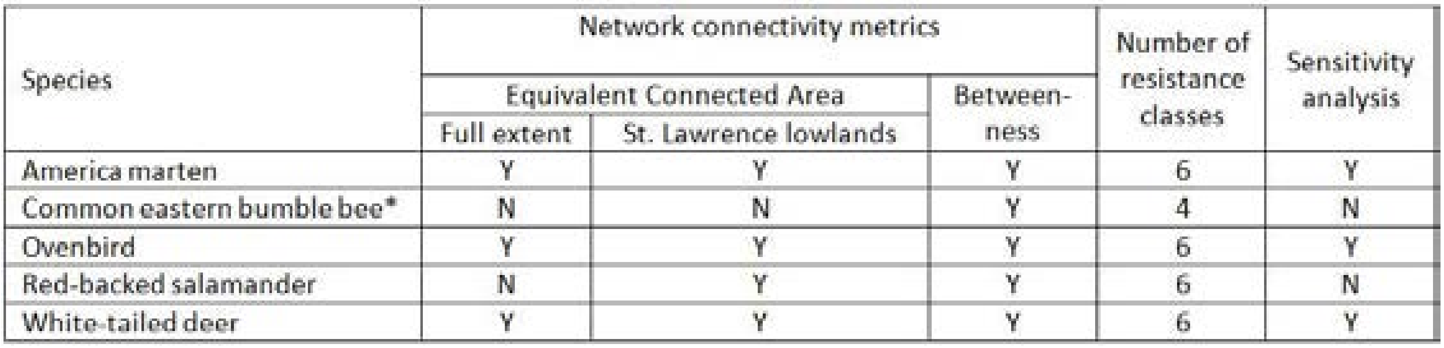
2 Identifying species' habitat networks

2.1 Delineating nodes and links

We modelled connectivity of the habitat networks for five focal species based on the quality of habitat patches and the degree of landscape resistance to their movements. Habitat quality was assessed in each map pixel as described in Chapter 3. This assessment of habitat quality formed the basis of the habitat patch definition. Habitat patches were defined as nodes in the habitat network.

The landscape resistance map for the focal species quantifies the relative ease with which an individual can move through each grid cell relative to its movement ability through a cell of forest habitat (Figure 6-1; Adriaensen et al. 2003). Landscape resistance in the non-habitat pixels (i.e., the matrix) was derived from the habitat quality layer through a 3-stage process. First, the habitat quality layer was inverted such that high quality pixels had low resistance. Second, the range of resistances obtained in step 1 was binned into equal-sized resistance classes (Table 6-1). Third, the resistance classes were assigned relative resistance values that were in fixed ratio with the preceding and subsequent classes. Preferred habitat had a resistance value of 1 and subsequent resistance values doubled between classes (i.e., 2, 4, 8, 16, 32). The species-specific resistance surfaces were indirectly based on the literature review that parameterized the habitat quality layer. No data was available however to translate habitat quality into quantitative resistance values hence we developed this standardized 3-step process to apply to all species. To test the sensitivity of our results to the relative resistance values, we repeated out network analysis for three of the focal species (see Table 6-1) with relative resistance ratios that increased by a factor of five (i.e., 1, 5, 25, 125, 625, 3125). The results of this sensitivity analysis are presented in section 5 below (Figure 6-8).

Table 6-1. Species-specific connectivity analyses. One or two network statistics (Equivalent Connected Area and Betweenness) were calculated for each species with the Equivalent Connected Area calculated at two possible scales (full extent of the study region or only the agricultural ecoprovince of the St. Lawrence Lowlands). *The Common eastern bumble bee has too many patches in its habitat network to allow for the calculation of Equivalent Connected Area.



Species	Network connectivity metrics			Number of resistance classes	Sensitivity analysis
	Equivalent Connected Area		Betweenness		
	Full extent	St. Lawrence lowlands			
America marten	Y	Y	Y	6	Y
Common eastern bumble bee*	N	N	Y	4	N
Ovenbird	Y	Y	Y	6	Y
Red-backed salamander	N	Y	Y	6	N
White-tailed deer	Y	Y	Y	6	Y

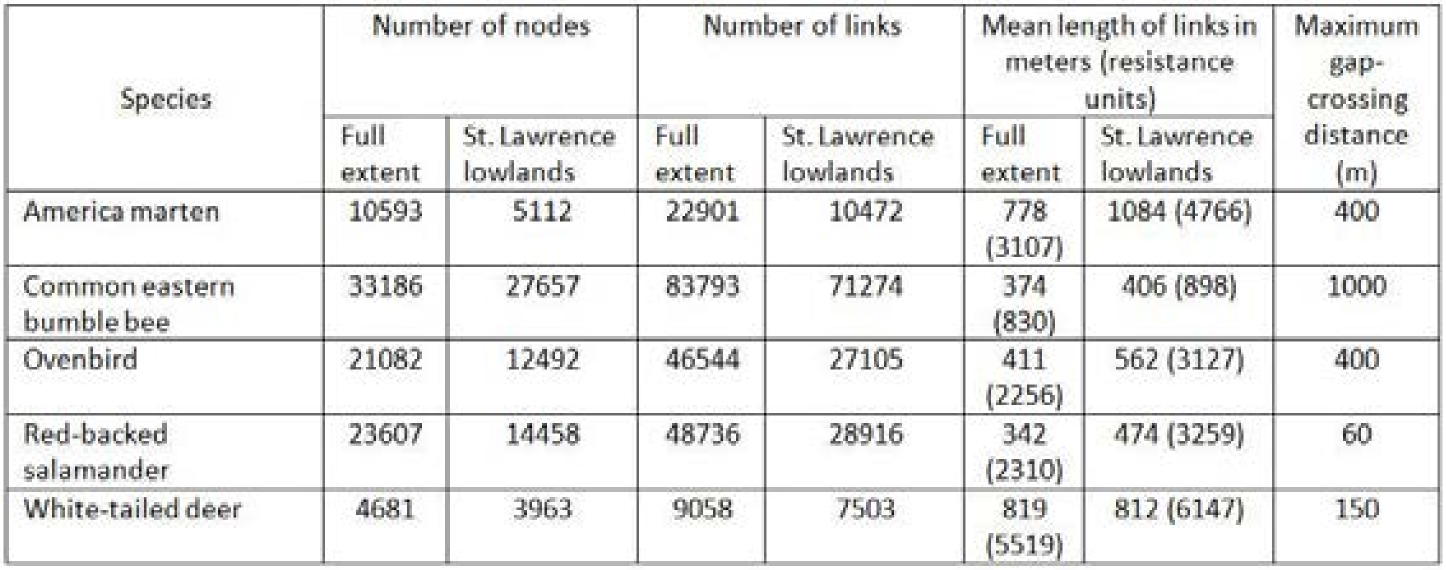
2.2 Connecting nodes within species-specific habitat networks

Inter-patch connectivity was assessed using spatial graph analysis in which forest habitat patches (i.e., nodes) are connected from edge-to-edge via least-cost links to form a habitat network (Fall et al. 2007, Dale and Fortin 2010). A least-cost link between two patches is identified by an optimization algorithm that minimizes cumulative resistance along its length based on the underlying resistance surface (Adriaensen et al. 2003). Modelling edge-to-edge connections between patches encapsulates the tendency for species to explore habitat patch edges in order to minimize the gap-crossing distances. Habitat patches were connected into a stepping-stone formation (Urban et al. 2009, Fortin et al. 2012) based on a minimum planar graph model (Fall et al. 2007, Dale and Fortin 2010). In the minimum planar graph, only topological neighbors are directly connected with least-cost links but all patches are indirectly connected along paths that pass through intermediate nodes and links. This stepping-stone movement hypothesis reflects the preference of forest species to travel through forest rather than cross open areas despite the open area presenting a substantial short cut (Bélisle et al. 2001, Bélisle and Desrochers 2002, Desrochers et al. 2011). Moreover, the minimum planar graph is particularly well suited to broad-scale conservation applications for which the complete graph (i.e., a graph model in which all nodes are directly connected) is too computationally demanding to construct (Fall et al. 2007, Galpern et al. in prep-a).

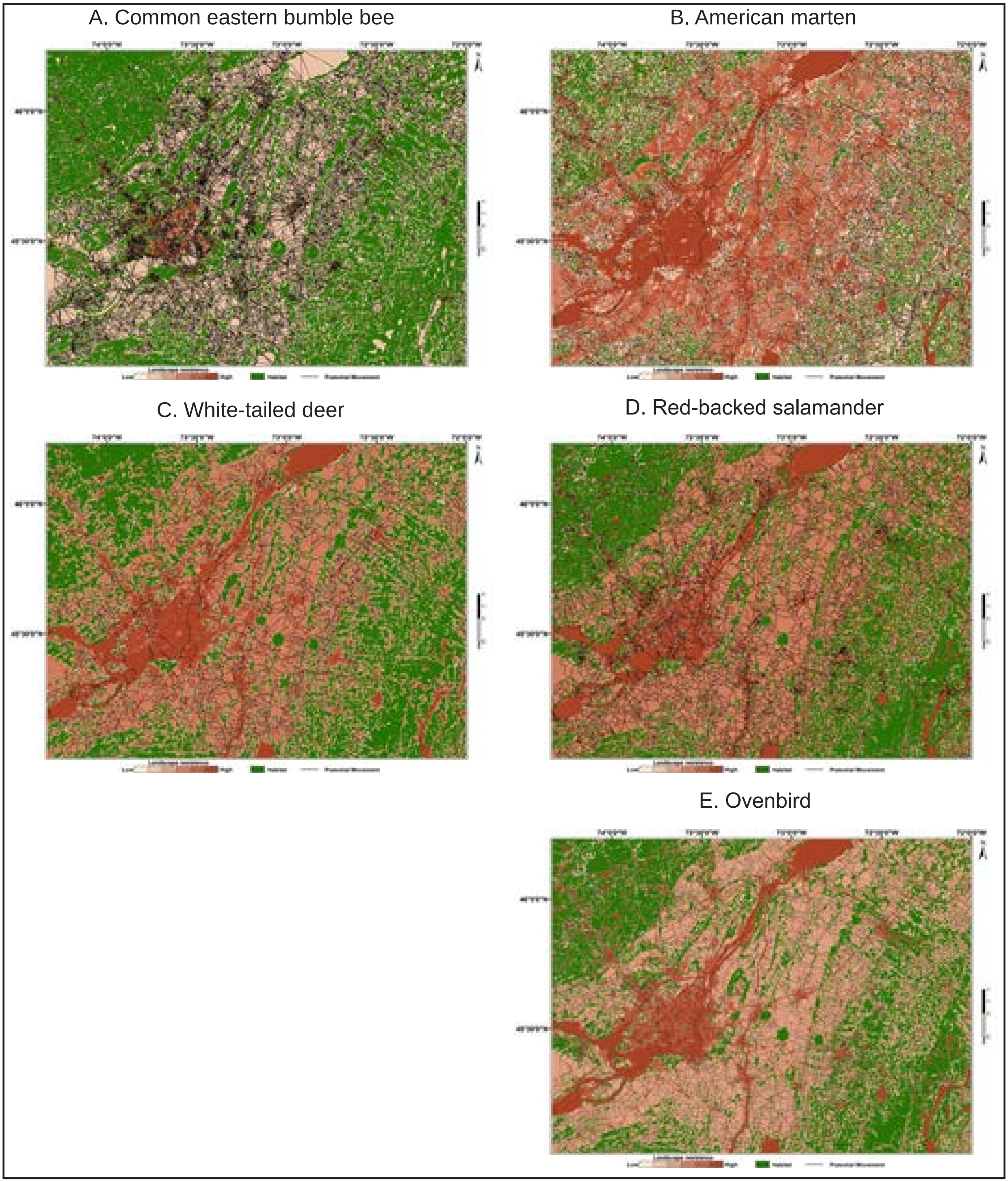
We constructed the minimum planar of each species' habitat patches for the entire study area based on the resistance surface as shown in Figure 6-1, hereafter simply referred to as the habitat network. Links in the species' habitat networks each had two associated weights: length (m) and cumulative resistance. Nodes were also weighted based on two properties: area and quality (Chapter 3). Both node weights were transformed to indices ranging from 0 to 1. The dispersal probability associated with each link was calculated as a function of the size and quality of the end nodes and the link length relative to the gap-crossing ability of the species (see description of Equivalent Connected Area below for more details).

Figure 6-2 shows those links in the habitat network that have a dispersal probability above the 25th percentile. Most of the longer links are associated with a lower probability of dispersal because our focal species have relatively small gap-crossing abilities. These maps emphasize that the entire study region is in fact comprised of connected sub-components for our focal species where the connectivity within components is greater than the connectivity between components. Due to the size of the landscape (~27 x 10^6 pixels), the minimum planar graph was constructed in 11 overlapping subsections of the landscape and then stitched together to produce the final forest network. This network extraction step was performed in R 2.15.2 (R Development Core Team 2012) using the 'gsMPGstitch' function in the 'grainscape' package (Galpern et al. in prep-b; available at http://grainscape.r-forge.r-project.org). Constructing the network in each subsection was done by grainscape using the spatial graphs model (Fall et al. 2007) in SELES v.3.4 software (Fall and Fall 2001) that is bundled with the package. Species' habitat networks were variable with regards to the number of nodes and links they comprised (Table 6-2).

Table 6-2. Species' habitat network descriptions at initial conditions (year 2000).



Species	Number of nodes		Number of links		Mean length of links in meters (resistance units)		Maximum gap-crossing distance (m)
	Full extent	St. Lawrence lowlands	Full extent	St. Lawrence lowlands	Full extent	St. Lawrence lowlands	
America marten	10593	5112	22901	10472	778 (3107)	1084 (4766)	400
Common eastern bumble bee	33186	27657	83793	71274	374 (830)	406 (898)	1000
Ovenbird	21082	12492	46544	27105	411 (2256)	562 (3127)	400
Red-backed salamander	23607	14458	48736	28916	342 (2310)	474 (3259)	60
White-tailed deer	4681	3963	9058	7503	819 (5519)	812 (6147)	150



A. Common eastern bumble bee

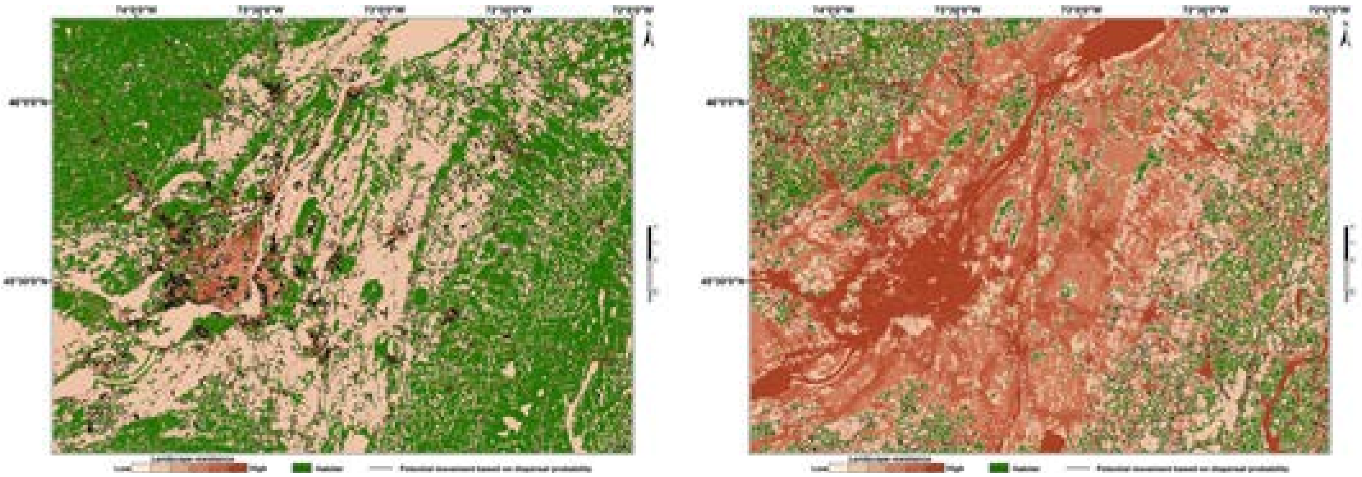
B. American marten

C. White-tailed deer

D. Red-backed salamander

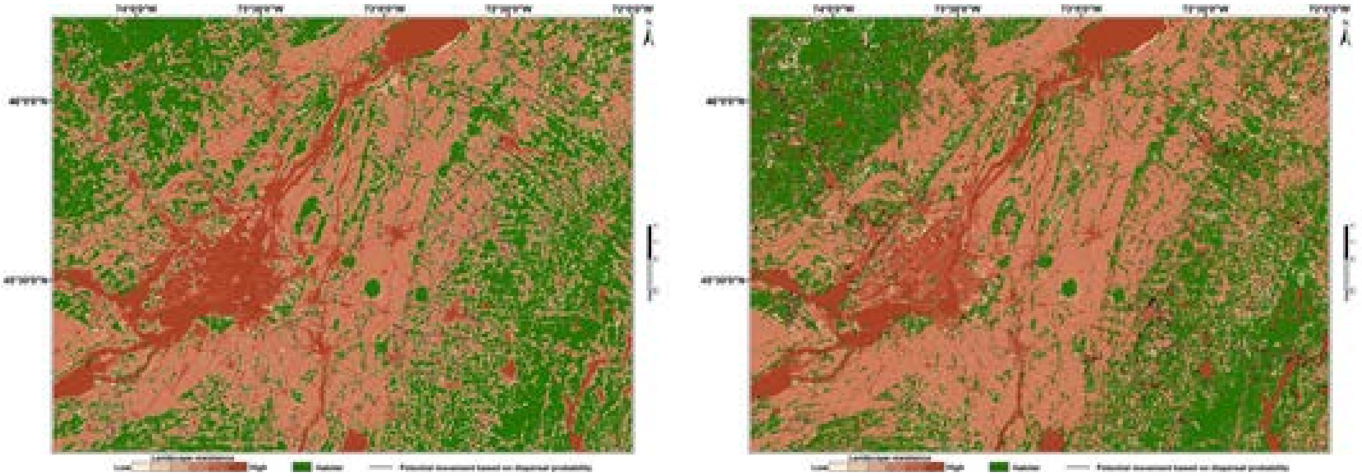
E. Ovenbird

Figure 6-1: Minimum planar networks for each of the focal species showing the resistance surface used to derive least-cost links.



A. Common eastern bumble bee

B. American marten



C. White-tailed deer

D. Red-backed salamander

E. Ovenbird

Figure 6-2. Links within the minimum planar graph of each species that had a high (above the 25th percentile) dispersal probability based on the dispersal ability of the species, the length of the least-cost links, and the size and quality of nodes. These link subsets represent those links that will most likely be used by the focal species.

3 Estimating habitat connectivity with network theory

3.1 Equivalent Connected Area (ECA)

We calculated the Equivalent Connected Area (Saura et al. 2011) of the species' habitat networks which provides a measure of the area of a single patch that would have the same probability of connectivity (Saura and Pascual-Hortal 2007) as the forest network. This measure is closely related to the metapopulation capacity measure (Hanski and Ovaskainen 2000) in that they are both based on a square 'landscape' matrix, M, with dimensions equal to the number of patches in the forest network. The elements of the landscape matrix are $m_{ij} = \exp(-\alpha d_{ij}) A_i Q_i A_i Q_i$ for $i \neq j$ and $m_{ij} = 0$, where A_i and Q_i are the area and quality indices for patch i respectively. In our analysis, the distance, d^*_{ij}, between patches *i* and *j* was constrained by the structure of the habitat network to be the length of the shortest path connecting the two patches. If patches *i* and *j* were connected directly then d^*_{ij} was equal to the length of the least-cost link between them ($d^*_{ij} = d_{ij}$); however, if the patches were not directly connected then d^*_{ij} was the sum of the lengths of the least-cost links along the shortest path between them. The alpha is a distance-decay constant that characterizes the rate of dispersal. Species-specific gap-crossing estimates derived from the literature (Table 6-2 and 1-1 – Species' descriptions chapter) were assumed to correspond to a 0.05 dispersal probability to calculate alpha (Urban and Keitt 2001). The equivalent connected area is the square root of the sum of the elements of *M* (weighted flux; Urban and Keitt 2001, Urban et al. 2009) divided by the total area of the landscape whereas the metapopulation capacity is the leading eigenvalue of *M*.

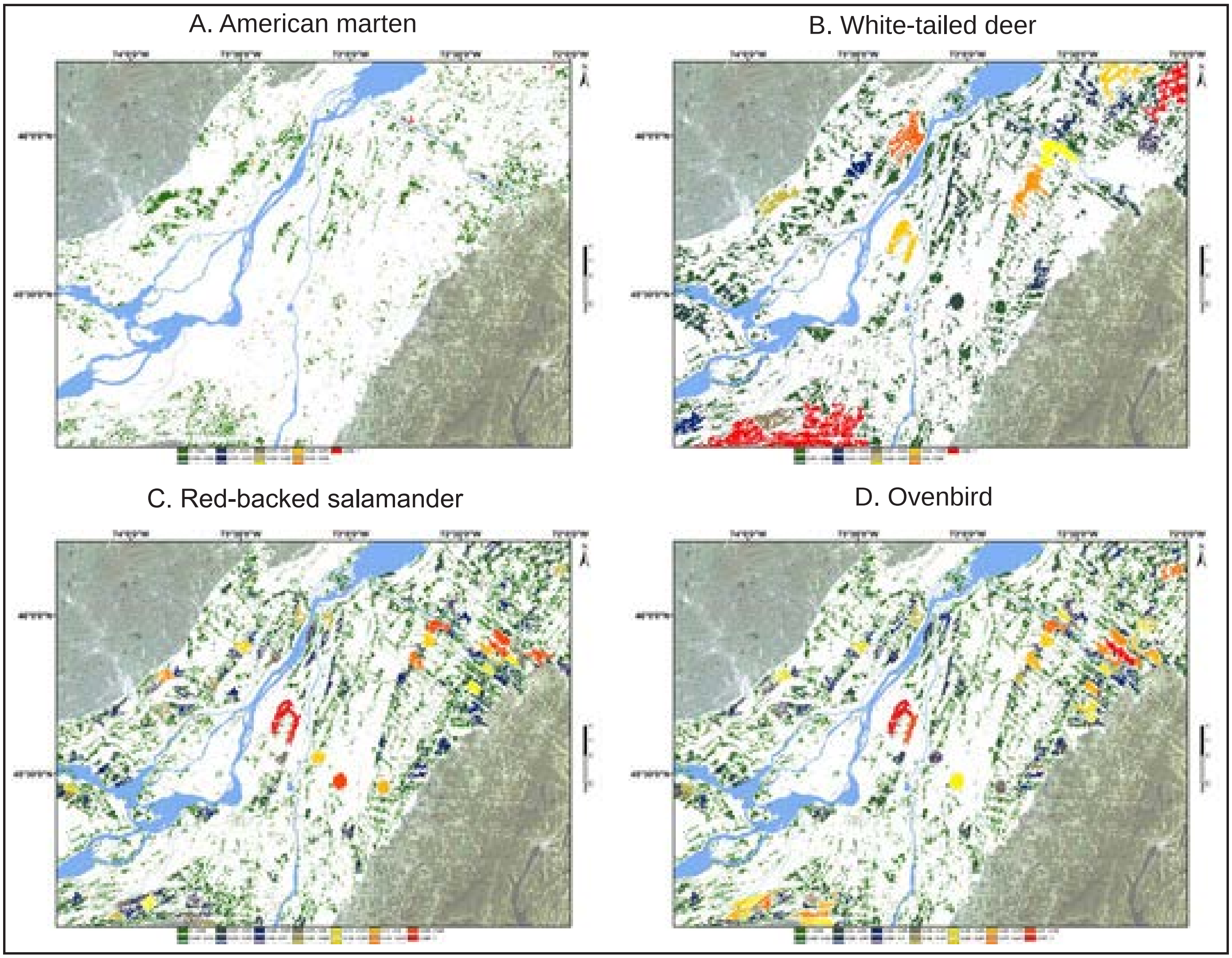
ECA was calculated for the full extent of the study region and for the fragmented, agricultural landscape of the St. Lawrence Central Lowlands (Table 6-1). Only those habitat patches that had at least 80% of their area within this eco-province were considered nodes during the ECA analysis of the St. Lawrence lowlands. Forest is more continuous in the other ecoprovinces within our study area; therefore, when restricting our focus to the portion of the forest that is embedded in the agricultural matrix of the St. Lawrence Lowlands we concentrated on the viability of populations spread across discrete habitat fragments (Pulliam 1988, Hanski 1999).

We assessed the importance of each habitat patch to the maintenance of the overall metapopulation by systematically removing each patch and evaluating its individual impact on the calculated value of equivalent connected area (Urban and Keitt 2001, Pascual-Hortal and Saura 2006, Saura and Pascual-Hortal 2007). The results of this node-removal analysis for the St. Lawrence Lowlands for the year 2000 can be seen in Figure 6-3. The species-specific network structure determines the importance of each patch, hence the observed differences in patch importance among species is to be expected. In our analyses, patch importance was largely driven by the node properties of patch area and quality rather than the link property (i.e., length).

3.2 Node betweenness

We also calculated the centrality of each node in the species' habitat networks using weighted betweenness (Freeman 1978, Brandes 2001) which measures the proportion of all weighted shortest paths (g_{jk}) in a network that pass through the node ($g_{jk}^{(i)}$). Link weights were calculated using the same negative exponential dispersal kernels used in the ECA calculation above: $w_{ij} = \exp(-\alpha d^*_{ij})$. Weighted betweenness of node *i*, defined as $b(i) = \sum_{i \neq j \neq k} \frac{g_{jk}^{(i)}}{g_{jk}}$, quantifies the degree to which the node plays serves as a stepping stone to connect other non-adjacent nodes in the forest network. The ECA and weighted betweenness analyses produced complimentary, spatial, node-level descriptions of the conservation importance of patches based on two different ways that they contribute to the inter-patch connectivity of the forest network (Bodin and Saura 2010). All network analyses done using the igraph v0.6.5-1 (Csárdi and Nepusz 2006) and raster v2.0-41 (Hijmans and van Etten 2011) packages in R.

Network betweenness (Figure 6-4) is driven by the pattern of links connecting nodes and the links. Nodes are prioritised independently from their area and quality attributes. Hence we see the prioritization of stepping-stone nodes that serve to connect sub-components within the network. These stepping stones may be small in surface area. Again we see variation between species in network betweenness, although certain habitat nodes, such as the horseshoe shaped forest surrounding Saint Amable is identified as a priority for all species except the American marten.

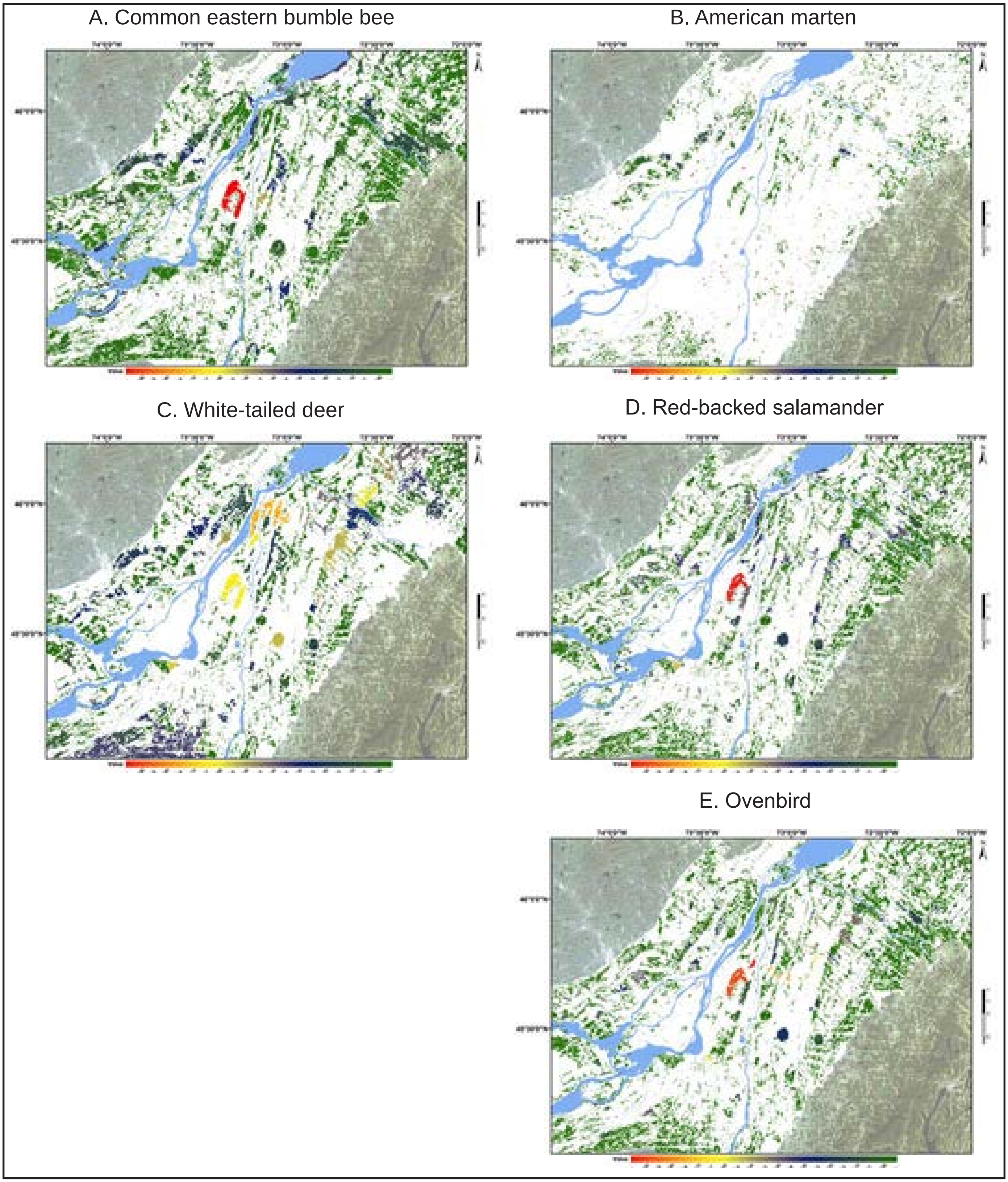

A. American marten

B. White-tailed deer

C. Red-backed salamander

D. Ovenbird

Figure 6-3. Node importance based on the Equivalent connected area (ECA) of the species' habitat networks. Node importance was determined by deleting each node and calculating the resulting loss in ECA. Warmer colours indicate nodes whose removal had a large effect on ECA.



A. Common eastern bumble bee

B. American marten

C. White-tailed deer

D. Red-backed salamander

E. Ovenbird

Figure 6-4. Node centrality measures as node betweenness for the species' habitat networks. Warmer colours indicate nodes that have high betweenness and serve as stepping stones to connect the network.

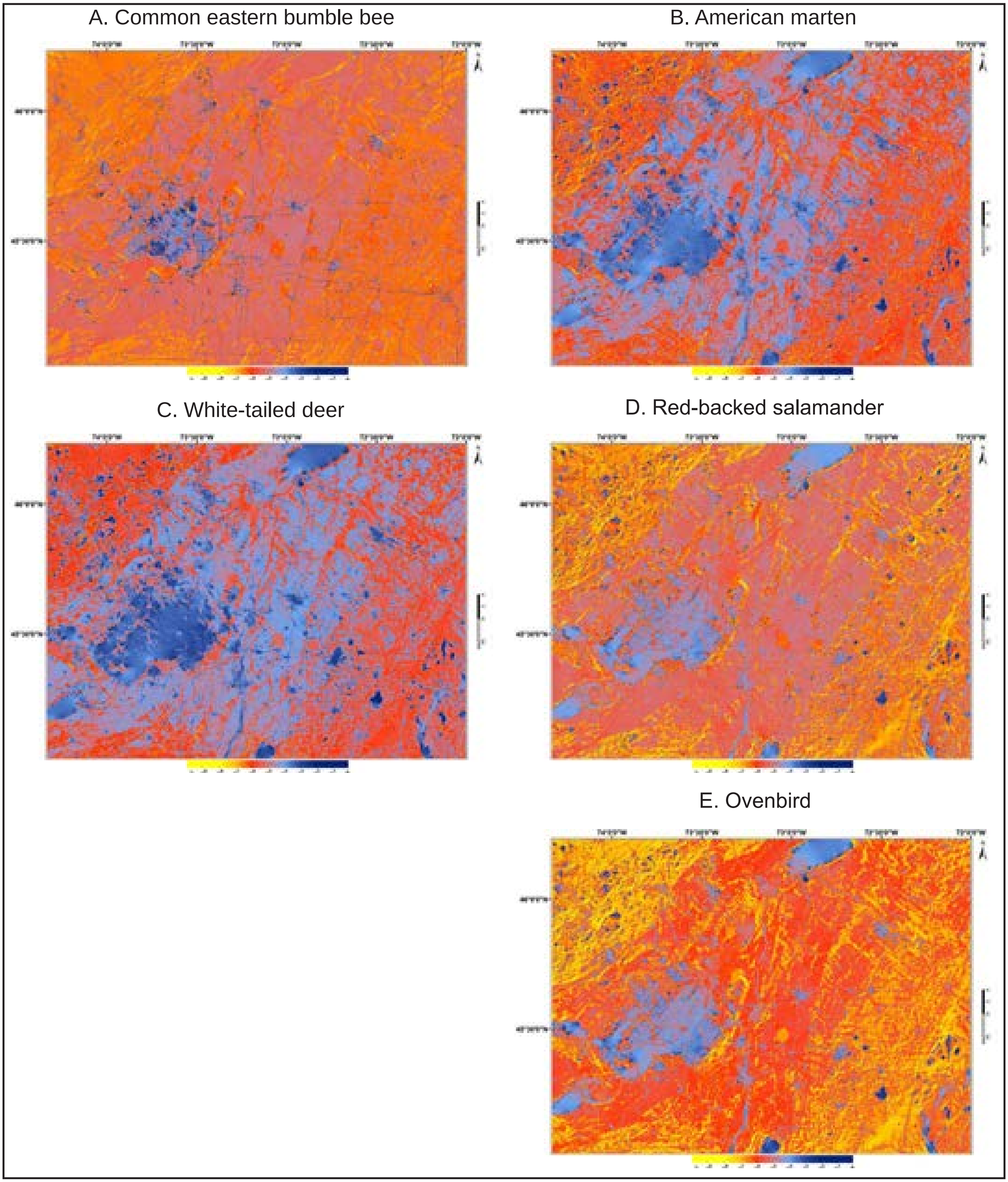
4 Estimating habitat traversability with circuit theory

Connectivity across the entire study area was assessed through the application of circuit theory which predicts movement pathways between regions based on the conductance of the intervening landscape (McRae 2006, McRae et al. 2008).Conductance was calculated as the inverse of the resistance map for each species and was used as the base for the circuit analysis to determine the pattern of current density (i.e., flow) across the landscape. In order to assess traversability across the whole area we used the tiling approach described in Pelletier et al. (submitted). The resistance map was cut in 30 square tiles of 1000x1000 cells. A buffer of 2000 cells made of real data was added, where possible, on all sides of each tile. We defined source and destination regions in each tile as a single parallel row or column of pixels from which current entered and exited the landscape respectively (Pelletier et al. submitted). Patterns of current density could then be identified along north-south or east-west axes based on the orientation of the source and destination strips. In the absence of any spatial structure, current flows from source to destination equally across the landscape producing a homogeneous map of current density. In the presence of spatial structure, current flows unequally as it is channeled through areas of high conductance or low resistance, producing a heterogeneous map of current density (McRae et al. 2008). We removed the buffer of each tile after current density was computed in Circuitscape and reassembled them to create directional maps in the east-west and north-south directions for the full study area. To create an omni-directional map of current density, we multiplied each cell of the north-south and east-west directional maps together (Pelletier et al. submitted). Circuit analyses were conducted using Circuitscape version 3.5 (McRae 2006). This analysis produced a spatial, pixel-level description of traversability based on a pixel's contribution towards maintaining connectivity across rather than within the forest network (Figure 6-5).

The current density maps consistently identified relatively low current flow through the St. Lawrence lowlands and high current flow through the contiguous tract of forest comprised within the Appalachian Mountains eco-region to the east (Figure 6-5). Current was strongly channeled around the island of Montreal, smaller urban settlements, and major roads (emerging as blue, low current areas) illustrating the dramatic anthropogenic footprint on the traversability within the St. Lawrence Lowlands. However, urban developments were not homogeneous barriers to movement and indeed some movement channels were consistently identified on the northern part of Montreal island for all species.

5 Estimating the change in connectivity through time under 'Business As Usual' Landuse Scenario in the absence of climate change

We examined trends in connectivity through time for each of the focal species' habitat networks subject to the 'Business as usual' scenario of land use change in the absence of climate change (Chapter 4). We examined changes in habitat network connectivity at the scale of the entire study region and also restricted within the St. Lawrence Lowlands eco-region. Quality-weighted area of habitat nodes decreased through time at both scales of analysis in a similar fashion for all species (Figure 6-6). These changes were largely driven by a reduction in node area as development encroached upon forested habitat patches. Quality-weighted area was calculated as the product of node quality and node area summed across all nodes in the habitat network. This measure does not take into account the pattern of connections among nodes. Equivalent connected area (ECA) is an integrative measure of habitat network connectivity that incorporates both the node properties and the length of links relative to the dispersal abilities of the species. The ECA of species' habitat networks within the St. Lawrence Lowlands decreased for all species under the 'Business as usual' landuse change scenario (Figure 6-7), most dramatically for the white-tailed deer. At the scale of the entire study region, the white-tailed deer and ovenbird habitat networks became increasingly connected by 5 to 15% while the marten habitat net-



A. Common eastern bumble bee

B. American marten

C. White-tailed deer

D. Red-backed salamander

E. Ovenbird

Figure 6-5. Current density maps for the focal species. Areas of high current density (warm colours) indicate that movement is channelled through these regions whereas areas of low current density (blue) indicate dispersal barriers.

work became less connected by 5%. The difference in percent ECA lost at the regional and eco-regional scales was most likely driven by the presence of larger, contiguous forest patches that have low development pressure outside of the St. Lawrence Lowlands eco-region. In these areas, forest successional changes through time will serve to increase overall habitat network connectivity but these effects would be counteracted in the St. Lawrence Lowlands due to a concentration of development activities.

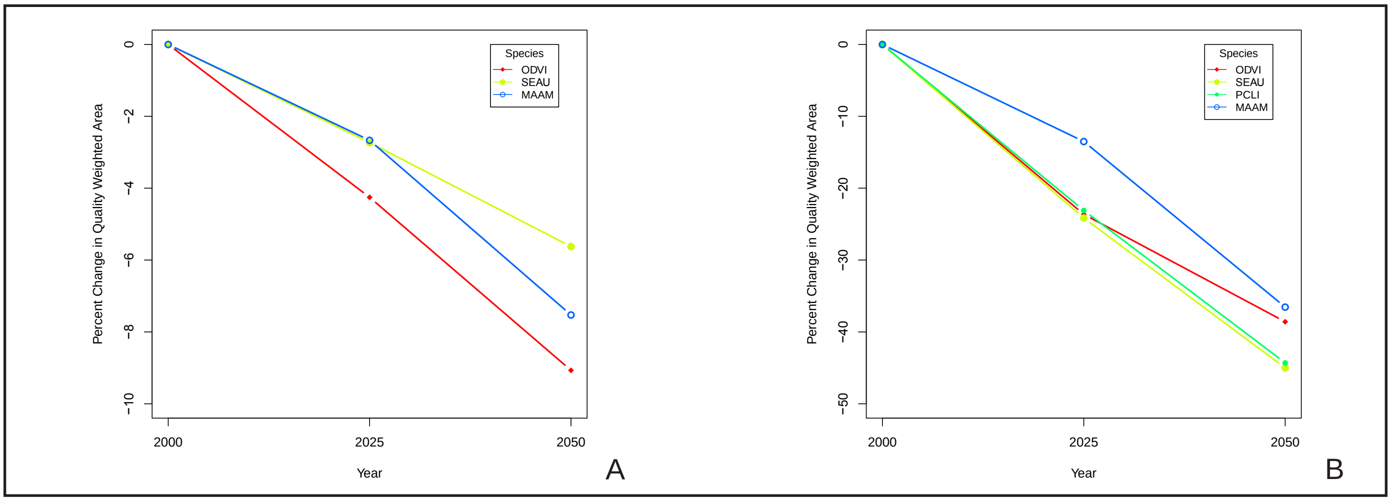


Figure 6-6. Percent change in quality-weighted area of nodes within species' habitat networks at the scale of A) the full study region and B) the St. Lawrence Lowlands eco-region. ODVI: White-tailed deer; SEAU: Ovenbird; PCLI:Red-backed salamander; MAAM: American marten

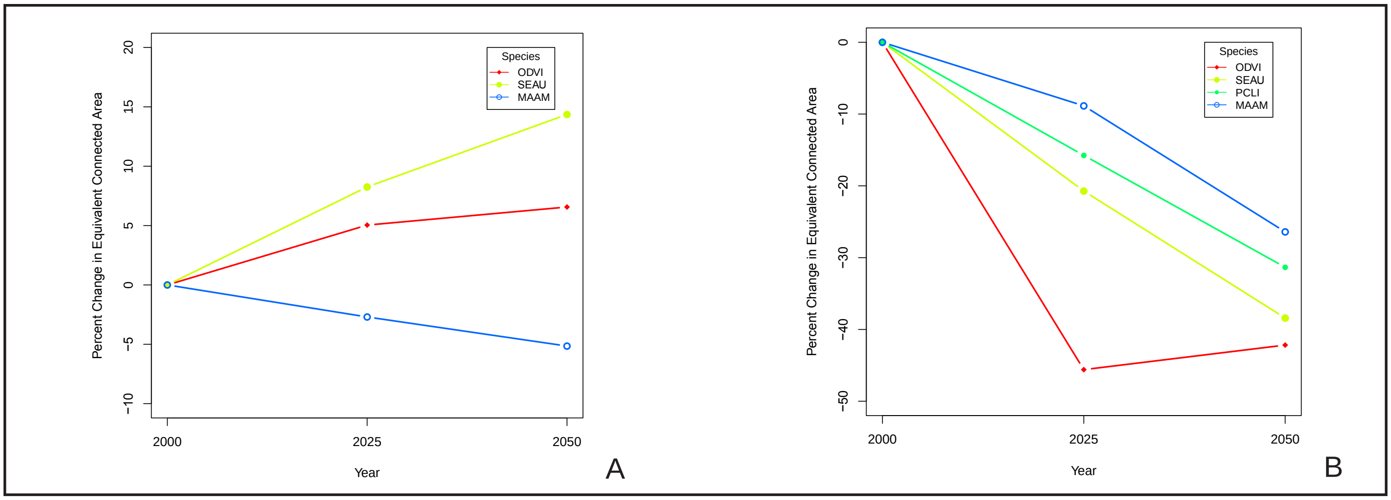


Figure 6-7. Percent change in Equivalent Connected Area (ECA) of species' habitat networks at the scale of A) the full study region and B) the St. Lawrence Lowlands eco-region. ODVI: White-tailed deer; SEAU: Ovenbird; PCLI:Red-backed salamander; MAAM: American marten

We assessed the sensitivity of these results to the relative resistance values in the resistance surface that formed the basis of species' network delineation. The range of variability in ECA and percent change in ECA was relatively small for all of the species we examined (Figure 6-8). When resistance values increased by a factor of five, the estimates of ECA were consistently slightly lower (Figure 6-8a). This sensitivity analysis increases confidence in the results of our network connectivity analysis as results are not highly sensitive to the resistance values we used as inputs

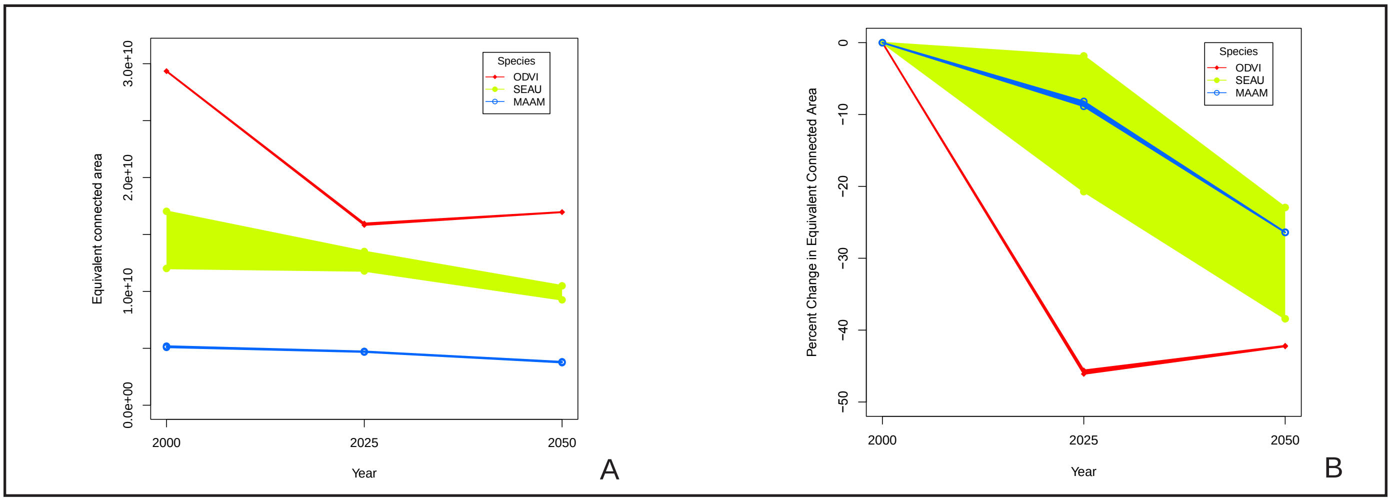


Figure 6-8. Sensitivity of A) Equivalent Connected Area (ECA) and B) percent change in ECA within species' habitat networks. The upper line in A) corresponds to ECA calculated from habitat networks based on a resistance cost ratios that doubles between resistance classes (i.e., 1, 2, 4, 8, 16, 32). The lower line in A) corresponds to ECA calculated from habitat networks based on a resistance cost ratios that increase by a factor of five between resistance classes (i.e., 1, 5, 25, 125, 625, 3125). The area between the two lines represents the potential range of ECA values under intermediate relative resistance ratios. ODVI: White-tailed deer; SEAU: Ovenbird; PCLI:Red-backed salamander; MAAM: American marten

6 Estimating the change in connectivity through time under 'Business As Usual' Landuse Scenario and climate change

To explore changes in habitat network connectivity in response to climate change in addition to both 'Business As Usual' (BAU) landuse, we tracked quality-weighted area and ECA through time for three of the focal species at the scale of the entire study region: American marten, white-tailed deer, and ovenbird. The habitat networks of the red-back salamander and the common eastern bumble bee had too many nodes in their networks to compute this network metric. We contrasted the changes in connectivity due exclusively to BAU landuse with those due to BAU landuse operating simultaneously with one of two climate scenarios (climate scenario 1 or 3; Chapter 5).

The total quality-weighted area of nodes in the habitat networks was calculated in a similar fashion as described in section 5 but now we summed the product of node quality, node area, and node suitability (based on climate) across all nodes. Quality-weighted area decreased in all species' habitat networks in all scenarios (Figure 6-9). White-tailed deer and ovenbird habitat networks were degraded at a relatively constant rate under all combinations of landuse and climate scenarios, decreasing by 9% and 6% respectively by the year 2050 (Figure 6-9a,b). The habitat network for American marten was degraded at a similar rate and to a similar degree under the BAU landuse alone scenario (8% by 2050; Figure 6-9c). However, the rate of degradation under BAU landuse and climate change was dramatically different depending on the climate change scenario. In climate scenario 1 there was no longer any suitable habitat by the year 2025, whereas in climate scenario 3 habitat was still suitable in 2025 but became completely unsuitable by 2050.

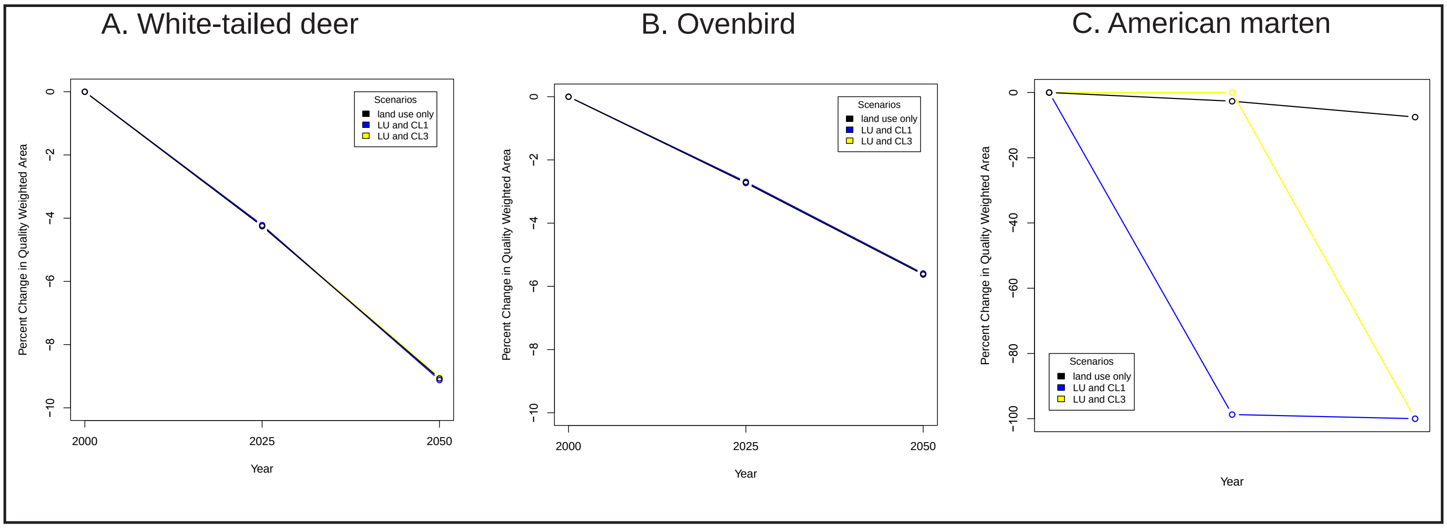


Figure 6-9: Percent change in quality-weighted area of nodes within species' habitat networks at the scale of the full study region under different simulated landscape scenarios for A) white-tailed deer, B) ovenbird, and C) American marten. This measure also accounts for changes in node climatic suitability. Landuse (LU) refers to 'Business As Usual' landuse scenario described in chapter 4. Climate1 and climate 3 scenarios are described in chapter 5.

The connectivity of nodes in the habitat networks, measured by ECA, increased through time under BAU landuse and climate changes for white-tailed deer and ovenbird in all scenarios (Figure 6-10a,b). White-tailed deer habitat networks became more connected by 5% and ovenbird habitat networks became more connected by 15% in all scenarios (as was also observed in Figure 6-7a). The connectivity of American marten habitat networks decreased in all scenarios (Figure 6-10c) following a similar pattern to decreases in quality-weighted area (Figure 6-9c); the scenario simulating BAU landuse and climate 3 retained connectivity for longer than the scenario simulating BAU landuse and climate 1. It would be reasonable to conclude that decreases in the ECA of the marten habitat were driven by decreases in the quality-weighted area of its habitat. For white-tailed deer and ovenbird, however, increases in habitat network ECA cannot be attributed to increases in the quality-weighted area of the nodes. Hence, ECA changes for these species must be due to changes in the length of links in the network, or a rewiring of links resulting in a different pattern of connections among nodes.

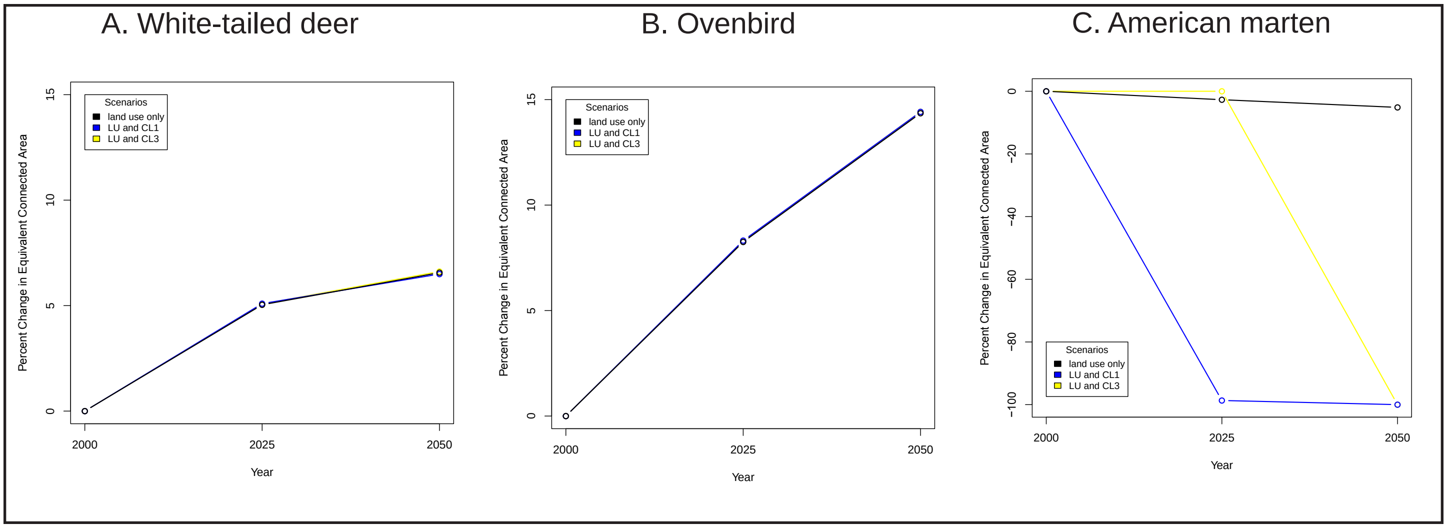


Figure 6-10: Percent change in equivalent connected area of species' habitat networks at the scale of the full study region under different simulated landscape scenarios for A) white-tailed deer, B) ovenbird, and C) American marten. Landuse (LU) refers to 'Business As Usual' landuse scenario described in chapter 4. Climate1 and climate 3 scenarios are described in chapter 5.

7 - Conclusion

The framework that we have presented to estimate habitat network connectivity in this region arose from a synthesis of network and circuit theory applications in landscape ecology. Synthetic approaches to connectivity planning are increasingly required as land use changes impede species from being able to track habitat in suitable climate (Nunez et al. 2013). We explicitly quantify interpatch connectivity that will promote the persistence of biodiversity within the St. Lawrence Lowlands ecoregion and traversal connectivity that will allow species to migrate and shift their distribution as climate changes. These two types of connectivity can be used to inform conservation initiatives aiming to promote species movements in fragmented landscapes subject to changing climates (Chapter 7). We showed that our results are robust to the assumptions we applied in our framework to parameterize species' resistance surfaces. These simplifying assumptions were necessary due to a lack of data available to parameterize resistance surfaces and allowed us to apply our framework to model the connectivity of multiple species under a single generalized framework.

When applying our framework to track changes in species' habitat network connectivity through time under simulated scenarios of landuse and climate changes, we found that the quality-weighted area of nodes will decrease in all species networks under all scenarios. For some species this decrease in node quality-weighted area will translate to a decrease in connected area at the network scale (i.e., for the American marten). For other species however, a decrease in node quality-weighted area did not result in a decrease in connected area possibly due to the configuration of nodes in the habitat network (i.e., for the white-tailed deer and ovenbird). This provides some grounds for optimism because systematic conservation planning, may keep current habitat network intact. Species with a protected habitat network will fair a far better chance of persisting in the context of ongoing landscape and climate dynamics.

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Chapter 7

Multispecies network selection using Zonation

1 Introduction

The most popular strategy among conservation planners for conserving biodiversity in a changing climate is the maintenance of habitat connectivity (Berger et al. 2010a; Heller & Zavaleta 2009). Central to these conservation plans is the identification of areas that will allow species movements to track suitable climate (Hannah 2011). While these areas are certainly important, so too are areas that promote connectivity and persistence within current species' ranges. Incorporating connectivity objectives into systematic conservation planning is a relatively recent development within conservation science and has predominately focussed on structural rather than functional measures of habitat connectivity (e.g., Moilanen and Wintle 2006; Ball et al. 2009). This is due in large part to the difficulties associated with quantifying functional connectivity, which is a measure that accounts for species-specific responses to landscape structure. Some efforts to incorporate simple surrogates of functional connectivity have been included in the major systematic conservation planning tools, Marxan (e.g., Berger et al. 2010b) and Zonation (e.g., Moilanen and Wintle 2007); however the most recent techniques that use network and circuit theory to estimate functional habitat connectivity (Bergerot et al. 2013, Nunez et al. 2013, Urban et al. 2009) have not yet been integrated into spatial optimization tools. Research at the interface of connectivity science and conservation science is needed to operationalize connectivity theory into conservation planning.

In this chapter, we describe how we used habitat network analyses (Chapter 6) to support connectivity planning in the study region. We sought to attain two conservation objectives within the network of forest patches in our study region: 1) the long-term maintenance of populations within habitat networks; and 2) the persistence of large-scale migrations and potential for distributional changes across the habitat network in response to climate. Conservation planning based on these objectives was repeated through time to contrast current prioritizations with future prioritizations under alternate climate change scenarios. The spatial prioritizations obtained under future climatic conditions were also used to inform current conservation priorities. In this way, we can immediately prioritize habitat that will become suitable in the future and deprioritize habitat that will become unsuitable.

2 Multi-objective conservation prioritization using Zonation

We used the spatial prioritization software Zonation v3.1 (Moilanen et al. 2005, Moilanen et al. 2011a, Moilanen et al. 2012) to find optimal trade-offs between habitat quality, inter-patch connectivity, and traversability objectives for each of the focal species. Zonation has been widely applied to identify spatial conservation priorities using the distribution of multiple biodiversity features such as species, habitats, ecosystem services (Moilanen 2007, Moilanen et al. 2011b, Moilanen 2012). We used spatial, node-level and pixel-level descriptions of species' habitat patch connectivity and habitat quality as the biodiversity feature layers for Zonation analyses.

Zonation produces a priority-rank map and set of performance curves that quantify the fraction of the conservation feature remaining at any stage of the priority ranking. The priority ranking proceeds by iteratively discarding the pixel with the lowest conservation value and recalculating the conservation value for each remaining pixel, accounting for the occurrences of each feature in the cell and in the remaining landscape. The order of pixel removal therefore provides the priority ranking such that the lowest priority pixels are removed first. The calculation of the conservation value of each pixel is determined by the pixel-removal rule, which we selected to be additive across features so that the priority would be given to pixels of high quality that contributed simultaneously to habitat quality, inter-patch connectivity, and traversability for all species (additive benefit function with z=1; Moilanen 2007). Habitat quality, inter-patch connectivity, and traversability feature layers for all species were given equal weight in the all scenarios described below.

3 Conservation planning scenarios

3.1 Prioritizing inter-patch connectivity and traversability based on current landscape structure

This scenario illustrates a method to concurrently promote inter-patch connectivity and network traversability for all five focal species in spatial conservation prioritization. We used four spatial input layers for each of the focal species. Two spatial, node-level descriptions of species' specific patch connectivity (based on patch importance for equivalent connected area and weighted betweenness; Chapter 6) were used with the exception of the Common eastern bumble bee which did not have a spatial input layer of equivalent connected area because its habitat network comprised too many nodes to allow for the calculation of this connectivity metric. These node-connectivity input layers were computed solely for patches within the St. Lawrence lowlands habitat networks in order to allow us to explicitly prioritize inter-patch connectivity in this ecoregion (see Moilanen et al. 2005, Moilanen et al. 2006, Lehtomäki et al. 2009, Rayfield et al. 2009 for other connectivity criteria currently implemented in Zonation). We complemented these patch-level descriptions with pixel-level habitat quality and current density maps for all five focal species (Chapter 6) at the full extent of the study region to allow for a finer grained prioritization of the landscape that promotes traversability. All input layers in this scenario were derived from the initial landscape structure data at year 2000 prior to any simulated land-use or climate change.

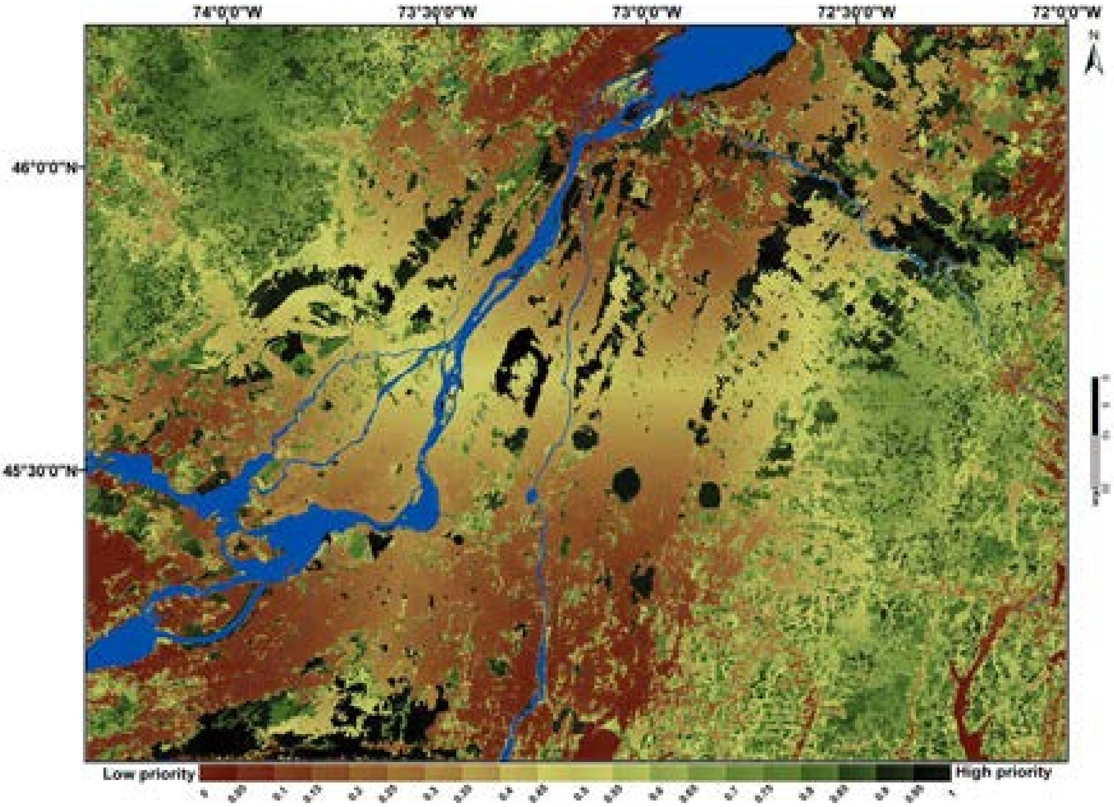


Figure 7-1: Landscape prioritization based on both inter-patch connectivity and traversability planning objectives (section 3-1). Four spatial input layers for each of the five focal species formed the basis of the prioritization: node betweenness, patch importance based on equivalent connected area, pixel-level habitat quality, and current density. All input layers were derived from current conditions in the year 2000. Colours range from maroon (low priority) to dark green (high priority).

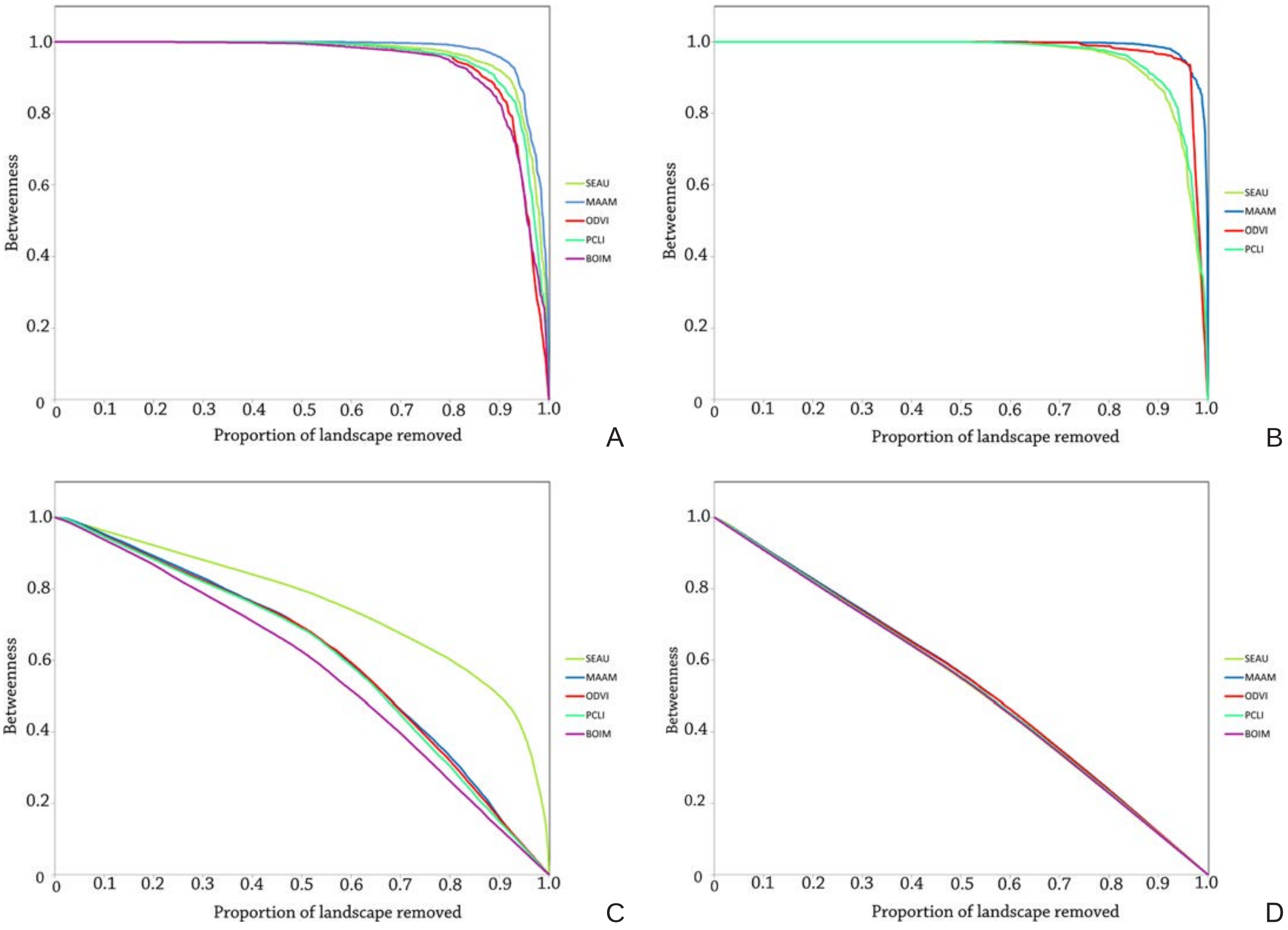


Figure 7-2: Proportion of original A) node betweenness B) patch importance based on equivalent connected area C) pixel-level habitat quality and D) current density retained for each of the focal species in the conservation scenario described in section 3-1 (Figure 7-1) as a function of proportion of landscape remaining as lower priority pixels are removed. SEAU: Ovenbird; MAAM: American marten ODVI: White-tailed deer; PCLI:Red-backed salamander; BIOM: Common eastern bumble bee.

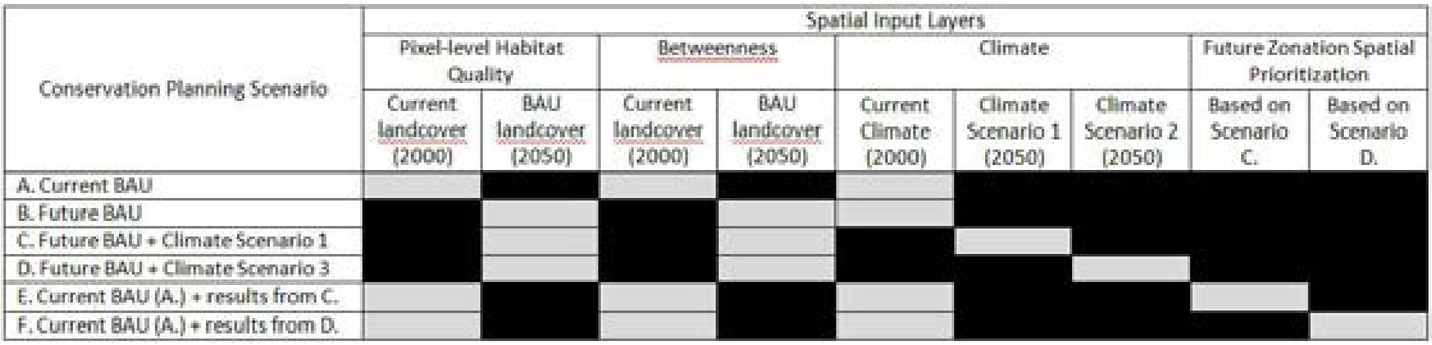
The spatial ranking of conservation priorities within the landscape for this scenario are mapped in Figure 7-1. This map highlights the most important areas of the landscape for connectivity conservation based on current conditions. It represents a hierarchy of solutions depending on what fraction of the landscape can be protected. Highest conservation priority is given to the core areas of the forest fragments within the St. Lawrence lowlands (shown in dark green; Figure 7-1). Forest swaths within the Laurentian and Appalachian Mountain ecoregions are also of conservation importance due to their high quality and their role in maintaining landscape traversability; habitat patches within these regions were not included in the node-level descriptions of habitat connectivity based on equivalent connected area and betweenness. Conservation priority is heterogeneous within the agricultural matrix surrounding forest patches. The top-ranked, non-habitat pixels within the agriculture form a distinct “Y”-shape (in yellow) oriented in the middle of the study region (Figure 7-1). This “Y”-shaped zone could represent an important region within which forest restoration activities could be encouraged as it encompasses many of the top priority habitat fragments and could serve to connect large forested areas to the south, east, and west.

This ranking of map pixels in terms of their conservation priority represents the requirements of all five focal species (each given equal weight) for the study region because we simultaneously optimized for their connectivity requirements. To compare how well each of the species is represented within the prioritization, we can examine the fraction of their spatial habitat quality and connectivity input layers that are retained during the Zonation priority ranking (Figure 7-2). For any proportion of landscape remaining during the Zonation prioritization, there is a spatial pattern remaining in each of the input layers, and from this spatial pattern the fraction remaining of the original full distribution of each input layer was calculated to produce Figure 7-2. For all species, their pixel-level features (habitat quality and current density; Figure 7-2 C and D) decrease at a relatively constant rate compared to their patch-level features (patch importance for ECA and betweenness; Figure 7-2 A and B) which remain intact until approximately 80% of the landscape is removed. This difference arose because pixel-level features within the matrix (i.e., non-habitat pixels) were removed immediately but node-level features were maintained until habitat pixels began to be removed during the removal sequence. This also explains why more than 80% of the original patch importance based on ECA was maintained for American marten and white-tailed deer in just the top 3% of pixels as they both have relatively fewer patches in their habitat networks (Figure 7-2 C). The same fraction of the original patch importance for ECA for the red-backed salamander and ovenbird required approximately twice as many pixels (7%). However, the ovenbird maintained the highest fraction of its total original pixel-level habitat quality during the prioritization compared to the other species. Roughly 50% of the original ovenbird habitat quality was maintained in the top 5% of the landscape (Figure 7-2 A).

3.2 Comparing spatial conservation priorities through time under 'Business As Usual' landuse and climate scenarios

We compared four conservation planning scenarios that differed in terms of the spatial input criteria used to inform conservation priorities (Table 7-1). For all of these scenarios, we used three spatial input layers calculated across the full extent of the study region for each of the five focal species: 1) pixel-level habitat quality, 2) node betweenness, and 3) climate suitability. The first scenario (A) was a baseline scenario producing a conservation prioritisation based only on current landuse and climate at year 2000. The second scenario (B) prioritised the landscape for conservation based on landuse changes in 2050 in the absence of any climate change. Conservation scenarios C and D were based on landuse changes in 2050 and climate changes following climate scenario 1 and 3 respectively.

Table 7-1. Conservation planning scenario parameter matrix. Grey and black cells indicate the inclusion and exclusion respectively of spatial input layers during the conservation scenario. BAU refers to the 'Business As Usual' landuse scenario (Chapter 4). Climate scenarios are described in Chapter 5.



Conservation Planning Scenario	Spatial Input Layers								
	Pixel-level Habitat Quality		Betweenness		Climate			Future Zonation Spatial Prioritization	
	Current landcover (2000)	BAU landcover (2050)	Current landcover (2000)	BAU landcover (2050)	Current Climate (2000)	Climate Scenario 1 (2050)	Climate Scenario 2 (2050)	Based on Scenario C.	Based on Scenario D.
A. Current BAU	▨	■	▨	■	▨	■	■	■	■
B. Future BAU	■	▨	■	▨	▨	■	■	■	■
C. Future BAU + Climate Scenario 1	■	▨	■	▨	■	▨	■	■	■
D. Future BAU + Climate Scenario 3	■	▨	■	▨	■	■	▨	■	■
E. Current BAU (A.) + results from C.	▨	■	▨	■	▨	■	■	▨	■
F. Current BAU (A.) + results from D.	▨	■	▨	■	▨	■	■	■	▨

The baseline scenario A (Figure 7-3) reprioritized the landscape based on current conditions with a different set of spatial inputs from the scenario described in section 3.1 (Figure 7-1). These two prioritizations of the current landscape show concordance on the high priority given to central habitat fragments within the St. Lawrence lowlands; however, they differ strongly in their prioritizations within the Laurentian and Appalachian Mountain ecoregions. Scenario A included climate suitability layers which had a coarse spatial resolution (one decimal degree) accounting for the rectangular array visible in the resulting prioritization (Figure 7-3). The

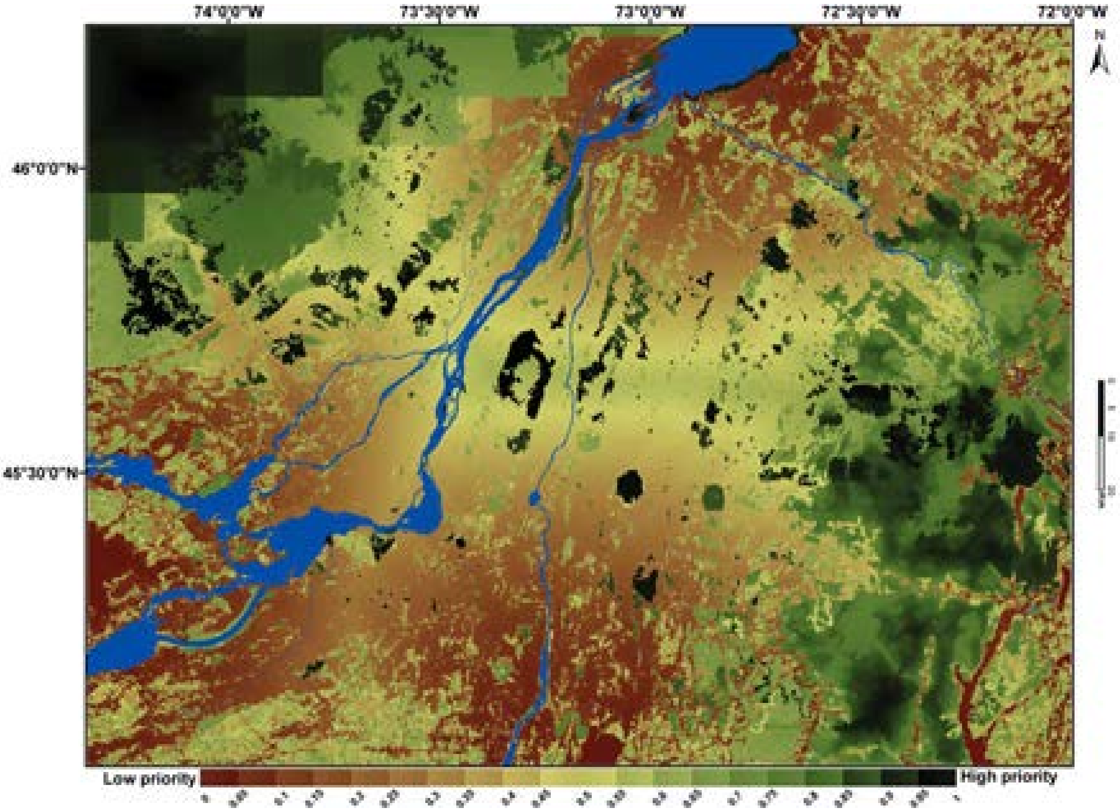


Figure 7-3: Landscape prioritization based on current conditions in the year 2000 (scenario A; Table 7-1). Colours range from maroon (low priority) to dark green (high priority).

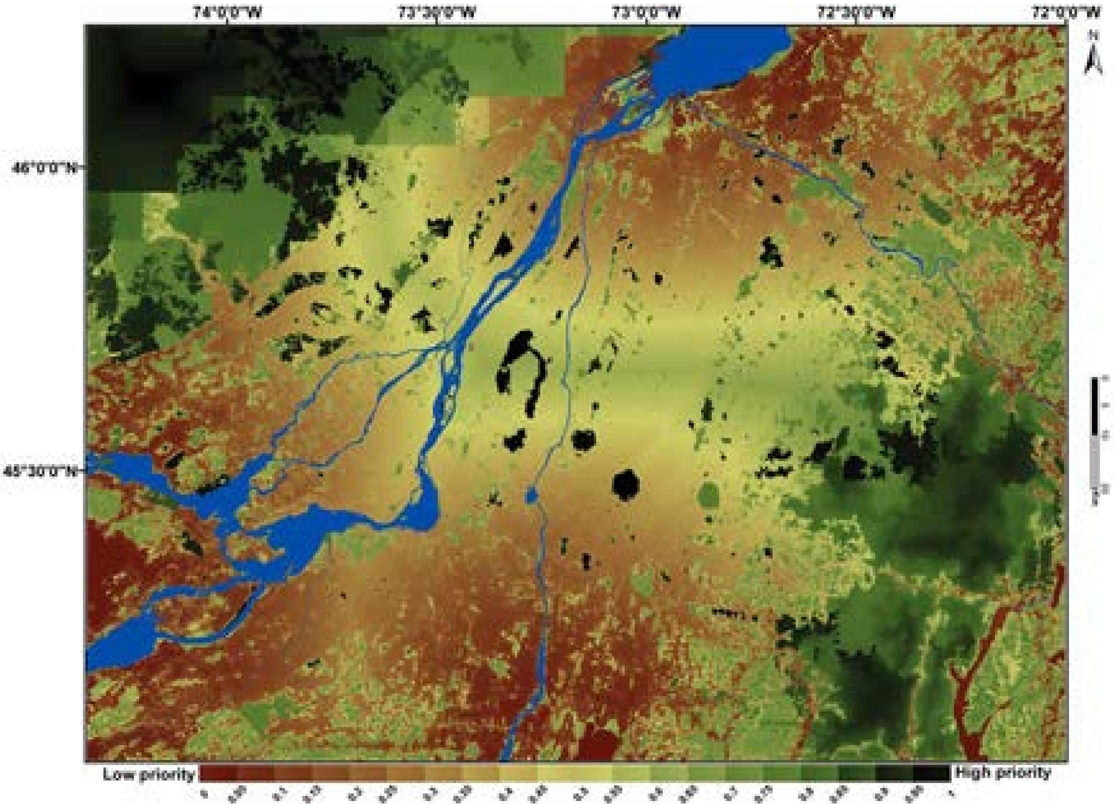


Figure 7-4: Landscape prioritization based on landcover conditions in 2050 under 'Business As Usual' landuse in the absence of climate change (scenario B; Table 7-1). Colours range from maroon (low priority) to dark green (high priority).

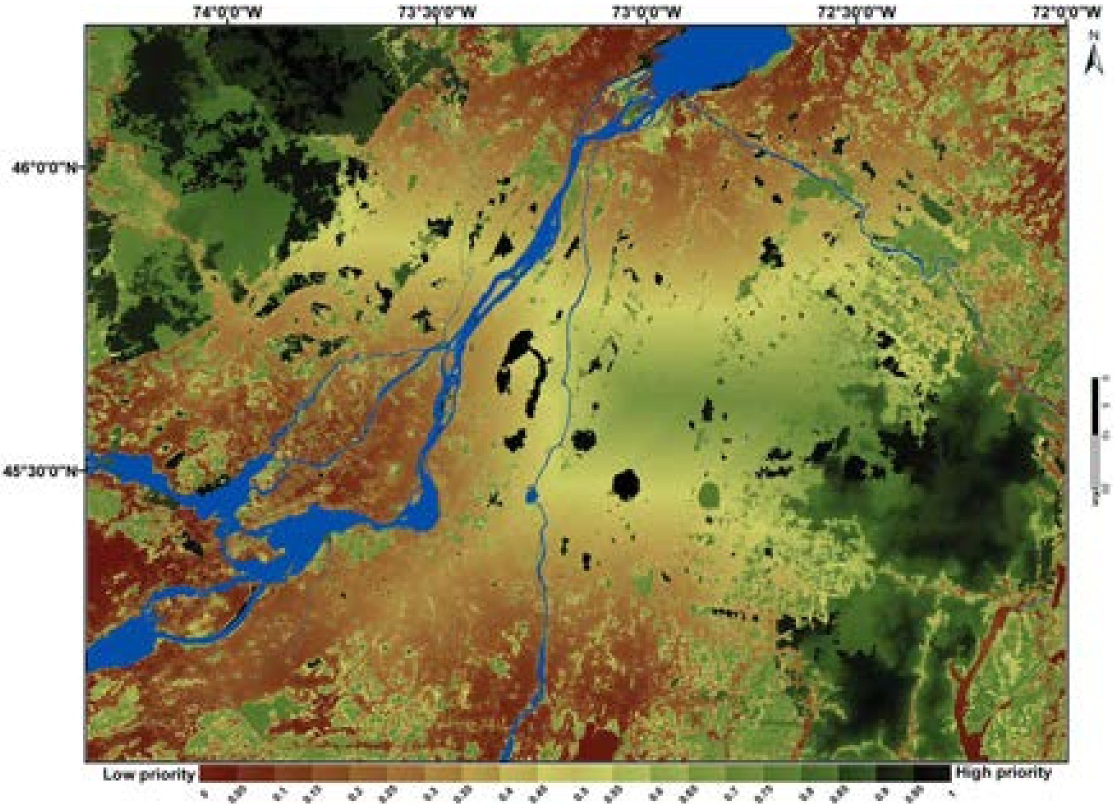


Figure 7-5: Landscape prioritization based on landcover conditions in 2050 under ‘Business As Usual’ landuse and climate scenario 1 (scenario C; Table 7-1). Colours range from maroon (low priority) to dark green (high priority).

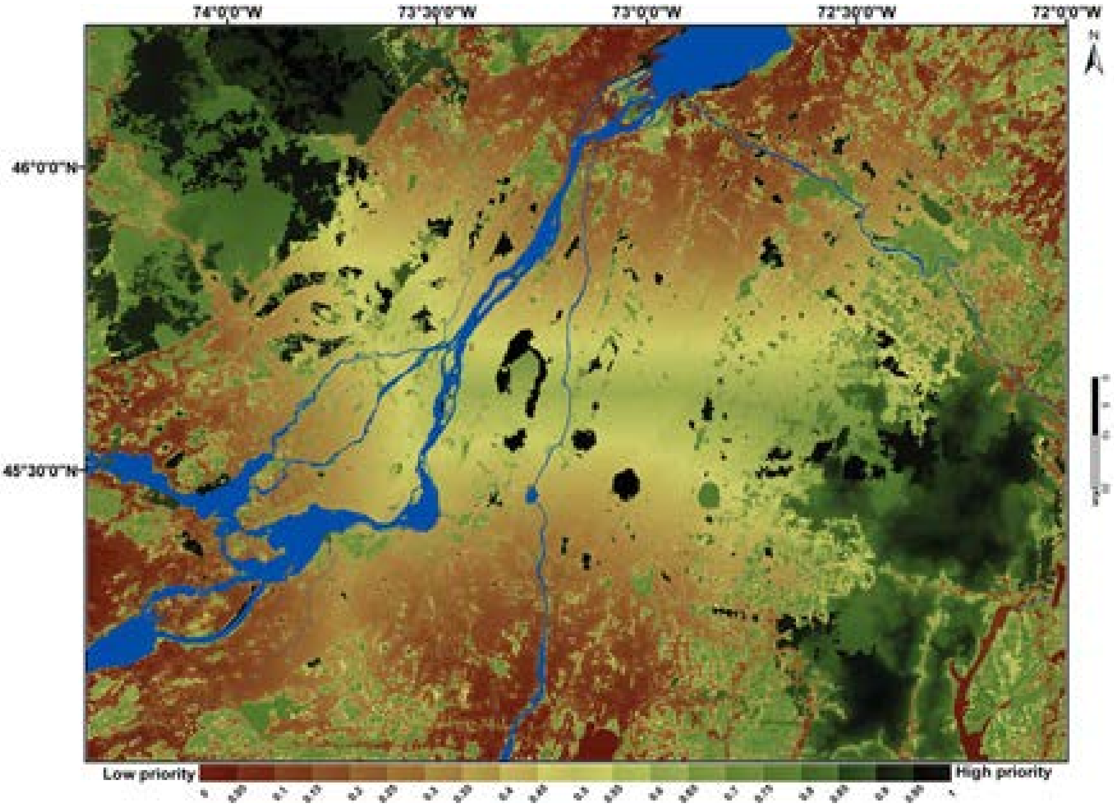


Figure 7-6: Landscape prioritization based on landcover conditions in 2050 under ‘Business As Usual’ landuse and climate scenario 3 (scenario D; Table 7-1). Colours range from maroon (low priority) to dark green (high priority).

climate suitability patterning is most visible in the north-west corner of the map which received high prioritization as it was the only region suitable for the American Marten. The highest priority areas within the agricultural matrix identified originally in section 3.1 were reconfirmed in scenario A. In scenario A, priority was transferred from the habitat fragments at the northern and southern extremes of the St. Lawrence lowlands to habitats within the more contiguous forest lying to the east and west.

The consequences of 50 years of ‘Business As Usual’ (BAU) landuse on conservation priorities can be examined by comparing the baseline scenario A (Figure 7-3) with scenario B (Figure 7-4) which was based on landcover in the year 2050 under BAU assuming no climate change. Major conservation priority patterns are conserved but the dramatic erosion and elimination of forest fragments in the St. Lawrence lowlands under BAU landuse changes the importance of small forest fragments. The top-ranked forest fragments for conservation in scenario B are considerably smaller than in scenario A. Also, some fragments lose or gain priority based on the changes to the species’ habitat networks.

The effect of climate change under climate scenarios 1 and 3 in addition to BAU landuse on spatial conservation priorities in 2050 are shown in Figure 7-5 (scenario C) and Figure 7-6 (scenario D) respectively. Both climate scenarios (scenarios C and D) predict that our study region will be entirely unsuitable for American marten, hence the north-west corner no longer represents a suitable area for marten and is not prioritized as strongly for conservation (Figures 7-5 and 7-6). When we compare the scenarios that account for both BAU landuse and climate change (scenarios C and D) with scenario B (Figure 7-4) that accounts for BAU in the absence of climate change, we observe a reprioritization of the non-habitat pixels that occur in the matrix surrounding forest fragments. Including climate scenario 3 with BAU landuse (Figure 7-6) did not result in any significant changes to the conservation priorities when compared with the priorities identified under BAU landuse in the absence of climate change (Figure 7-4) which leads us to conclude that the most important driver of conservation priorities in 2050 was the landuse pattern. However, including climate scenario 1 with BAU landuse (Figure 7-5) noticeably shifts the conservation prioritization within the matrix upwards such that the high priority band through the agricultural matrix falls well above the island of Montreal and is concentrated in the eastern portion of the St. Lawrence lowlands north of the Monteregian hills. The upward shift in conservation priority can be mainly attributed to changes in the habitat suitability for white-tailed deer (Chapter 5).

3.3 Informing current conservation priorities with future climate scenarios

We ran two final scenarios to illustrate a method to inform current conservation priorities with future climate scenarios (Table 7-1). Scenario E was the same as scenario A with the addition of an extra spatial input layer which was the conservation prioritization resulting from scenario C (i.e., Future BAU + Climate Scenario 1). Likewise, scenario F also repeated scenario A with the addition of an extra spatial input layer which was the conservation prioritization resulting from scenario D (i.e., Future BAU + Climate Scenario 3).

Re-evaluating conservation priorities under current conditions with additional information about conservation priorities in the future under BAU landuse and climate scenarios (Figures 7-7 and 7-8) did not result in major changes to current priorities (Figures 7-3). In fact the minor differences appear to be constrained to the south east corner of the map. While this consistency in conservation priorities may be comforting, it should be kept in mind that all of the habitat quality, betweenness and suitability layers used as inputs were based on current conditions hence the effect of the changes in priorities due to landuse and climate changes were diluted (i.e., there were 15 input layers based on current conditions and only 1 input layer based on simulated future conditions). Future analyses could adjust the weight given to the future conservation priority layer or could include other spatial input layers based on simulated future conditions.

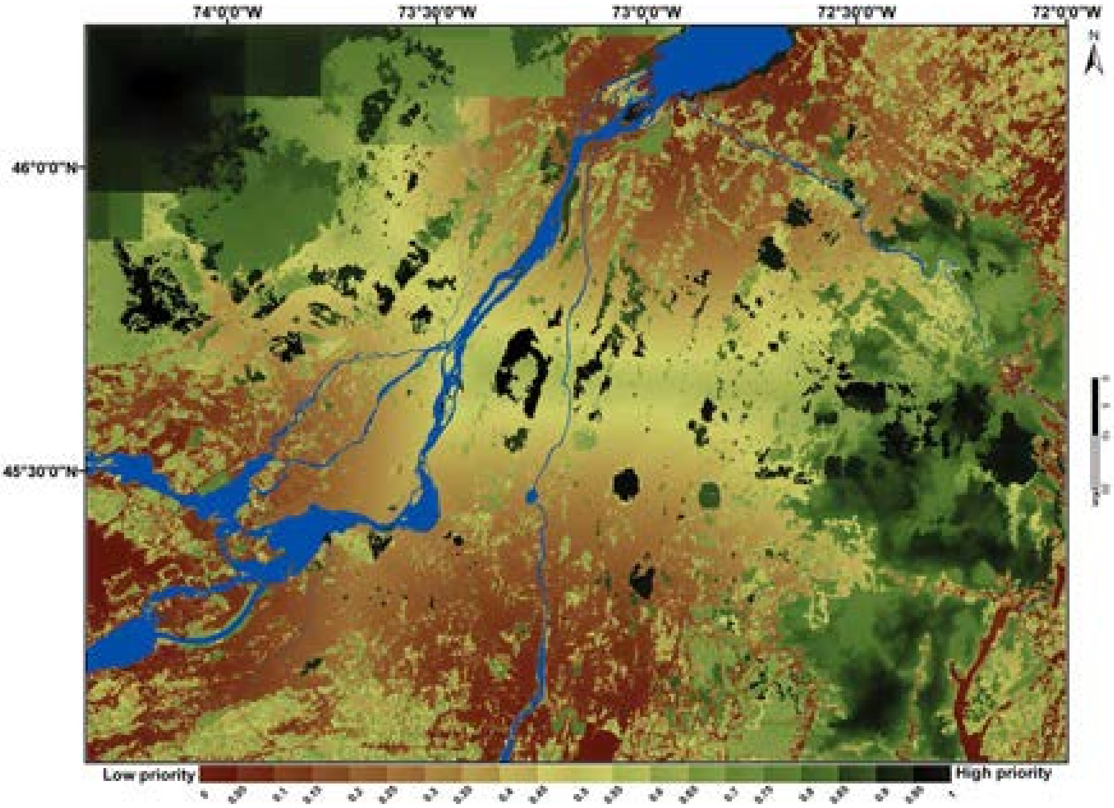


Figure 7-7: Landscape prioritization based on current conditions in the year 2000 used in scenario A and conservation priorities derived from scenario C (Table 7-1). Colours range from maroon (low priority) to dark green (high priority).

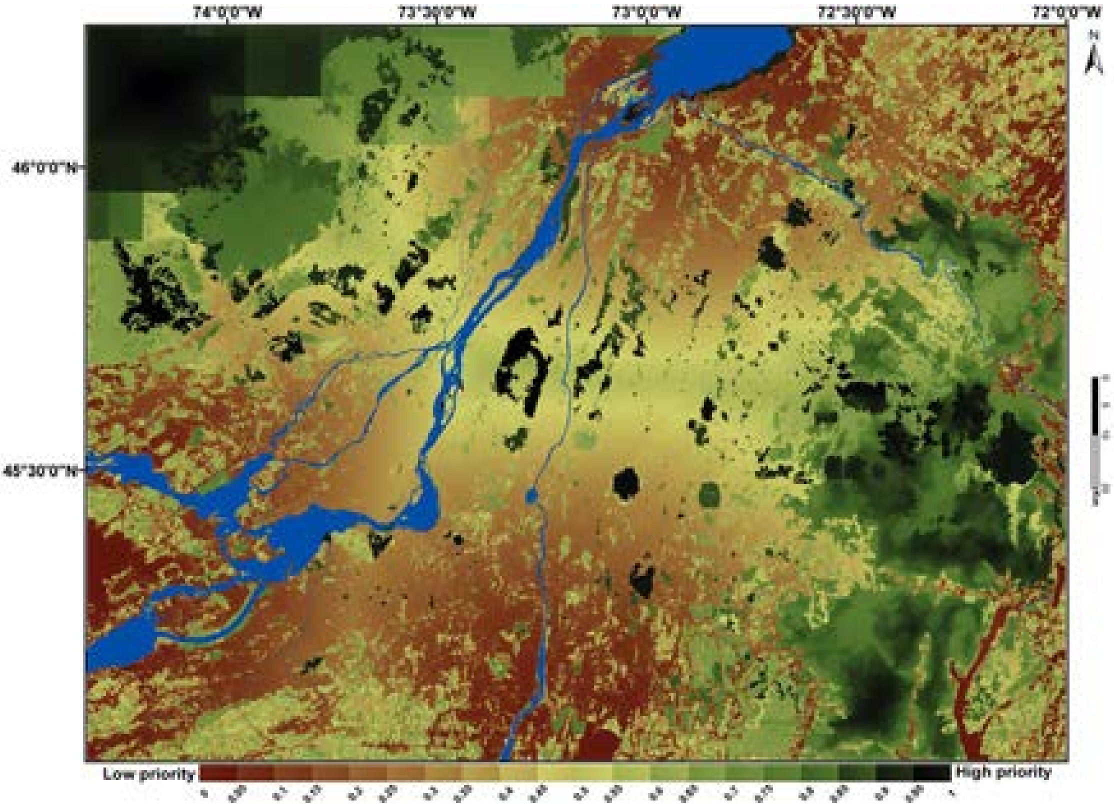


Figure 7-8: Landscape prioritization based on current conditions in the year 2000 used in scenario A and conservation priorities derived from scenario D (Table 7-1). Colours range from maroon (low priority) to dark green (high priority).

4 Conclusion

Ecosystems are valued based on their ability to simultaneously maintain many species and multiple ecosystem functions and services (Gonzalez et al. 2011; Zavaleta et al. 2010). We have shown how to design habitat networks that can simultaneously sustain a variety of species in a region undergoing climate change and in which landscape connectivity is eroded. Habitat networks have been useful in previous attempts to quantify multiple connectivity properties at several structural levels, from individual nodes up to whole-network properties (Rayfield et al. 2011). The innovation of our method is that it represents a convergence of connectivity conservation approaches focused on inter-patch connectivity within habitat networks and long-distance movements typical of migration across habitat networks. We identified key patches for conservation where these conservation priorities intersect. Furthermore, our approach tackles the problem that the effectiveness of a habitat network may be compromised under landuse and climate changes. The resulting multifunctional habitat networks will better integrate the current and future needs of organisms residing within the network and those that rely on the network to displace and track changing environments.

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Appendices

Appendix A Data Table: Geospatial data summary

Table summarizing the geospatial data used for the project

Data type	Title	Short Description	Content Date	Published Date	Coverage for our area	Scale / Resolution/vector format	Publisher	Source
Agriculture / Soil	Base de données des cultures assurées (BDCA)	Quebec assured crop database (BDCA) - hay, corn, wheat, barley, oats, soya, canola, other cereals, market vegetables, small fruits, mixed crops,etc.	2009	2009	almost complete (missing the upper left	1:50 000	La Financière agricole du Québec	McGill Library. Walter Hitschfeld Geographic Information Centre
	Données pédologiques du Québec (IRDA)	IRDA digital Quebec soil survey according to their morphological, physical and chemical properties.	1943'2005		complete	1:20 000	Institut de recherche et de développement en agroenvironnement Inc.	McGill Library. Walter Hitschfeld Geographic Information Centre
	Carte numériques des dépôts de surface	Glacial,fluvioglacial,fluvial,lacustrine,marine,litoral-marine,organic,slope and weathering,eolien and rock deposits	2004	2004	complete	1:50 000	Ministère des Ressources Naturelles et de la Faune Faune du Québec	McGill Library. Walter Hitschfeld Geographic Information Centre
Species plants/animals distribution	Digital representation of Atlas of United States Trees	Tree species distribution maps in North America		1999	complete	1:2 000 000	U.S. Geological Survey/Geology and Environmental Change Science	Digital Representations of Tree Species Range Maps: http://esp.cr.usgs.gov/data/little/
	Données d'occurrence de gros gibier	Hunting data for black bear, white tailed deer, wild turkey, moose,..	2010	2010	complete	points	Ministère des Ressources Naturelles et de la Faune Faune du Québec	not available for download
	Atlas des Amphibiens et Reptiles du Quebec	Occurrence data for all amphibians and reptiles	1900-2011	2011	complete	points	Atlas des Amphibiens et Reptiles du Quebec	not available for download
	Occurrences d'espèces de la faune et de la flore à statut particulier	Occurrence for rare and endangered species	1980-2011	2011	complete	points	CDPNQ_MRNF	not available for download
	Micromammiferes	Occurrence data for micromammifers	1980-2011	2011	complete	points	CDPNQ_MRNF	not available for download
	Red List	Broad scale occurrences for climatic suitability models			Eastern North America	shapefiles	Red List	Spatial Data Download: http://tinyurl.com/br6jqm8
	Nature Serve	Digital Representations of Tree Species Range Maps: http://esp.cr.usgs.gov/data/little/			Eastern North America	shapefiles	Nature Serve	Natureserve Download: http://www.natureserve.org/getData/index.jsp
	GBIF(Global Biodiversity Information Facility)	Broad scale occurrences for climatic suitability models			Eastern North America	shapefiles	GBIF	GBIF Data Portal: http://tinyurl.com/blr6xrr
Climatology	Mean annual temperature	for the present and the future	1971-2005 / 2041-2050		Eastern North America	10 X 10 km	Ouranos	not available for download
	Yearly total precipitation	for the present and the future	1971-2005 / 2041-2050		Eastern North America	10 X 10 km	Ouranos	not available for download
	Percentage of precipitation in summer	for the present and the future	1971-2005 / 2041-2050		Eastern North America	10 X 10 km	Ouranos	not available for download
Digital Elevation Models	Digital Elevation Models (DMTI)	30 m resolutions: extracted from the 1:50 000 scale interpolation of the National Topographic Database (NTDB).	various, as from NTDB		complete	30 m	DMTI Spatial Inc.	McGill Library. Walter Hitschfeld Geographic Information Centre
Environmental Assessment	Conservation Area and Tracking System (CARTS)	Web-based application		2010	complete		Canadian Council on Ecological Areas	CARTS Shapefile database: http://tinyurl.com/brpsflg
	CanMap Parks and Recreation	Representing > 1600 national, provincial and territorial parks and over 14 000 recreation areas across canada.		2009	complete		DMTI Spatial Inc.	McGill Library. Walter Hitschfeld Geographic Information Centre
	Territoires récréatifs et protégés au Québec	Quebec recreational and protected areas. Containing over 450 recreation and protected areas in Quebec: wildlife management areas, conservation and wildlife preserves, forest research station and migratory bird sanctuaries.		2002	complete	1: 250 000	Ministère des Ressources Naturelles et de la Faune Faune du Québec	McGill Library. Walter Hitschfeld Geographic Information Centre
Forestry / Ecology	Cadre écologique de référence (CER)	Ecological framework developed by MDDEP that contains multiple levels of classification: natural province, natural region,ecological district,etc.	various		complete	varies depending on CER calssification level	Ministère du Développement durable, de l'Environnement et des Parcs	Le Cadre écologique de référence en bref (not available for download): http://tinyurl.com/ca9ly6s
	Système d'information écoforestière (SIEF)	Ecoforestry information system: forest types, tree species, groupings, age, height, density, slope, class, land categories, disturbances (windfall, disease, burn etc.) and interventions (clear cuts, plantations, etc.) surface deposits, soil hydrology	1991-2003 (3rd inventory)	2004	complete	1: 20 000	Ministère des Ressources Naturelles et de la Faune Faune du Québec	McGill Library. Walter Hitschfeld Geographic Information Centre
	PEP (Placettes Échantillons Permanentes) fourth ecoforestry inventory	Plot data from the forest monitoring program that contains information about the trees, like the tree type,diameter at the breast height,age,density,etc	2003-2010	2011	complete	1: 20 000	Ministère des Ressources Naturelles et de la Faune Faune du Québec	Geoboutique: http://tinyurl.com/c2953qu
	Canada's Ecological Values within Intact Forest Landscapes	"key ecological values" within intact forest landscapes = the most valuable areas from an ecological perspective		2010	complete	1km	Global Forest Watch Canada	geobase: http://www.geobase.ca

Data type	Title	Short Description	Content Date	Published Date	Coverage for our area	Scale / Resolution/vector format	Publisher	Source
Water and Wetland Resources	Portrait des pertes de superficies forestières en Montérégie entre 1999 et 2004	Forest loss between 1999 - 2004 in Monteregie area	1999-2004	2005	Monteregie		GéoMont (et al.)	download not available any more
	Portrait des pertes de superficies forestières en Montérégie entre 2005 et 2009	Forest loss between 2004 - 2009 in Monteregie area	2005-2009	2010	Monteregie		GéoMont (et al.)	download not available any more
	Canada's Intact Foreset Landscapes	A contiguous mosaic of naturally occurring ecosystems, including forest, bog, water, tundra, and rock outcrops, that is witin a forest ecozone, and that is essentially undisurbed by significant human influence visible on Landsat satellite images.	1988-2006	2010	complete		Global Forest Watch Canada	Global Forest Watch Canada Data Layers: http://tinyurl.com/bqafa8v
	Cartographie détaillée des milieux humides du territoire de la communauté métropolitaine de Montréal	Aerial Photo-interpreting wetlands > 0.3 ha in the region of Montreal metropolitain area. (for canada wetland inventory http://maps.ducks.ca/cwi/)		2010	Montreal metropolitaine area		Canards Illimités (CI) & MDDEP	http://www.canards.ca (downloading data no longer available)
	Cartographie de base des millieux humides de la Montérégie	Wetlands in Monteregie region		2008	Monteregie		GéoMont (et al.)	www.geomont.ca (downloading data no longer available)
	National Hydro Network (NHN)	Containing completeness level 1 (CL1) data - lakes, reservoirs, watercourses (river and stream), canals, islands, drainage linear network, toponyms or geographical names, constructions and obstacles.	1985-1995	2007	complete	1: 50 000	Natural Resources Canada	geobase: http://www.geobase.ca
	CanMap Water	Detailed water features from national topographic database (NTDB) 1: 50 000 and 1: 250 000 scaled hydrographic mapping data - Major water; intermittent water, minor water		2010	complete	1: 50 000 & 1: 250 000	DMTI Spatial Inc.	McGill Library. Walter Hitschfeld Geographic Information Centre
Land Use / Land Cover	Canadian Watershed Boundaries	Extracted from a published Environment Canada Map depicting active and discontinued hydrometric stations operated by Water Resources Branch. Containing primary, secondary and tertiary drainage basins across canada	1972-1977		complete		Natural Resources Canada	Global Forest Watch Data Warehouse: http://tinyurl.com/bwakd4t
	Canada Land Inventory (1: 50 000) - Land Capability for Agriculture	Classes of land capability for agriculture are based on mineral soils grouped according to their potential and limitation for agricultural use.	1968-1990		complete	1: 50 000	Natural Resources canada	Canada Land Inventory - Land Capability for Agriculture: http://tinyurl.com/cfa5gr2
	Canada Land Inventory - Land Capability for Forestry	7 classes on its capabiity to grwo commercial termber in areas stocked with the optimum number and species of trees	1966-1985		complete	1: 250 000	Natural Resources Canada	Canada Land Inventory (1:250,000) - Land Capability for Forestry: http://tinyurl.com/c5sjs2p
	National forest inventory - Earth observation for sustainale development of forest (EOSD)	A space-based earth observation (EO) technologies to create products for forest inventory, forest carbon accounting, monitoring sustainable development, and landscape management.		2006	complete	1: 250 000	Natural Resources Canada - Earth obervation for sustainable development of forests (EOSD)	Earth Observation for Sustainable Development of Forests: http://tinyurl.com/6asmden
	Canada Land Use Monitoring Program (CLUMP) - Prime Resource Lands	Monitoring land use change across the country. Complimenting the land capability and land use surveys of the Canada Land Inventory (CLI). Components: urban-centred regions, prime resource lands, rural areas and wetlands.	1966, 1971, 1976, 1981, 1986	2002	Montreal metropolitaine area	1: 50 000	Natural Resources Canada	Canada Land Use Monitoring Program (CLUMP) Prime Resource Lands: http://tinyurl.com/c36df2s
	Canada Land Inventory (1: 50 000)- Land Use (circa 1966)	The mapping of land use capability is prepared from an analysis of the individual sector capability maps, supplemented by information on present land use and socio-economic conditions.	1966	2002	complete	1: 50 000	Natural Resources Canada	Canada Land Inventory (1:50 000) - Land Use (circa 1966): http://tinyurl.com/d8g9reo
	Base de Données Topographiques du Quebec (BDTQ)	The data set includes 25 land cover classes : hydrography, roads, buildings, equipment, vegetation (forest,hedges,openings), wetlands,fluvial deposits,etc.	1998 to 2003 and 2008		complete	1: 20 000	Ministère des Ressources Naturelles	McGill Library. Walter Hitschfeld Geographic Information Centre and Geoboutique
Imagery	National Road Network	Contains the entire Canadian road network like:highways,arterys,local roads,express roads,etc.		2010	complete	lines	Direction générale de l'information géographique, Ministère des Ressources naturelles et de la Faune	http://www.geobase.ca
	Canada Land Inventory - Land Capability for Recreation	7 Classes of inventory for recreational landuse capability	1966-1987	2002	complete	1: 250 000	Natural Resources Canada	Canada Land Inventory (1:250,000) - Land Capability for Recreation: http://tinyurl.com/cprg68h
	Landsat 5 TM	Five remote sensing images with have 7 spectral bands used to derive land cover information	2009	2009	complete	30cm	U.S Geological Survey	Earth Explorer: http://earthexplorer.usgs.gov
	Mosaïques orthophographique Montérégie	18 Mosaic orthophotos	2009	2009	partially (Montérégie)	30 cm	Ministère des Ressources naturelles et Faune - Geoboutique	McGill Library. Walter Hitschfeld Geographic Information Centre and Geoboutique

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