

# Integrating land use and land cover change simulations and connectivity modelling: a case study in the Montérégie region in southern Quebec

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## **Dedication**

To be completed.

## **Abstract**

Connectivity conservation science, whose goal is to preserve the continuity of habitat throughout a given landscape, proceeds by identifying priority areas given the current configuration of the landscape. However, current connectivity conservation planning methods suffer from at least two flaws: their prioritization process fails to take into account risks associated with future land use change, and also fails to confront the results of the prioritization with the priorities perceived by stakeholders. In this thesis, we show an attempt to remedy those two issues in an ongoing effort of connectivity conservation planning for the region of Montérégie in Southern Quebec, Canada. In the first chapter, we built on past work of connectivity modelling using circuit theory in the region and complemented it with land use change modelling that uses a combination of statistical modelling and MCMC-based simulations. Models trained on past land use data were used to project future land use changes and estimate future changes in functional connectivity for 5 different umbrella species. We derived conservation priorities for the design of a local network of connected protected areas resilient to future landscape change. In a second chapter, we compare those results with the perceived conservation priorities in the region. We conducted a day-long workshop with stakeholders involved in the ongoing connectivity conservation planning effort in the region and collected information on landscape features considered “core” and “linkages” priority areas. We discuss the importance of considering land use changes to produce a resilient network of protected areas and highlight the need for a multi- stakeholder approach in the definition of conservation priorities.

## **Abrégé**

To be completed.

## **Acknowledgements**

To be completed.

## **Contribution of Authors**

I am the first author for all chapters and the appendix in this thesis.

**Chapter 1:** I wrote the manuscript with input from my supervisor.

**Chapter 2:** I wrote the manuscript with input from my supervisor.

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## **General Introduction**

Space is a finite resource. How we, as a community, manage and govern space is a reflection of the trade-offs and choices made by different people and organizations at different spatial and temporal scales. Those choices determine and regulate land use: if and how the resources held on the land are exploited, transformed or conserved. The results of those choices, referred to as land use and land cover change, is an important threat to the biodiversity and ecosystem function.

One example of ecosystem function affected by land use that is of crucial importance to biodiversity is ecological connectivity. Ecological connectivity is the extent to which the landscape supports the movements of organisms (Gonzalez et al., 2017), and is paramount for the resilience of both populations and ecosystem services (Mitchell et al., 2015) in heterogeneous and fragmented landscapes. Land use changes such as urban sprawl can cause deforestation, fragmenting habitats, and slowly eroding ecological connectivity. Many urban landscapes are experiencing uncontrolled urban sprawl and have suffered losses in connectivity and ecosystem services in consequence. Examples include cities like Barcelona (Marulli and Mallarach, 2005), New York City (McPhearson et al., 2014), and also Montreal (Dupras and Alam, 2015). The forces behind those land use changes are complex and understanding them is an obstacle to conservation planning (Worboys et al., 2010). Because land use change is a social process with consequences of both social and ecological nature, it is best understood within the concept of social-ecological system (Ostrom, 2009). A social-ecological system (SES) can be understood as the set of human and non-human actors, the set of natural habitats they inhabit and resources and use, and the set of interactions that are maintained between all the components of the system. SESs thus form complex and integrated aggregates of interactions (Hinkel et al., 2014). Those interactions also impact governance, the process by which actors in power establish rules and laws (Bissonnette et al., 2018).

Connectivity conservation planning refers to the enterprise that engages multiple actors such as academics, NGOs, governmental bodies at different scales and in a common goal to conserve the ecological connectivity of the landscape. Connectivity conservation methods usually entails modelling connectivity of the landscape of interest and using a prioritization method to determine conservation priorities. However, current connectivity conservation planning methods have at least two major limitations: their prioritization process fails to take into account risks associated with future land use change, and also fails to confront the results of the prioritization with the priorities perceived by stakeholders. Not taking into account risks of land use change would in theory lead to ill-informed conservation planned that would be over-optimistic with regard to their probability of success. In addition, failing to integrate the perceptions of stakeholders is detrimental to conservation for two reasons: first, it most likely mean that conservation will fail to gather enough local momentum to lead to actual policy change, and second, it means that the only tool for decision making will be the model results, whereas these are incomplete representation of the landscape and would benefit from inputs from stakeholders. This is especially true in landscapes where a considerable effort of connectivity modelling has already been conducted, like in the landscape of interest in this thesis, the southern Quebec region of Montérégie.

Montérégie is situated southeast of the city of Montreal, and contains parts of the Greater Montreal Area (GMA). The ecological connectivity of the GMA and its benefits as a provider of ecosystem services has recently been assessed in a report to the Quebec ministry of the environment (Rayfield 2018, unpublished). This study focused on identifying regions of highest connectivity, and therefore of highest priority for the conservation of biodiversity and ecosystem services. Other work by Rayfield et al. (2019, unpublished) has extended the analysis of connectivity to the whole of the Saint Lawrence Lowlands.

Although the map produced by this analysis is a snapshot of the current state of connectivity in the region, methods are available for including future land use and climate

change impacts (Albert et al., 2017). Those methods rely on established the use of land use and land cover change models whose complexity has increased from simple probabilistic state transition models to more advanced approaches using targets, discrete events and accounting for the time elapsed since the last transition (Verburg and Overmars, 2009; Daniel et al., 2016).

Methods are also available to include stakeholder's input in connectivity conservation planning. Some of those methods have been developed through the methodology of participatory modelling, which can be defined as a modelling framework that can integrate knowledge from multiple sources, even if this knowledge is generated by different processes. For instance, it is possible landscape perceptions by different actors and quantitative modelling. Those methods often rely on collecting data through a community-driven process during workshops. Those methods are time consuming and require a long term engagement with a given community over many years. Other workshop-based methods are less involved, and allow researchers to simply collect data to be confronted with the results of traditional modelling techniques.

In this thesis, we show an attempt to remedy the two issues we identified above, in an ongoing effort of connectivity conservation planning for the region of Montérégie in Southern Quebec, Canada. In the first chapter, we built on past work of connectivity modelling using circuit theory in the region and complemented it with land use change modelling that uses a combination of statistical modelling and MCMC-based simulations. In the second chapter, we compare those results with the perceived conservation priorities in the landscape, using data collected during a day-long workshop with stakeholders. The Montérégie is relevant for our questions given the recent political momentum gained by connectivity conservation. There is a strong political will in the region for the conservation of ecological connectivity.

# CHAPTER 1

## Integrating Land Use Change Modelling with Connectivity Modelling

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### 1.1 Abstract

Ecological connectivity, defined as the extent to which the landscape supports the movements of organisms, can be strongly affected by land use. It is an important component of the resilience of populations in heterogeneous and fragmented landscapes. Land use changes such as urban sprawl and agricultural intensification intensify habitat fragmentation and landscape homogenization, leading to the erosion of ecological connectivity. The Montérégie region in southern Quebec, where this work takes place, is experiencing urban growth and sprawl. We present a framework that integrates land-use change and connectivity modeling to forecast future changes in connectivity, using a combination of statistical modeling, MCMC-based simulations, and circuit theory. We used a hybrid modeling approach to project future land use changes using different climate scenarios, and estimate future changes in functional connectivity flow for 5 different umbrella species. We explore the flexibility of a scenario approach in forecasting the range of possible futures for ecological connectivity in the region, derive insights for the hypothetical design of a local network of connected protected areas resilient to future landscape change. In conclusion, we highlight the need for a multi stakeholder approach in the definition of scenarios and conservation priorities.

## 1.2 Introduction

The goal of connectivity conservation planning is to preserve the continuity of habitat throughout a given landscape, by identifying priority areas and corridors important for the preservation of ecological connectivity (Keeley et al., 2019). Ecological connectivity, defined as the extent to which the landscape facilitates or impedes the movement of organisms (Taylor et al., 2006), is a critical component of the resilience of populations in heterogeneous and fragmented landscapes (Gonzalez et al., 2017). Connectivity conservation planning methods do not typically account for risks associated with future land use and climate change, two main drivers of the erosion of ecological connectivity. Here, we ask whether those methods can be improved by taking into account those risks. To do so, we integrate a connectivity model with a land use change model including climate scenarios.

Connectivity conservation has often been pointed out as a method of adaptation against both climate and land use change (Costanza and Terando, 2019). One recurring argument is that preserving landscape connectivity could be critical for ensuring the adequate protection of shifting species ranges (Krosby et al., 2010; Keeley et al., 2018) due to climate change. Another is that it is more important than ever to connect habitats in landscapes increasingly hostile to species movement (Ellis et al., 2010). These arguments make the case for the design of Connected Protected Area Networks (CPAN, Stewart et al., 2019). Those networks are meant to allow the movement of species across multiple scales, which may require them to include both natural and semi-natural habitat, with different levels of protections (D'Aloia et al., 2019). This heterogeneity is likely to be reinforced by the multiplicity of urban and land use planning practices that exist on the landscape, making CPAN designs particularly vulnerable to changes in land use. It is therefore important to test which specific CPAN design would be most resilient to future change. One possible approach to exploring this resilience is to use landscape-level forecast models.

Land use change models have often used in conservation planning (for example, see Echeverria et al., 2008 or Lesschen et al., 2007). They allow researchers to test the efficiency of a given conservation plan in the face of expected land use change. Similarly, climate models are often used in conservation, for example to assess whether protected areas will be able to track the current changes in species ranges due to climate change (Araújo et al., 2004; Heller et al., 2015). They are central in species distribution models (Porfirio et al., 2014), a classic tool in conservation research.

Both types of models are increasingly common In approaches that focus on ecological connectivity. Connectivity researchers have long been interested how past changes in land use can explain current connectivity patterns (Dupras and Alam, 2015; Henareh Khalyani and Mayer, 2013; Vergara et al., 2013; Pătru-Stupariu et al., 2013) and multiple connectivity measures have been developed, one specifically in this optic (Saura and Pascual-Hortal, 2007). But beyond these historical analyses, land use forecast models are becoming more common (Correa Ayram et al., 2015). For example, Rubio et al., 2012 aimed at identifying a network of forest patches resilient to land use change under multiple scenarios in Spain. Similarly, Piquer-Rodríguez et al., 2012 integrated land use change and connectivity models to identify under-protected areas by projecting land use change trends. Huang et al., 2018 also used land use change models to assess potential impacts on functional connectivity in China. From these examples, we can see that combining land use change modeling and connectivity modeling does not yet have a fully established methodology. In its emerging form, it simply consists of running a land use change model on a given landscape, and comparing changes in the connectivity measure of choice between time steps (Perkl et al., 2018).

Climate change can interact with land use change in destructive ways for biodiversity (Oliver and Morecroft, 2014) It is therefore likely that connectivity models integrating these two drivers would improve connectivity conservation methods such as CPAN design. Yet, in a recent review, Costanza and Terando, 2019 have found that connectivity models

frameworks rarely combine land use change and climate change. Here, we build on recent connectivity modeling work using circuit theory, by pairing it with a hybrid land use and climate change model. The model we develop uses a combination of statistical modeling and simulations based on a Markov Chain Monte Carlo (MCMC) method, combining Random forests (RF) models with a Cellular automaton (CA) model. We use this RF-CA model to project future land use changes and estimate the changes in potential functional connectivity for five different umbrella species, under different climate change scenarios. We also derive conservation insights for the design of a hypothetical regional network of connected protected areas resilient to future landscape change. In addition, we provide a cursory analysis of past land use change trends in our study region, the Montérégie region in southern Quebec.

This work is the continuation of recent research efforts on the connectivity of the region: Albert et al., 2017 and (Rayfield et al., 2018). In a seminal paper, Albert et al., 2017 laid out some of the methodological steps we follow such as umbrella species selection and habitat suitability analysis. They also included a simple land use change model that was parameterized to replicate plausible change in the region. Meurant et al., 2018 developed the criteria for reducing the number of focal species from fourteen to five. They showed that because species had redundant connectivity needs, modeling the needs for 5 species resulted in qualitatively similar results than when modeling the needs of all 14 species, such as in Albert et al. (2017). While Rayfield et al. (2018) extended the spatial scale of the analysis to include the Saint Lawrence lowlands ecoregion, they demonstrated that we could exploit this redundancy to reduce the computing time needed for the connectivity analysis. This is an important development because land use change simulations are also computationally intensive.

Connectivity is a dynamic property of the landscape: it changes across time and space (Beyer et al., 2013). It is also scale and species specific, varying according to the needs of each species and because those needs also vary depending on the time of

the year, life history, and on the species' habitat range and preference (Anderson et al., 2005). It is important to distinguish structural connectivity from functional connectivity (Kindlmann and Burel, 2008). While structural connectivity strictly refers to how animal movement is mediated by the configuration of habitat features in the landscape, functional connectivity is based on species' preferences for such features and how they move among them. Functional connectivity modeling therefore attempts to model the extent to which the landscape meets the need of a specific species or set of species.

There has been a trend in the recent literature to focus on functional connectivity, as it is regarded as a more realistic representation of the landscape's capacity to facilitate species movement than structural connectivity. However, functional connectivity analyses require direct animal movement data or genetic data for model fitting and for validation (for example, see Beyer et al., 2013; Milanesi et al., 2017). This type of data is costly to acquire, especially when needed for many species. For this reason, much of current functional connectivity modeling, including the methods of this chapter are in fact modeling "potential functional connectivity", or PFC. PFC models do not necessarily rely on actual movement data, but are based on other kinds of knowledge of species habitat preferences and movement behaviors, for instance, from expert knowledge and literature reviews. This makes PFC well suited to the task of this paper.

Here we model PFC for the 5 focal species identified by Meurant et al., 2018 and use the workflow of (Rayfield et al., 2018) for habitat suitability and connectivity analysis. We complement this framework with the RF-CA land use model. It is important to note that the primary goal of this chapter is not to explain the drivers of land use change in the region, but to provide a sufficiently realistic simulation to replicate the trends in land use change that have been observed historically, and to project those trends forward into the future.

A classic spatially defined land use change model is what can be called a "state change model", where the landscape is divided in a grid and each grid element (pixel) is assigned a state that changes in discrete time (Daniel et al., 2016). The difficulty of land use change

modeling resides in setting the transition probabilities that define the probability of a pixel transitioning to another state (or to remain as is), given its current state and given a set of conditions both intrinsic and extrinsic to that pixel.

A simple land use change model will assume that the rules of state changes obey markovian laws: i.e. that the next state will always only depend on the current timestep and not previous timesteps. This is a simplification: in real landscapes, the history of the pixel (beyond its present state) can play a large role in the rules governing state change. Probably due to their simplicity, markovian models such as cellular automata have a long history in land use change models (Agarwal et al., 2002). They have been shown to deliver accurate results, notably in urban spread modeling (Soares-Filho et al., 2002; Jokar Arsanjani et al., 2013; Iacono et al., 2015). They are yet another application of markov chains, and are fairly easy to set up and to run. Markov chain models represent a phenomenological approach to land use change, because the model applies the rules of transition without encoding the mechanisms underlying the change. For example, the model defines that the state “forest” has a probability of 0.23 to transition into urban if it contains at least 2 urban pixels in a 4 pixel radius (this is an adjacency rule), but it is oblivious to the drivers of land use change.

In comparison to the phenomenological approach of cellular automata, a mechanistic approach to land use change modeling would fully consider that land change happens because of processes of multi-scale decision making, and will attempt to model those processes directly. Agent-Based Models (ABMs) are probably the best example of a mechanistic approach to land use change modeling. ABMs simulate the behavior of individuals in a network of decision processes whose effects are designed to sum up to the observed change (Parker et al., 2002; Filatova et al., 2013). Those models are promising for the future of land use change modeling, but tend to be applied at smaller spatial scales, and tend to rely on expert knowledge or on a rather involved data collection procedure (such as interviews with actors, Taylor et al., 2016). This makes the the modeling process more

difficult (albeit rewarding) as it requires a deeper understanding of the specific drivers of change in the region.

In the absence of a solid body of methodological comparisons between statistical frameworks in land use change modeling, it is difficult to decide on the best framework for raster-based (i.e. based on grids) models. The RF-CA model presented in this chapter is a hybrid approach in which a statistical approach is taken (statistical modeling through random forest) and combined with a more mechanistic approach (a cellular automaton with transition targets and spatial dependency rules, CA). The RF-CA model is similar to other popular approaches like the CLUE family of models (Conversion of Land Use and its Effects Verburg et al., 2002; Verburg and Overmars, 2009), which are some of the most commonly used models in land system science. However In CLUE, the allocation is determined by the local and regional “demand” for each land use. This demand is a latent variable for the complex and multi-scalar social-environmental processes that determine land use change, and which more mechanistic models attempt to simulate (Verburg and Overmars, 2009).

We choose here to present the two steps of probability modeling and allocation as separate because they are methodologically distinct in our model. But it is worthwhile to note that recent efforts in land use change modeling have managed to integrate those steps. Those recent methods can integrate suitability and allocation because the model is capable of encoding both processes at the same time. We can mention important work on modeling land use change with machine learning techniques such as Neural Networks (NNs) (Tayyebi, 2013) or exploiting the potential of non frequentist statistics in the case of Belief Networks (BBNs, see Celio et al., 2014 for a great example). BBNs, like ABMs are promising methods but tend to be applied at smaller spatial scales.

Scenarios are a flexible approach to forecasting the range of possible futures in landscapes (Peterson et al., 2003). We integrate land use change and connectivity modeling

under two “warming” scenarios (Baseline and RCP 8.5) and one “control” scenario (Historic). Depending on the scenario, the model generates different forest change dynamics. The Historic scenario assumes no change in forest composition and stands as our control. While the baseline scenario assumes no further warming and status quo forest change dynamics, the RCP 8.5 scenario is one of the most severe climate change scenarios, and the trends observed the in the baseline scenario are exacerbated **IPCC**. We also derive two simple land use change scenarios: Business as usual (BAU) and Reforestation. Those two scenarios are meant to represent two extremes in land use change, and it is likely that the most probable trajectories for our landscape will be within those two boundaries. In combination with the climate scenarios, this brings our total scenario number to 6. What predictions can be made as to how connectivity will be affected under our model? There has been a significant research effort to study and predict forest dynamics under climate change in Quebec. It has been shown that the distributions of many of the most abundant trees occurring in the region are out of equilibrium with climate at the margin of their range (Talluto et al., 2017). Some papers points to existing and expected lags in the response of forest to climate change (Savage and Vellend, 2015), and others have commented on how disturbances and forest management practices are likely to fasten and facilitate range shifts (Leithead et al., 2010; Boulanger et al., 2019; Vieira et al., 2020). A major prediction that can be made is that although boreal type (coniferous) forest is likely to respond more slowly to climate range than deciduous type, both coniferous and mixed population types in southern Quebec are likely to become more rarer, and be replaced by deciduous stands. We can therefore derive different predictions as to how connectivity will be affected for each species under our model. Three main predictions can be made. First, under the BAU scenario, we can expect that our land use change model will simulate an decrease in connectivity change for our focal species. We can also expect connectivity to maintain itself under the Reforestation scenario. Finally. we can expect climate change to impact

more strongly species that prefer coniferous and mixed forest types.

### 1.3 Methods

Our workflow is divided into two major steps: land use change modeling and connectivity modeling. Two workflow figures describe the steps and methods involved (figure 1–1 and 1–2).

#### *Software tools and reproducibility*

All work was conducted in the R statistical software version 3.6.2 "Dark and Stormy Night" (see R Core Team, 2020)). The data and code for this analysis are available at this GitHub repository.

We used ST-Sim version 2.2.10, scripted in R with the help of the rsyncosim package version 1.2.0. ST-Sim ran on Linux (Ubuntu 18.04) via Mono 6.4. Many steps of data preparation were conducted in GRASS GIS 7.8.

A note should be added on data availability and reproducibility. A few datasets were not obtained from open sources. These datasets are marked in red in figure 1–1. The Canadian census data was obtained through the University of Toronto's CHASS (Computing in the Humanities and Social Sciences) Data Centre, which requires institutional access. This makes the Random Forest analysis not reproducible. In addition, data on protected areas in Montérégie was obtained via the RMN (Réseaux des milieux naturels protégés du Québec) under a limited license, which makes the Land use change modeling via ST-Sim not fully reproducible. However, the results of those steps are made open, and the subsequent steps (habitat modeling, connectivity analysis) are reproducible via the use of various software (i.e. docker, renv, and more). Please consult the appendix on reproducibility for the steps to take to reproduce those results.

### 1.3.1 Land Use Change Modelling

Land use change modelling is a prolific subfield of land systems science which has spurred a broad diversity of approaches (Dang and Kawasaki, 2016; Noszczyk, 2018). Beyond the many methods published, there is a large number of applications and software tools available for research - although their openness and accessibility varies (Moulds et al., 2015). Papers that compare frameworks and results across tools and methods are rare (Pontius et al., 2008; Pontius and Malanson, 2005; Sun and Robinson, 2018). Although a full review of land use change modelling methods is beyond the scope of this chapter and this thesis, I will introduce the key concepts.

Land use change models can be classified according to their level of focus on land use change drivers, from phenomenological (“top down”) to more mechanistic approaches (“bottom up”). Given the simplicity and ease of use of phenomenological models, and the extra demands of mechanistic models, most approaches to land use change modelling fall between these two extremes, and a certain number of “hybrid” approaches have been developed (Sun and Robinson, 2018; Jokar Arsanjani et al., 2013). The approach we take in this chapter is not strictly phenomenological and introduces some mechanistic understanding of land use change, and can therefore be qualified as a hybrid method.

Our land use change model is set up in two steps: a land use suitability analysis and an allocation algorithm. In a nutshell, the suitability analysis step determines how likely each pixel is to acquire a given state by producing a probability surface, predicted based on spatial data, and the allocation step simulates change over that surface. The allocation is a Markov process informed by the results of the first step. This Markov process is embellished to include conditions such as neighboring rules and transition size distributions.

The two steps framework we just outlined allows us to combine the power of markov chains with the flexibility of statistics. Any method can in theory be used to determine the probability surface (although linear and logistic regression techniques are most common),

and complex algorithms can be written to determine rules of allocation. The simplicity and flexibility of this framework explains the popularity of common land use change modelling frameworks like CLUE (Conversion of Land Use and its Effects Verburg et al., 2002; Verburg and Overmars, 2009).

### 1.3.1.1 The RF-CA modelling framework

Our choice of statistical framework was done considering at least three factors: computing time, prediction power and capacity to deal with spatial processes. Computing time is an important factor because fitting models to large datasets can be time consuming. Capacity for dealing with spatial processes varies across methods. Finally, statistical frameworks sit along a continuum that emphasises more or less inference and prediction. A Bayesian model will be more easily thought of as a tool for statistical inference, whereas a neural network will be used more with predictive power in mind.

We chose Random Forests (RF) as a statistical framework. RFs are a “tree-based machine learning algorithm that generates a “forest” of randomized independent to each other and identically distributed decision trees”. RFs can be easily “grown” in parallel, which reduces computation time. RFs possess a strong predictive power, but can still provide metrics of variable importance, providing an interesting balance between inference and predictive power.

For the allocation step, we use an advanced cellular automata (CA) modelling tool (markov-chain based) called ST-Sim, a package of the free software SyncroSim. ST-Sim allows for more complex simulation than a classic CA as it allows for complex neighbouring rules with state and age cell tracking. It is also built to handle large datasets and can be scripted to run in parallel. It is important to note that although it is the first time RF is used with ST-Sim (to our knowledge), this hybrid modelling approach (coined “RF-CA”) has been used successfully in other land use change modelling projects (Kamusoko and Gamba, 2015; Gounaris et al., 2019). ST-Sim can be customized to function under

multiple different types of inputs. The two main inputs are transition probability and transition targets. Readers should refer to Daniel et al. (2016) for a more in-depth overview of how ST-Sim and SyncroSim functions.

### 1.3.1.2 Data sources and preparation

#### *Land use change data*

For most modelling frameworks, the raw source of land use change data is remote sensing data. Because producing land use change data from remotely sensed imagery was beyond the scope of this thesis, we looked for a curated dataset. Agriculture and Agri-Food Canada (AAFC) produces a dataset of land use in Canada at a 10 years interval and at the resolution of 30 meters (the resolution is the dimension of a pixel in a spatial grid, or raster data, and is an important property of land use datasets). This dataset provides land use data for the years of 1990, 2000, 2010. We found this data product, referred to hereafter as the AAFC data to be the right fit for our approach: the data production method of the AAFC data is consistent, meaning that similar methods have been used to produce all three maps at different time points. Consistency in data production methods is key as it makes the computation of change between time points more reliable.

This data is not without limitations: compared to other data products - such as the Quebec Ministry of the Environment land use dataset or the Statistique Quebec land accounting dataset - the AAFC dataset is not very detailed: only a few land use categories are identified, and important information for suitability analysis such as forest age and forest density are missing.

Another limitation is the coordinate reference system (CRS) in which this dataset is available: it is projected in a UTM projection system, which is not the standard CRS used by other data products that usually covers Quebec and emanates from open data portals in the province. This makes direct comparison (pixel by pixel) to those others datasets difficult. Finally, the AAFC data does not differentiate between road types, which has

implications for habitat suitability analysis (see the habitat suitability analysis section).

### ***Forest types and dynamics under climate change***

The AAFC data does not differentiate between different forest types. However, our connectivity analysis relies on an analysis of habitat suitability, which is reliant on knowing the preferences of different species for different forest types (see section of habitat suitability analysis for more details). In order to integrate dynamics of forest types into our simulations, we relied on the results of a separate set of simulations that were run in LANDIS, a free and open source source designed to model forest growth. Those simulations were run by Larocque and Rayfield (unpublished report to the Quebec Ministry of the Environment) for the extent of the Saint-Lawrence lowlands ecoregion, in the context of a research contract with the MELCC (Ministère de l'Environnement et de la Lutte contre les changements climatiques). The LANDIS simulations do not include land use change and therefore can not be directly merged into our simulations. Instead, we parameterized the changes in forest types from the results of the LANDIS simulations. A more detailed methodological description of the LANDIS simulations is to be found in the appendix ([add ref to appendix]).

We source two different sets of "parameters" from these simulations: first, forest type data in 2010 was used as a starting point for the forecast scenarios. Second, a set of transition multipliers were extracted from the simulations and was used to reflect different forest dynamics under different climate change scenarios. These are described in more details in the "Model Execution" section.

### ***Explanatory variables***

A diversity of drivers of land-use change can be found in the literature. Some general group of variables can be identified: an important distinction can be made between physical

and social-economical variables. Proxy variables for land use change drivers used in this chapter were selected among commonly recognized predictors of land use change.

A digital elevation model was used to derive elevation data (continuous variable). We used the data product “SRTM 30m” available throughout the Google Earth Engine data portal to generate this variable. This data was already available at a 30 m resolution.

We used the Canadian Census for the years of 1991, 2001 and 2011, provided by Statistics Canada, to extract two variables: population change (1991 -2001) and average income. The data was not available in a spatial format and had to be turned into a spatial object in R before being rasterized. The data was collected at the lowest aggregation level available: the denomination area (DAs) or the Enumeration area (EAs) depending on the census year (see table 3–2 for the full description of variables and data sources).

### ***Data preparation***

The first step of preparing the data from the model consisted in reclassifying the AAFC land use dataset into only 5 categories: the 3 categories of our land use change model and supplemental categories of roads and wetlands. Then, all the pixels classified as forest were reclassified as null, and the resulting maps were patched with the forest cover from the LANDIS simulations’ starting conditions (state of forest types in 2010). At the end of this process, some cells remained null as the forest cover in 1990 was larger than that of 2010. We filled those NULL values using modal imputation under two different neighbourhood window sizes (13 and 25 pixels). Next, a 5km buffer was added around Montérégie so as to improve the Circuitscape results later down the pipeline (see the Connectivity Analysis section). Not all NA cells were due to the difference in forest cover between 1990 and 2010, some were due to the fact that the LANDIS run did not cover some parts of the 5km buffer. Those cells were filled with the value corresponding to the forest type Mixed Forest of Medium Age. We decided on this imputed value because it is among the most suitable for all species and therefore unlikely to cause significant changes in the Circuitscape runs,

even if it does not correspond to the mode or the mean for the region. In addition, because no change takes place in the buffer, those values can be equivalent to a "padding" around the landscape.

A second step was the preparation of the explanatory variables. Vector data was rasterized when needed. A significant effort was invested in working with the Canadian Census data, as Statistics Canada does not make available a spatial dataset for their census data. Therefore, the geometries of DAs and EAs had to be matched with the corresponding line in the Census dataset, based on the unique EA and DA IDs. Some of these (between 2 and 5 % of the total number of DAs or EAs, depending of the time steps) have remained unmatched due to discrepancies between the (spatial) boundaries datasets of EAs/DAs available and the EAs/DAs listed in the StatsCan dataset. This led to areas with NAs values. These areas could not be ignored in our random forest model and had to be imputed. We used mean imputation for lack of a better method but are aware of the large number of issues associated with this practice (see Lodder, 2014).

In order to reduce run time as well as memory requirements, we ran the entire simulation at a 90m resolution, which is an aggregation (resample) of all the data in the rasters by a factor of 3, using a majority rule (changing the resolution of our data to 90m). Finally, all variables were extracted and turned into tabular data. Only relevant pixels (i.e. rows in the dataset) were kept to model each transition. For instance, only forest and agricultural land pixels were kept to model urbanization. The variables were standardized prior to running the model. We used the `tidymodels` framework (version 0.1.0) in R to pre-process our tabular data and run our random forest models.

### 1.3.1.3 Preliminary analysis of past land use change

To better understand land use patterns in the region, we ran some preliminary analysis on land use change data at the municipality level. Montérégie is made up of 177 different municipalities. We generated land use matrices (amount of each land use category) and

land cover transition matrices (1990 to 2010) for each municipality and for the land use categories corresponding to our model. We then performed multivariate analyses by running a first ordination using PCA (Principal Component Analysis), and then using Ward clustering. Because municipalities in Montérégie have variable size, the amount of change in each municipality needs to be standardized. The data was normalized prior to the ordination to reflect relative amounts of change in each municipality. We used the vegan package in R to produce such plots.

#### 1.3.1.4 Model Execution

##### Random forest

###### *Calibration & validation*

Land use change data has a tendency to be highly unbalanced, because over a certain time period, the amount of pixels that have transitioned into a new state is usually small compared to the amount that did not transition into a new state. In the case of Random forest models, there are a few ways to deal with such imbalance. In this work, we simply down-sampled our dataset to reach a ratio of 2:1 (i.e. 2 pixels that did not transition for each pixel that did transition).

The RF model was calibrated on a training partition (70% of the down-sampled dataset) for the timestep of 1990 to 2000. The model was then spatially validated on a test partition (30% of the dataset), and then temporally validated for the timestep of 2000 to 2010 (100% of the dataset for this timestep).

###### *Performance evaluation*

There are a number of ways to evaluate model performance in the context of land use change predictions. We used three different approaches:

- We report the  $R^2$  resulting from the random forest model, as well as variable importance (evaluated as gini impurity score).

- We used a ROC curve with Area Under the Curve (AUC) to compare true observed change with the predicted probabilities of transition. This method is widely used in land use change modeling.
- We used a Conventional Cross Validation (CCV) method for the reporting of AUC values, with 10 folds, for which we also produce a measure of AUC with ROC curves.

### **ST-Sim**

ST-Sim (Daniel et al., 2016) is a State and Transition model (STM) and can therefore be provided with probabilities of land use change. However in order to integrate the results of our random forest models, we parameterized ST-Sim differently than a classic STM. All probabilities are set to 1, and we leverage the spatial multiplier feature of the software. We provide our fitted probability surfaces (outputs of the RF models) as spatial multipliers. Therefore, each pixel's probability of change is provided by that surface (multiplied by 1). This is not enough to reproduce past trends in land use change: we need to provide transition targets to the allocation algorithm. These targets are directly based on the amount of land change between 1990 and 2010 for time steps 1990 - 2010.

#### ***Model definition***

The ST-Sim model uses three states: Forest, Urban and Agriculture. Forest was further subdivided into classes of age and type, derived from the LANDIS outputs: three forest types (**deciduous**, **mixt**, and **coniferous**) and three age classes (**young**, **medium**, and **old**) for a total of 9 classes. The model allows for 4 groups of transitions:

- **Urbanisation**: groups **deforestation** (Forest  $\Rightarrow$  Urban) and **agricultural loss** (Agriculture  $\Rightarrow$  Urban).
- **Agricultural expansion** (Forest  $\Rightarrow$  Urban).
- **Forest Internals**: groups the 72 combinations of forest change between the 9 forest internal states.

The model takes in 3 different strata. A stratum in ST-Sim refers to a subset of the entire landscape being considered for analysis. Strata are typically used to divide the overall landscape into regions or zones, each of which can have different model parameters specified. The three stratum are:

- Primary stratum: delineates Montérégie from the surrounding buffer and highlights protected areas.
- Secondary stratum: delineates municipalities of the region, to allow to set targets specific to each municipality.
- Tertiary stratum: delineates LANDIS land types, to allow to set transition multipliers for forest types that match the LANDIS simulations.

### *Spatial dependency*

Under the parameters defined so far, ST-Sim takes care of transitioning the amount of land corresponding to the targets it is fed, and will do it probabilistically across the landscape according to the probability surface (spatial multipliers). There is an additional way to restrict this change via Adjacency parameters, which are essentially neighborhood rules. Adjacency rules were defined from basic assumptions about transition spread. The list of neighborhood rules given for each transition type (or group) is provided in the appendix table 3–3.

We added two more constraints for the Forest Internals group: the Time since Transition parameter which sets a minimum time of 20 years (2 timesteps) in between transitions between Forest types states. In addition, pathway autocorrelation settings allows to further isolate the characterization of transition rules to the specific land type to which a pixel belongs.

### *Scenario definition*

In the subsequent description, we make the distinction between:

- *historic runs*, parameterized to reproduce the changes that happened between 1990 and 2010 in the region, with a different set of transition targets for 1990-2000 and 2000-2010.
- *forecast runs*, parameterized to project forward an average of the trends observed in the two decades, with a single set of transition targets (average of the two 1990-2000 and 2000-2010 targets) and for which only certain set of spatial multipliers change depending on climatic scenarios.

We defined two land use change scenarios, crossed with two different climate change scenarios, plus a control climate scenario. Those six scenarios in total are designed to encompass the realm of possible future habitat changes for our 5 focal species. The two land use change scenarios are:

- **Business As Usual (BAU)**: the land use change trends are projected forward into the future with no alteration to those trends.
- **Business As Usual + Reforestation (BAU-R)**: the land use change trends are projected forward into the future, and reforestation is randomly occurring, converting to forest as much land as is lost through urbanization, for every timestep.

The climate scenarios influence the probability of transitions between forest types (i.e. succession and disturbances) they subsequently influence habitat suitability and connectivity.

The three climate scenarios are:

- **Historic (HIST)**: No forest change: forest remains as it was in 2010. This is equivalent to a control treatment.
- **Baseline (BASE)**: Forest change continues as it does in today's climate.
- **RCP 8.5 (RCP8)**: The forest changes according to the emissions scenario RCP 8.5, characterized by increasing green-house gas emissions, high rates of population growth, modest GDP growth and low rates of technological development and uptake. It is the most severe of the future scenarios (IPCC, 2013).

### ***Details of scenario parameters***

We ran a total of seven scenarios (one historic run and six forecast runs). Two behaviors remain constant in all seven scenarios: no land use change takes place in the 5km buffer. In addition, new forest laid by the reforestation transition does not change state for the remainder of the simulation (this is because LANDIS does not provide land type data for new pixels). Therefore, reforestation always produces a forest of the class "Medium Deciduous". In all scenarios described, ST-Sim with decadal time steps, for 10 iterations (10 MCMC realization).

The final list of scenarios is the following:

- Historic run - 1990 to 2010 (**HIST**). In this historic run, the forest type for all three time steps was taken from the LANDIS inputs (forest type data 2010). This is of course not accurate, but because no change is allowed to take place, this is not a problem and it is only there to allow consistency and comparison with the other scenarios.
- Forecast land use BAU - Historic climate - 2010 to 2100 (**BAU-HIST**)
- Forecast land use BAU - Baseline climate - 2010 to 2100 (**BAU-BASE**)
- Forecast land use BAU - RCP 8.5 climate - 2010 to 2100 (**BAU-RCP8**)
- Forecast land use reforestation - Historic climate - 2010 to 2100 (**BAU-R-HIST**)
- Forecast land use reforestation - Baseline climate - 2010 to 2100 (**BAU-R-BASE**)
- Forecast land use reforestation - RCP 8.5 climate - 2010 to 2100 (**BAU-R-RCP8**)

### **1.3.2 Habitat suitability and connectivity modelling**

Connectivity modeling is similar to land use change modeling inasmuch as the diversity of methods at the researcher's disposal is large (Calabrese and Fagan, 2004). As mentioned in the intro, we implemented an analysis of Potential Functional Connectivity, or PFC. A typical PFC modeling workflow can be broken down to 3 steps: species selection, Habitat suitability modeling and connectivity analysis. The three steps are described below,

and the methodology partially follows the methodology of Rayfield et al. This part of the methods is summarized in figure 1–2.

### 1.3.2.1 Species Selection

Species selection is unchanged from Rayfield et al. The five species chosen are presented in the appendix table 3–1. It was demonstrated that modeling the connectivity needs of those 5 species was equivalent to modeling the needs of 14 species in the study region (Meurant et al., 2018; Albert et al., 2017)

### 1.3.2.2 Habitat Suitability

Habitat suitability analysis consists in reclassifying land use data into a resistance surface which is then used to model connectivity. For each of the maps obtained from the land use change analysis (for each of the timestep in every iteration and for each of the 5 species), we followed the following steps to reclass land use into resistance:

1. Classify the landscape as **forest** and **non forest**.
2. Reclassify non-forest pixels into resistance following the supplementary tables in Rayfield et al., with only a few alterations. See table 3–5 for the reclassification key.
3. Clump the forest landscape into contiguous **patches** using queen case neighborhood (includes diagonal).
4. Reclassify pixels in all patches as suitable (value = 1) unsuitable (value = 0) or moderately suitable (value = 0.5), based on forest age and type, and following guidelines in the supplementary tables in Rayfield et al. The key for such reclassification is recorded in table 3–4.
5. Compute the mean patch value based on the clumped outputs.
6. Classify each patch as **possibly suitable** or **unsuitable**, with a cut-off value of 0.5.
7. Among the suitable patches, calculate their size.

8. Classify **possibly suitable** patches into **fully suitable** patches or **too small** patches based on their size, using the values provided by Rayfield et al. (see table 3–6).
9. Reclassify patches into resistance, once again following the guidelines in Rayfield et al.’s supplementary tables. See table 3–7 for the reclassification key.
10. Patch the re-classified non-forest map with the re-classified patches map.

Although these steps build on the work of Albert et al., 2017 and Rayfield et al., 2018, we apply a simpler habitat suitability modeling workflow. There are a number of reasons for why we were not able to apply the exact same workflow as in Rayfield et al. First, the resolution of the land use change data differs: we used a 90m resolution versus a 30m resolution for Rayfield et al. This has implications for the minimum patch size required for the two species (*Blarina* and *Plethodon*) which at the resolution of 90m becomes impossible to differentiate. In addition, we did not include a range of variables that were used in Rayfield et al.: forest density, soil drainage, distance from minor versus major roads,

### 1.3.2.3 Connectivity analysis

Methods of connectivity modeling are grounded in important concepts, the most important of which is graph theory (Dale and Fortin, 2010). Graph theory is the study of networks, and describes the properties of the elements (edges and vertices) that make up a network . Applying graph theory to a landscape comes down to collapsing that landscape into a network, from which metrics can be computed, and models can be fitted - for instance dispersal models, which makes metapopulation theory another important concept in connectivity(Hanski, 1999). Metapopulation theory describes how populations of a given species in a landscape persist due to dispersal and gene flow.

In this paper, we analyze connectivity using circuit theory-based software called Circuitscape. Circuit theory is used to simulate the movement of propagules. The software “borrows algorithms from electronic circuit theory to predict connectivity in heterogeneous

landscapes”. It is a free and open software under MIT license developed originally in Python, and now in its 5th version, in Julia (Anantharaman et al., 2019).

For each of the maps produced in the suitability analysis, Circuitscape was run in two directions (“wall to wall” run, McRae et al., 2016): east to west and north to south. This method allowed us to model omnidirectional animal movements, and required that we added the resulting North/South and East/West flow map. The results for each map were therefore added to produce a final set of flow maps for analysis. From these flow maps, we extracted the mean flow for each of the municipalities and for the entire flow map.

## 1.4 Results

We first describe the results of the preliminary analysis on land use change dynamics, then go on to describe the results of the hybrid land use change and connectivity model.

### 1.4.1 Analysis of past land use changes in Montérégie

The clustering and subsequent ordination of the land use change matrices of the 177 municipalities revealed that Montérégie has 5 profiles and land compositions (see figures 3–1, 1–3, and 1–4):

- **Forest - Dominant:** have the lowest level of fragmentation and are dominated by forest
- **Forest - Agriculture:** still have a healthy amount of forested areas but fragmentation is much more pronounced.
- **Agriculture - Dominant:** forested habitat is scarce and most of the remaining forest is classified as “Trees” in the AAFC dataset (forest fragment of less than 1 hectare)
- **Urban - Medium density:** correspond to the front of the wave of urban sprawling
- **Urban - High density:** urban cores make up most of the municipality

The clustering and subsequent ordination of land use change profiles showed that Montérégie has 4 different profiles (see figures 3–2, 1–5, and 1–6):

- **Urban Spread / Deforestation:** forest fragmentation is progressing mainly via the growth of urban land (in the west) or villegiatives pressures (in the east)
- **Urban Spread / Agricultural loss:** agriculture is losing ground to urban land
- **Agricultural Expansion / Fragmentation:** forest is losing ground to agriculture in those municipalities where forest is still quite present
- **Agricultural Expansion / Deforestation:** forest is already scare and is being replaced by agricultural lands These results show interesting regional trends with a front line of fragmentation and deforestation on each side of the region and along the Richelieu river.

## 1.4.2 Random forest Models

### 1.4.2.1 Variable importance

As previously mentioned, the primary goal of this chapter is not to draw strong inference with regards to land use change drivers in the region. It is still worth noting that the most important variables to predict urbanization and agricultural expansion in our model are the distance from urban land and size of forest patches, respectively (see 1–1). This demonstrates that small patches close to urban areas are the most under threat of conversion in the region.

### 1.4.2.2 Model performance

The reported adjusted  $R^2$  for our urbanization and agricultural expansion random forest models are 0.57 and 0.56 respectively. The values for AUC are comparatively higher: varying between 0.841 and 0.931 (depending of the validation set) for Agricultural Expansion and between 0.921 and 0.939 for Urbanization (see summary table 1–2 and see figures 3–3 and 3–4 for the spatial validation ROC curves). The resampled AUC (10-folds CCV) is equally as high with means of  $0.929 \pm .002$  and  $0.938 \pm 0.002$  respectively (see figure 3–5 for the 10-fold ROC curves).

### **1.4.3 Land Use Change Model**

#### **Historic run (1990 - 2010)**

Our land use change model managed to match appropriately the amount of change observed in the region (i.e. the number of pixel that transitioned between two time steps). However, it only managed to approximate the spatial patterns of change in the region, as can be seen in figures 1–7 and 1–8, where predictions from all iterations were averaged into one prediction surface. The patterns of change around built areas is rather fuzzily matched, with a large number of pixel with a small probability of change, indicating low certainty in most of the model predictions. Although the predictions retain a rather high AUC (0.858 for agricultural expansion and 0.784 for urbanization), they achieve low average precision (0.383 for agricultural expansion and 0.287 for urbanization). These numbers drop even lower if AUC and precision are calculated on a per-iteration basis and then averaged (see 1–4 for a detailed breakdown). On the one hand, this can be seen as a sign that the model did not over-fit the data. On the other hand, it is difficult to know at which point a land use change model has under-fitted the data, and therefore we should not hold too much confidence in the fact that our model has been able to accurately replicate the land use change patterns observed between 1990 and 2010. Instead, the model should be considered as an approximation and a generalization of the patterns that are observed in the region.

#### **Scenario runs (2010 - 2100)**

With the results of the Business as Usual scenario (BAU), we can give an idea of what the region will look like in 2100, if the same rate of urbanization, agricultural expansion and deforestation remain on par with the rates of 1990-2010. The projected land use at the 2100 horizon, as can be seen in ??, shows that most of the small remaining forest patches among the agricultural matrix have been replaced by agriculture, and that most of the urban centers have grown, leading to deforestation even in bigger patches surrounding urban zones. The two trends in terms of development are the expansion of the cities on the

south shore of the Saint Lawrence, and the growth of eastern city centers such as Granby. these patterns is on par with the results of the profiling of the municipalities described above, and illustrated in figure 1–6).

In the case of the Reforestation (R) scenario, which allows urban land to continue to increase following the 1990-2010 trend, but also enforces that as much forest is replanted, we see a decrease in agricultural land of about x% more in comparison of in the business as usual scenario, necessary to compensate for the increase in forest. As we can see in figure ??, [...].

#### 1.4.4 Connectivity Modelling

##### Historic run (1990 - 2010)

While our land use change model only managed to approximate the spatial patterns in land use change, it better managed to replicate the observed change in mean current flow in the region. Figure 1–10 illustrate that the model results are close to the observed changes. Whereas we observe a drop in about 1.5 to 3 % in mean flow (depending on the species), the model tends to overestimate the drop, and the difference in estimation range from 0.5 to 1 points. However, it is clear that given the distribution of flow values in the region, the mean is not capturing all of the nuances in the model predictions. As it can be seen in the histograms of the flow values in figure ??.

##### Scenario runs (2010 - 2100)

**Current flow** We observe a clear difference in changes to current flow between the two scenarios (**BAU** and **Reforestation**, with a significant difference in the slopes of the two scenarios, independently of the species that is considered (see 1–11). Although both scenarios still predict a trend of decreasing mean flow, not all species react with the same amplitude. Only the Black bear (and, to a lesser extent, the Short-tailed shrew), manage to maintain a similar level of mean flow under the Reforestation scenario. The fact that

the width of difference between those two extreme scenarios is larger for those two species possibly indicate more uncertainty with regards to the real future trajectory of the species to the 2100 horizon.

A second observation can be made about the impact of climate change on the species' response. For both the Black bear and the Wood frog, climate change seems to have no impact on their response. The short-tailed shrew and the Reb-back salamander both seem to experience less losses in scenarios with more intense warming - this was to be expected given their preference for deciduous and mixed forest over coniferous forest. Finally, as expected, the most extreme variation in responses is to be found in the American marten. Interestingly, a Baseline scenario improves the outcome over an Historic scenario for this species. However, the RCP8.5 scenario brings about a significantly lower average mean flow, regardless of the scenario considered (see 1–12 for a radar representation of outcomes from figure 1–11).

Finally, while we see that all species reacted linearly to the BAU scenario, we see some non-linear responses to the Reforestation scenario in the Short-tailed shrew, the Black bear and the American marten. This non-linearity is only observed under non-Historic climate scenarios (i.e. changing climate), indicating a possible interaction between climate and land use change. The Reb-back salamander and the Wood frog's responses remain linear under this scenario.

Finally, it is important to remark on the extremely low uncertainty around the line in figure 1–11, indicating all 10 iterations in our model behaved similarly and lead to extremely low variability in terms of change in mean flow.

***Histograms*** [...]

## 1.5 Discussion

## 1.6 Conclusion

## Figures & Tables

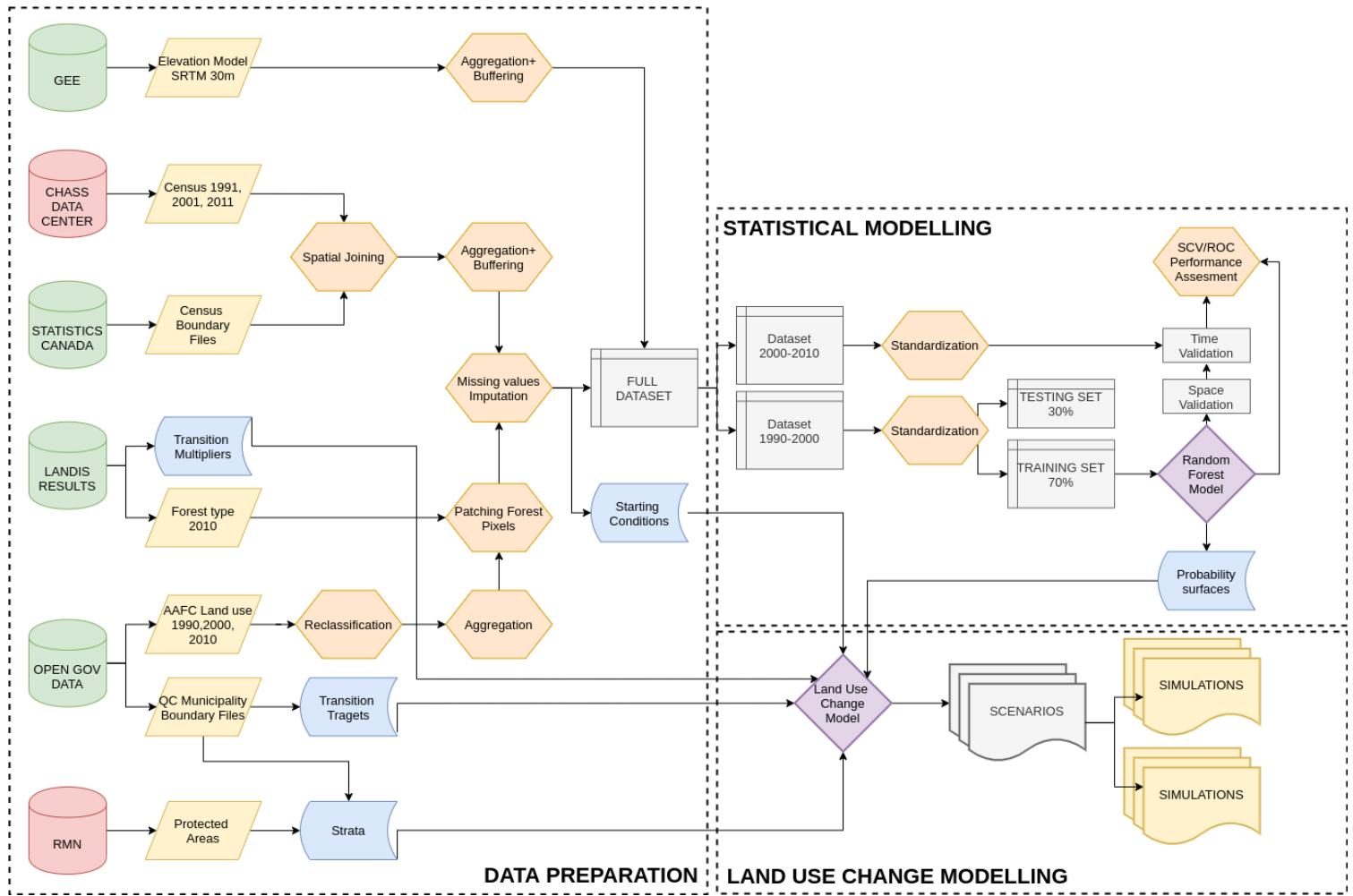


Figure 1–1: Workflow for data preparation, statistical modelling and land use change modelling.

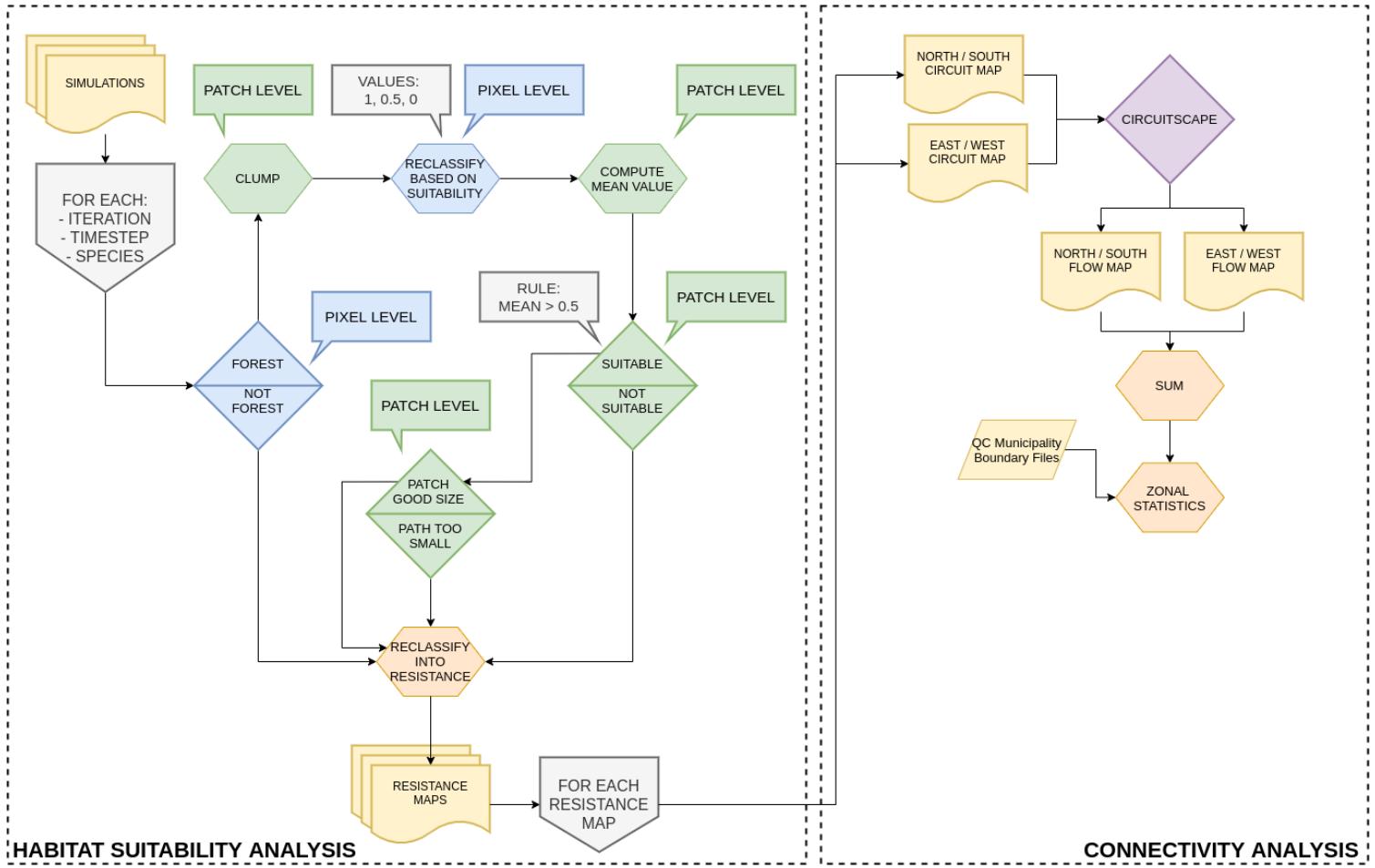


Figure 1–2: Workflow for the habitat suitability and connectivity analyses.

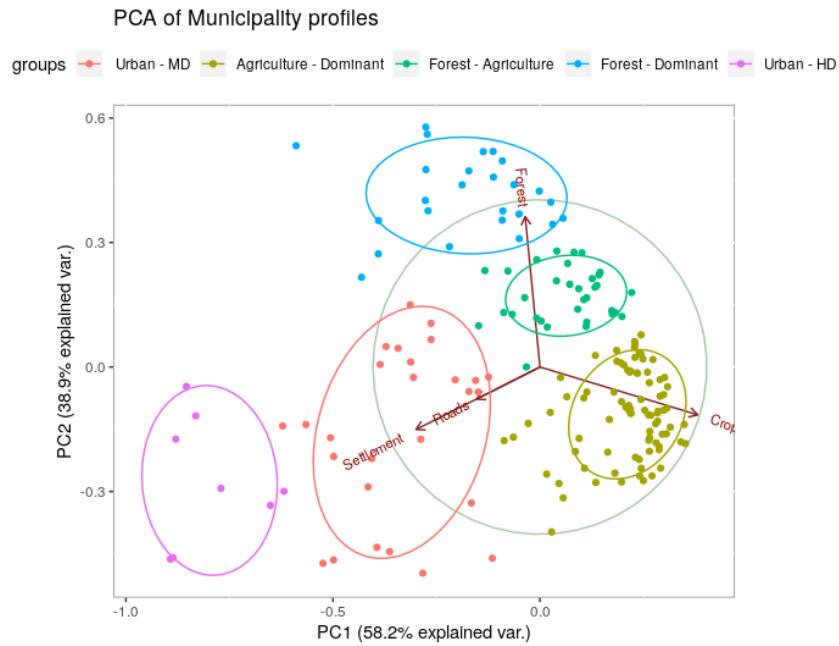


Figure 1–3: Ordination of land use data (proportions) for municipalities. Groups are derived from clustering in 3–1

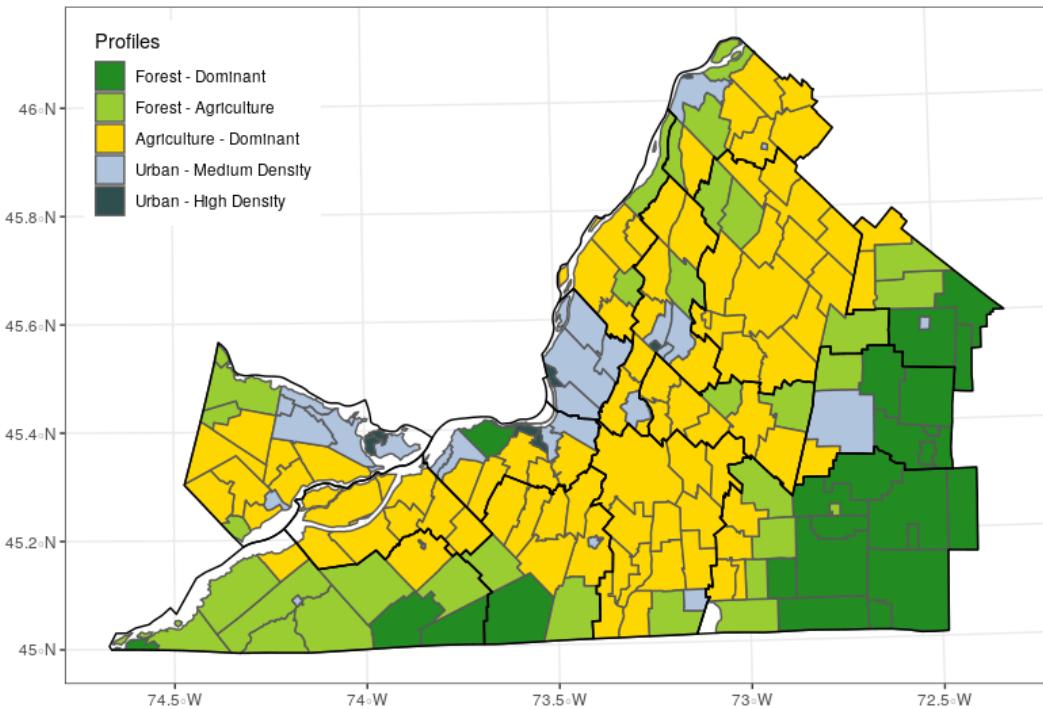


Figure 1–4: Geographical distribution of the 5 profiles identified in 3–1 and 1–3.

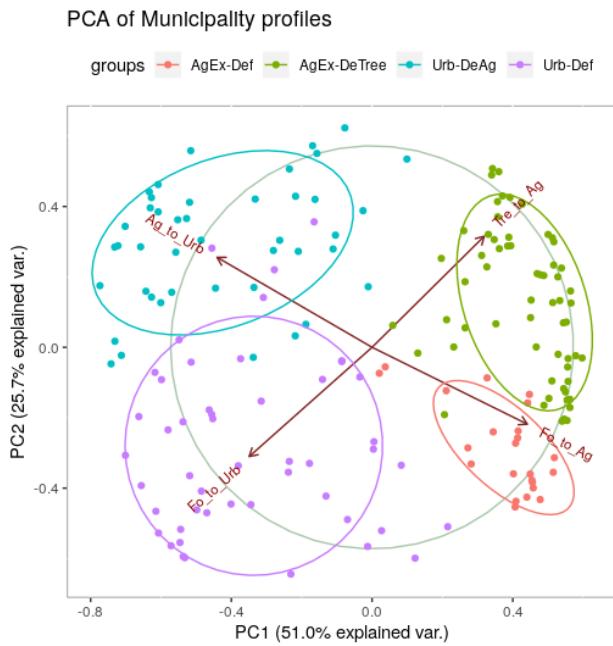


Figure 1–5: Ordination of land use transition data for municipalities. Groups are derived from clustering 3–2

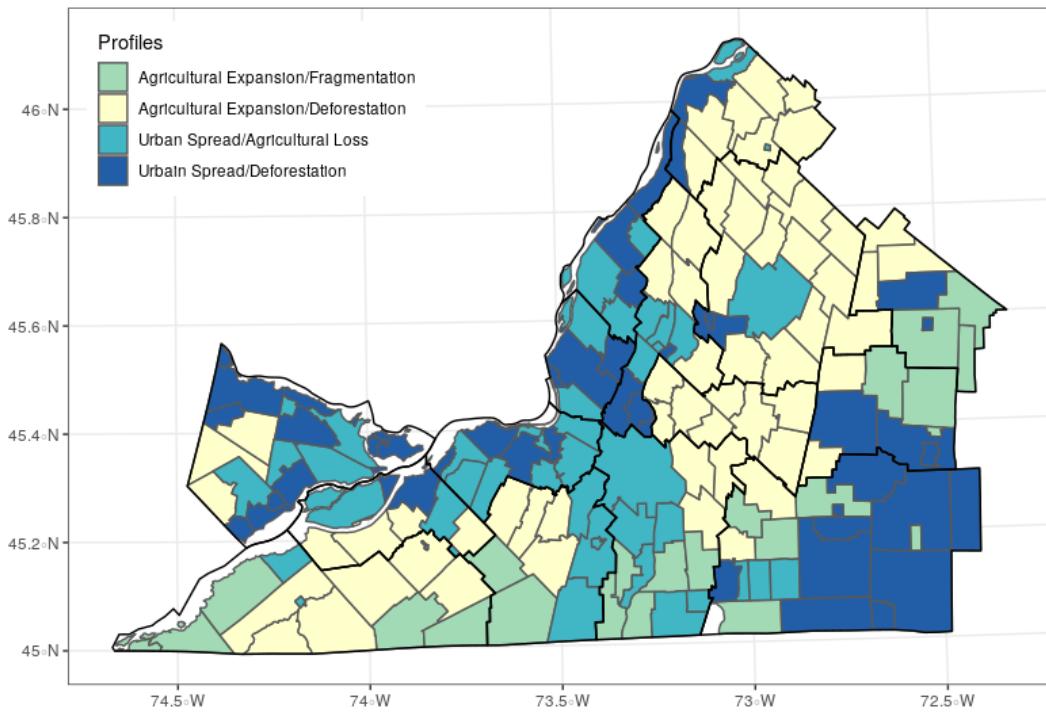


Figure 1–6: Geographical distribution of the 4 change profiles identified in 3–2 and 1–5.

Table 1–1: Variable importance (gini impurity index) for both models - non-categorical variables only

Variable	Model	
	Urbanisation	Agricultural expansion
Distance from urban land	756.8292	1787.357
Size of forest patch	548.5826	5373.270
Elevation	580.9726	1823.918
Population change	447.1120	1138.319
Income	390.5668	1108.612

Table 1–2:  $R^2$ , AUC, and average precision values for both models and both validation sets.

Model	Validation set	$R^2$	AUC	Average Precision
Agricultural Expansion	Spatial	0.566	0.931	0.652
Agricultural Expansion	Temporal	0.566	0.841	0.023
Urbanization	Spatial	0.573	0.939	0.234
Urbanization	Temporal	0.573	0.921	0.250

Table 1–3: AUC values for both models in resampled 10 folds CCV.

Model	Mean AUC +/- Std
Agricultural Expansion	$0.929 \pm 0.002$
Urbanisation	$0.938 \pm 0.002$

Table 1–4: test

Model	Mean AUC (Averaged Surface)	Mean Precision (Averaged Surface)	Mean AUC +/- Std (All iterations averaged)	Mean Precision +/- Std (All Iterations averaged)
Agricultural Expansion	0.858	0.383	$0.669 \pm 0.001$	$0.105 \pm 0.001$
Urbanisation	0.784	0.287	$0.618 \pm 0.001$	$0.102 \pm 0.001$

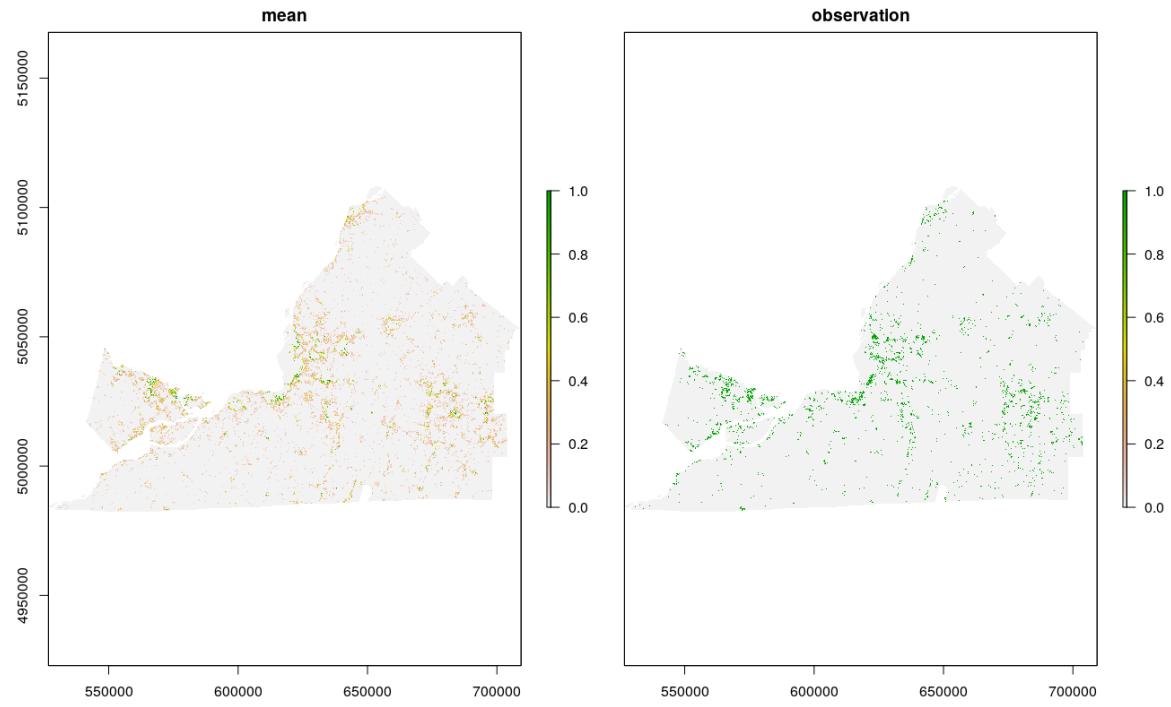


Figure 1–7: Comparison between mean probability of urbanization and actual urbanization observed between 1990 and 2010.

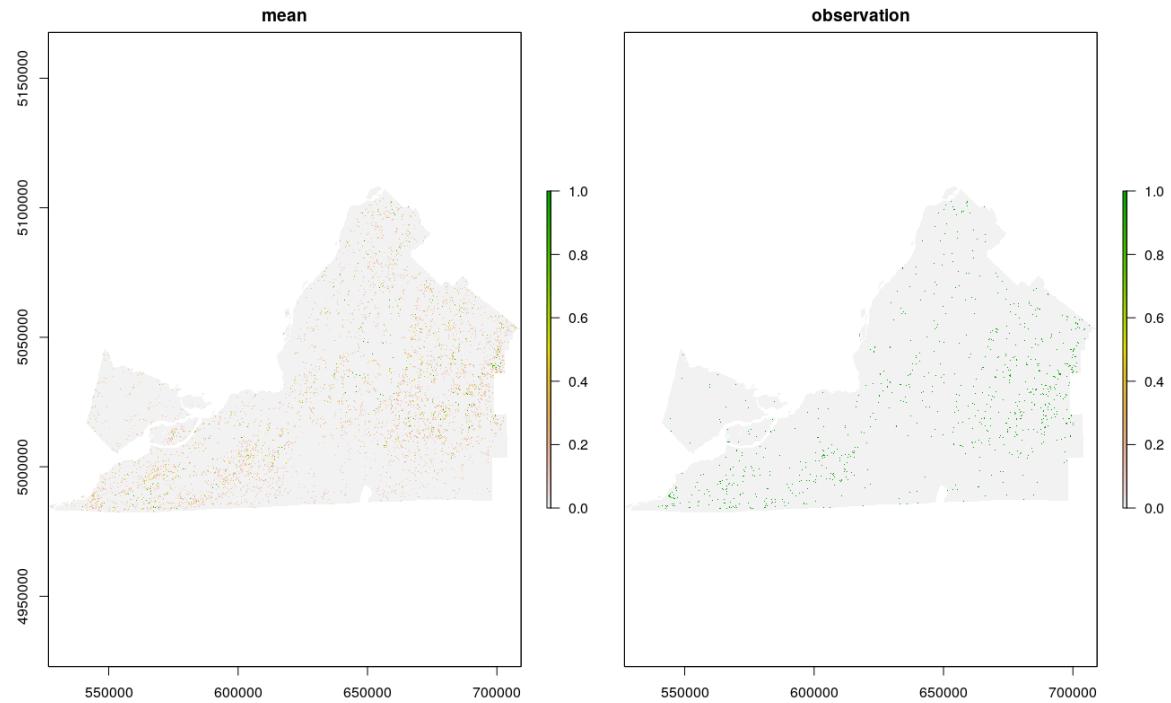


Figure 1–8: Comparison between mean probability of agricultural expansion and actual agricultural expansion observed between 1990 and 2010.

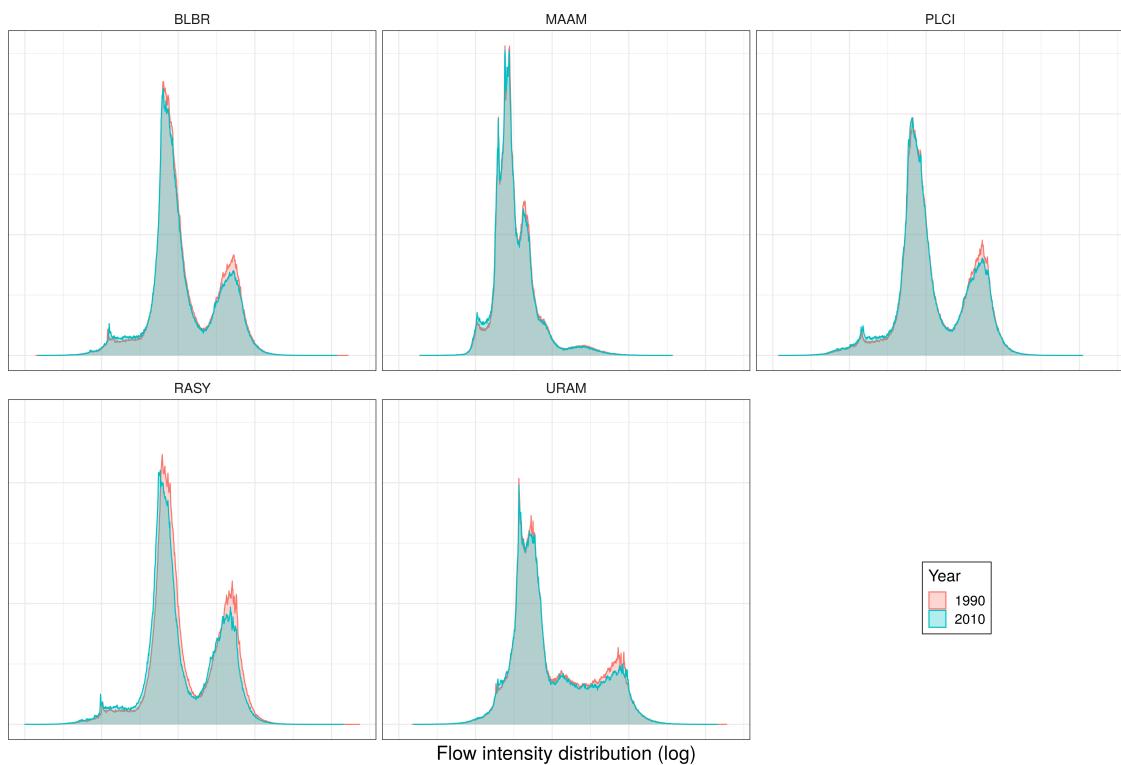


Figure 1–9: Histograms of flow values change between 1990 and 2010.

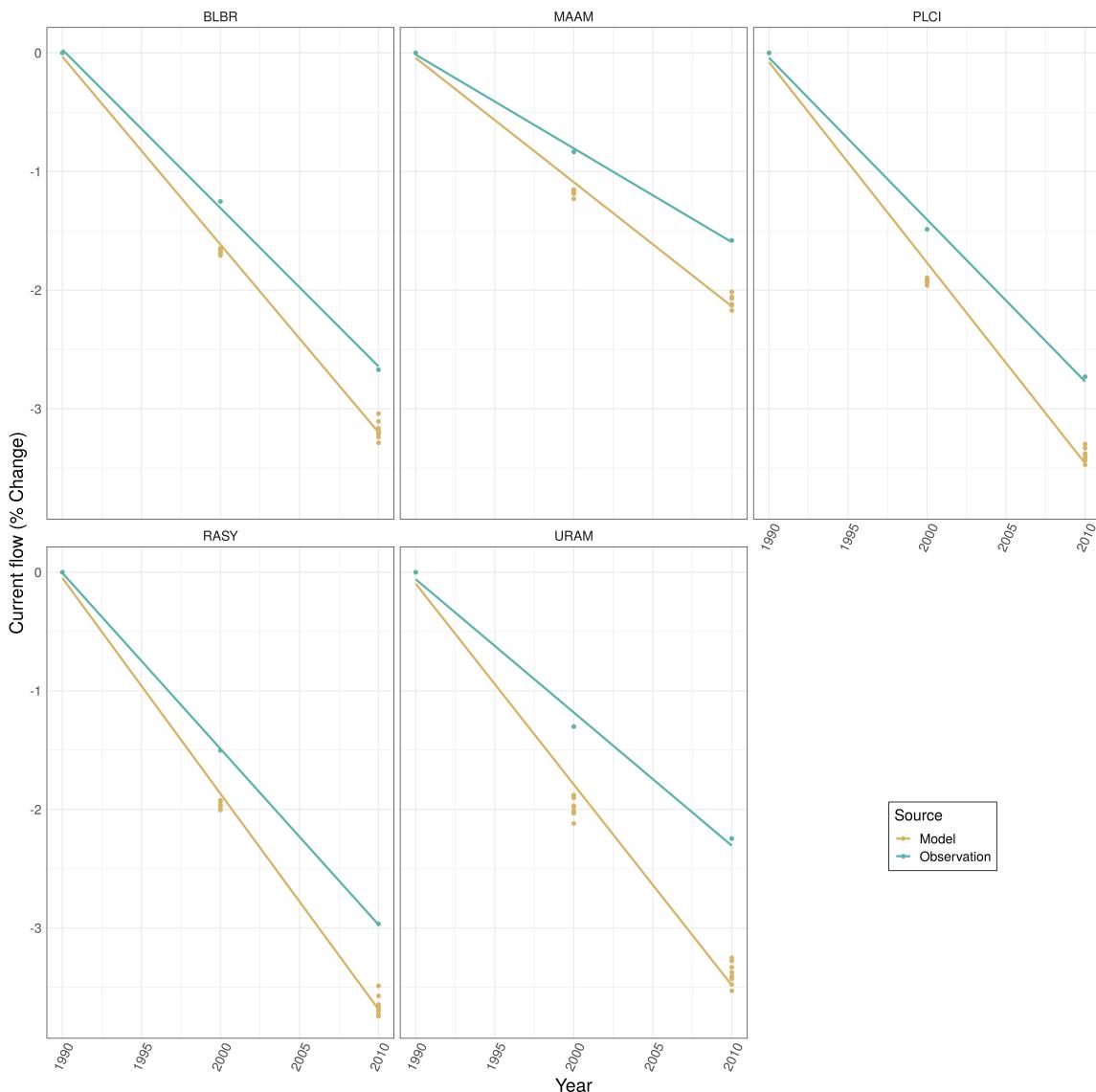


Figure 1–10: Change in mean flow (in % of the the 1990 flow) between 1990 and 2010, contrasting observed change and simulated chnage.

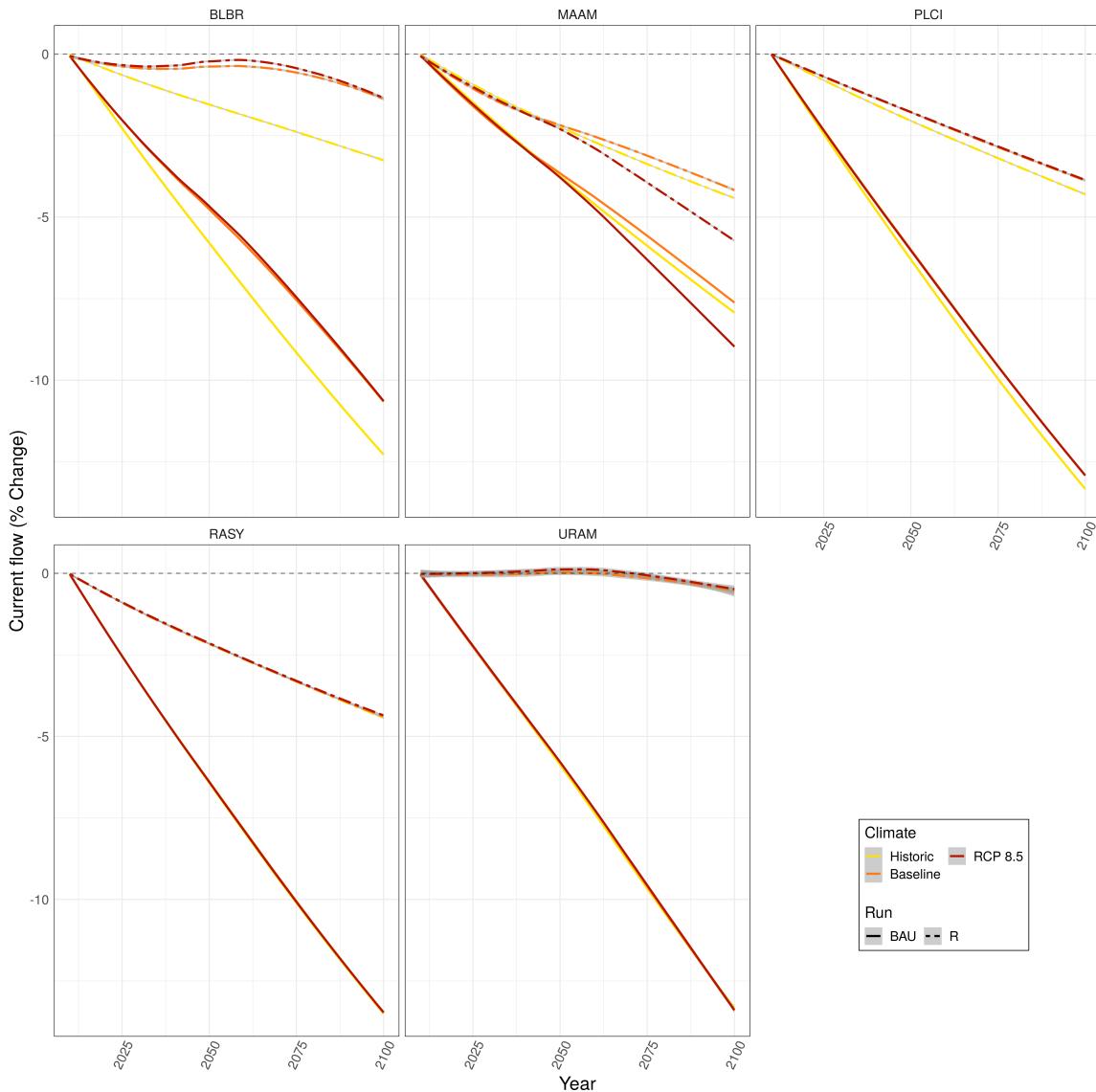


Figure 1–11: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with other land use change scenarios.

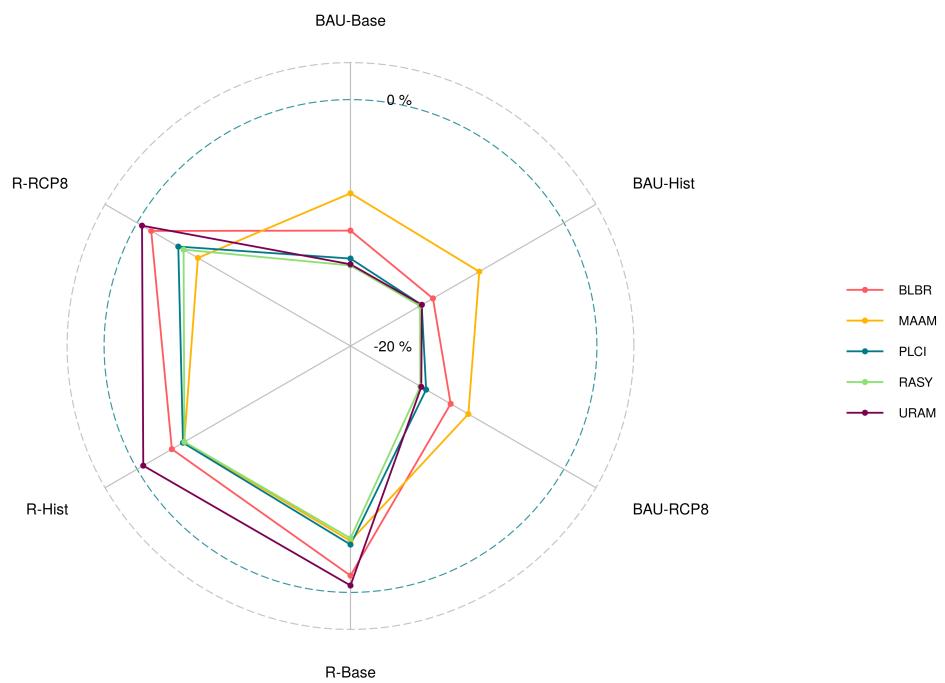


Figure 1–12: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with other land use change scenarios.

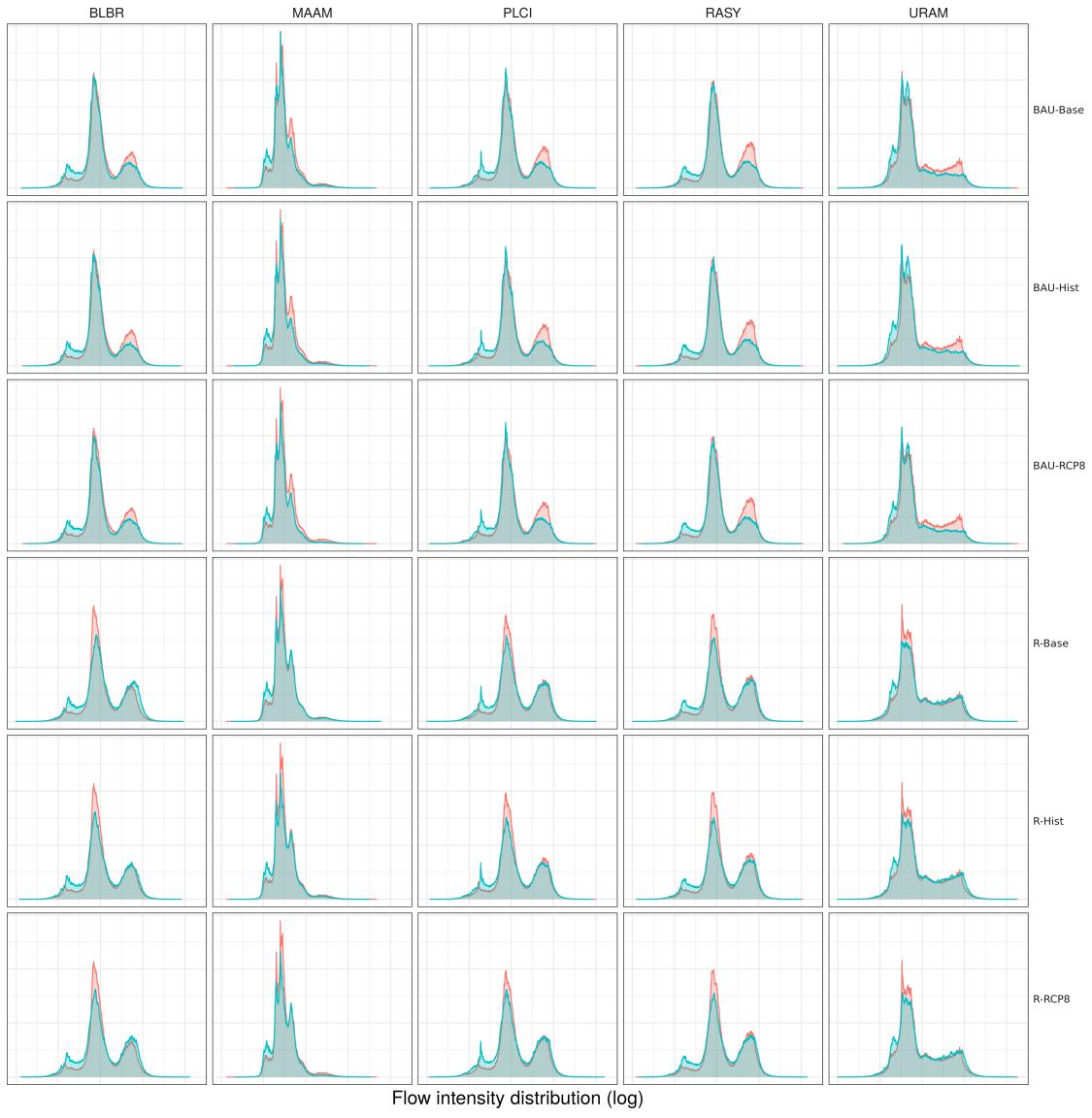


Figure 1–13: Histograms of flow values change.

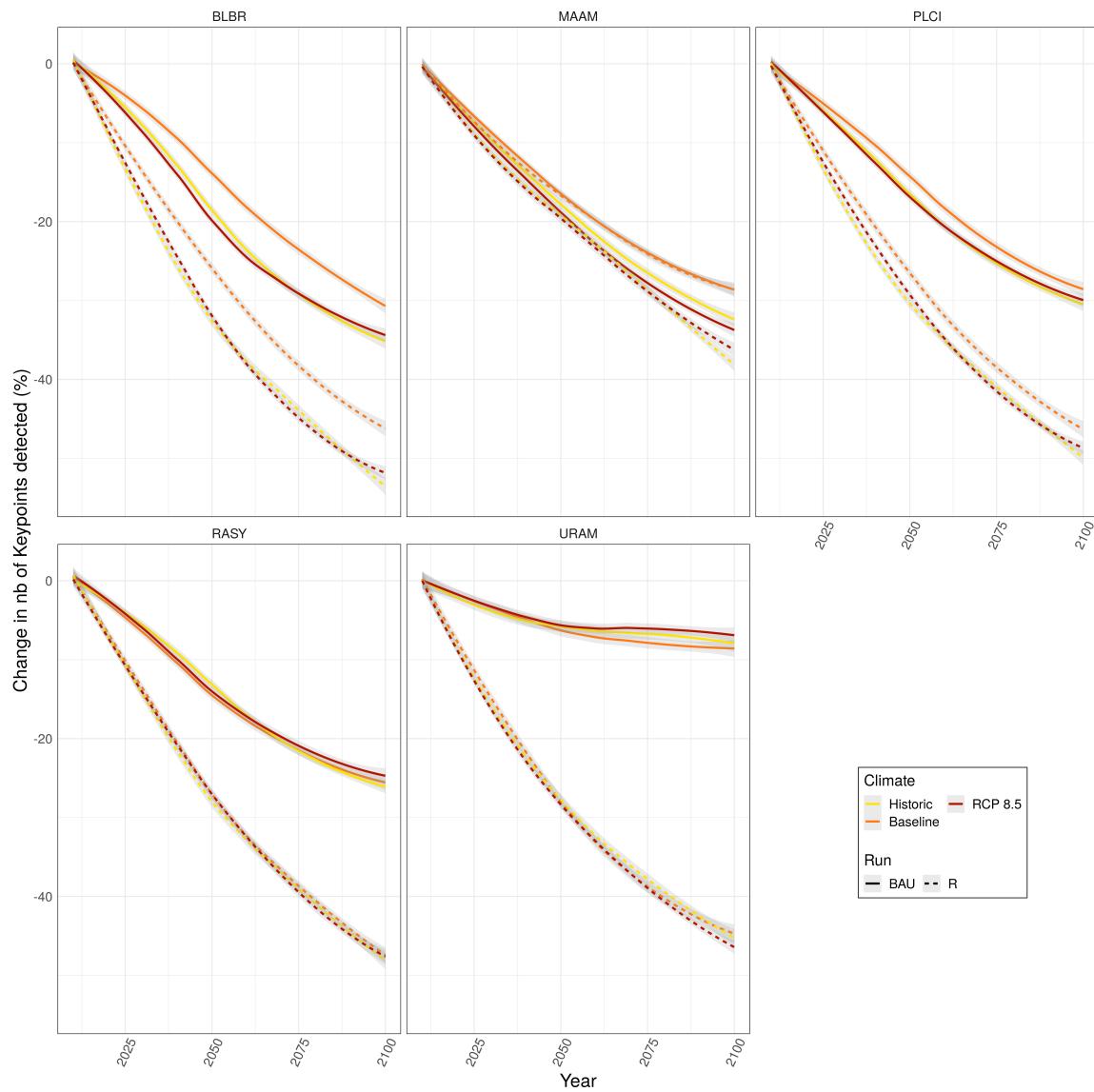


Figure 1–14: Change in identified features (partly pinch-points).

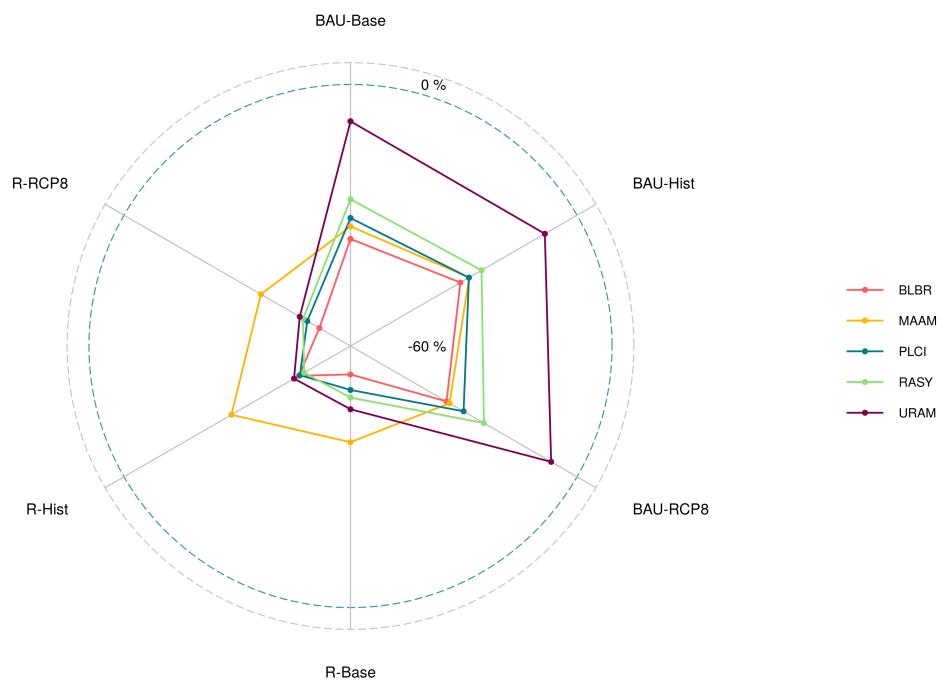


Figure 1–15: Change in identified features (partly pinch-points).

## **Linking Statement**

In Chapter I, I did this, in Chapter II I did that.

## CHAPTER 2

### **Integrating stakeholders perceptions of connectivity conservation priorities into a spatially explicit land use and connectivity change model**

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#### **2.1 Abstract**

#### **2.2 Introduction**

Connectivity conservation methods usually entails modelling connectivity of the landscape of interest and using a prioritisation method to determine conservation priorities. However, current connectivity conservation planning methods fail to confront the results of the prioritisation with the priorities perceived by stakeholders.

Failing to integrate the perceptions of stakeholders is detrimental to conservation for two reasons: first, it most likely mean that conservation will fail to gather enough local momentum to lead to actual policy change, and second, it means that the only tool for decision making will be the modelisations, whereas these are incomplete representation of the landscape and would benefit from inputs from stakeholders. This is especially true in landscapes where a considerable effort of connectivity modelling has already been conducted, like in the landscape of interest in this thesis, the southern Quebec region of Montérégie.

Connectivity conservation is often faced with the issue of understanding the processes driving land use change (Worboys et al. 2010). Because land use change is a social process with consequences of both social and ecological nature, it is best understood within the concept of social-ecological system. A social-ecological system (SES) can be understood as the set of human and non-human actors, the set of natural habitats they inhabit and resources and use, and the set of interactions that are maintained between all

the components of the system (Ostrom 2009). SESs thus form complex and integrated aggregates of interactions (Hinkel et al. 2014). Those interactions also impact governance, the process by which actors in power establish rules and laws (Bissonnette et al. 2018).

Our understanding of SESs often lacks two important elements: social realism and spatial explicitness. We need to build more realistic models for social-ecological systems by being more spatially explicit about the obstacles and opportunities presented by conservation as a land use type. Understanding how these obstacles and opportunities can influence management decisions is crucial for our understanding of connectivity conservation planning, where land-use conflicts can hinder the protection and restoration of connectivity. Although it is relatively easy to identify where land-use changes might conflict with connectivity conservation, evaluating to which extent these conflicts matter in a local conservation context is more difficult (Mitchell et al. 2015).

This study aims to start filling the gap identified by conducting participatory research in Montérégie, in south Quebec, where connectivity conservation has become an important stake. This project has been developed in collaboration with the non-profit NAQ (Nature action Quebec). NAQ invited the QCBS to contribute to their connectivity conservation project (called PADF, or Plan d’Aménagement Durable des Forêts) by co-developing the research described here.

The goal of this chapter is therefore twofold: gain a better understanding of conservation priorities in the region and then compare them to the results of chapter 1. We use a workshop and GIS as the main methodological tool.

### 2.3 Methods

In order to understand what stakeholders perceive as a conservation priority, and derive conservation scenarios from those perceptions, we conducted a community workshop. The workshop was approved by McGill University’s Research Ethics Board (see appendix x for the approval letter). The workshop was held on January 22nd 2020 in the public

library of Saint-Jean sur Richelieu.

### **2.3.1 Community Workshop**

The workshop aimed to gather stakeholders from multiple groups:

1. Representatives of Non-Governmental Organizations that are involved in the conservation of ecological connectivity within the study extent (i.e. Montérégie).
2. Land use planners (“amenagistes”) of the administrative regions covered by the study extent (the 15 MRCs in Montérégie).
3. Representatives of Ministries involved in conservation (MFFP, MELCC).
4. Representatives of the UPA (“Union des producteurs agricoles”) in Montérégie.
5. Representatives of the private forestry industry unions (“producteurs forestiers”)

Of all the groups, only the last group was not represented.

#### **2.3.1.1 Consensual mapping**

We employed a method coined “consensual participatory mapping in geographically structured focus groups”. Participants whose organisations operate in the same region (the same MRC) were seated at the same table. See table 2–1 for the breakdown of each MRC by table. In addition, for participants whose zone of influence or zone of action covered the whole region, two “transversal tables” were created. In the subsequent sections, the workshop results are divided between the regional and transversal tables. The general method proceeded in 3 exercises, each step involving the same focus groups.

- Exercise 1: mapping of forested cores of importance for ecological connectivity.
- Exercise 2: mapping of obstacles (for example: specific land use types, development projects in progress, local legislation) and opportunities for habitat connectivity in terms of social-economic activity and land use.

- Exercise 3: mapping of links (already recognized or potential) of importance between forested cores of importance, taking into account obstacles and opportunities on the landscape.

Each of these three exercises was conducted in 4 to 5 steps. Here we use exercise 1 to describe the method in more detail at each step.

1. Individual reflection - each participant thought on their own about the problem at hand. For instance, participants took time to think about what forested cores are important to connect in the landscape
2. Group discussion, at each table (i.e. in each focus group) each participant contributed their answer to the question posed by the exercise. For instance, participants shared what forested cores they found to be important.
3. Group discussion on the criteria that each participant used to answer the question. For instance, participants said why they thought they chose these forested cores.
4. Consensus building, participants voted for the most important criteria. For instance, participants used stickers that identify their group affiliation to vote for the criteria they found most important.
5. Room discussion: all participants exchanged on their decisions by sharing the results of their table's work to the rest of the room.

Each participant received a unique and neutral identifier of the form Affiliation-Geography. For example, a (hypothetical) land use planner from the table that brought together participants from the Maskoutains region received the code [A-1-1], and the UPA representatives from the Richelieu region received the codes [C-3 -1] and [C-3-2]. In addition, for certain activities, the affiliation of the participants is color-coded. For instance, blue for the land use planners and purple for the ministry representatives.

The coding system manifests itself in multiple ways, depending on the activity:

- When participants engage in activities involving drawing, the materials on which they draw will bear the aforementioned coding (A-1 etc..).

- When participants engaged in activities involving post-its, the color of their post-it represented their affiliation or bore the aforementioned coding, depending on the activity.
- When participants engaged in activities involving a weighting of choices with stickers, the color of their post-it or sticker represented their affiliation or had the aforementioned coding, depending on the activity.

To ensure that this system is used consistently throughout the workshop, each participant was given a personal folder with their own color-coded stickers and post-its. Participants were instructed to only use the stickers and material that have been personally handed to them.

### **Weighting system**

The participants were given a total of 6 stickers to cast their vote for the opportunities and obstacles that they thought were most important. They were given a total of 6 stickers: 2 blue (important), 2 yellow (very important) and 2 red (of the first importance).

#### **2.3.1.2 Data processing and analysis**

##### **Voting: opportunity and challenges**

The data from the opportunities and challenges activity (with post-its), and the weighting of these elements were treated with the following steps:

1. Each post-it (opportunity or challenge) received a unique ID.
2. A first score is calculated by summing the points for each sticker (each vote)
  - 1 point for a blue vote
  - 2 points for a yellow vote
  - 3 points for a red vote
3. This score was then weighted by multiplying it by the post-it's diversity score which served as a measure of consensus

- This diversity score is the inverse simpson index (R package Vegan). The more diverse the group the higher this index is.

These steps were carried out for each table and the results were treated separately for each table because not all tables had the same potential for diversity. For each table, the 10 post-its with the highest scores were retained, 5 among the post-its that had been placed on a specific area of the map (spatialized) and 5 for those that were not. The list of post-it contents, along with the scores, can be found in the appendix tables 3–8 and 3–9. In addition, a map synthetic map of the spatialized post-its was produced (see figures 2–1 and 2–2).

### **Digitization of results**

The priority areas and links were digitized by hand in QGIS. The smooth tool was used to generalize the trace of each area and corridors (see figures 2–3 and 2–4 for the final results). It is important to note that those maps are an approximate representation of reality, as the drawings done during the activity were an approximation of what the participant had in mind.

In order to integrate the results with the land use change model, we added a 5 km buffer around the linkages to simulate a corridor effect. This corridor width size is arbitrary and is in most cases an unrealistic expectation for how large a wildlife corridor can or should be.

#### **2.3.1.3 Conservation and land use change scenarios**

The conservation scenarios were derived with the goal to demonstrate how results of this type of community workshop can be integrated with other planning methods for connectivity conservation, such as land use change and connectivity modelling. They are not meant to be directly used as conservation guidelines. They are unrealistic by definition and are meant to reflect the most extreme bounds of connectivity change and/or protection measures imaginable for the region. More realistic scenarios featuring targeted

action would need to be devised in future community workshops. Although there exists a tremendous amount of work on scenario-building for conservation, specific examples for connectivity conservation are rare. The scenarios presented here are a “proof of concept” for the integration of qualitative results into a quantitative model.

We integrated the results of the workshop with the land use change and connectivity model devised in Chapter 1 by changing two attributes of the model: *conservation status* and *reforestation location*. These additional conservation scenarios are crossed with the climate change scenarios.

Conservation status determines whether or not forest can be cut down, and whether pixels can transition into urban and agricultural land. In Chapter 1, we gave this status to areas that were previously known as protected, but assumed no more forest would be added to this set of protected areas. In this chapter, a protection status is given to all pixels within the identified priority areas and within a 5km buffer around the identified priority linkage areas. All pixels under this status cannot transition into urban land and remain in their state. This represents an unrealistic proportion of the region under protection (about 33

The reforestation status modified what zones can be targeted for reforestation. In reforestation scenarios in Chapter 1, reforestation happened randomly (barring some neighboring rules). In this chapter, reforestation is targeted to the same areas identified in the workshop (all pixels within the identified priority areas and within a 5km buffer around the identified priority linkage areas). As in the model described in Chapter 1, all new reforested area takes the value of medium aged (30-50 yr) deciduous forest and remain in this state for the rest of the simulation. As previously mentioned, this assumption is necessary because LANDIS surface types are not available for newly forested areas. For the same reason, no forest transitions are allowed for this forest type. These two assumptions are conservative: we do not impose succession or disturbance on these newly forested areas and assume medium age as an average age class.

The three modified conservation and land use change scenarios are therefore:

1. Business as usual land use change + corridor protection (**BAU-Corr**)
2. Business as usual land use change + corridor protection + reforestation (**BAU-R-Corr**)
3. Business as usual land use change + corridor protection + targeted reforestation (**BAU-R(T)-Corr**)

#### **2.3.1.4 Connectivity analyses**

In order to be able to compare the results of these new scenarios with those developed in Chapter 1, we conducted the same connectivity analyses using the Circuitscape software. The software “borrows algorithms from electronic circuit theory to predict connectivity in heterogeneous landscapes”. It is a free and open software under MIT license developed originally in Python, and now in its 5th version, in Julia (Anantharaman et al., 2019).

For each of the maps produced in the suitability analysis, Circuitscape was run in two directions (“wall to wall” run, McRae et al., 2016): east to west and north to south. This method allowed us to model omnidirectional animal movements, and required that we added the resulting North/South and East/West flow map. The results for each map were therefore added to produce a final set of flow maps for analysis. From these flow maps, we extracted the mean flow for each of the municipalities and for the entire flow map.

## **2.4 Results**

## **2.5 Discussion**

## **2.6 Conclusion**

## **Figures & Tables**

Table 2–1: Breakdown of the area covered by each table in the workshop

<b>Table</b>	<b>MRCs</b>
Ouest (West)	Vaudreuil, Haut SL, Beauharnois
Centre (Center)	Jardins, Haut Richelieu, Rouville, Roussillon
Nord (North)	Longueuil, Marguerite d'Youville, Vallée du richelieu, Pierre de Saurel, Les Maskoutains
Est	Brome-Missisquoi, Haute Yamaska, Acton
Transversal (x2)	Toute la Montérégie (All of Montérégie)

# Cartographie Consensuelle de la Connectivité Écologique en Montérégie

Résultats de l'atelier du 22 janvier 2020

Tables Régionales

- ◆ Atout
- ◆ Contrainte
- Ensembles à connecter en priorité
- - - Limites des tables de travail

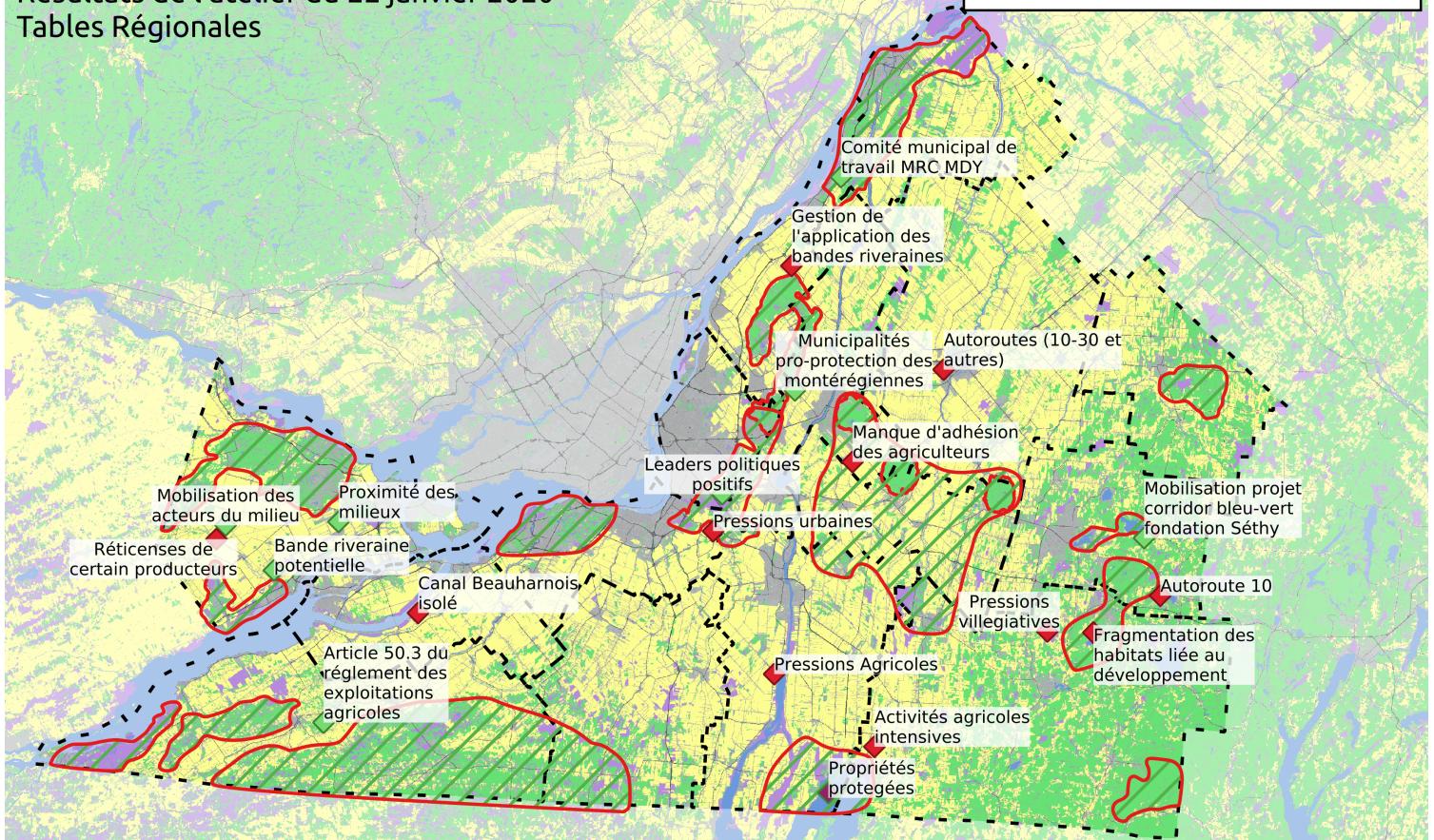


Figure 2–1: Cartography of opportunity and challenges with the highest importance and diversity metric (Regional tables).

# Cartographie Consensuelle de la Connectivité Écologique en Montérégie

Résultats de l'atelier du 22 janvier 2020

Tables Transversales

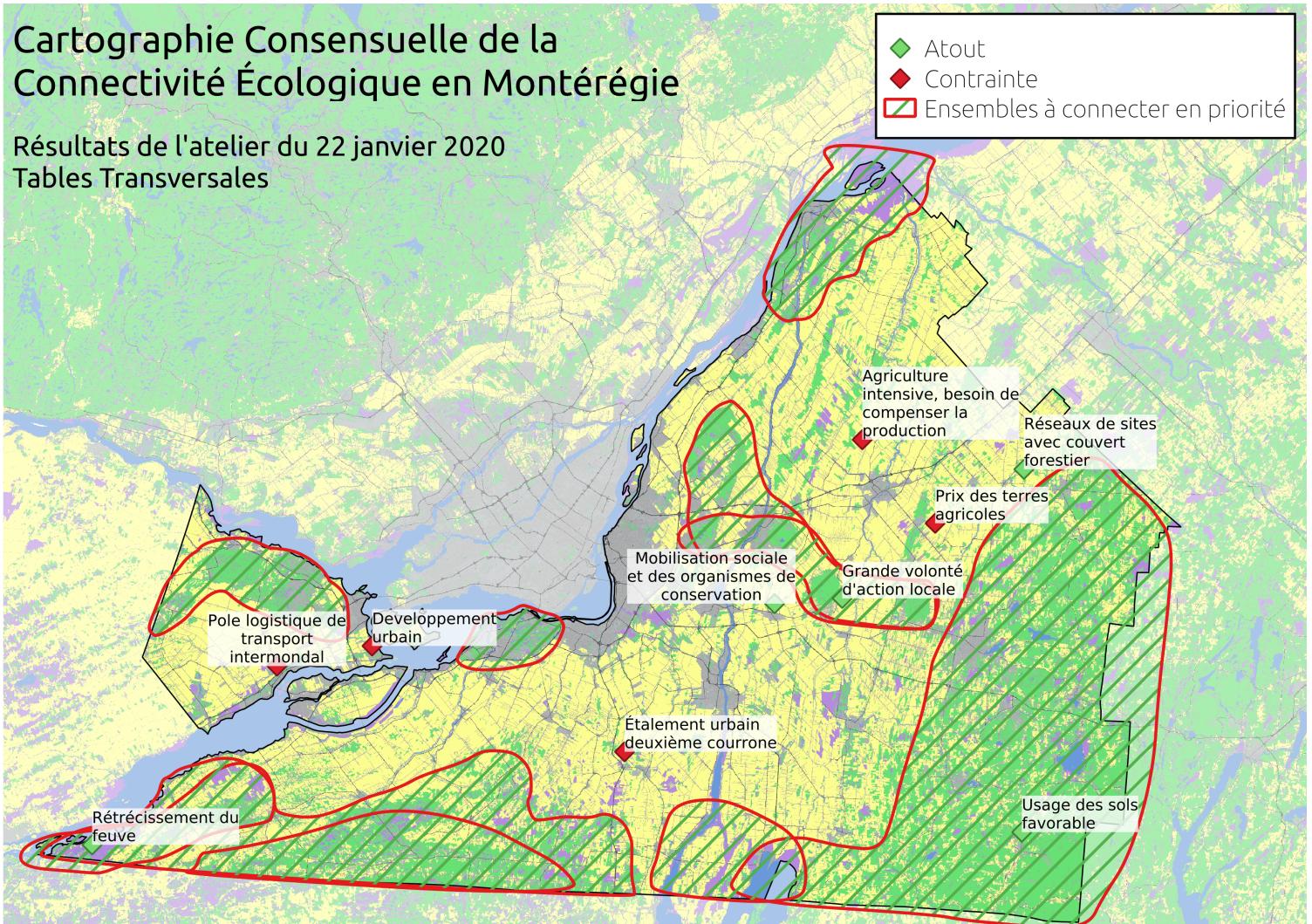


Figure 2–2: Cartography of opportunity and challenges with the highest importance and diversity metric (Transversal tables).

# Cartographie Consensuelle de la Connectivité Écologique en Montérégie

Résultats de l'atelier du 22 janvier 2020

Tables Régionales

- Lien prioritaires
- Ensembles à connecter en priorité
- - Limites des tables de travail

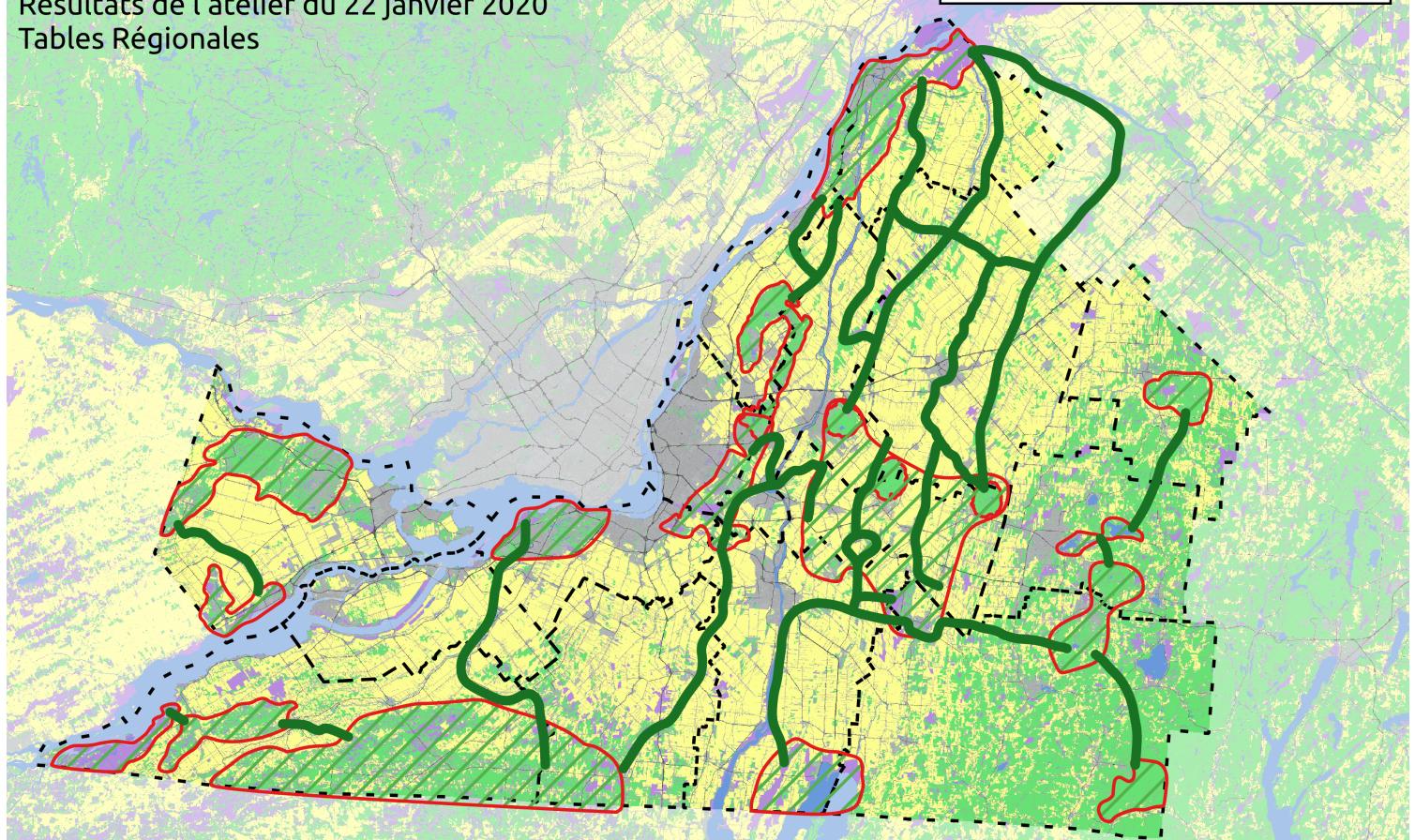


Figure 2–3: Cartography of priority areas and links (Regional tables).

# Cartographie Consensuelle de la Connectivité Écologique en Montérégie

Résultats de l'atelier du 22 janvier 2020

Tables Transversales

- Lien prioritaires
- Ensembles à connecter en priorité

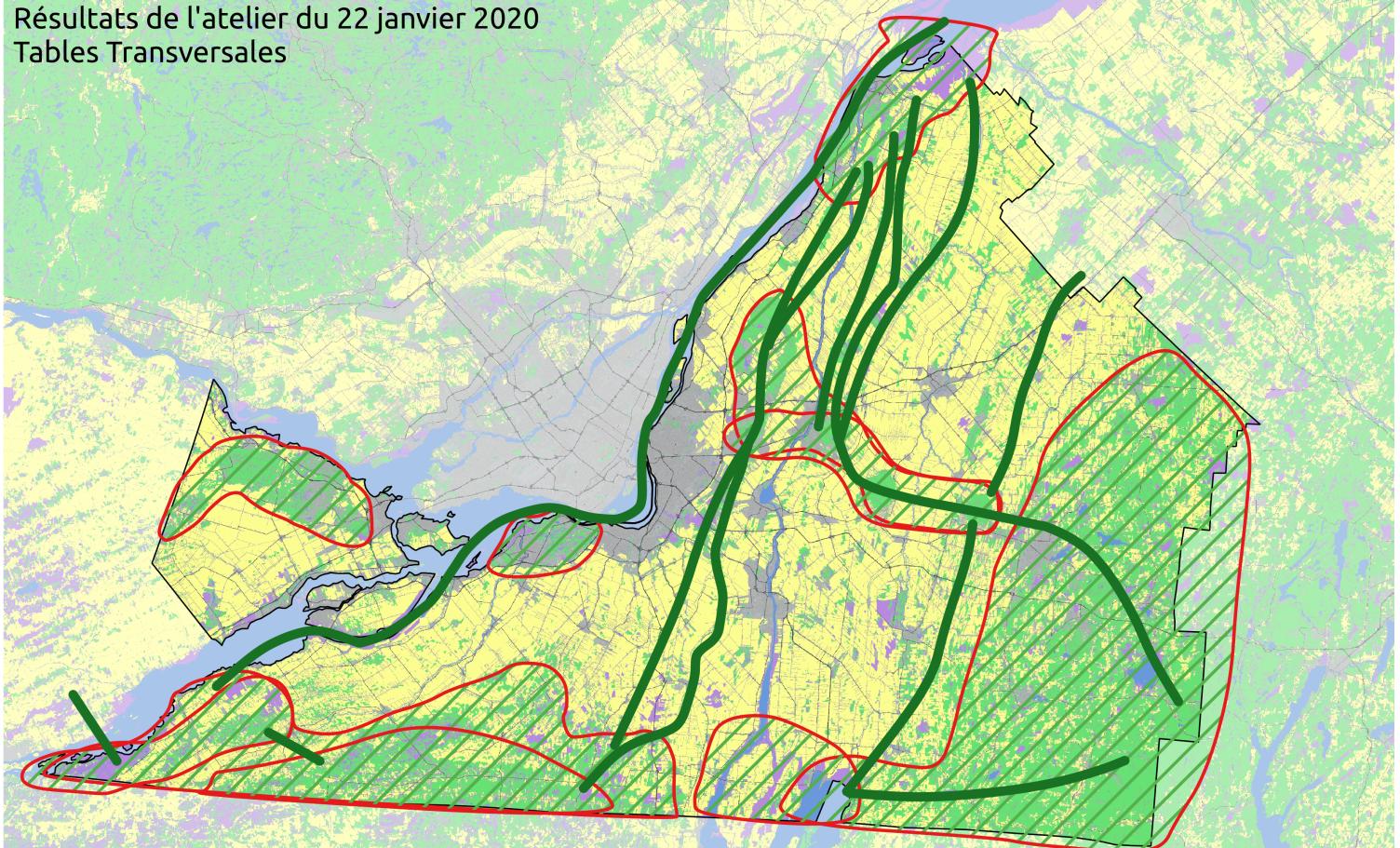


Figure 2–4: Cartography of priority areas and links (Transversal tables).

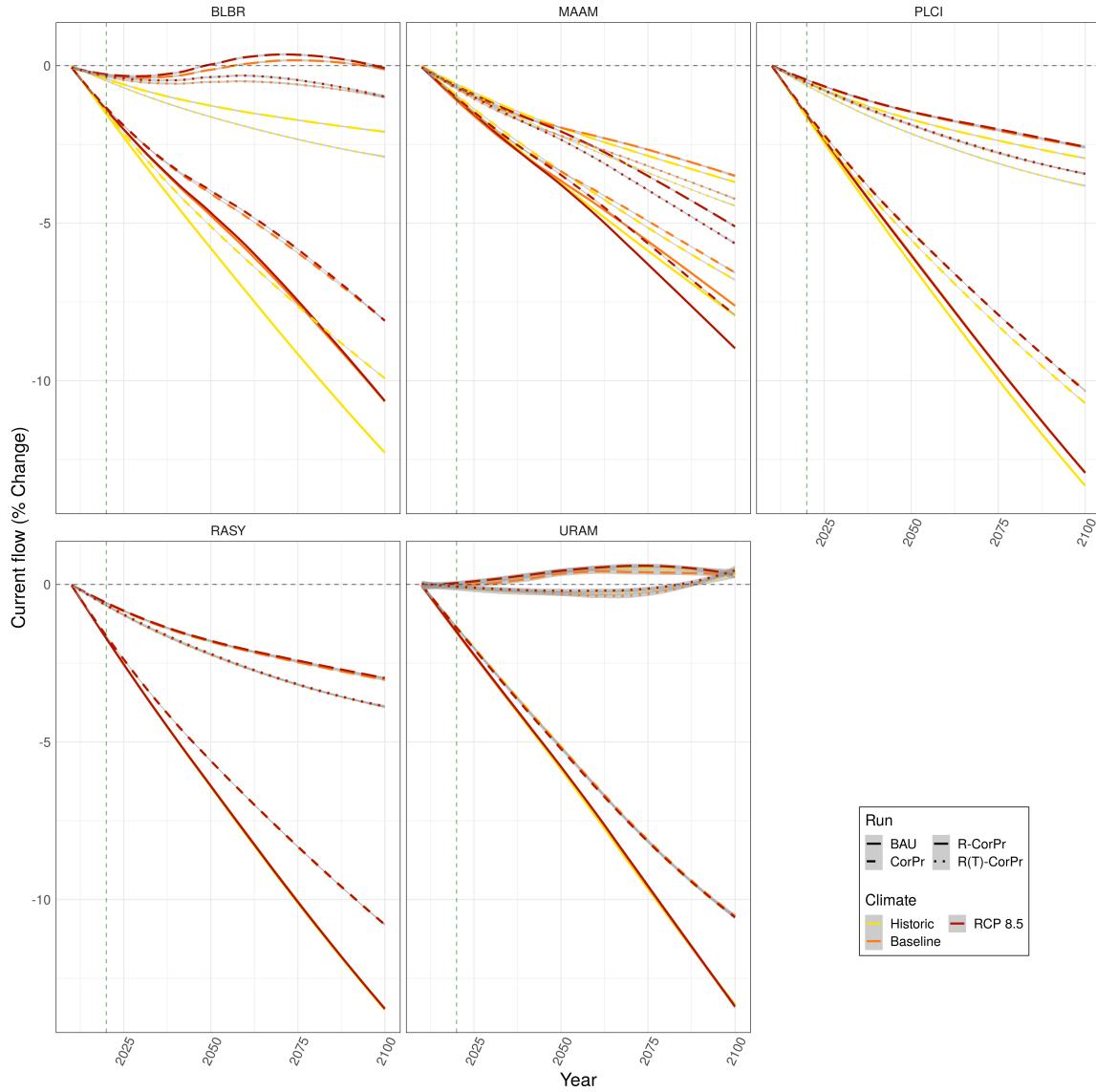


Figure 2–5: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with conservation scenarios.

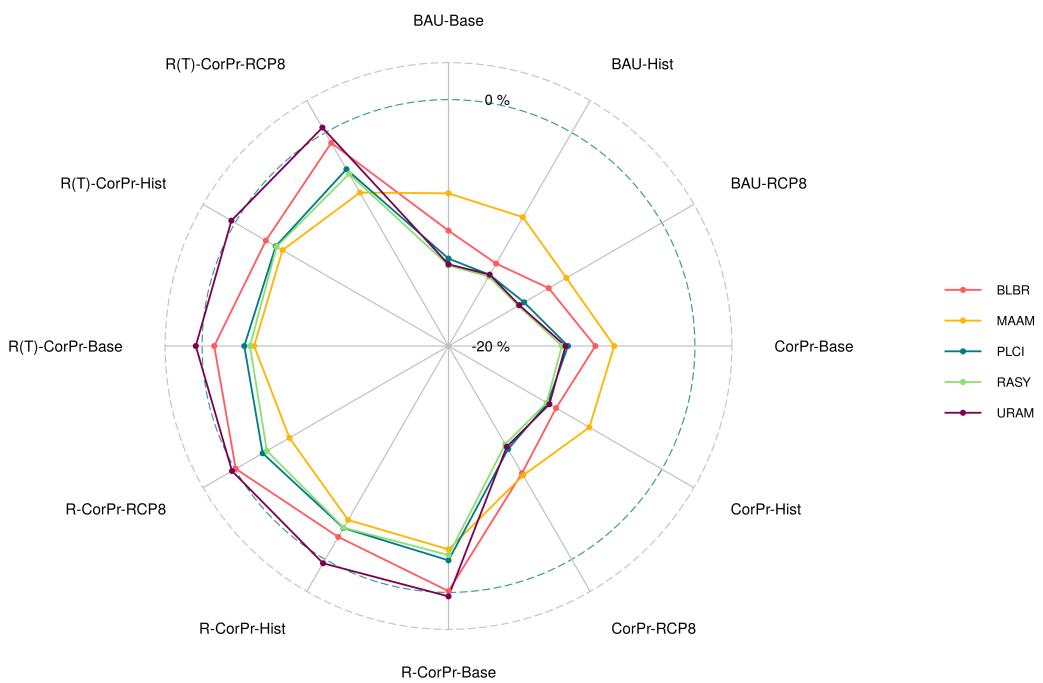


Figure 2–6: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with conservation scenarios.

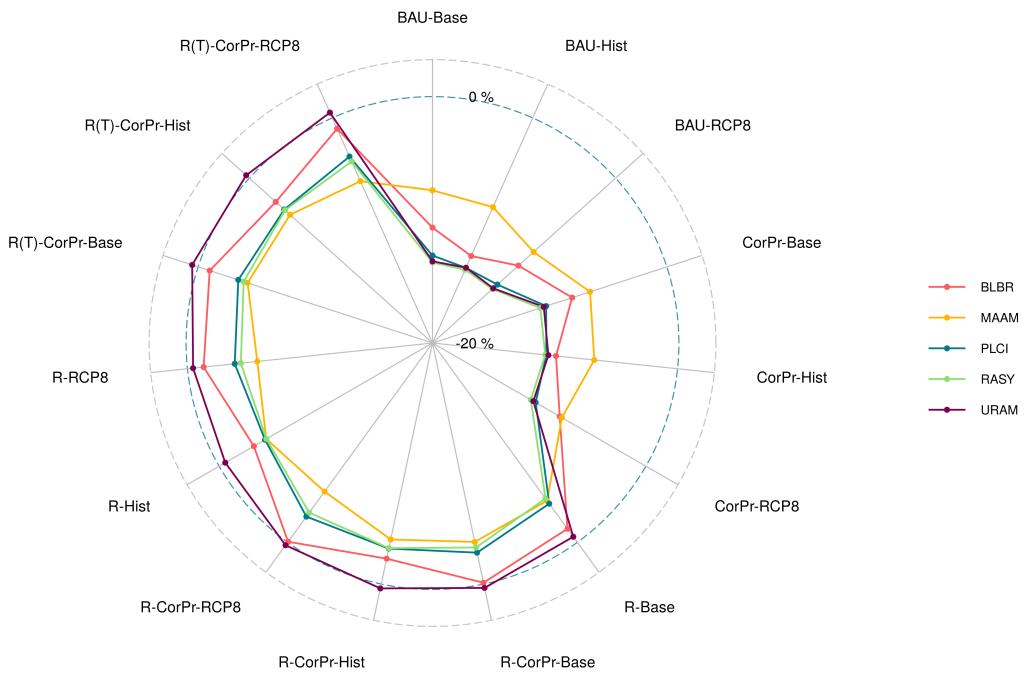


Figure 2–7: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with both other land use change and conservation scenarios.

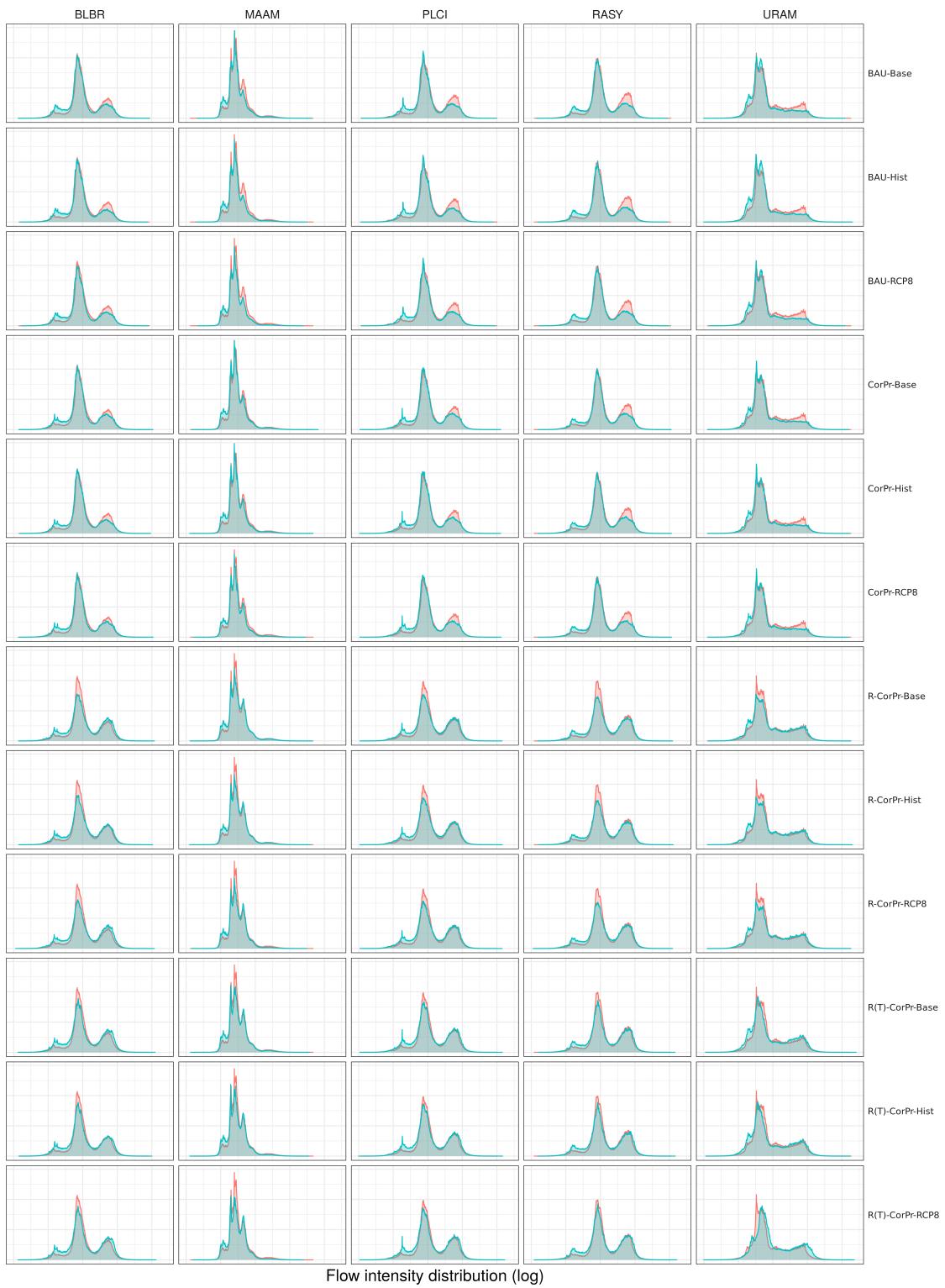


Figure 2–8: Histograms of flow values change.

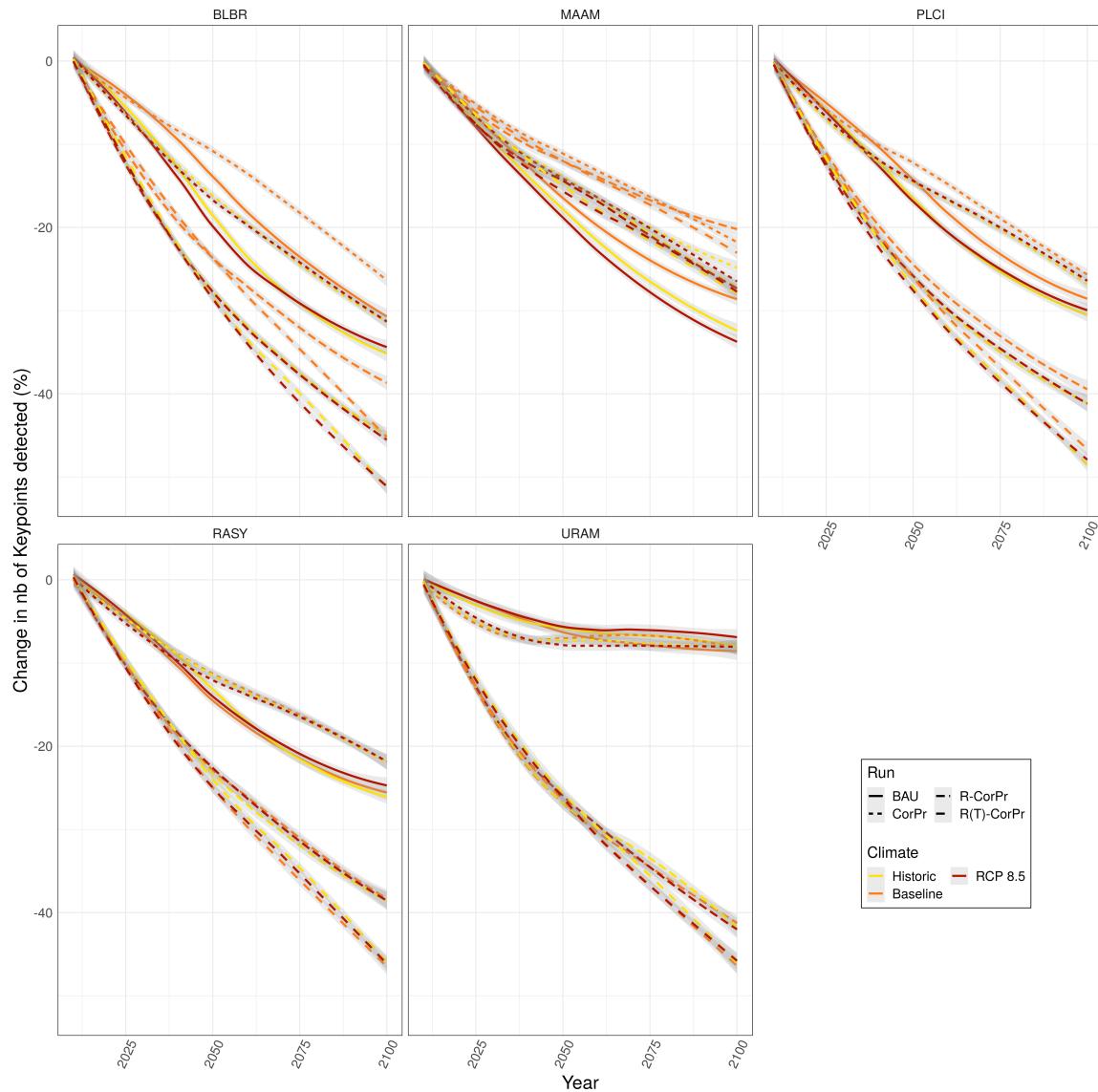


Figure 2–9: Change in identified features (partly pinch-points).

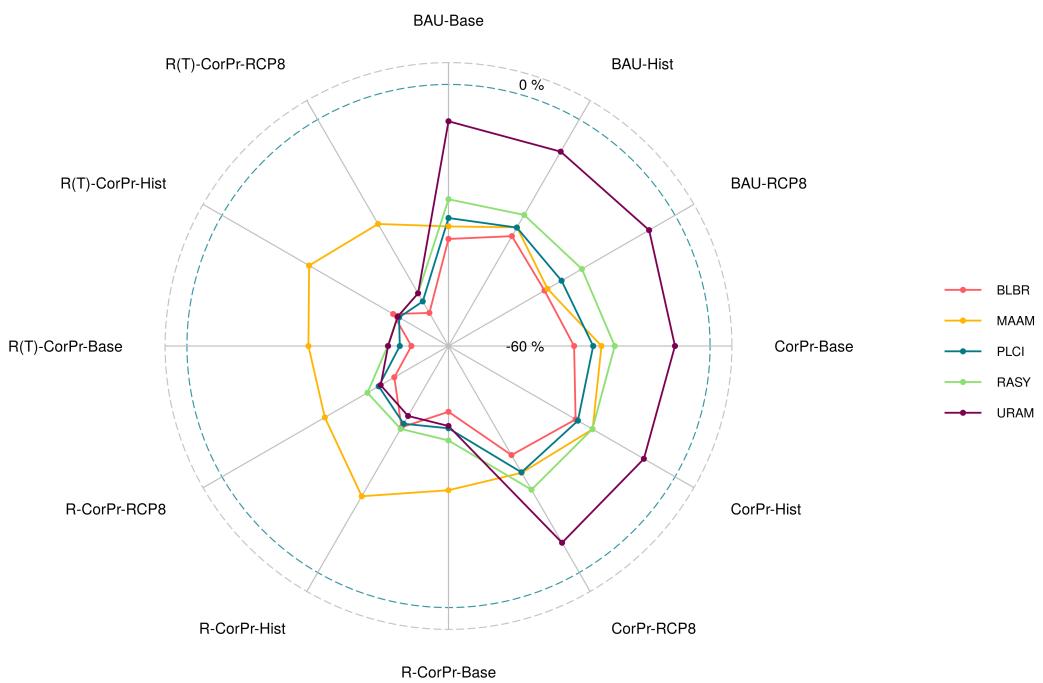


Figure 2–10: Change in identified features (partly pinch-points).

## **General Discussion & Conclusion**

To be completed.

## Chapter I Supplementary Material

Table 3–1: Description of the 5 species used in the connectivity model (taken from Rayfield et al. 2018)

Species	Description
Northern short-tailed Shrew <i>Blarina brevicauda</i>	Abundant small fossorial mammal. This highly active species can live in a diversity of habitats (grasslands, old fields, marshy areas, gardens, and some developed areas) but is mainly found in deciduous and mixed old forests with thick understories that provide good cover for hiding from predators. It feeds primarily on earthworms found in areas with moist soils. It has a high reproductive rate and is generally a poor disperser although it can cross gaps of 50-100m.
American Marten <i>Martes americana</i>	Small vagile carnivorous predator. Found in core areas of dense (>60% cover) and old (>70 yr) coniferous or mixed forests with complex vertical and horizontal structure. It requires large home ranges (above hundreds of ha). It generally avoids large openings and clearings (above few hundred meters wide) but crosses roads and frozen rivers easily. Deep persistent snow pack is a habitat critical element as it excludes predators ( <i>Canis latrans</i> ) and competitors ( <i>Martes pennanti</i> ) and provides good hunting conditions. This forest specialist is particularly sensitive to human activities. Juveniles are able to cover tens of kilometers when dispersing, more than what would be expected from body mass-based estimates. Trapped for its fur, this species has patrimonial and economical importance.

Red-Backed Salamander <i>Plethodon cinereus</i>	Terrestrial salamander. This sedentary and territorial forest-dwelling species lives under the leaf litter or coarse woody debris in mature and moist deciduous and mixed forests. It is a poor disperser that uses tens of square meters as a home range and rarely ventures more than 50 m in open fields. Roads and edges (up to 20-30 m) have a negative effect on populations' densities and reduce individual movements.
Wood Frog <i>Rana sylvatica</i>	Forest-specialist amphibian. This species prefers mixed and coniferous stands with closed canopy (>40%) and moist soil covered with woody debris (for egg deposition) but can adapt to other closed habitats. Both aquatic (palustrine, fish-free wetlands, not open and permanent ones) and terrestrial habitats are essential, and distance between both should not exceed ca. 600 m. It is sensitive to forest edge (25-35 m), gaps, high intensity agriculture, human developments and recent clearcuts that can act as barriers to movement. This poor disperser is particularly sensitive to roads and habitat loss (fidelity to first breeding pond).

Black Bear <i>Ursus americanus</i>	Large opportunistic omnivorous mammal. This species likes deciduous and mixed mature forest with dense cover interspersed with small clearings and early-successional stages of forest that are rich in berry production (depends on main soil surface deposit). It uses broad territories (tens to hundreds of square km) to follow fruiting season by going upslope with the season. It is an effective seed disperser because it can travel long distances (up to 390 km), in particular male juveniles. It clearly avoids human activity (up to 5 km) and roads (up to 800 m), in particular highways, and is likely to take a detour instead of crossing a 60 m gap.
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Table 3–2: Description and data sources for all variables used in the RF-CA model

Variable	Format	Source
Distance from urban land		Generated from land cover data
Size of forest patch	Raster	SRTM 30m from Google Earth Engine data library
Elevation		
Population change	Tabular data joined to vector data and rasterized	Canadian Census for 1991, 2001 and 2011
Income		

Table 3–3: Neighborhood rules for ST-Sim transitions

Transition	State counted	Neighborhood (m)	Minimum Proportion
Urbanization	Urban	500	0.7
Agricultural Expansion	Agriculture	250	0.9
Reforestation	Forest (any type)	250	0.9
Forest Internals	Forest (specific type)	225	0.15

Table 3–4: Pixel suitability based on forest types and age.

Species	Forest									
	Deciduous			Mixt			Coniferous			
	Young	Medium	Old	Young	Medium	Old	Young	Medium	Old	
<i>Blarina brevicauda</i>	0	0.5	1	0	0.5	1	0	0	0	
<i>Martes americana</i>	0	0	0	0	1	1	1	1	1	
<i>Plethodon cinereus</i>	1	1	1	1	0.5	1	0	0	0	
<i>Rana sylvatica</i>	1	1	1	1	1	1	1	1	1	
<i>Ursus americanus</i>	1	1	1	0.5	0.5	0.5	1	1	1	

Table 3–5: Resistance reclassification key for non-forest pixels.

Species	Urban land	Roads	Agricultural land	Wetlands	Water	Other
<i>Blarina brevicauda</i>	32	32	8	8	16	8
<i>Martes americana</i>	32	32	16	8	16	8
<i>Plethodon cinereus</i>	32	32	8	8	32	8
<i>Rana sylvatica</i>	32	32	8	2	8	8
<i>Ursus americanus</i>	32	32	16	2	16	8

Table 3–6: Minimum patch size for suitability of a patch in the habitat suitability analysis.

<b>Species</b>	<b>Minimum patch size (hectares)</b>
<i>Blarina brevicauda</i>	1
<i>Martes americana</i>	150
<i>Plethodon cinereus</i>	1
<i>Rana sylvatica</i>	1
<i>Ursus americanus</i>	1200

Table 3–7: Resistance reclassification key for different forest patches types.

<b>Species</b>	<b>Habitat patch</b>	<b>Habitat patch - too small</b>	<b>Non-habitat patch</b>
<i>Blarina brevicauda</i>	1	2	4
<i>Martes americana</i>	1	4	8
<i>Plethodon cinereus</i>	1	2	4
<i>Rana sylvatica</i>	1	2	4
<i>Ursus americanus</i>	1	4	16

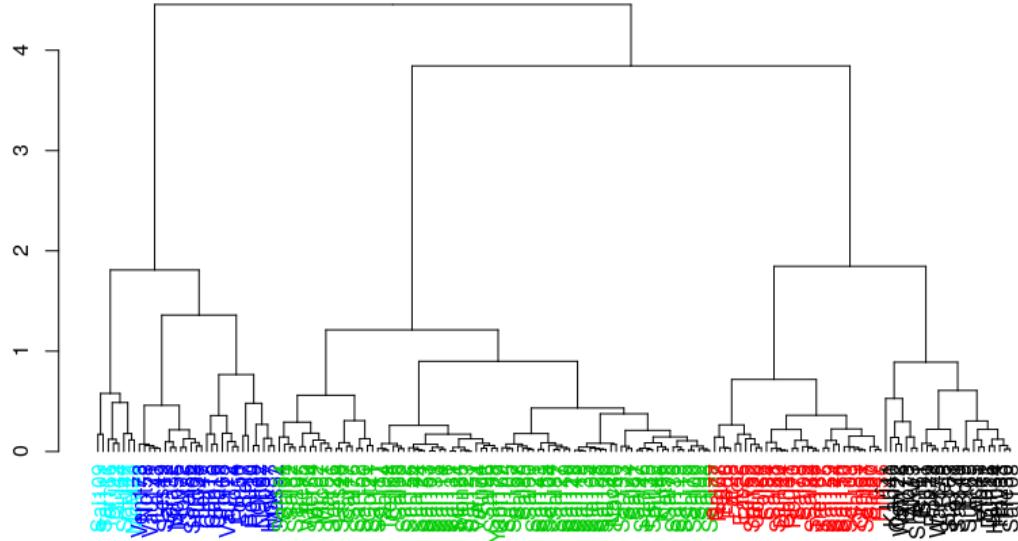


Figure 3–1: Results of Ward clustering for land use for municipalities (cut at 5 groups)

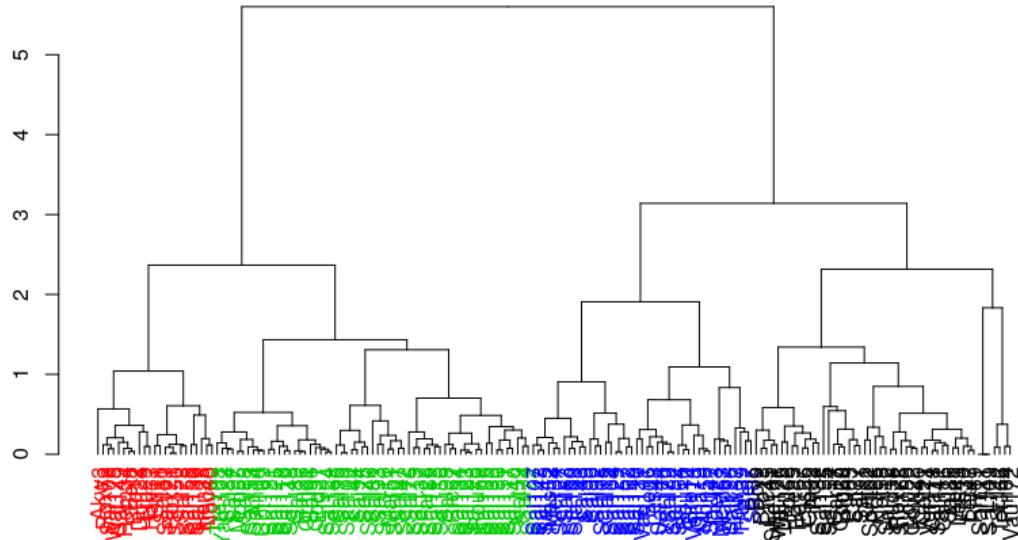


Figure 3–2: Results of Ward clustering for transition data for municipalities (cut at 4 groups)

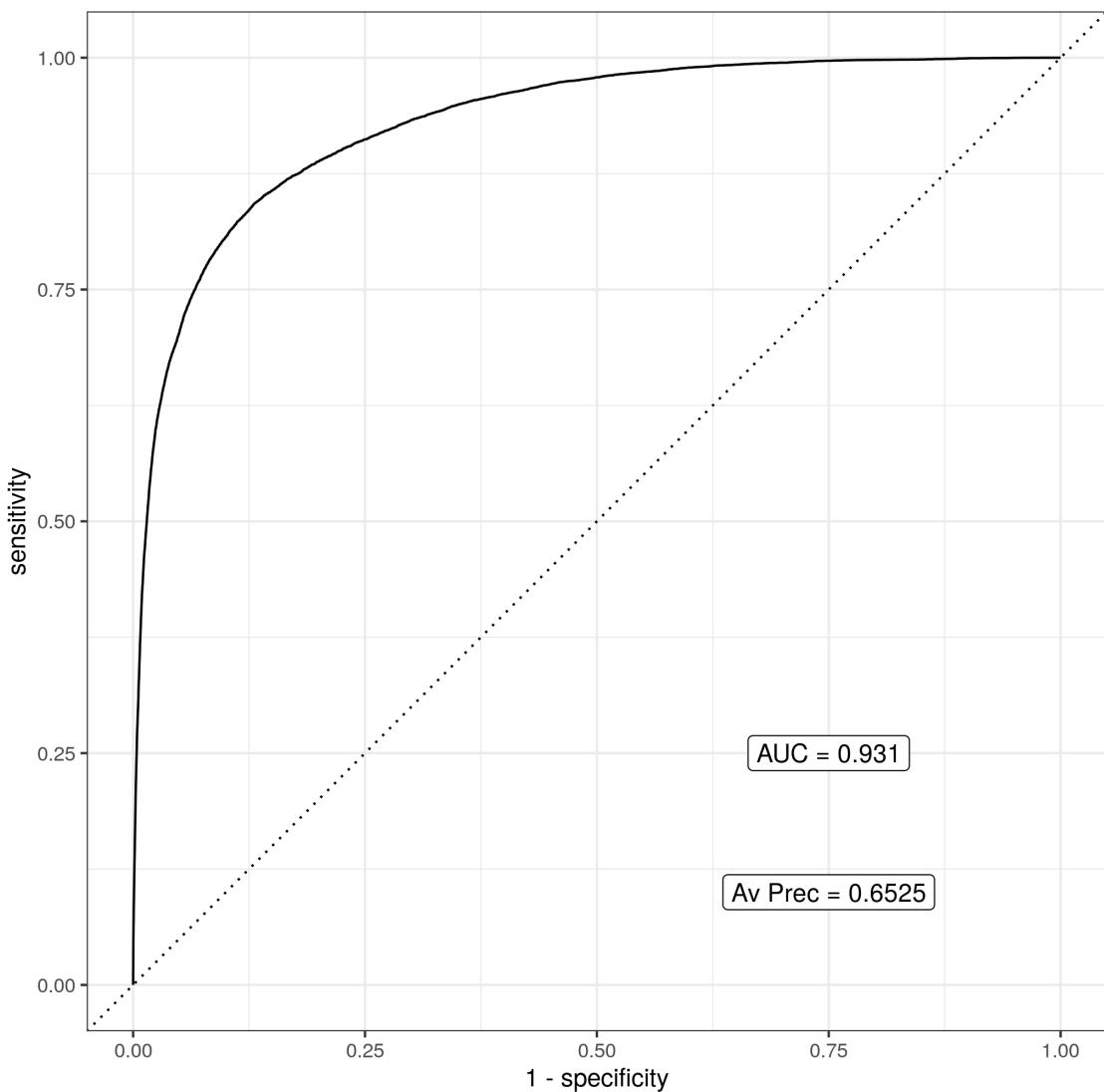


Figure 3–3: ROC Curve for Agricultural Expansion

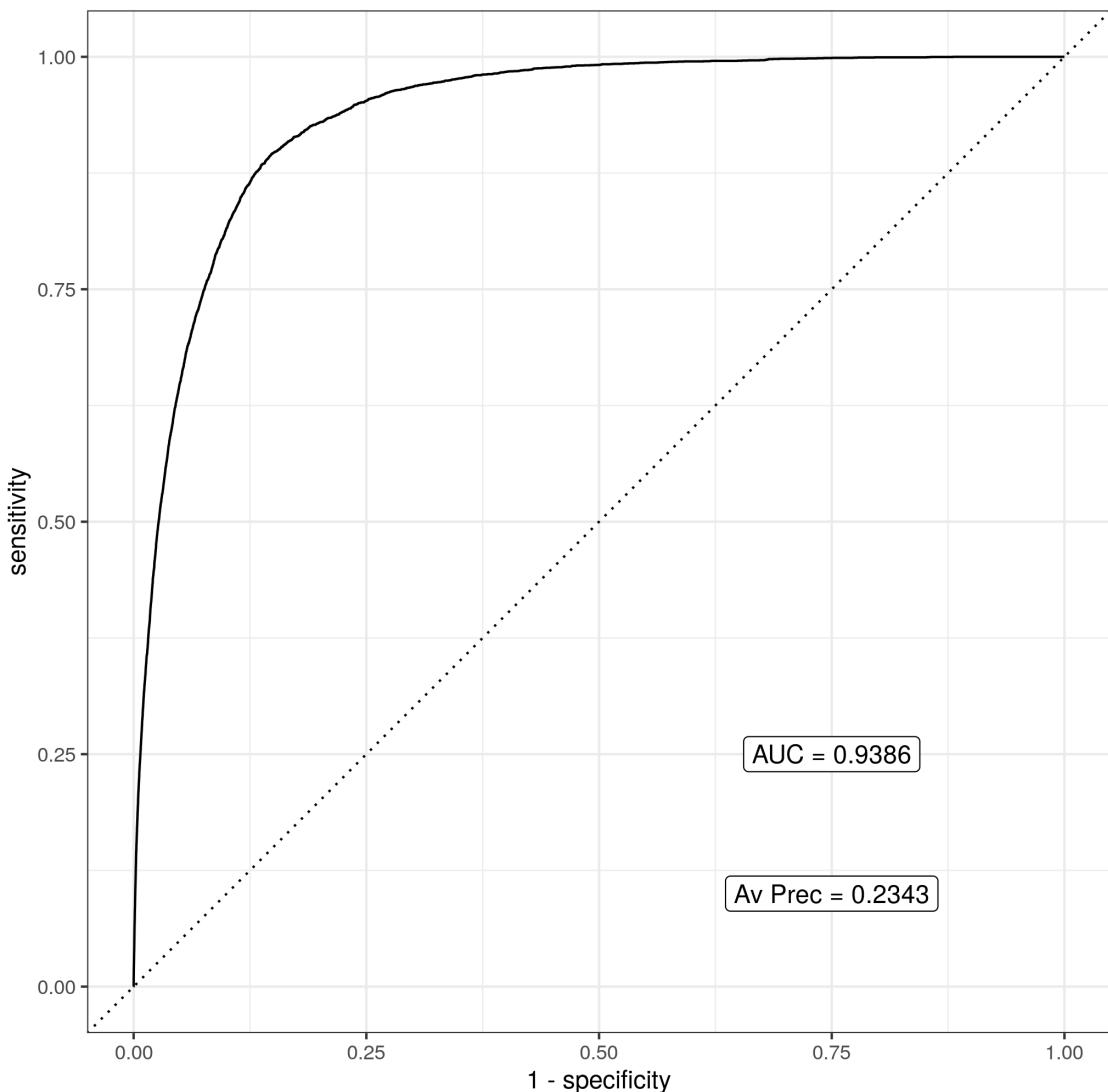


Figure 3–4: ROC Curve for urbanisation

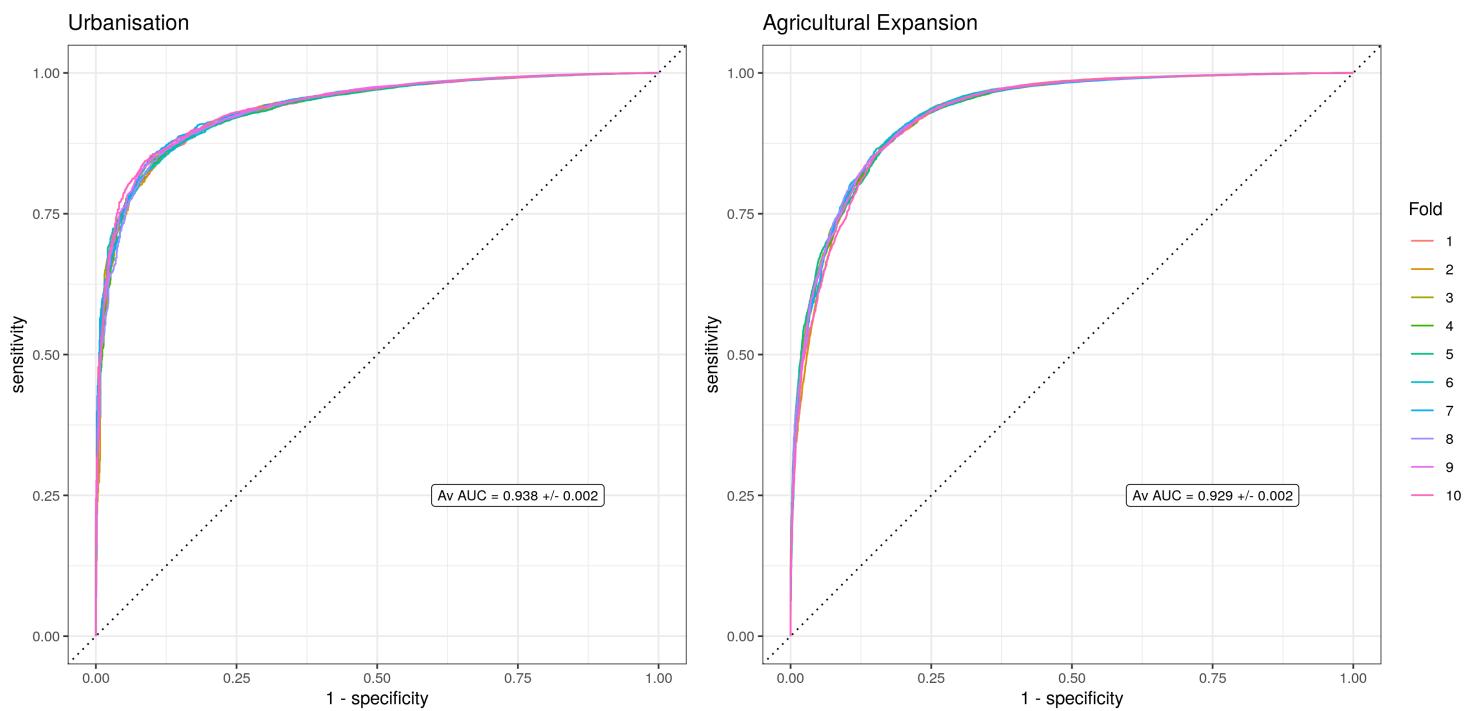


Figure 3–5: ROC Curves for re-samples

## Chapter II Supplementary Material

Table 3–8: Opportunity and challenge table (Non Spatial).

<b>Table</b>	<b>Atout/Contrainte (Opportunity/Challenge)</b>	<b>Contenu (Content)</b>	<b>Score</b>
Centre	Atouts	Présence d'organisme environnementaux	8.00
		Basses terres: lien prioritaire l'échelle nationale	4.00
	Contraintes	Programme ALUS	1.00
		CPTAQ	18.00
Est	Atouts	Besoin de rentabilité des entreprises agricoles	5.00
		Vocation forestière existante	8.00
	Contraintes	Tenure privée des terres	2.00
		Plusieurs territoires couverts	1.00
Nord	Atouts	Réglementation favorable maintien couvert bois et corridor métropolitain	16.20
		PRMHH	10.80
	Contraintes	Usage agricole prédominant	44.33
		Compréhension et participation citoyenne	14.40
Ouest	Atouts	Coûts pour faire de la connectivité	10.80
		Routes cours d'eau	3.00
	Contraintes	Présence de sols pauvre	3.00
		Les réalités économiques	50.00
Montérégie	Atouts	Terres privées	12.00
		LPTAA	7.20
	Contraintes	Le monde politique	4.00
		Milieu agricole: potentiel de faire des corridors si un levier est trouvé	12.60
	Atouts	Présence d'acteurs locaux et éducation	8.00
		PRMHH	3.00
	Contraintes	Permettre l'aménagement forestier	3.00
		Routes et autoroutes	4.00
		Terres privées, présence prédominantes	3.00

Table 3–9: Opportunity and challenge table (Spatial).

<b>Table</b>	<b>Atout/Contrainte (Opportunity/Challenge)</b>	<b>Contenu (Content)</b>	<b>Score</b>
Centre	Atouts	Leaders politiques positifs	33.33
	Les deux	Propriétés protégées	26.67
		Pressions urbaines	42.86
	Contraintes	Manque d'adhésion des agriculteurs	39.29
		Pressions agricoles	16.20
Est	Atouts	Mobilisation projet corridor bleu vert fondation séthy	18.00
		Autoroute 10	26.67
	Contraintes	Pressions villeggiatives	22.2
		Fragmentation des habitats liées au dev	18.00
		Activites agricoles intensives	16.2
Nord	Atouts	Municipalite pro-protection des monteregiennes ex. st bruno mont saint hilaire	8.00
		Comité municipal travail MRC MDY	1.00
	Contraintes	Autoroute 10 20 30 et autres	1.00
		Gestion de l'application des bandes riveraines	1.00
		Proximité des milieux	24.00
Ouest	Atouts	Article 50.3 du règlement des exploitations agricoles	19.20
		Mobilisation des acteurs du milieux	12.00
		Bande riveraine potentielle	10.00
	Contraintes	Canal beauharnois isole	24.00
		Réticences de certains producteurs	10.00
Montérégie 1	Atouts	Réseaux de sites avec couvert forestier	14.4
		Grande volonté d'action locale pour créer de la connectivité	12.60
		Rétrécissement du fleuve	7.20
	Contraintes	Agriculture intensive compenser la production	16.20
		Développement urbain	12.00
Montérégie 2	Atouts	Mobilisation sociale organisme conservation sensibilisation	12.00
		Usage des sols favorable	10.00
		Prix des terres agricoles	12.00
	Contraintes	Étalement urbain deuxième couronne	10.00
		Pole logistique de transport	10.00

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