

# 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 often do not take into account risks associated with future land use change, and might not go as far as to confront the results of the prioritization with the priorities perceived by stakeholders. In this thesis, we attempted 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 and climate 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 potential functional connectivity for 5 different umbrella species. 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 showed 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 scenarios and the identification of regional priorities.

## Abrégé

La science de la conservation de la connectivité, dont le but est de préserver la continuité de l'habitat dans un paysage donné, procède par l'identification des zones prioritaires compte tenu de la configuration actuelle du paysage. Toutefois, les méthodes actuelles de planification de la conservation de la connectivité ne tiennent souvent pas compte des risques associés aux changements futurs d'utilisation des terres, et vont rarement jusqu'à confronter les résultats de la priorisation avec les priorités perçues par les parties prenantes. Dans cette thèse, nous avons tenté de remédier à ces deux problèmes dans le cadre d'un effort continu de planification de la conservation de la connectivité pour la région de la Montérégie, dans le sud du Québec, au Canada. Dans le premier chapitre, nous nous sommes appuyés sur les travaux antérieurs de modélisation de la connectivité basés sur la théorie des circuits dans la région et nous les avons complétés par une modélisation de l'utilisation des terres et du changement climatique qui utilise une combinaison de modélisation statistique et de simulations à base de chaînes Markov Monte Carlo. Le modèle construit à partir des données d'utilisation des terres passées ont été utilisés pour projeter les changements futurs d'utilisation des terres et estimer les changements futurs de la connectivité fonctionnelle potentielle pour 5 espèces de parapluie différentes. Dans un deuxième chapitre, nous comparons ces résultats avec les priorités de conservation perçues dans la région. Nous avons organisé un atelier d'une journée avec les parties prenantes impliquées dans l'effort continu de planification de la conservation de la connectivité dans la région et nous avons recueilli des informations sur les caractéristiques du paysage considérées comme des zones prioritaires "centrales" et "de liaison". Nous avons montré l'importance de prendre en compte les changements d'utilisation des terres pour produire un réseau de zones protégées résilient et avons souligné la nécessité d'une approche multipartite dans la définition des scénarios de conservation et l'identification des priorités régionales.

## **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

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 modelling 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 modelling (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 modelling would consider that land change happens because of multi-scale decision making, and attempts to model those processes directly. Agent-Based Models (ABMs) are probably the best example of a mechanistic approach to land use change modelling. 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

modelling, 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 modelling 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 modelling, 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 modelling 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, Soepboer, 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 modelling 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 modelling 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 modelling 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 modelling 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.

# 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 in a landscape, by identifying and protecting habitat patches and corridors necessary to maintain the movement of plants and animals (Keeley, Beier, 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 identified out as a method for adaptation to climate and land use change (Costanza and Terando, 2019). One recurring argument is that preserving landscape connectivity could be critical for ensuring that species can shift their ranges (Krosby et al., 2010; Keeley, Basson, et al., 2018) in response to climate change. Another argument 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, Opdam et al., 2006; Stewart et al., 2019; Gonzalez et al., 2017). 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 designs would be most resilient to future change. One possible approach to exploring this resilience is to use landscape-level models that project the future state of land-cover.

Land use change models have often been 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 include future species ranges that are shifting due to climate change (Araújo et al., 2004; Heller et al., 2015). They are also central in species distribution models (Porfirio et al., 2014), a classic tool in conservation research. Both types of models are increasingly common in research focused on landscape planning for ecological connectivity.

Connectivity researchers have studied 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 context (Saura and Pascual-Hortal, 2007). But beyond these historical analyses, land use models are becoming more common (Correa Ayram et al., 2015). For example, Rubio et al., 2012 identified 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. Albert et al., 2017 used a land use change model to forecast changes in species networks. From these examples, we can see that combining land use change modelling and connectivity modelling 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 ways that impact 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 methodological frameworks rarely combine land use change and climate change. Here, we build on recent connectivity modelling work using circuit theory, by pairing it with a hybrid land use and climate change model (Albert et al., 2017). The model we develop uses a combination of statistical modelling 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 an analysis of past land use change trends in our study region, the Montereigie 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, modelling the needs for 5 species resulted in qualitatively similar results than when modelling 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 modelling 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 modelling, including the methods of this chapter are in fact modelling "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.

## 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 (R. G. Pontius et al., 2008; G. R. 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, Soepboer, 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 el 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, distance from wetlands, etc.

### 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, B. 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. In addition, we extracted the distribution (logged) of pixel flow values under the form of histograms.

### **Flow feature and pinch point detection**

In an attempt to go beyond the simple analysis of current flow value, we reproduced the workflow for pinch point analysis laid out in Pelletier et al., 2017. In their analysis of connectivity at the scale of Canada, using Circuitscape Pelletier et al. used the SURF algorithm (Speeded Up Robust Features) to detect narrow regions of high contrast in the flow surface (or ”pinch points”, as described in B. H. McRae et al., 2008). SURF is a computer vision algorithm used to reliably detect and match features in images, regardless of their orientation (see Bay et al., 2006 for an in-depth description of the algorithm). We attempted to reproduce the results of Pelletier et al., although no code was publically available. We use the OpenCV4 python Library implementation of the SURF software.

In order to get to a certain level of reliability in the results across iterations, it was found that it was important to equalize the histograms of pixel flow values. With this modification, we allow for areas of lower local contrast to gain a higher contrast. This is achieved by taking most frequent intensity values and spreading them out. This method usually increases the global contrast of images (Garg, 2017). But even with this helpful modification to the flow surfaces, it was difficult to accurately identify pinch points in the

images. However, the method still served to identify and detect relevant flow features in the images. In their implementation of the method, Pelletier et al. mention that SURF could potentially be used to measure of "flow complexity". Therefore, we hope this step of the analysis can serve as a way to measure the changes in complexity of the flow that arise under different scenarios. We recognize the limitations of this method at this stage but it does provide an interesting use case for the application of computer vision methods to the interpretation of mapped results from connectivity analyses.

Following the advice in Pelletier et al., we ran SURF for each of our flow surfaces and counted up the number of features identified, using it as a measure of flow complexity. Some of those features include identified pinch points. There exists no guidelines to parameterize SURF for pinch-point detection. We decided on our parameters by testing multiple values and visually assessing the results. The parameters used for the SURF analysis can be found in table 3–8.

## 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 main 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:** they still have a significant area of forest 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 the majority of the municipality’ area (*i.e.* 50%).

The clustering and subsequent ordination of land use change profiles showed that Montérégie has 4 different transition 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 development for holiday cottages (“villagiations pressures”, in the east).
- **Urban Spread / Agricultural loss:** agriculture is losing ground to urban land.
- **Agricultural Expansion / Fragmentation:** forest is being lost to agriculture in those municipalities where forest is still quite present.
- **Agricultural Expansion / Deforestation:** forest is already scarce and is being replaced by agricultural land. These results show marked regional trends with a front line of fragmentation and deforestation on both sides 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 about the underlying causes, or drivers, of land use change in the region. However, it is worth noting that the best predictors of urbanization and agricultural expansion in our model are the distance from urban land and the size of forest patches, respectively (see 1–1). This demonstrates that small patches close to urban areas are the most threatened with 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 on 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 matched the amount of change observed in the region (i.e. the number of pixels that transitioned between two time steps). However, the model only approximated 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 pixels 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 table 1–4 for details).

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

The results of the Business as Usual scenario (BAU) give an idea of what the region could look like in 2100 if the same rates of urbanization, agricultural expansion and deforestation observed for the period 1990-2010 are maintained. The projected land use for

2100, as seen in figure 3–6, shows that most of the small remaining forest patches within the agricultural matrix have been replaced by agriculture, and that most of the urban centres 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 centres such as Granby. These patterns match well the results of the profiling of the municipalities described above, and illustrated in figure 1–6).

In the Reforestation (R) scenario, urban land is allowed to continue to increase following the 1990-2010 trend, but about as much forest is replanted at every time step. This comes at the cost of agricultural land, for which we see a decrease of about 14.7% (on average), in comparison to the slowing that is observed in the BAU scenario. This loss is necessary to compensate for the increase in forest and urban land (see figure 1–9 for a detailed breakdown in the form of a bar chart). Under this scenario, we observe similar urbanization patterns, and some forest patches on the south shore of the Saint Lawrence cannot be maintained. However, many smaller forest patches are conserved and some forested areas grow to surround urban areas (see 3–7).

Changes to the makeup of different forest types only differ in one major way between the two scenarios: The amount of deciduous forest of medium age increases by 24%, in comparison to the decrease by 16.9% in the BAU scenario. This is to be expected from the model parameterization, as it is the only (and unchanging) forest type that is replanted in the region under the Reforestation scenario (see figure 1–9).

#### 1.4.4 Connectivity model

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

While our land use change model only approximated the spatial patterns in land use change, it better replicated the observed change in mean current flow in the region. Figure 1–11 illustrates 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 slightly overestimate the drop, and the difference in estimation ranges from 0.5 to 1 point. However, the distribution of flow values is multimodal. Therefore, to only consider the mean of flow does not capture all the details of the model's predictions. To do this, we compared the results of the historic run with the observed flow values (see figure 1–10). We can see that the model approximated well the flow values for most of our species, except for the wood frog (*Rana sylvatica*) (note that this figure is based on one of the iteration only, but all iterations show a similar pattern).

### Scenario runs (2010 - 2100)

**Current flow** We see 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, independent of the species considered (see figure 1–12 for a linear graph and 1–12 for a radar representation). Although both scenarios still predict a trend of decreasing mean flow, not all species react to the same degree. Only the black bear (*Ursus americanus*) - and, to a lesser extent, the short-tailed shrew (*Blarina brevicauda*) - manage to maintain a similar level of mean flow under the Reforestation scenario.

A second observation can be made about the impact of climate change on the species' responses. Climate change seems to have no impact on the mean current flow of both the black bear and the wood frog. The short-tailed shrew and the redbacked salamander (*Plethodon cinereus*) both seem to experience less percentage decrease in flow in scenarios with more intense warming - this was to be expected given their preference for deciduous and mixed forest over coniferous forest. Finally, as predicted, the most extreme variation in responses was found for the american marten (*Marten americana*). Interestingly, a Baseline scenario improves the mean flow 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 1–13. Finally, while we see that all species reacted linearly to the

BAU scenario, we see some non-linear responses to the Reforestation scenario by the short-tailed shrew, the black bear and the american marten. This nonlinearity is only observed under climate change scenarios (i.e. changing climate), indicating a possible interaction between climate and land use change. However, the redbacked salamander and the wood frog's responses remain linear under this scenario.

Finally, it is important to note the extremely low uncertainty around the line in figure 1–12, indicating that all 10 iterations in our model behaved similarly and led to extremely low variability in terms of change in mean flow.

**Flow distributions** Due to the multimodal distributions of flow values, it is important to go beyond looking at mean values and visualize the effect on the histograms of flow values (see figure 1–14). We can see that species usually have a trimodal distribution of high, medium and low flow values (only the american marten displays a more compact distribution with lower variance). The two scenarios have different effects on these distributions of flow values

Under the BAU scenarios, it can be seen that high flow values are being eroded into low flow values (and to a lesser extent, medium flow values), signifying the replacement of very high quality pixels for connectivity into very low quality pixels. We can therefore label the effects of the BAU scenarios as "directional". On the other hand, in the Reforestation scenario, high quality pixels are not being eroded (or are being matched by reforestation), but pixels of medium quality are being replaced by pixels of low quality. We can therefore label the effects of this scenario as "polarizing". Finally, we can mention that climate does not seem to noticeably change the distribution of values.

**Feature detection** The results of the feature detection analysis seem to identify similar trends as those observed for the changes in flow values. As in the mean flow analysis, we see a continual decrease in the number of features detected across all species and scenarios,

except for the black bear for which a small initial decrease seems to stabilize around 10% under the BAU scenario (see figures 1–15 and 1–16). We see a much stronger decrease in the number of features under the Reforestation scenario than under the BAU scenario.

The impact of climate varies depending on the species considered. For the black bear and the wood frog, we see no noticeable differences between the different climate scenarios. However, we find different responses to climate change among the short-tailed shrew, the american marten and the redbacked salamander. The pattern that emerges is that both the baseline and RCP 8.5 scenarios lead to a greater decrease in the number of features detected than in the absence of warming (historic scenario), with little noticeable differences between them, except for the american Marten. Finally, it is interesting to remark that, similar to the mean current flow, the width of difference between the two extreme scenarios is smaller for the american marten than for the other species.

## 1.5 Discussion

Integrations of land use change models with climate change models are increasingly common in connectivity conservation research, but remain insufficiently frequent in the face of the threat posed by the combined effects of land use and climate change (Costanza and Terando, 2019). Land use change models, in particular, are lacking in biodiversity scenarios (Titeux et al., 2016). This absence can be explained by a range of issues, each of which the methodology and results presented in this chapter contribute to solve.

The paucity of land use change simulations, in comparison to the slew of established global climate change models available, is mentioned by Costanza and Terando, 2019 as a contributing factor. This paucity, we argue, can be explained by the lack of long-term land use data, but also by the opacity that surrounds land use change modelling practices. Although the former is becoming less and less of an issue with the advent of easily accessible remotely sensed data, the latter is a real obstacle to integrating land use

change into connectivity models (Moulds et al., 2015). Here, we show a flexible framework with transparent parameterization using open-source software, which can be used to simulate landscape change in conjunction with climate change to assess connectivity or any other relevant landscape-level metric. This effort for transparency comes with a concern for taking into account uncertainty in land use change simulations, another obstacle to integration mentioned by Costanza and Terando, 2019. By using MCMC (Markov Chain Monte Carlo) based simulations, we can propagate uncertainty surrounding both climate and land use change models. This is crucial, because another critique against the lack of integration is that designing conservation corridors without taking into account future land use and climate change could lead to a false sense of certainty in the efficiency of corridor designs, a mistake that could be reproduced if the uncertainty of integrated models is not better taken into account. Finally, land use change and CC are seen by the research community as impacting connectivity at different scales, with climate change models often being used in larger-scale connectivity studies than land use change. For instance, corridors designed to be adaptive to climate change often span very long distances (McGuire et al., 2016). Yet our results show that even noticeable differences between climate scenarios can be observed, even at small scales (i.e. below the ecoregion level).

Other studies have attempted to go beyond those issues and managed to integrate climate and land use change models to some degree. For example, Albert et al., 2017, on which this work is based, considered which habitat patches network would be most resilient to future change using multi scale metrics in Monterege. Leonard et al., 2017 used systematic conservation planning methods to identify core areas and linkages under an energy development land use change scenario in the northeastern US. In another study, Dilts et al., 2016 used a range of graph theory-based metrics to forecast the changes to diverse aspects of habitat connectivity for the Mohave ground squirrel under multiple climate and land use change scenarios. Although our results, contrary to those studies, do not allow us to derive tangible predictions for our study species such as a plan for a

protected area network, we still provide valuable insight for the design of such hypothetical networks.

For instance, by looking at a simple metric (mean flow), we have shown that some species will react more simply and linearly than others. We saw a simple and linear response to change for species which, in our model, had dependency on forest types that were expected to be impacted only by land use change, such as the Redbacked salamander and the Wood frog. This was not the case for species which are dependent on coniferous forests or mixed type forests, more at risk from climate change, and therefore more likely to suffer from the interaction of the two drivers. The results of our simple reforestation scenario highlights that it might be hard to plan for species with different needs. Restoration actions remain very uncertain: the impact of reforesting will depend on what is replanted and where it is replanted. Forest management could turn out to be critical for species dependent on forest types more vulnerable to a changing climate. A final insight is given by the width of difference between the outcome of the two scenarios for each of the species. The fact that this difference is larger for some species than for others possibly indicates more uncertainty with regards to the real future trajectory of those species at the 2100 horizon.

Our implementation of the feature detection algorithm opens the door to more research on how future land use and climate change will impact the complexity of the species' flow. What flow complexity is and what it means for different species are open questions, and simulations such as the one presented in this chapter could represent a good opportunity to push these questions further. Although the results are imperfect in comparison to those of Pelletier et al., 2017, we still observe that the reforestation scenario manages to change some properties of the flow surfaces in such a way that we see a rather consistent pattern in the number of features detected, possibly indicating that reforestation minimize the number of pinch points and allows for less restricted flow. More research on this feature detection technique is needed to assess its relevance in the analysis of connectivity simulation

This work constitutes progress over past projects on which this work is built. We covered a larger extent, improved on the land use change model from Albert et al., 2017, and demonstrated the flexibility of our framework for supporting alternative scenarios. But besides the important methodological contribution of this chapter, it is not without limitations. We see four main axes along with this work is limited and could be improved. To begin, different steps of the modelling process were limited computationally by time and computing resources, which led us to having to aggregate the raw data from a 30 meter resolution to a 90 meter resolution, leading to a loss of data and a loss in the quality of the data. A major consequence of this aggregation is that roads, which constitute an important barrier to connectivity, would have been broken up by the aggregation process. Instead, they had to be aggregated out of the raster surface and a road network was rasterized and overimposed onto the newly aggregated raster. They led us on only to keep major roads, which is still a limitation given the assumption that roads 90m wide represent accurately the extent to which they represent a barrier to connectivity. One possible improvement in that method would be to aggregate all roads but to weight the resistance differently based on the type.

The lack of accuracy of our land use change simulations also needs to be addressed. On the one hand, this can be seen as a sign that the model did not overfit the data, while on the other hand, it is difficult to know at which point a land use change model has underfitted 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. This is possibly a good thing for planning at a regional scale, but should indicate that the results of this model should not be used for planning at smaller, local scales.

A third limitation is found in the habitat suitability analysis. The steps and parameters of the analysis were modified from Rayfield et al., 2018 to fit our dataset and those modifications prevent us from comparing our results to their results. The analysis is also limited in the sense that multiple factors that were originally included in Rayfield's original analysis are not taken into account. For instance, the fact that Black bear habitat would receive a negative multiplier if it is close to urban land is not included in our analysis (whereas it was included in Rayfield's), and should indicate that the results observed for the bear might be overestimated. Similarly, in Rayfield's analysis, the Wood frog is dependent on wetlands and habitat receives a negative multiplier if it is far from wetland. Including this might change the response of this species.

Another critique could be made on the analysis of flow surfaces. Contrary to a lot of published work that wishes to capture a range of connectivity measures, by looking both at flow and at graph-based indices we have not pushed this analysis this far. Rayfield et al., 2018 argues that there is a complementarity between outputs of Circuitscape (flow surfaces), and the outputs of graphs from habitat analyses. A more in-depth analysis of such graphs, through indices such as Probability of Connectivity for instance (Saura and Pascual-Hortal, 2007) would be a good next step in the analysis of the results presented in this thesis.

Finally, a final limitation we want to emphasize is to be found in our reforestation scenario. This scenario has two major issues: first, it is random and overly ambitious, growing any forest patch on the landscape, and at the same rate as land is urbanized. It is very unlikely that such a scenario could be realistic. Therefore, the fact that some species are able to maintain mean flow under this scenario could be unlikely, and this scenario might represent an overly optimistic outcome, even for a scenario whose main goal is to represent an extreme of the realm of possible futures for the region.

## 1.6 Conclusion

We successfully integrated a potential functional connectivity model for 5 umbrella species with a land use and climate change model, using circuit theory as our main method of analysis. We analyzed simple properties of the resulting flow surfaces and looked at the differences in the species response. Species who depend on forest types that are both vulnerable to land use and climate change responded in more complex, less linear, and less consistent ways than species who only depend on forest types that are mostly threatened by land use changes. While improving on related past work in the region, we open the door for other methods of flow analysis and for a more rigorous implementation of the modelling process. We hope this work can serve as a reminder that connectivity conservation planning needs to better take into account the joint effects of interacting drivers such as land use and climate change.

## Figures & Tables

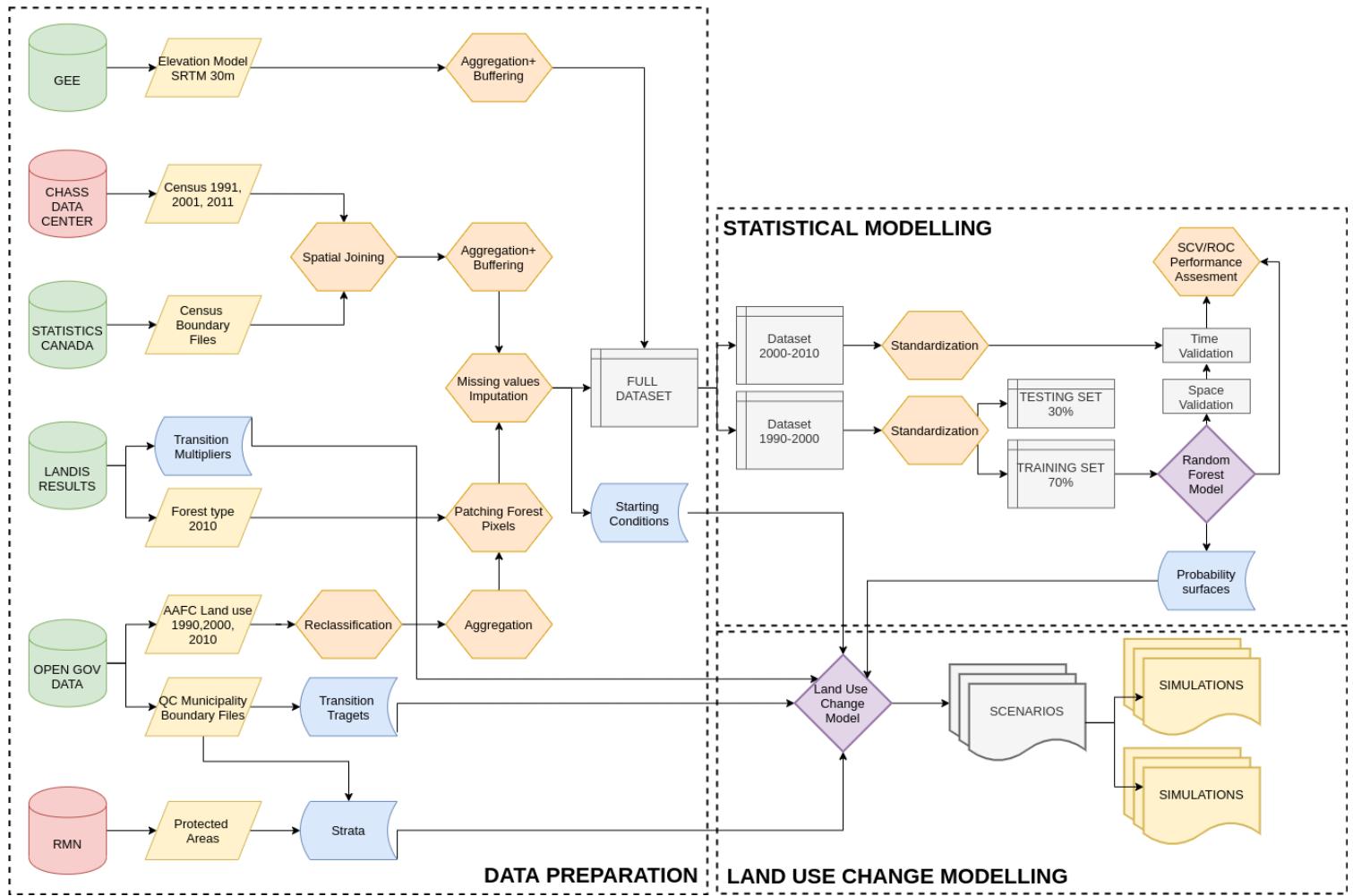


Figure 1–1: Workflow for data preparation, statistical modelling and land use change modelling.

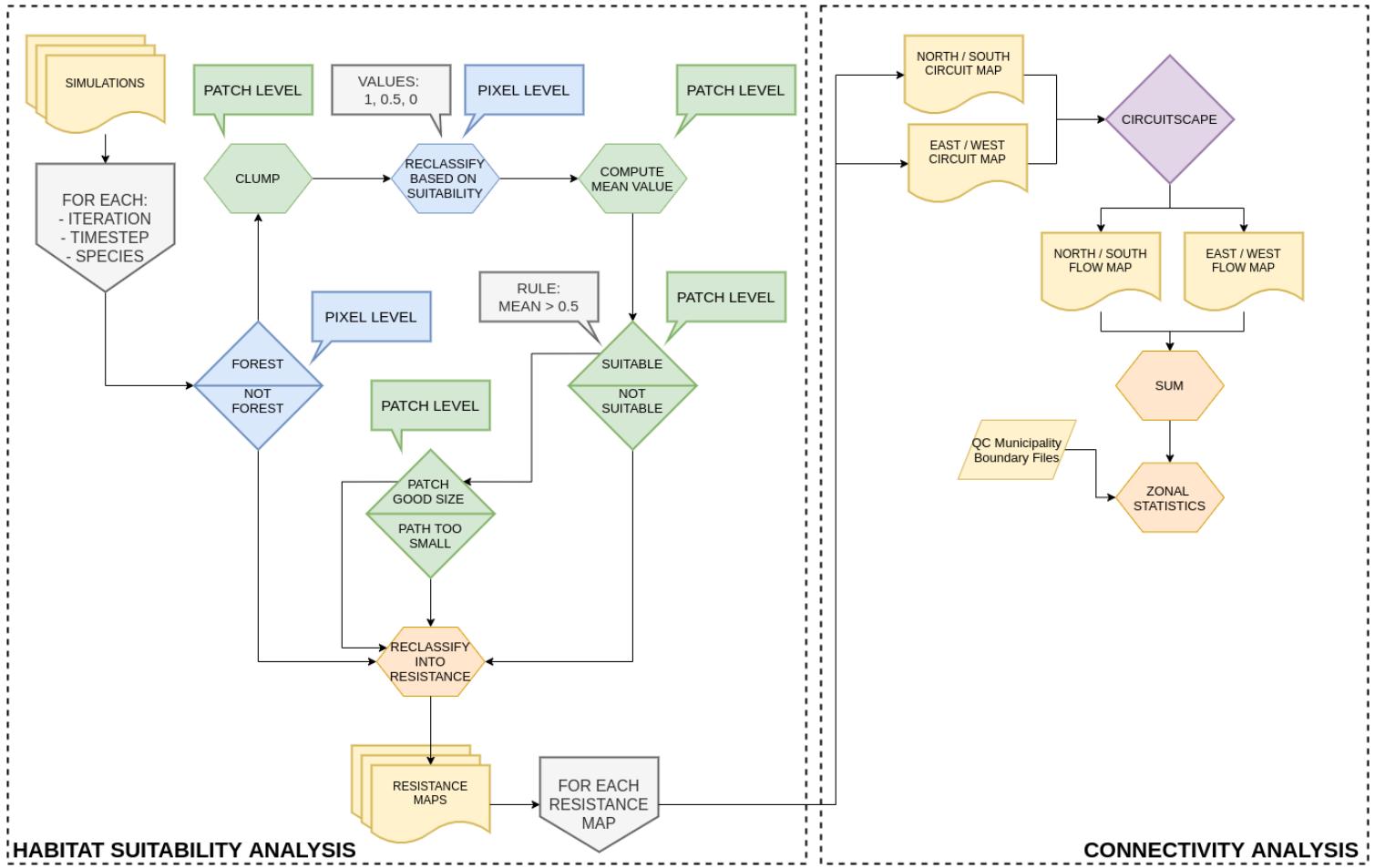


Figure 1–2: Workflow for the habitat suitability and connectivity analyses.

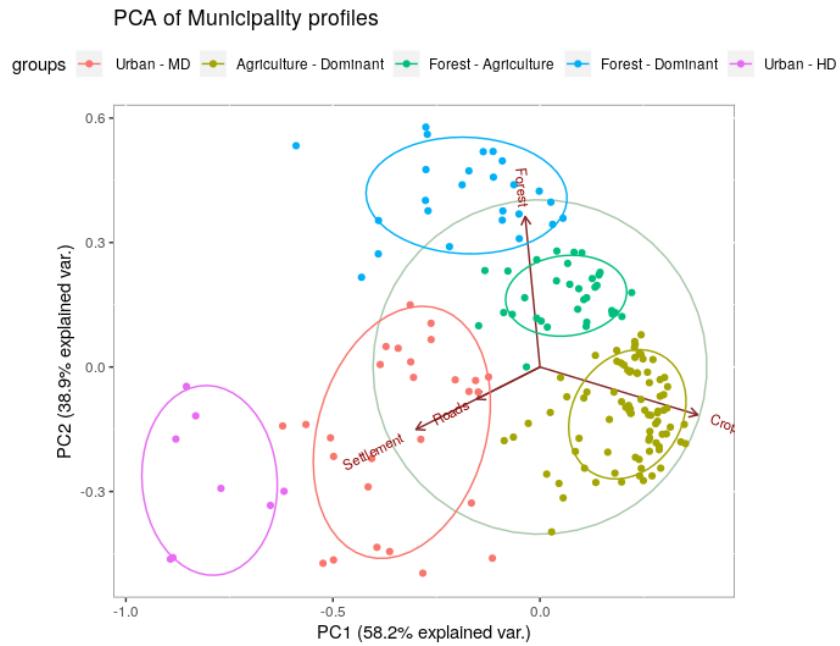


Figure 1–3: Ordination of land use data (proportions) for municipalities. Groups are derived from clustering in 3–1

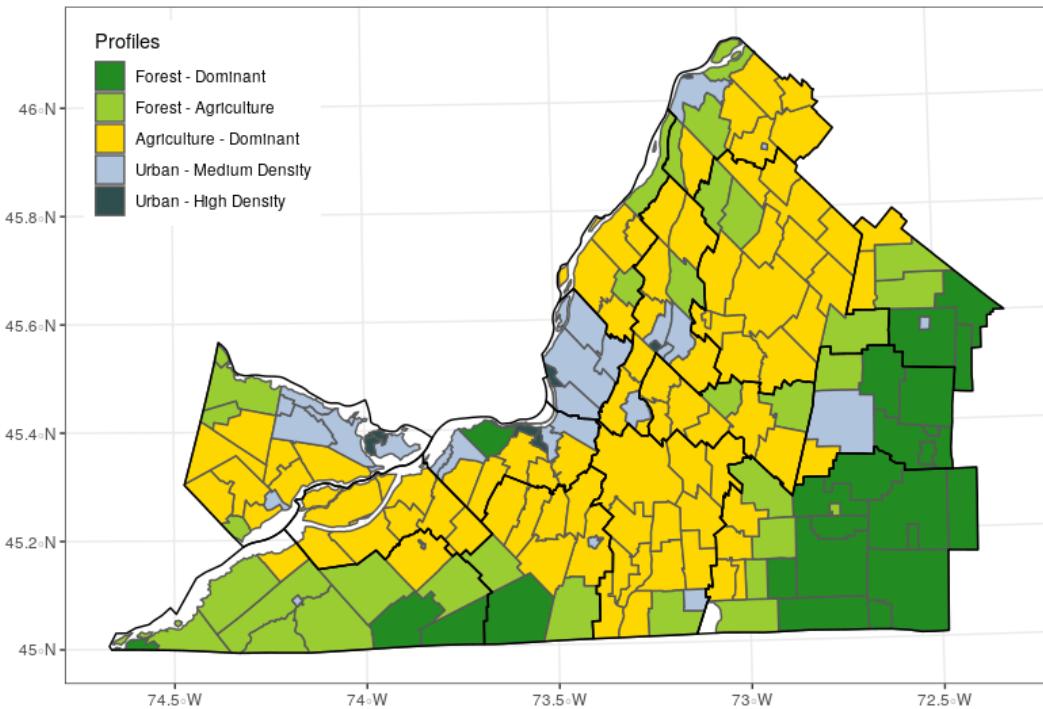


Figure 1–4: Geographical distribution of the 5 profiles identified in 3–1 and 1–3.

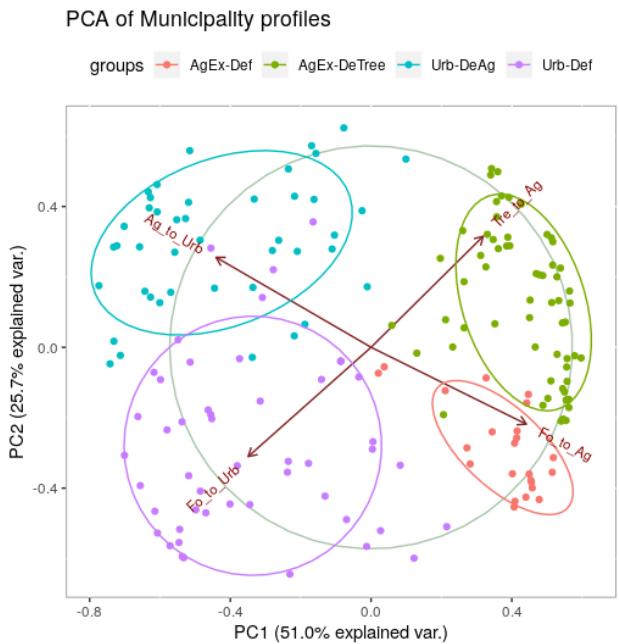


Figure 1–5: Ordination of land use transition data for municipalities. Groups are derived from clustering 3–2

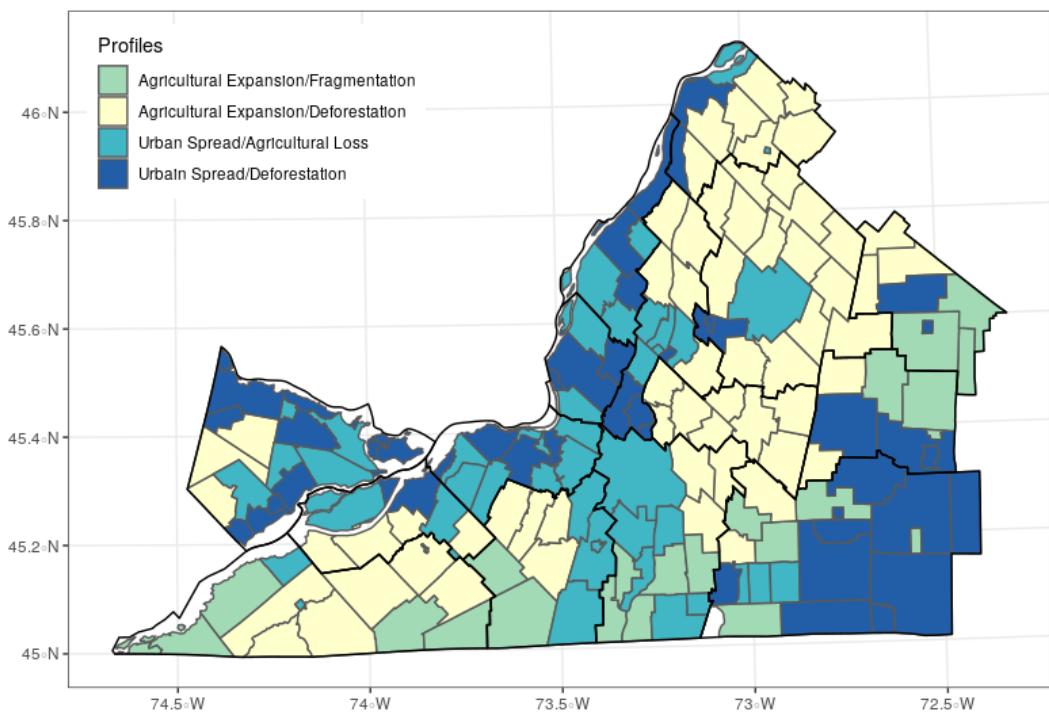


Figure 1–6: Geographical distribution of the 4 change profiles identified in 3–2 and 1–5.

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: AUC and average precision values for the predictions of the land use change model.

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	$0.618 \pm 0.001$	$0.102 \pm 0.001$

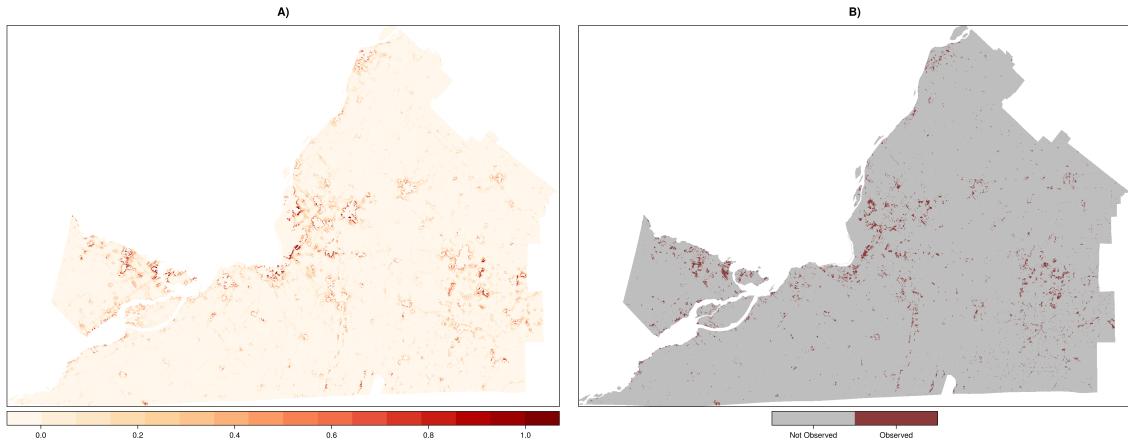


Figure 1–7: Comparison between mean probability of urbanization and actual urbanization observed between 1990 and 2010.

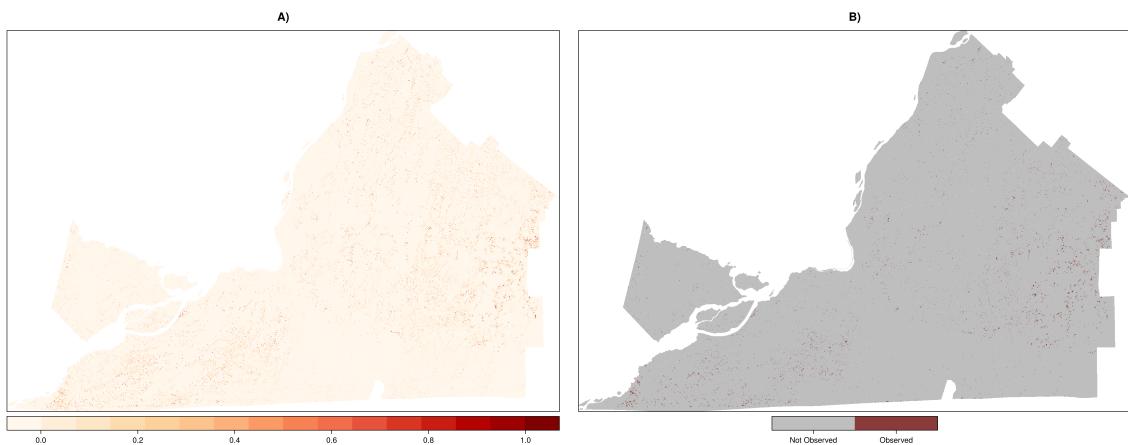


Figure 1–8: Comparison between mean probability of agricultural expansion and actual agricultural expansion observed between 1990 and 2010.

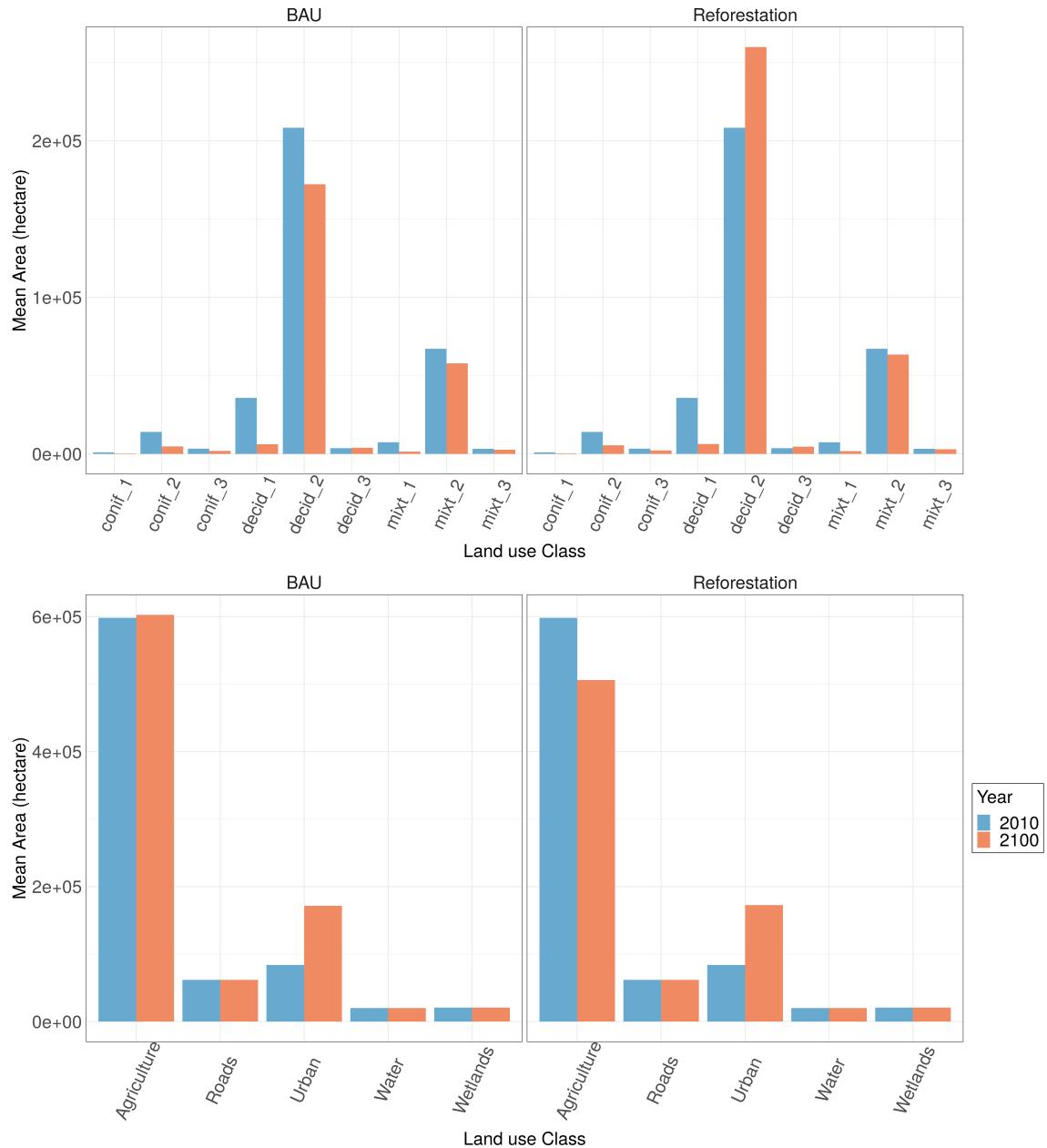


Figure 1–9: Comparison land use class frequencies in 2010, and 2100 for both the BAU and Reforestation scenarios.

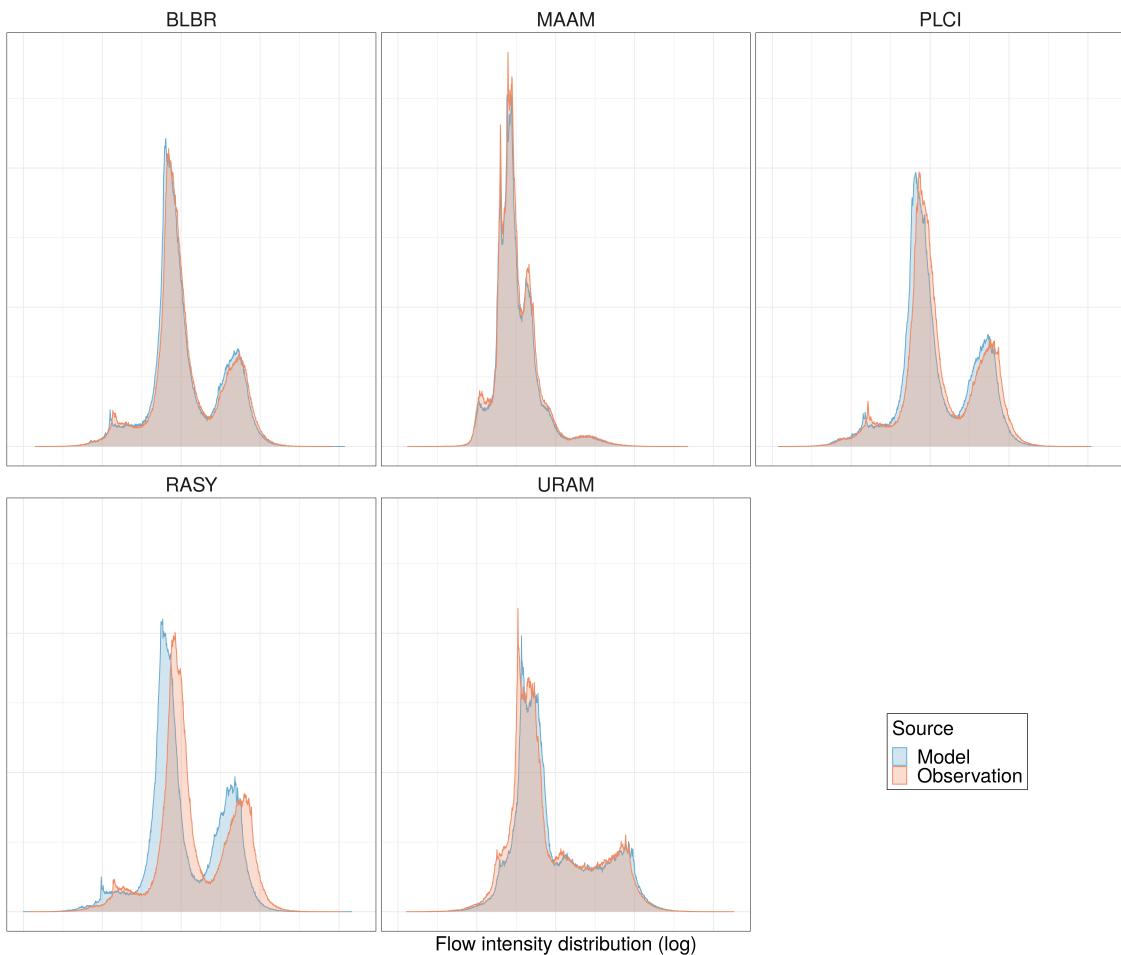


Figure 1–10: Histograms of flow values for the year 2010 comparing the historic model run with observations.

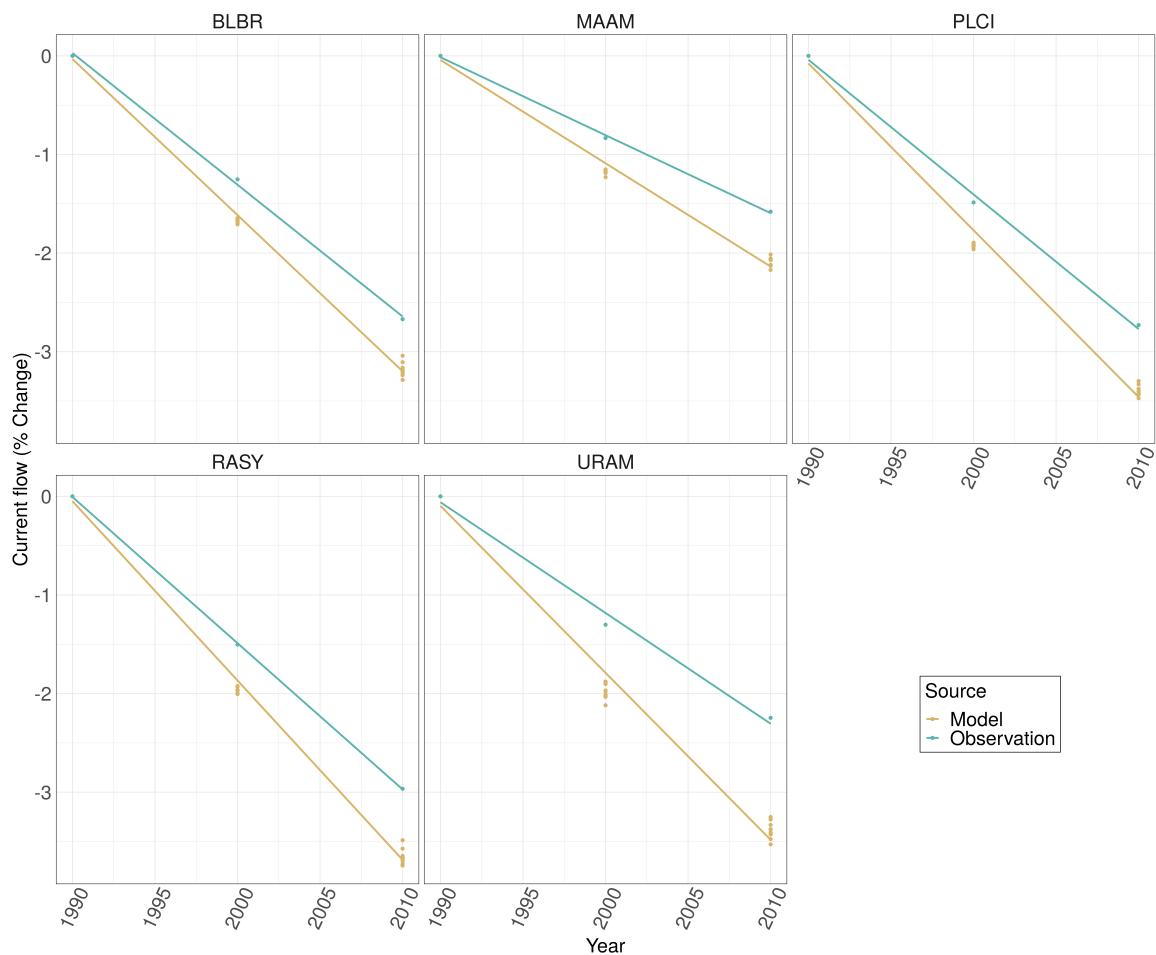


Figure 1–11: Change in mean flow (in % of the the 1990 flow) between 1990 and 2010, contrasting observed change and simulated chnage.

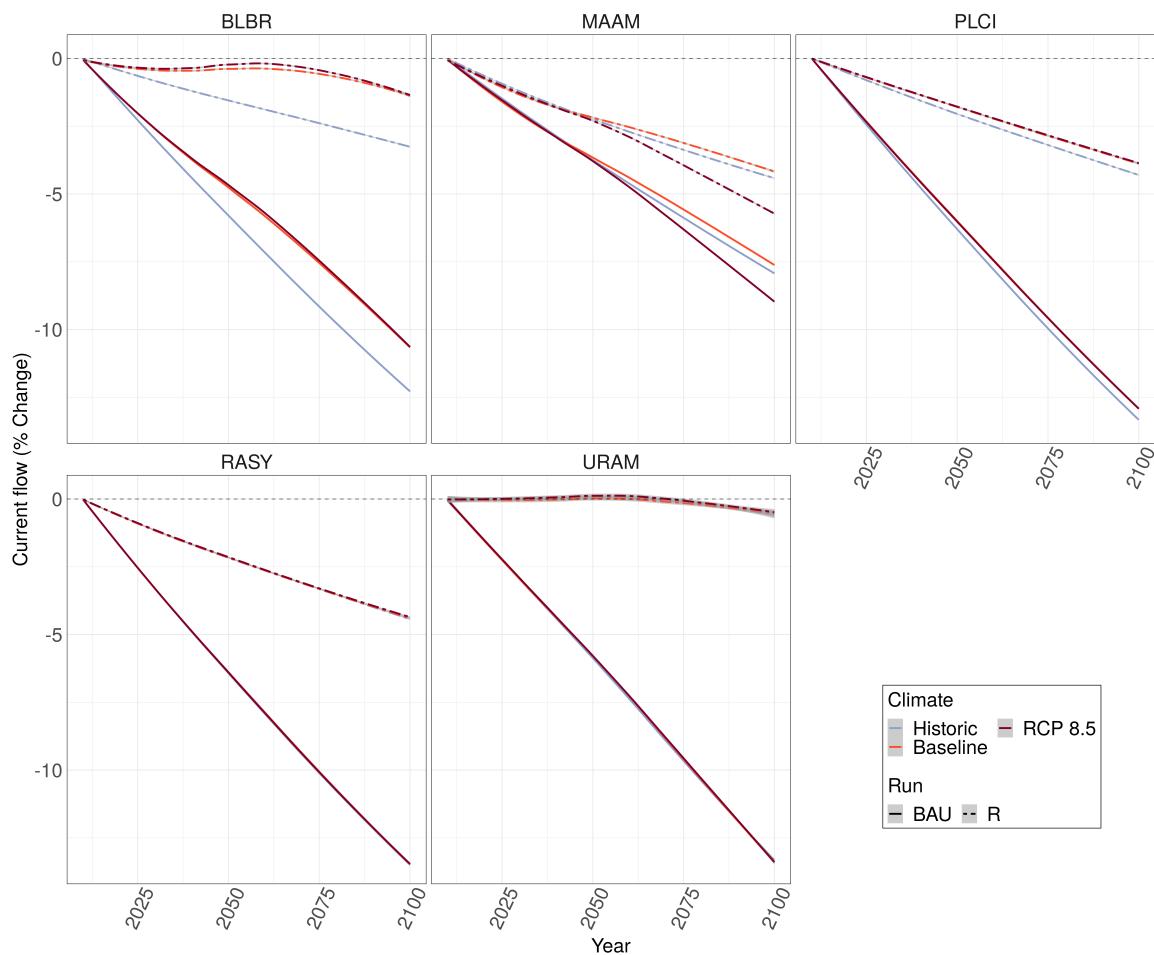


Figure 1–12: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with other land use change scenarios.

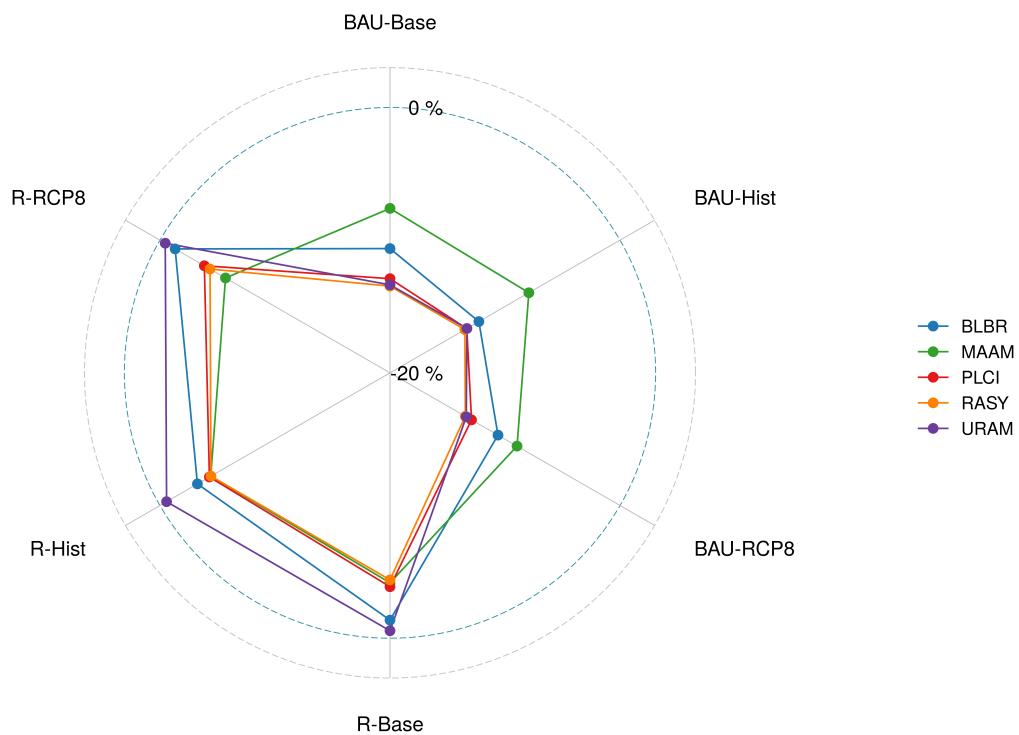


Figure 1–13: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with other land use change scenarios.

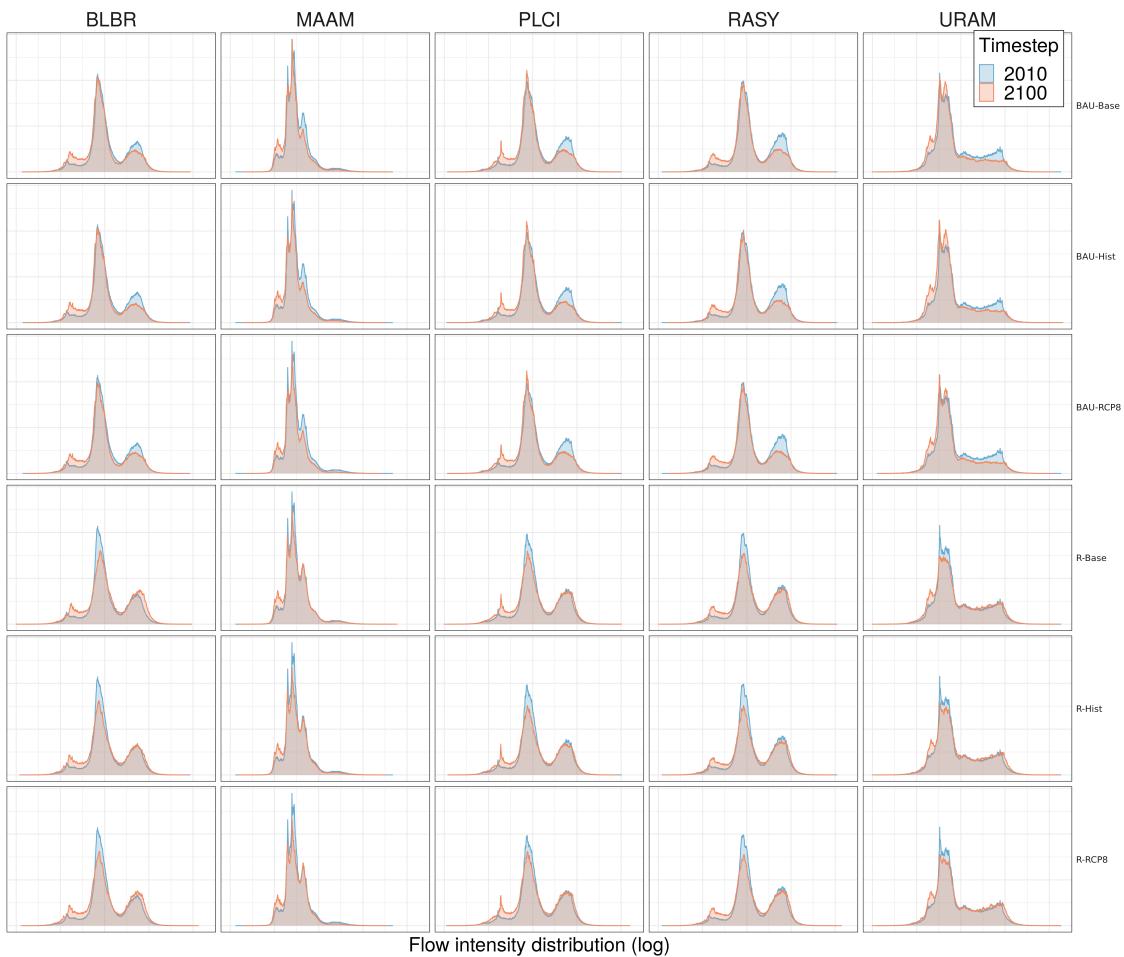


Figure 1–14: Histograms of flow values change.

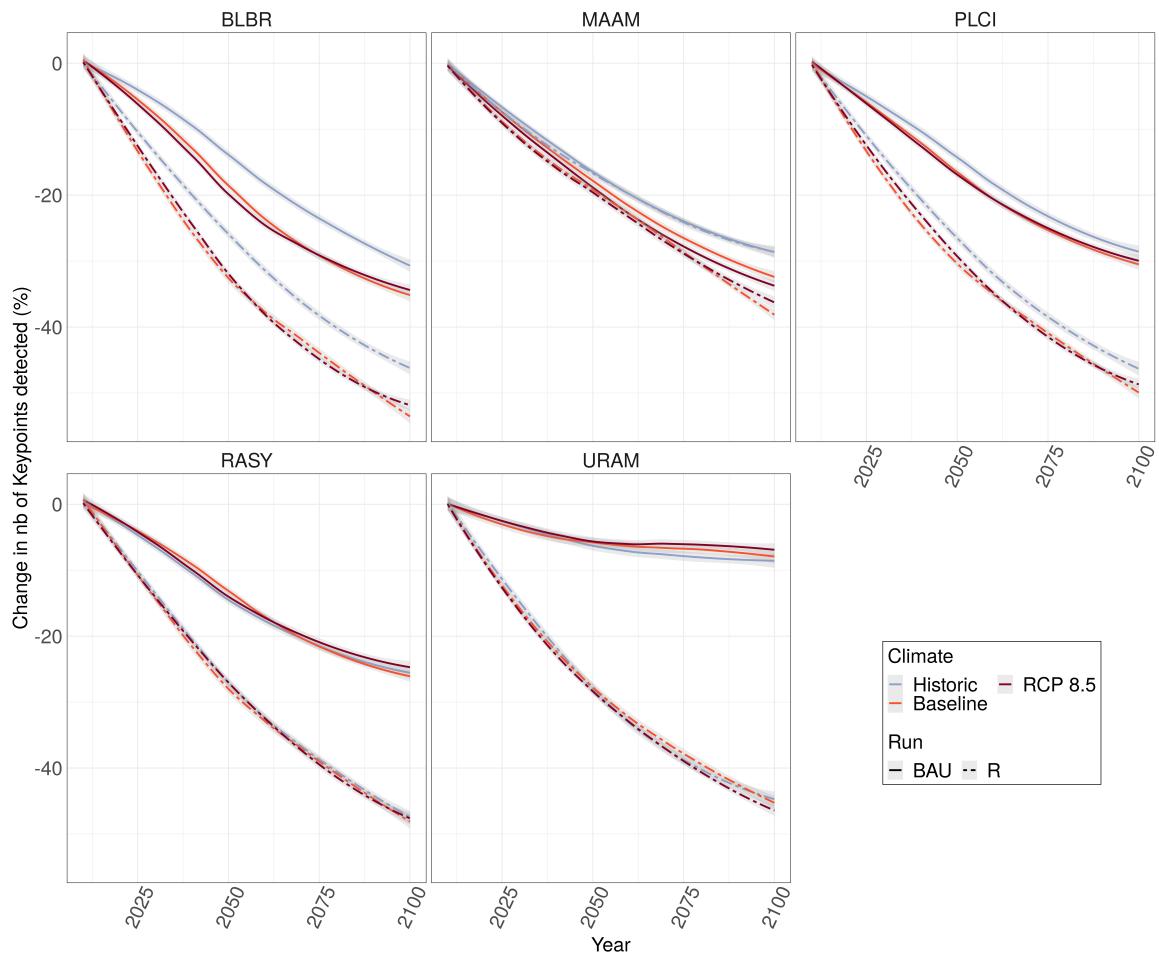


Figure 1–15: Change in identified features (partly pinch-points).

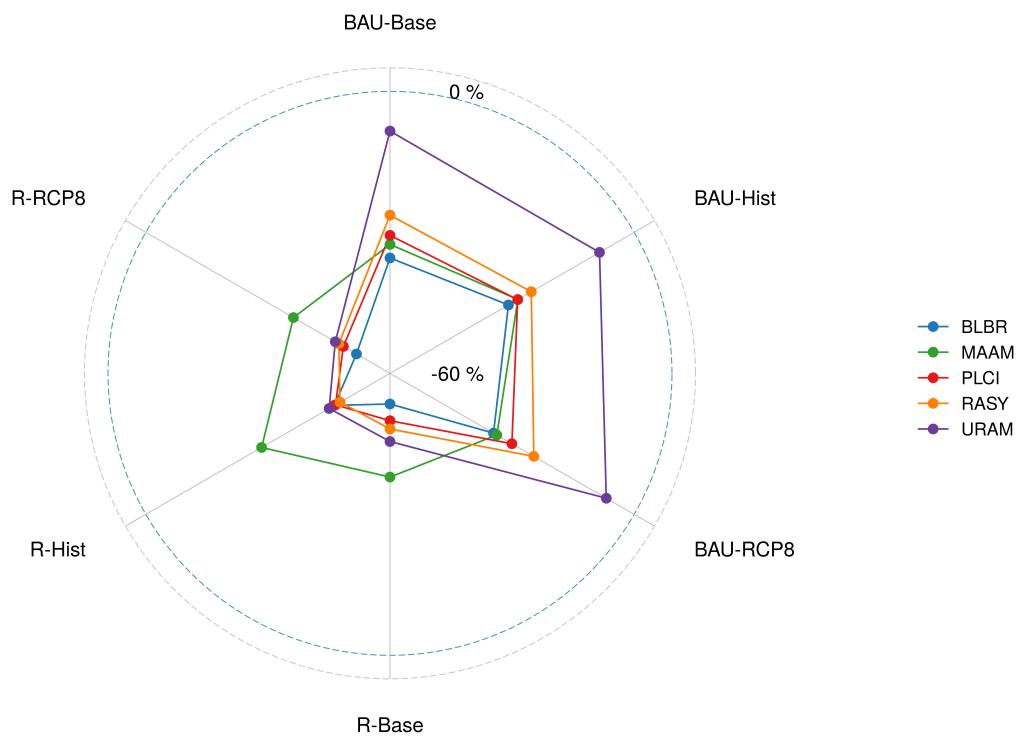


Figure 1–16: Change in identified features (partly pinch-points).

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## **Linking Statement**

In Chapter I, we integrated a land use model and a climate change model with a habitat suitability and connectivity model. We then explored outcomes under different scenarios for land use and climate change. We showed how different species might react to changes in land use and climate by analyzing the resulting flow surfaces. We provided a reproducible yet perfectible methodology that takes into account important drivers like land use and climate change. We applied these methods to the case of the Montérégie in Québec.. We demonstrate the power of simple scenarios to identify the boundaries of the prediction space for potential functional connectivity. However, we recognize the need for scenarios that take into account the needs and perceptions of stakeholders of the region. In Chapter 2, we take a first step toward deriving the basis for such community-driven scenarios by presenting the results of a community workshop organized between multiple stakeholders in Montérégie. We use those results to derive simple land use change scenarios and use those scenarios to constrain the integrated model from Chapter 1. These scenarios can serve as a basis with which to iterate a community-driven process of conservation scenario building. We derive the same analysis for the species described in Chapter 1 and compare and contrast the results between scenarios.

## 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**

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 often do not confront the results of the prioritization with the priorities perceived by stakeholders. There is a need for planning tools to allow for this confrontation to happen. The Montérégie region in southern Quebec, where this work takes place, is experiencing urban growth and sprawl, and stakeholders show an increasing interest in connectivity conservation tools. Those tools need to be able to guide stakeholders through an iterative process of conservation and land use scenario building. We take a first step toward deriving the basis for such community-driven scenarios and tools by presenting the results of a community workshop organized between multiple stakeholders in Montérégie. We use those results to derive simple land use change scenarios and use those scenarios to constrain the integrated model previously derived. We discuss the importance of considering stakeholder inputs to produce a resilient network of protected areas and highlight the need for a multi-stakeholder approach in the definition of conservation priorities.

## 2.2 Introduction

The goal of connectivity conservation planning is to preserve the continuity of habitat in a landscape, by identifying and protecting habitat patches and corridors necessary to maintain the movement of plants and animals (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, nor confront the perceptions of stakeholders concerning connectivity conservation priorities. Here, we ask how those methods can progress by taking into account those perceptions. To do so, we integrate a connectivity and land use change model (developed in chapter 1) with the results of a community workshop organized with stakeholders, through simple conservation scenarios.

Conservation planning methods are now recognizing that landscapes constitute social-ecological-systems. A social-ecological system (SES) can be understood as the ensemble of human and non-human actors in a given landscape, the set of natural habitats they inhabit and resources they 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). To understand a landscape as an SES has important implications for land use planning and therefore for connectivity conservation planning, and pushes connectivity scientists to integrate stakeholder's perceptions and priorities into their models.

It is important to integrate the perceptions of stakeholders in connectivity planning methods for a multiplicity of reasons. It engages stakeholders in the planning process early on, contributing to better consensus on priorities and, hopefully, to faster action. It also means that connectivity models are enriched by integrating local knowledge into the decision making process, showing that inputs from stakeholders are valued and considered

essential to build a conservation plan. More specifically, 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, questions of land use and connectivity planning cannot be answered without input from stakeholders. Recent studies in land use modeling have shown the value of using stakeholder's inputs for parameterizing and validating models (Hewitt et al., 2014; Voinov and Bousquet, 2010), leading to a much better understanding of land use processes at play within a landscape.

Connectivity conservation research therefore has a lot to gain from the wide set of participatory research methods already being used in social-ecological research. Participatory research methods are designed to conduct the research process “with those people whose life-world and meaningful actions are under study” (Bergold and Thomas, 2012). Participatory research methods can include scenario design. A scenario is “an account of a plausible future” (Peterson et al., 2003), and scenario design is a flexible tool for conservation scientists and practitioners. Although scenarios are often derived from expert knowledge, they can be built in a participatory setting. In this context, it is often conceived by researchers as an iterative process, through which scenarios are imagined, reviewed and re-imagined in a set of stakeholder meetings with the goal to build consensus on the desirability of each scenario.

Scenarios have been widely applied in conservation research, both at global (Tscharntke et al., 2012; Brussaard et al., 2010), regional and local (Carlson et al., 2011; Delevaux et al., 2018) scales. In a participatory setting, other methods can be used to help in scenario design: those methods include participatory mapping, a participatory GIS method. Participatory mapping involves leveraging the knowledge that stakeholders hold about the geography of their landscape, in order to achieve a community-driven objective. It has been widely used in social-ecological research (Plieninger et al., 2013; Lynam et al., 2007).

Participatory GIS methods such as participatory mapping can allow connectivity conservation models to be more spatially explicit about the obstacles and opportunities presented by connectivity conservation. 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.

Here we do not present a scenario design exercise, but a community workshop with a consensus building and participatory mapping exercise, whose results were engineered as simple scenarios in an integrated land use, climate change, and connectivity model (developed in chapter 1). We improve our understanding of the obstacles and opportunities to connectivity conservation in the region, and provide a good starting ground for an iterative process of scenario building. We focused on the region of Montérégie, in southern Quebec, where connectivity conservation has become the focus of land use planning decisions. This project has been developed in collaboration with the non-profit NAQ (Nature action Quebec) in the context of a multi-stakeholder conservation project, the PADF (Plan d’Aménagement Durable des Forêts). The PADF aims at building consensus on priorities for the management and possible conservation of forested land in the region.

This research is pursued in continuation of the project “Monteregie Connection”, whose goal was to engage stakeholders around a discussion of the ecosystem services provided by natural habitat in the region. In the context of this stakeholder-driven project, Mitchell et al., 2015 conducted a non-spatially explicit scenario building exercise for a subset of the Monterege region, the Vallée-de-Richelieu Municipalité Region Comté. The outcome was the 4 scenarios, going from “Periurban Development” to “Green Development”, describing different land use change trends. The Monterege connection project improved our understanding of the relationship between forest connectivity and ecosystem

services. However, there was no effort to estimate the impact of each scenario onto the ecosystem services. This is partially due to a lack of tools able to translate these scenarios into simulations. We contribute to the development of such tools by integrating the results of the workshop into the land use change model developed in chapter 1. The goal of this chapter is therefore twofold: gain a better understanding of conservation priorities in the region, and to provide a basis for an iterative scenario-building process.

## 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 3–11 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 “regional tables” were created. In the subsequent sections, the workshop results are divided between the regional and regional 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. All participants were given a visual aid to remind them of the agenda of the workshop. Facilitators were also present at almost every table and helped facilitate the discussion. They were given a document to help them in this role. All workshop materials, including the ethics approval document for this research project can be found in Appendix

2.

## **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 3–9 and 3–10. 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.

#### **2.3.2 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**)

### **2.3.2.1 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.

In addition, similarly to in Chapter 1 we extracted the distribution (logged) of pixel flow values under the form of histograms. We also ran the SURF analysis in the same way and counted up the number detected feature for each surface, in order to derive a measure of flow complexity.

## **2.4 Results**

### **2.4.1 Community workshop**

During our community workshop, participants identified connectivity conservation priorities in Monterege. Participants quickly built consensus on which key cores areas and corridors should be prioritized for protection or restoration. They mainly identified large forested regions and protected areas as key cores areas. As key corridors, participants were strongly drawn to linear strips of connecting “stepping-stone” patches. They were rarely drawn to redundant corridor design. When participants were asked what factors would make a link a priority, they emphasized the quality of habitats to be linked, as well as a diversity of constraining and facilitating factors.

Participants also workshopped constraints and assets to connectivity conservation in Montréal. We divided the results into elements that had been spatialized (i.e. placed on a specific location of the map during the exercise), and non spatialized (i.e. not placed on a specific location ), and scored them for the level of consensus they generated. Constraints scored higher, on average, than assets, indicating a focus of participants on constraints. The elements in the spatialized set scored higher on average than in the non spatialized set, indicating that participants tended to focus on more tangible and local issues and assets.

Non-spatialized elements seemed to speak to more general and large scale aspects. The main theme among these elements was predominance of agriculture in the landscape, and the difficulties to reconcile agricultural production with conservation. On the other hand, spatialized elements seemed to reflect local realities for connectivity conservation, such as the presence of highways or specific trends in land use change such as speculative pressures.

#### **2.4.1.1 Forested cores of importance**

Protected areas are well represented in the identified key core areas, for example the protected areas of the Green Mountains in the MRC of Brome-Missisquoi, or parts of the Montréal Hills such as the Mount Saint-Hilaire.

The participants at the sub-regional (figure 2–1) and regional (figure 2–2) tables identified redundant groups of forest patches. Because regional tables covered the whole of Montréal, they often identified cores that contained the cores identified by the sub-regional table.

#### **2.4.1.2 Obstacles and assets**

The tables identified a total of 63 items as opportunities or assets, and 56 as constraints or obstacles. Tables 3–10 and 3–9 displays the 5 assets or obstacles that scored the highest for each workshop table.

Non-spatialized elements seemed to speak to more general and large scale aspects. Among them, the assets that scored the highest varied according to the sub-region under consideration. In the Centre table participants emphasized the strong presence of environmental NGOs, whereas the North and East tables emphasized elements linked to forest management. Interestingly, the presence of a strong agricultural matrix in the region scored high as an asset at the regional tables, and very high as a constraint on a sub-regional table, highlighting the polarizing status of the agricultural land use type in the region. Another constraint linked to agriculture is the CPTAQ - an agency responsible for the protection of agricultural lands often involved in discussions around land use planning - mentioned for the Centre sub-region. Similarly, the East table mentioned the issues that farmers have to make their farm profitable as another constraint. Besides agriculture, participants emphasized other constraints, such as economic realities making conservation a less likely investment, given the cost of implementing connectivity conservation measures - also mentioned as a perceived constraint. Finally, the participants mentioned that the overwhelming majority of forests are situated on private lands, along with the existing road infrastructure.

Spatialized elements seemed to reflect local realities for connectivity conservation. They are summarized in maps 2–2 and 2–1, which shows the single highest scoring element (asset or constraints) for each sub region. the Centre, East and North tables mentioned positive local inclinations toward conservation. Similarly, the West and regional tables mentioned local legislation and the active mobilization of stakeholders, highlighting that connectivity conservation is a concern for many stakeholders in the region. Concerning constraints, participants emphasized once again elements related to the predominance of agriculture in the region. The lack of engagement from farmers was mentioned in the Centre and West tables, along with land use "pressures" coming both from agriculture and urban spread. The East table emphasized on the similar "vilegiative" pressures, along with more local concern such as the Highway 10 and the intensity of local agriculture practices.

The North table also mentions its highways. The regional tables mentioned the price of agricultural lands and the need for compensating the loss of agricultural production due to conservation.

#### **2.4.1.3 Links of importance at the regional scale**

##### **Factors of priority**

Among the factors that were designated as a priority for the identification of links, participants emphasized the characteristics of the natural environments that make up the nodes that are to be connected. They mentioned the importance of the "quality" of these nodes themselves: for instance, the protection status of habitats, their diversity (variety of habitats), their surface area, isolation or proximity, and the pre-existence of connectivity potential. This highlights that stakeholders agree on the value of high quality habitats and on the need to protect them.

Participants debated the importance of both "facilitating" and "constraining" factors in deciding whether a link is a priority. Facilitating factors included the feasibility of establishing the link, social facilitators such as political and social buy-in, and territorial facilitators, such as appropriate land use. There were several types of constraints: financial, social, territorial and physical, and must be considered in relation to the socio-political and spatial planning context in which they emerge.

The presence of species at risk was identified as an important factor, along with other elements such as social factors (available economic means and the level of local interest in conservation) and characteristics of the link itself, including the functionality of the corridor. Consideration of threats such as the level of fragmentation was also noted. Finally, the fact that the environment is to be protected or restored was also deemed important. Interestingly, regulations are among the factors that were cited less often, such as Quebec's PRMHH ("Plans régionaux des milieux humides et hydriques", or regional

wetlands conservation plans), and migration routes.

### **Priority link mapping**

The consensual mapping process identified important links between the key areas identified in the previous steps at both sub-regional (figure 2–3) and regional tables (figure 2–4). At sub-regional tables, participants displayed what could be called ”corridor opportunism”: participants wanted to link areas by joining patches they judged to be organized in a linear or corridor-like fashion.

Participants were rarely drawn to redundant corridors. Tables were asked to limit themselves in the amount of links they were to prioritize, but were not given an exact number. Only one table (North) felt that corridor redundancy was important enough to include redundant design in their priorities. It can be clearly seen in figure 2–3 most participants decided to sacrifice redundancy for parsimony, as only the northern part of the region displays redundant (yet arguably still parsimonious), corridor design.

As for the forested cores, there was a lot of redundancy between links identified at the sub-regional and regional tables. Because the regional tables covered the entire region, they were able to identify links at a larger scale (see figure 2–4). This allowed the participants to designate a larger scale link along the Saint Lawrence River, as well as links between the lake Champlain region and the easternmost parts of the region, and between the Saint-Francois wildlife area and mount Rigaud, mentioning that this last link would need to be implemented in collaboration with Ontario. It was clear that participants at regional tables felt that a broader discussion of links with outside of the region was necessary.

#### **2.4.2 Conservation scenarios**

##### **2.4.2.1 Land use change model**

The projected land use maps for each of the conservation scenarios allowed us to visualize some of the possible futures for the region, if connectivity conservation, as it is

conceived by the participating stakeholders, were to become a priority for regional land use planning. Figures 3–8, 3–9 and 3–10 compares land use maps from 2010 with the projected maps for 2100 for each of the conservation scenarios.

The information contained in those maps is summarized with a bar chart showing changes in Agricultural, Urban and Forested land use area for 2010 and 2100 (see figure 2–5). For all scenarios, the urban area was allowed to almost double. This is apparent in all maps, where urban land has spread in a similar fashion to the BAU scenario in Chapter 1. Forest is maintained for all scenarios except for the BAU-Corr scenario, which only differs from the BAU scenario of chapter 1 in that the links and areas identified by stakeholders are protected from urbanization and agricultural expansion. In this scenario, agriculture is also allowed to maintain its area. This is not the case for the other scenarios, which include reforestation, which, in the context of spreading urban land, must result in the loss in agricultural land (similarly to what was observed under the reforestation scenario in Chapter 1).

Although the two conservation scenarios that include reforestation do not differ in their changes to the different land use area, they display different spatial patterns. Under the BAU-R-Corr scenario we observe a similar pattern of growing forest patches than under Chapter 1's Reforestation scenario : small patches have disappeared (except in the corridors) and bigger patches have grown. But we see the most striking difference with the last conservation scenario, BAU-R(T)-Corr, for which reforestation is targeted to the corridors identified by the stakeholders. Under this scenario, we still assume that forests grow from existing patches. The consequence of these two constraints is that where forest can grow easily in a linear fashion, it tends to do so. Therefore we see that corridors of forest are delineated, within the 5km buffer around identified links that were given to the model. The pattern is especially striking in the north of the region. In the south and the west of the region, we see a different pattern under which the model generated the growth

of the identified forested cores.

#### 2.4.2.2 Connectivity modelling

**Current flow** The three conservation scenarios impacted the mean flow values for our five species differently, but we can derive a few common patterns from figures 2–6 (linear graph) and 2–7 (radar graph). In comparison to the species BAU scenario (for which the responses are described in Chapter 1), we see that the conservation scenarios usually manage to slow the decrease in mean flow. As in chapter 1, only the black bear (*Ursus americanus*) - and, to some extent, the short-tailed shrew (*Blarina brevicauda*) - manage to maintain a similar level of mean flow under the conservation scenarios that include reforestation.

In terms of decrease in mean flow, the smallest departure from the outcome predicted by the BAU scenario is observed in the BAU-Corr scenario (protection of identified areas). The mean flow at the end of the simulation is systematically better than for the BAU, but always worse than the two other conservation scenarios, except under RCP 8.5 climate for the american marten, for which the outcome is on par with the BAU scenario under baseline climate. Similarly to chapter 1, we see that some species's response is more linear than others, but in general all species under all scenarios (except for the BAU scenario) show some curving in their response. it is important to note that the conservation of areas and links of importance is only triggered in 2020 - not at the start of the simulation in 2010 - which could contribute to the non-linearity by providing a point of inflection in the response.

We can note the variations on which of the two reforestation scenarios is most effective at curbing the decrease in mean flow, the degree of which tends to depend on the climate scenario as well as the species. For the wood frog, random reforestation performs better than targeted reforestation, invariant on climate. Same pattern for the redbacked salamander, but for it warming scenarios are consistently better and lead to less loss in mean flow.

For the back bear, the two reforestation scenarios ended with the same amount of loss in 2100 (despite some early divergence), and did not depend on the climate scenario. The flow values for the short-tailed shrew also decrease less under the random reforestation scenario, and displays larger differences between historic and climate change scenarios. Finally, the most complex patterns are observed for the american marten. Although it also seems to do better under random reforestation, the response varies with the climate scenario; the response curves are staggered in such a way that targeted reforestation under the baseline climate scenario predicted higher mean flow than random reforestation under RCP 8.5. Similarly, the BAU scenario under baseline climate predicts higher flow values than the BAU-Corr scenario under RCP 8.5. This highlights an apparent non-linear response to climate by the american marten, for which baseline climate seems worse than RCP 8.5 but better than historical change.

**Flow distributions** In chapter 1, we showed the importance of looking beyond the mean flow values and searching for patterns in how the distribution of flow values change. We also characterized two different effects on those distributions: a "directional" effect, which acted to shift high flow pixels toward lower flow intensities, and a "polarizing" effect, which pushed middle level values toward low values, with small to no effect on high value pixels.

In the conservation scenarios of this chapter we see that the BAU-Corr scenario has a clear directional effect across all species' histograms (see figure 2–8) toward smaller flow values, whereas the other two scenarios which include reforestation have a polarizing effect, similarly to in Chapter 1. However, in the case of the black bear, we see a directional shift toward more positive values.

**Feature detection** The results of the feature detection via SURF vary a lot depending on the species. The simplest response is from the black bear, for which, as in Chapter 1, less features are lost in scenarios without reforestation (there was no apparent impact

of climate) than in scenarios with reforestation. The redbacked salamander and the wood frog responses were similar: less features are lost in scenarios without reforestation, but differences between scenario outcomes are more strongly marked and we see an effect of climate, with warming scenarios leading to more losses in features. The responses of the short-tailed shrew and the american marten are more complex. Although for the shrew, scenarios without reforestation seem to lead to the loss of fewer features, the curves are bundled in such a way that differences are less stark. Finally, the american marten shows the opposite pattern: scenarios without reforestation lead to more losses in features than scenarios with reforestation. In addition, there is a hierarchical pattern between the outcomes of the different climate scenarios: warming scenarios lead to more losses in features than the historic scenario (absence of climate change).

## 2.5 Discussion

Conducting participatory research in Montereigie led us to a better understanding of the obstacles and assets to connectivity conservation in the region. The predominance of the agricultural land cover and its implications for land use planning and the regional economy was revealed as the most important source of obstacles for the region's conservation goals, but also as a source of opportunities to develop more biodiversity-friendly farming practices. The expansion of urban infrastructure ranked high in more forested regions of the landscape. A range of assets was identified in the region: the strong engagement of local actors in connectivity conservation was a key factor. Through a consensual mapping workshop, we also mapped consensual priority core areas and links, showing how participants think corridors should make the best use of linear strips of the remaining forest in the region. Specifically, this demonstrates that participants saw small patches as important for corridor design and perceived corridors as an important tool to conserve and restore the potential of fragmented patches. However, it also means that designing corridors in such

a way might mean that an otherwise important patch could be ignored because its location does not fit a linear corridor design.

Interestingly, Different tables also identified corridors with variable redundancy. Redundancy is an important connectivity conservation design, increasingly being explored in connectivity experiments (Fletcher et al., 2014). It is possible that participants at the north table though redundancy was necessary to make the best use of the layout of forest, which are interspersed in the agricultural matrix. This is by opposition to the corridors of the south table, where forest patches are smaller and more scarce. Participants at this table might have thought that one non redundant linear corridor was all they could ask for in a predominant agricultural matrix. Those results represent a first step toward a better model of how stakeholders could make complex conservation-related decisions.

The integration of those corridors to the land use change model shows how qualitative priorities from a participatory process can be turned into model inputs. It is interesting to see that some changes anticipated by workshop participants are observed in our land use change business as usual scenario. For instance, the increasing land development in the east of the region toward estrie, coined as “village pressure” by participants to designate the building of cottages and country houses. This demonstrates that participants are in tune with current land use change in the region and that our model was able to replicate them. Concerning connectivity results, it is important to see how they compare to the business as usual scenario. These results complement those of chapter 1 and show similar patterns with regards to species response. When only looking at mean flow values, species with linear and simple response are those who seem to depend on forest types that are only under threat by land use change. On the other hand, species dependent on forest types that are under threat both by land use change and climate change show a more complex response, with more variations in the final outcome (2100 horizon) of the scenarios.

Concerning flow complexity, it is interesting to note that the number of features detected by the SURF algorithm is consistently lower through time for all species under

targeted reforestation (in corridors) - except for the Marten. It is possible that corridors allow to streamline current flow and prevents complexification that arises with fragmentation, although, as pointed out in chapter 1, the link between number of features and complexity would need to be examined in more details before drawing a final conclusion.

We extend on the work of Albert et al., 2017, which implemented a simple land use change model, but did not attempt to generate any alternative scenarios. In many ways, this work can be compared to recent work that looked at how connectivity could change under a range of scenarios. One example is Rubio et al., 2012 who tested whether a network of forested patches resilient to different land use change scenarios, for a species of nuthatch. They found that although identifying such a network was possible, its effectiveness and efficiency was under threat under certain scenarios. Our results suggest that findings of that sort are likely to change when climate change is considered, if the species under study is dependent on sensitive forest types.

The results of our simple scenarios have implications for connectivity conservation in the region. The reforestation scenario suggests that reforesting as much land as is urbanized is what is necessary to maintain mean current flow. But this is only one simple measure of connectivity, and therefore those results suggest that more work is needed to explore which metric would be most appropriate to look at in this context, and more importantly what land use practices (protection, reforestation, urban densification) would be enough to maintain this metric. In the light of the results from our workshop, it is clear that reforesting the same amount that we are urbanizing is possibly socially unacceptable, given the amount of agricultural loss it generates. Even such a simple scenario echoes the long debated question of land sparing versus land sharing, a dichotomy that is now largely questioned as it fails to address the complexity of both food systems and the diversity of farming practices Tscharntke et al., 2012; Bennett, 2017. In fact our reforestation scenario can be seen as an agricultural intensification model, in which farmers are able to cultivate less land to allow for more space for forest. Yet our workshop results suggest that stakeholders

would not think along those lines, and are more likely to propose compensations to farmers for the loss in productive surface or for changes in practices. This is likely reinforced by the fact that some stakeholders are opposed to further intensification of agricultural practices (also cited as an obstacle by participants). New compensation schemes such as ALUS (Alternative Land Use Services) are being experimented in Monterege and are looking promising in their capacity to federate a bottom up movement of conservation in agrosystems Ouellet et al., 2020.

The simple approach to the sparing vs sharing question that is brought about by our scenario overlooks the question of scale. At the scale of Monterege, it is unclear to which extent the reduction in agricultural land can be promoted by the regional government. Like all modern farming systems, Quebec's agriculture is embedded in a global market which might make it likely to prioritize global trends over local interests. Therefore, we are overlooking important variables for the design of credible alternative scenarios for conservation in the region, variables that are more likely to be elucidated in a participatory setting like the one we used.

Our methodology would allow us to explore alternative scenarios with ease. We imagined simple scenarios and therefore served as an intermediary between the workshop output and the model inputs. However, given the flexibility of the STSIM land use change model framework, steps could be taken to reduce that distance between stakeholders outputs and model inputs. The interest of stakeholders in participating in our workshop demonstrates that local actors are longing for tools that allow them to close the loop between what they think should be done and what it would effectively mean for species on the ground, to explore where and how much reforestation would provide the optimal corridor design, or how much redundancy is really needed. To make this a reality, we are missing some knowledge about specific parameters - for instance, what the ideal width of a corridor for a given species, or how much agricultural loss is acceptable to reforestation. But we are also missing specific tools, and this project demonstrates that it is now easier to get there.

The STSIM framework has been used in a participatory setting before. For instance, in Jarnevich et al., 2019, STSIM was used to produce a model for invasive species spread and fire management, using expert knowledge collected in a participatory setting. The authors also highlight the value to be found in involving “end users” of model results (i.e. stakeholders) in the modelling process. There remains a lot of work to be done to put these analyses in the hands of stakeholders. Making the analysis open and the code reproducible is one step in this direction.

Perhaps the most important limitation of this work is the fact that the strong consensus which was quickly built during the workshop is fragilized by the absence of some key stakeholders which, in spite of being invited, were not able to partake in the activity. This further illustrates the need for consensual mapping and the need for an iterative process with the goal to involve a larger diversity of stakeholders. Participatory research scholars have discussed the importance to consult and involve a diverse set of participants, representative of different knowledge systems, in efforts of participatory modelling Gray et al., 2012. The lack of representatives from the forestry and farming industries, important stakeholders in forest management, limits the impact of consensus building.

Similar limitations to those raised in chapter 1 also apply. For instance, the habitat suitability analysis, and the analysis of flow surfaces have important flaws that would need to be addressed (see chapter 1 for more details). Another critique could be made about the targeted reforestation scenario: due to the parameterization of the reforestation, it was easier for patches in the north of the region to grow into linear strips of corridors. This happened at a lower rate in the southern part of the region, due to the lack of the pre-existing patches of forest. Future scenarios will need to test if allowing for new patches to spawn on the map produces the same outputs - as long as this land use change trend is thought likely by stakeholders.

## **2.6 Conclusion**

Through participatory research we demonstrated the value of stakeholder engagement to models of connectivity conservation planning. We contributed a better understanding of obstacles to connectivity conservation and highlighted the flexibility of a scenario approach for the consideration of alternative scenarios of land use planning and connectivity conservation. Under our community-based scenarios, we observed similar types of response (linear versus nonlinear, simple versus complex) in our study species. Although we provided a basis for an iterative framework of community-driven scenario building, future research will need to achieve better representation in stakeholder groups.

## Figures & Tables

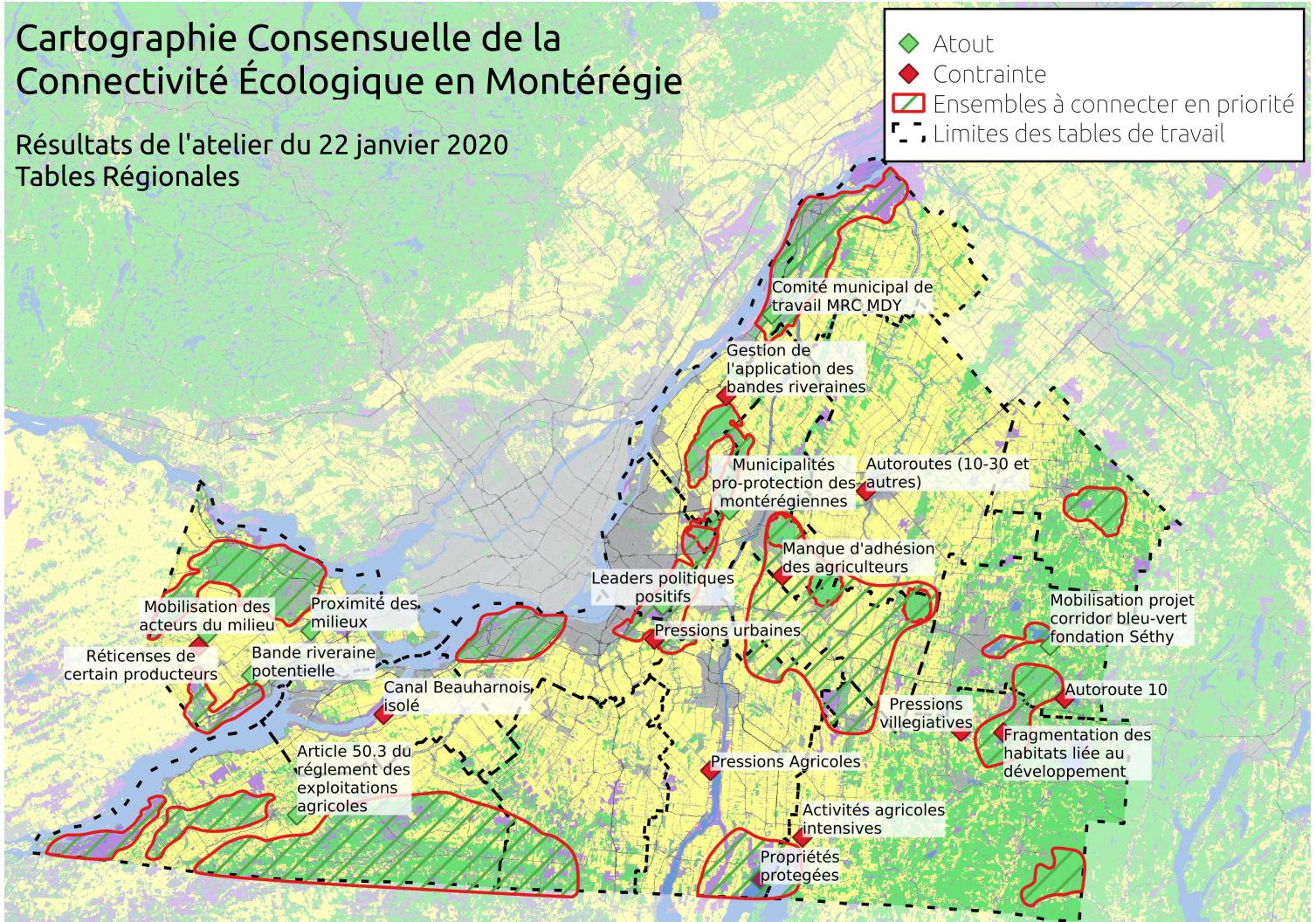


Figure 2–1: Cartography of opportunity and challenges with the highest importance and diversity metric (sub-regional tables).

# Cartographie Consensuelle de la Connectivité Écologique en Montérégie

Résultats de l'atelier du 22 janvier 2020

Tables Transversales

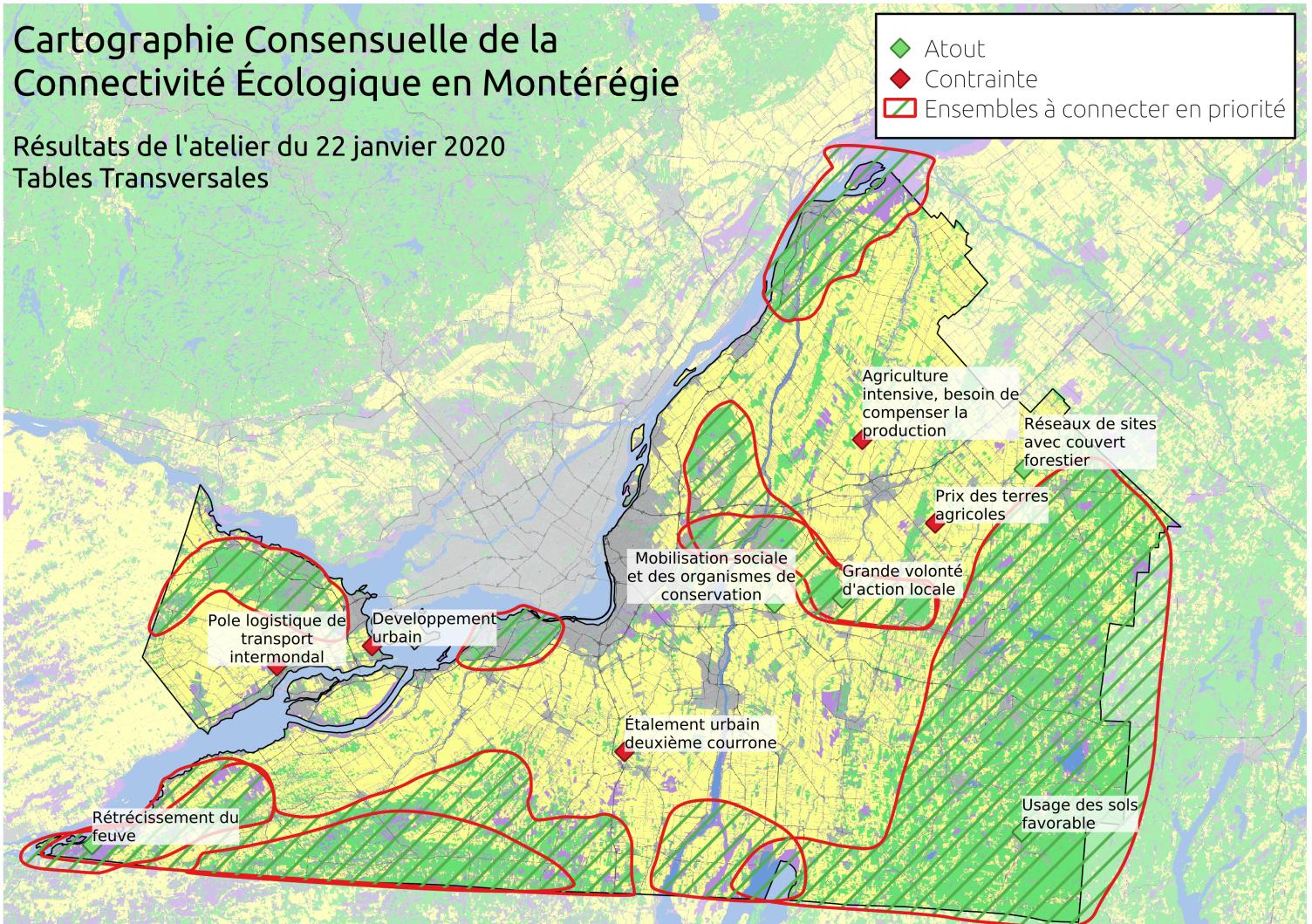


Figure 2–2: Cartography of opportunity and challenges with the highest importance and diversity metric (regional tables).

# 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

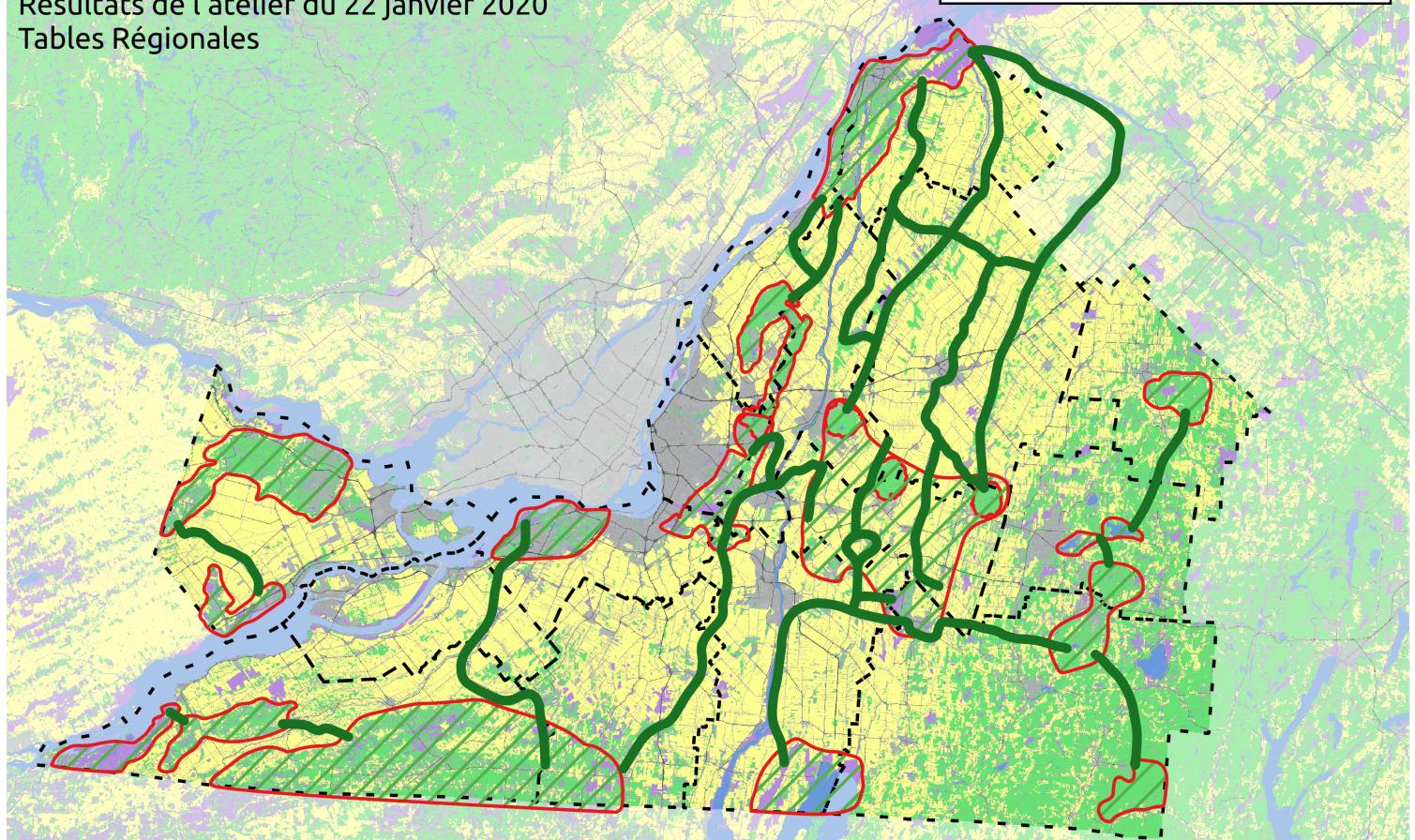


Figure 2–3: Cartography of priority areas and links (sub-regional tables).

# 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

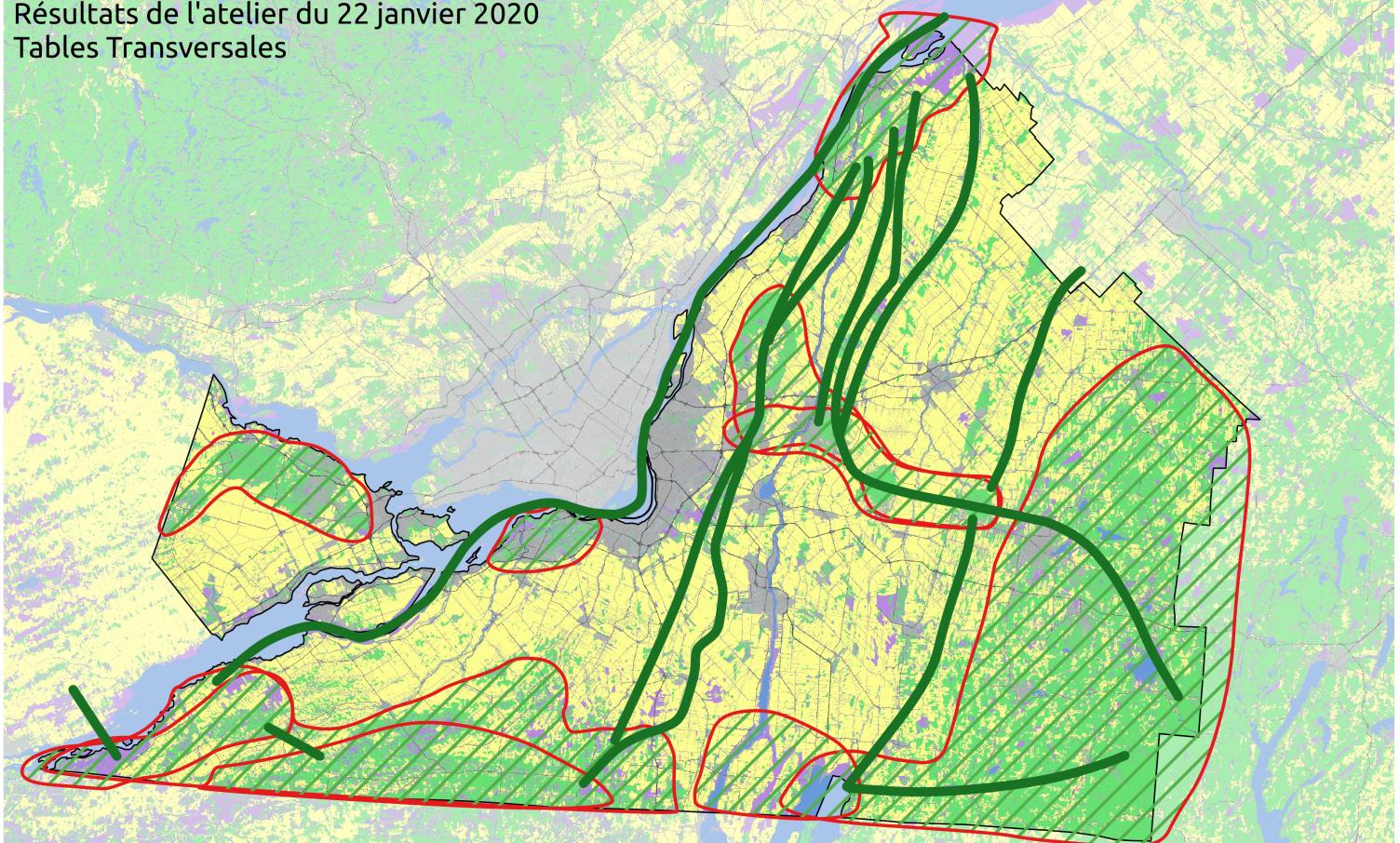


Figure 2–4: Cartography of priority areas and links (regional tables).

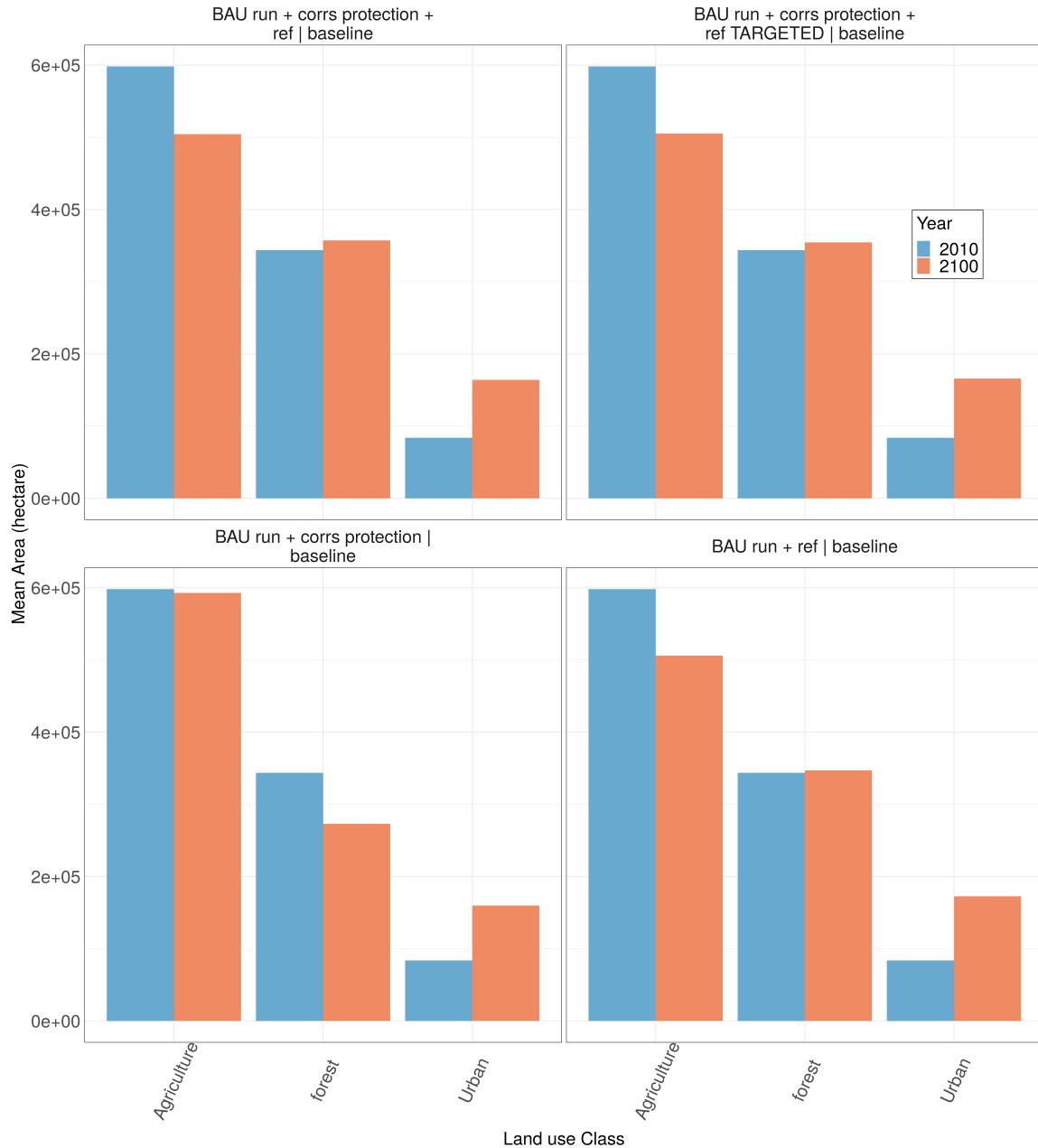


Figure 2–5: Land use composition.

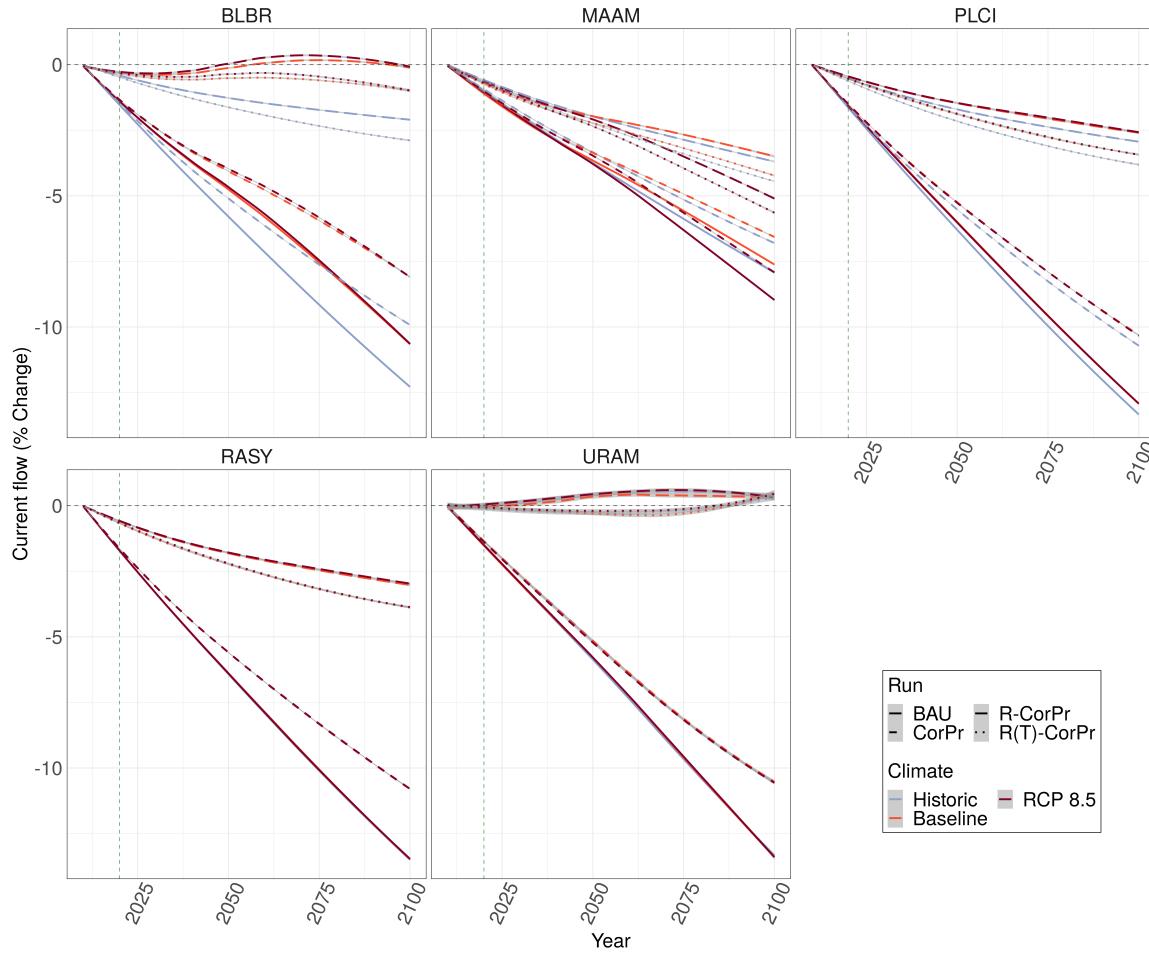


Figure 2–6: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with conservation scenarios.

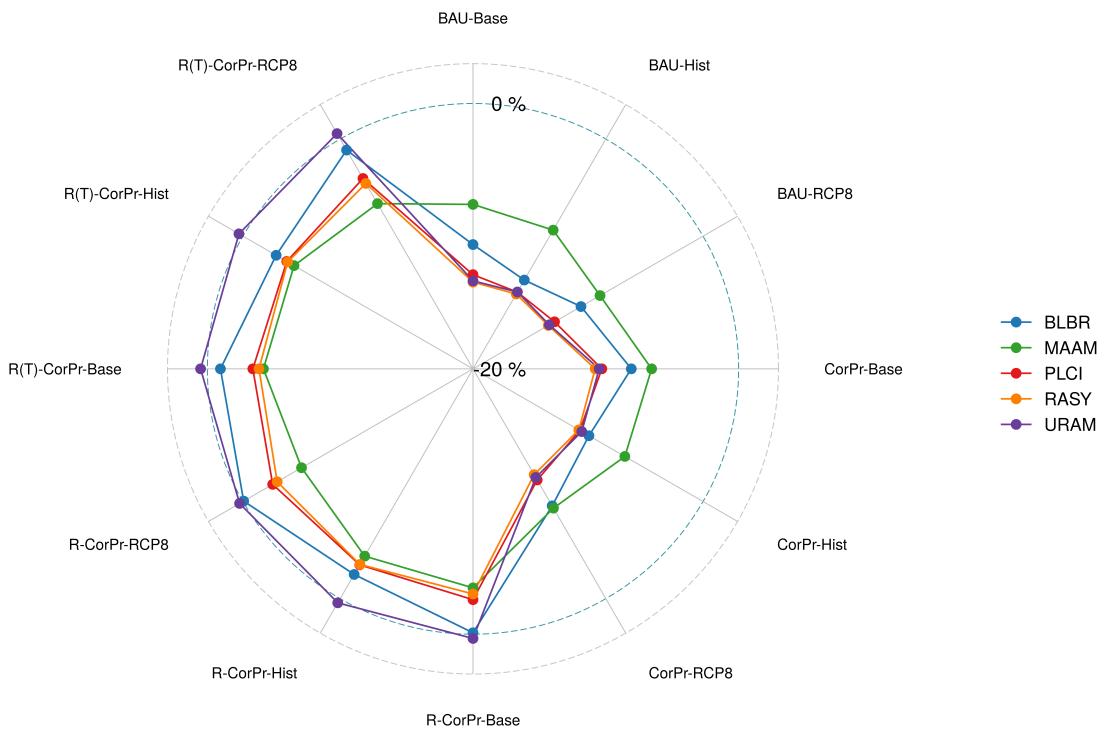


Figure 2–7: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with conservation scenarios.

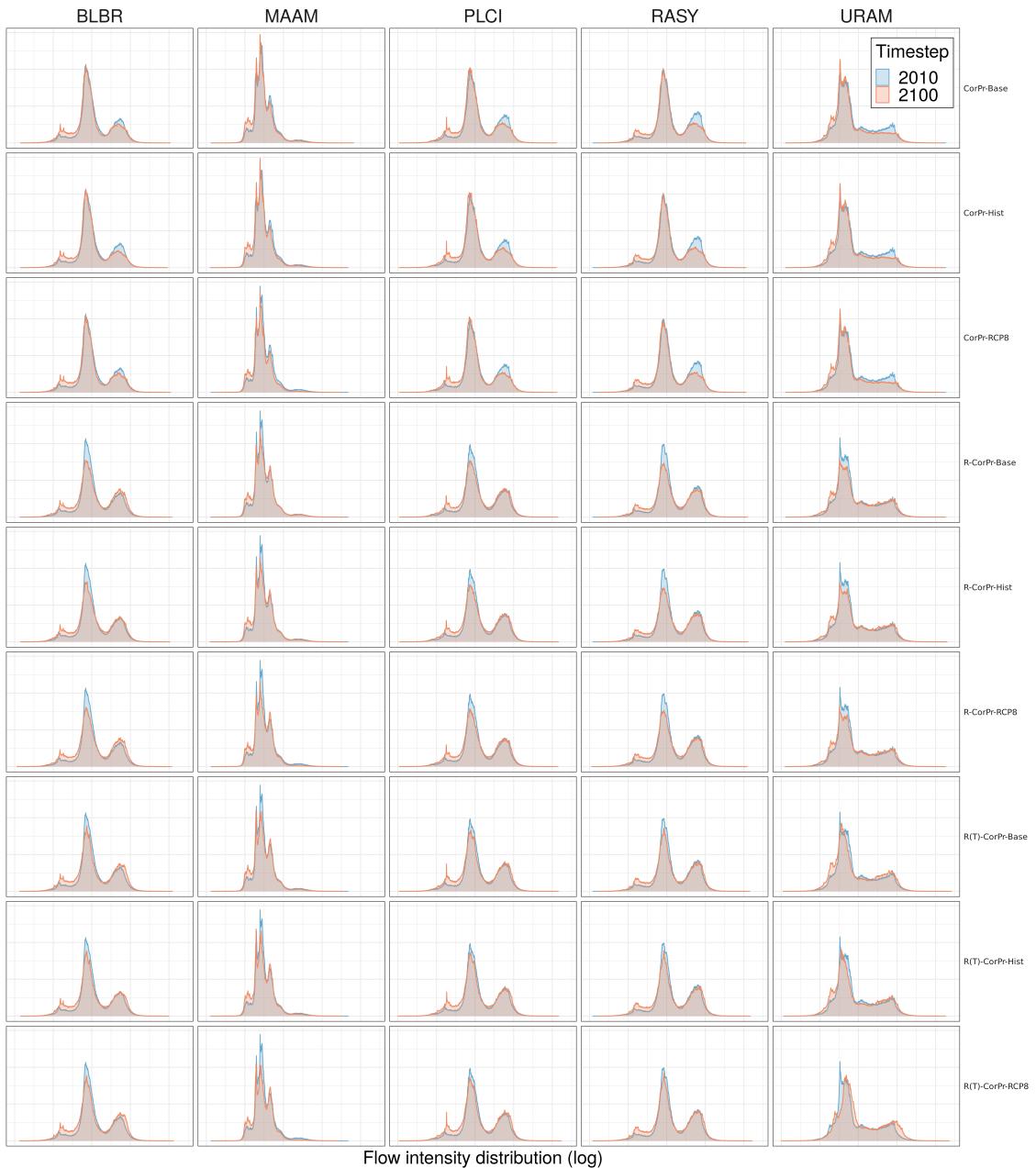


Figure 2–8: Histograms of flow values change.

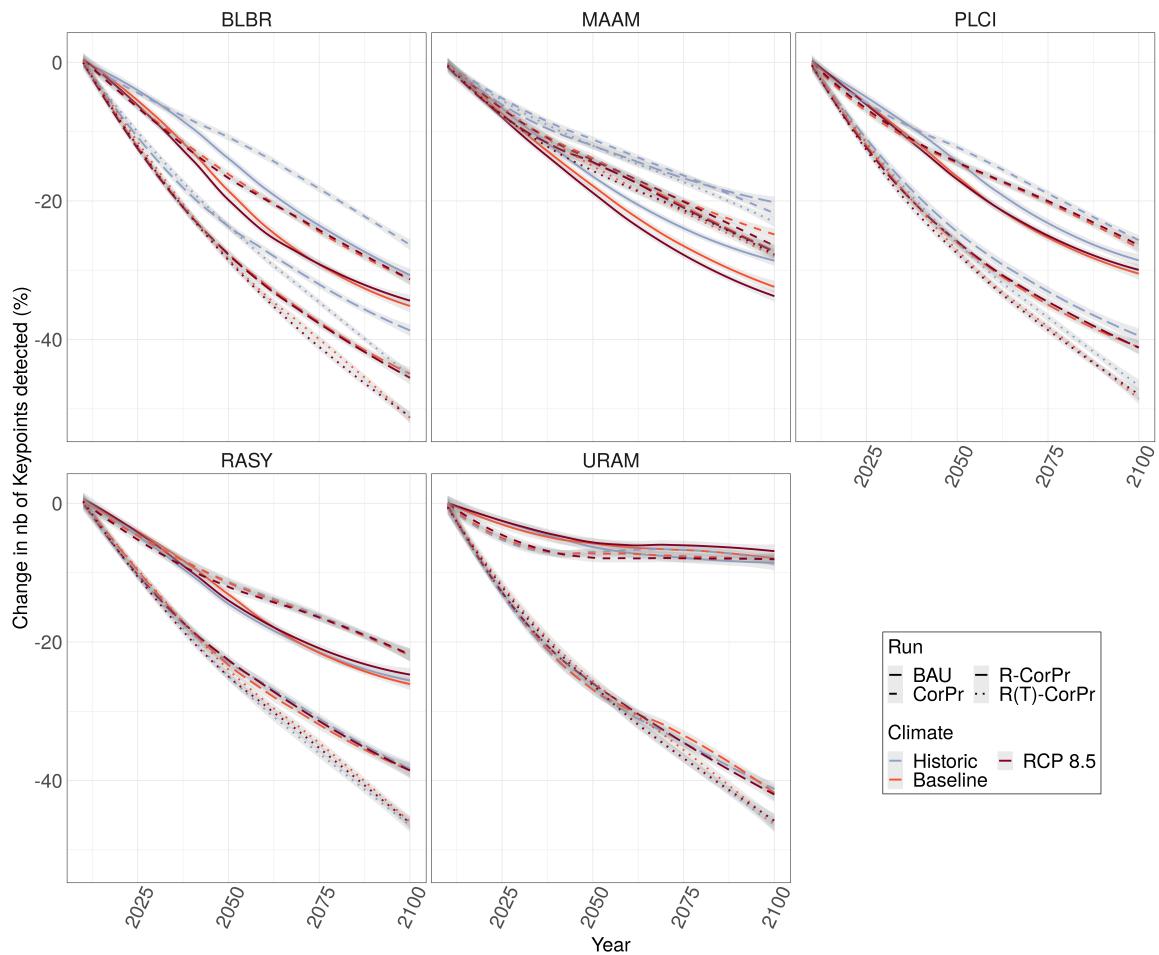


Figure 2–9: Change in identified features (partly pinch-points).

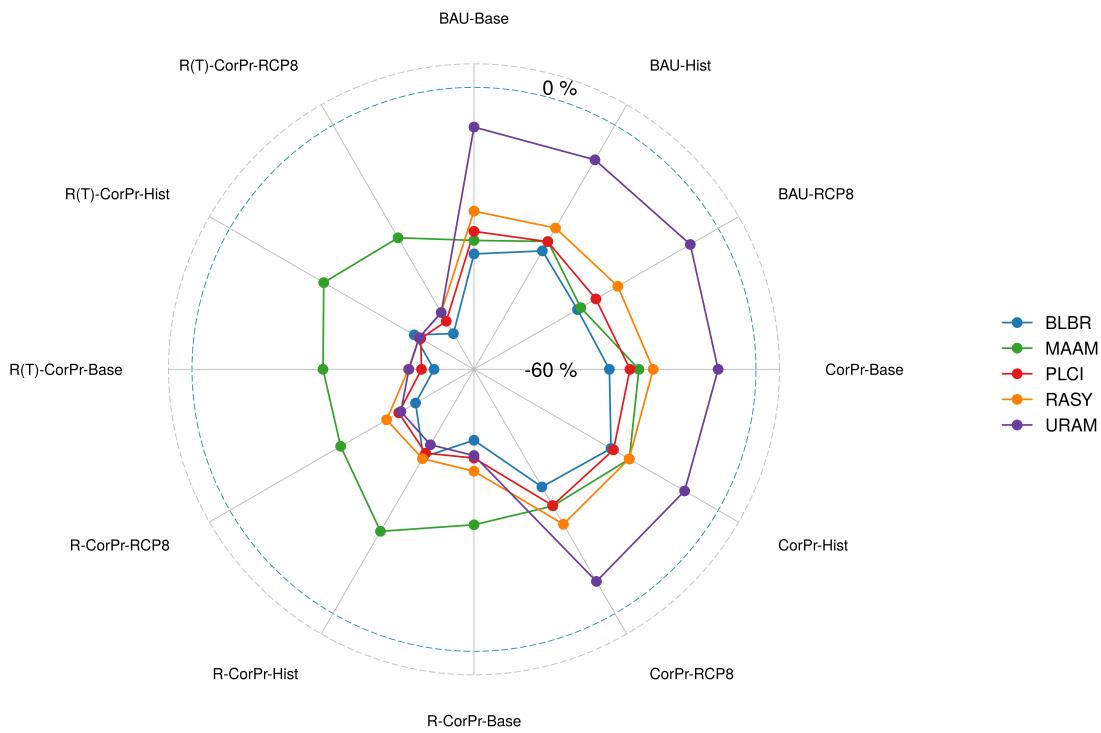


Figure 2–10: Change in identified features (partly pinch-points).

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## **General Discussion & Conclusion**

TEST — 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 (Frazer, 1984). The difficulty of land use change modelling 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. — TEST

## 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

Table 3–8: SURF analysis parameters

Parameter	Value
Hessian threshold	7000
Number of octaves	1
Number of octave layers	2

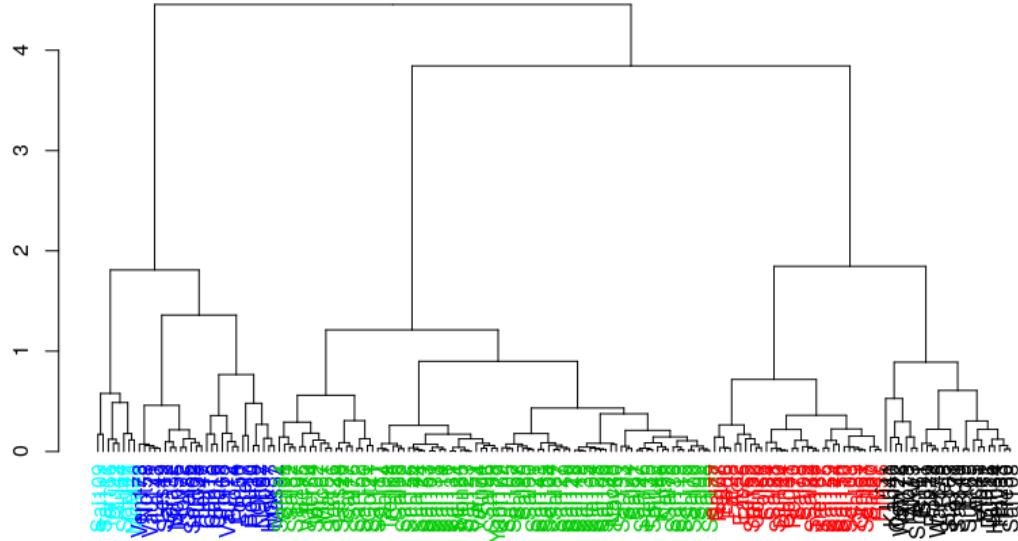


Figure 3–1: Results of Ward clustering for land use for municipalities (cut at 5 groups)

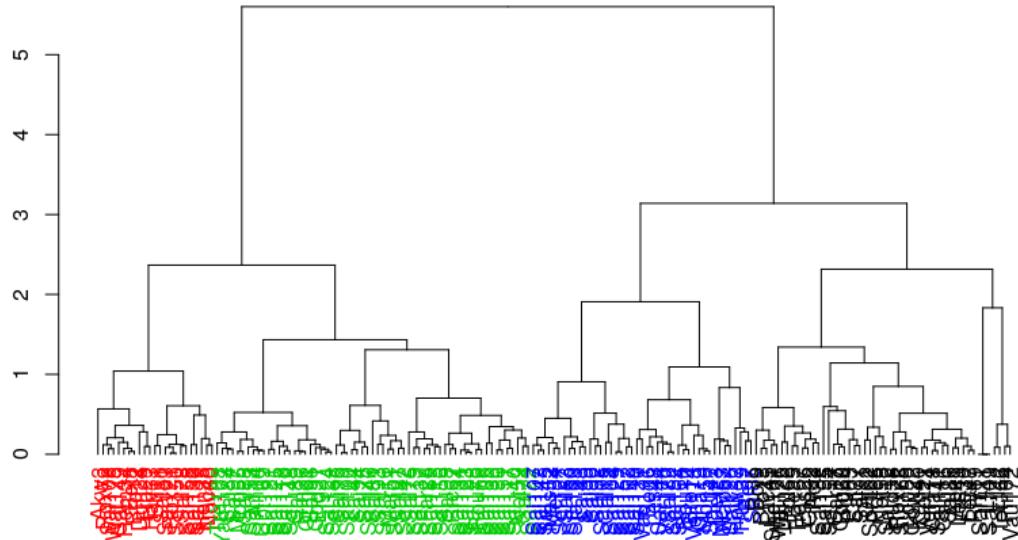


Figure 3–2: Results of Ward clustering for transition data for municipalities (cut at 4 groups)

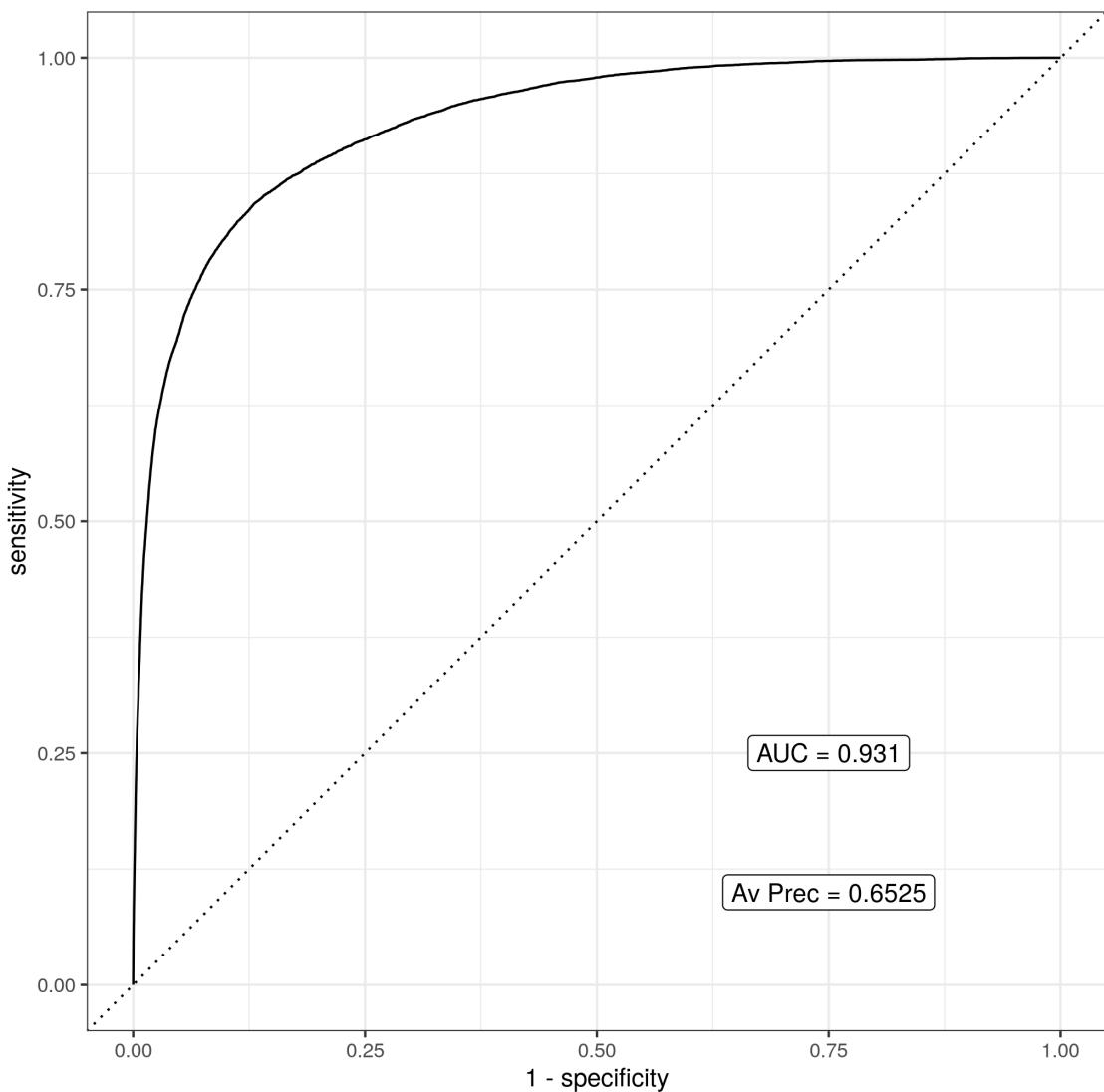


Figure 3–3: ROC Curve for Agricultural Expansion

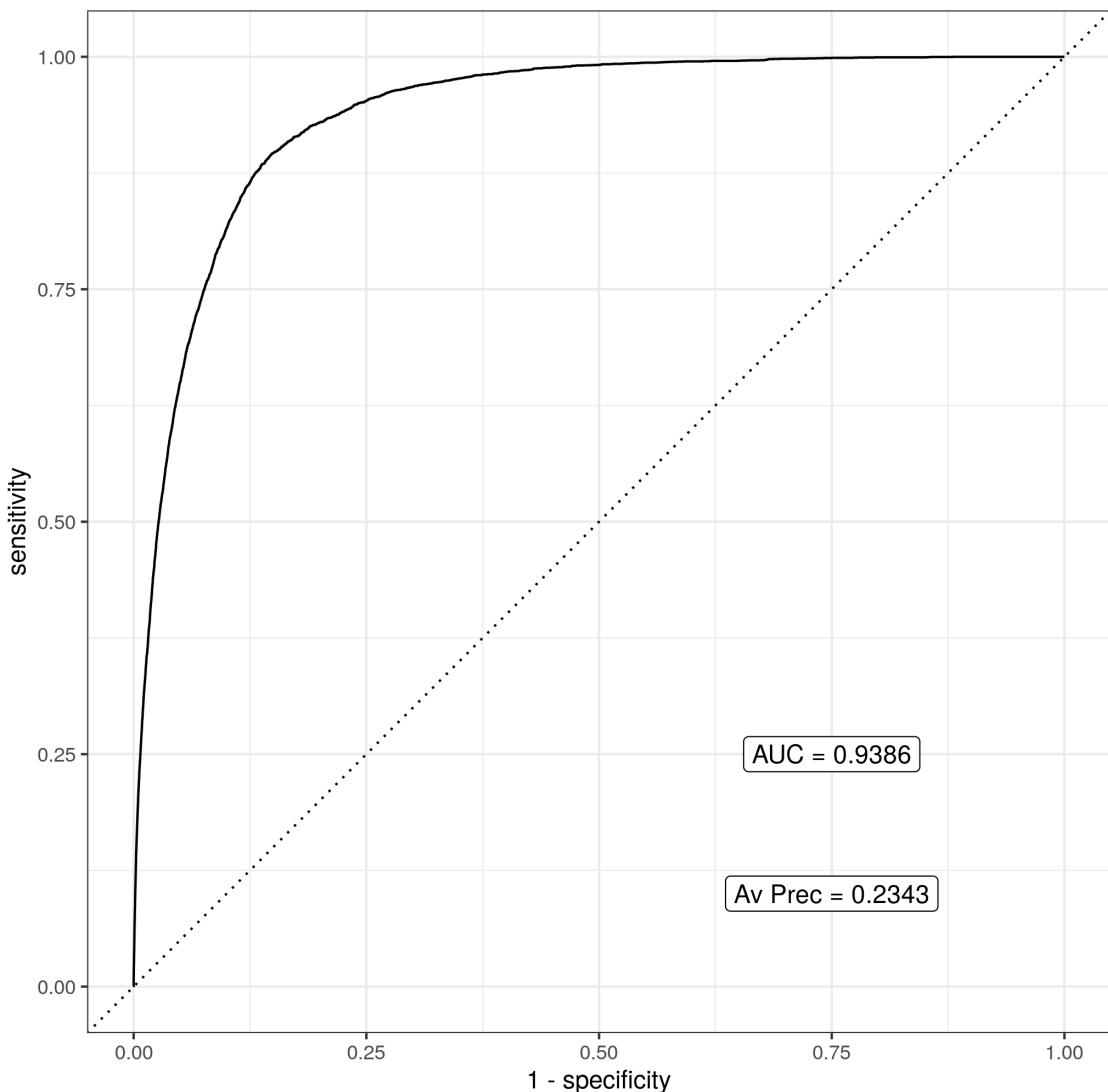


Figure 3–4: ROC Curve for urbanisation

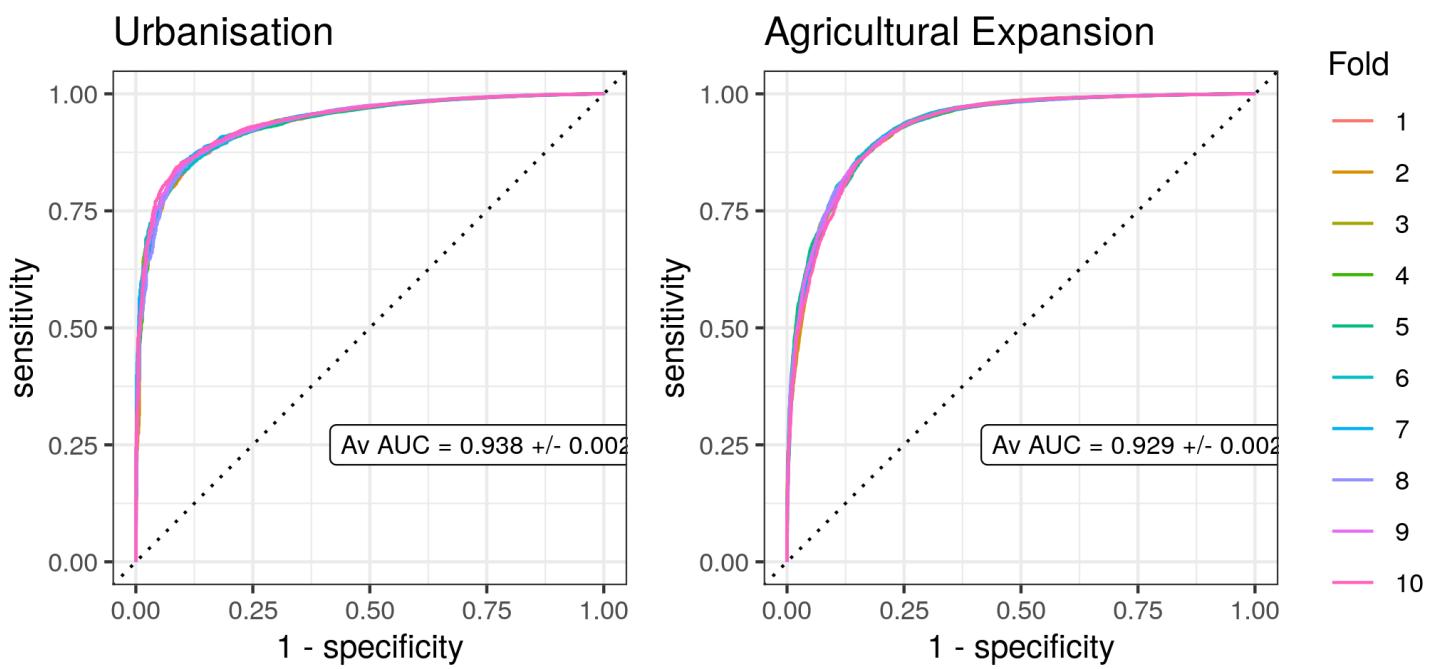


Figure 3–5: ROC Curves for re-samples

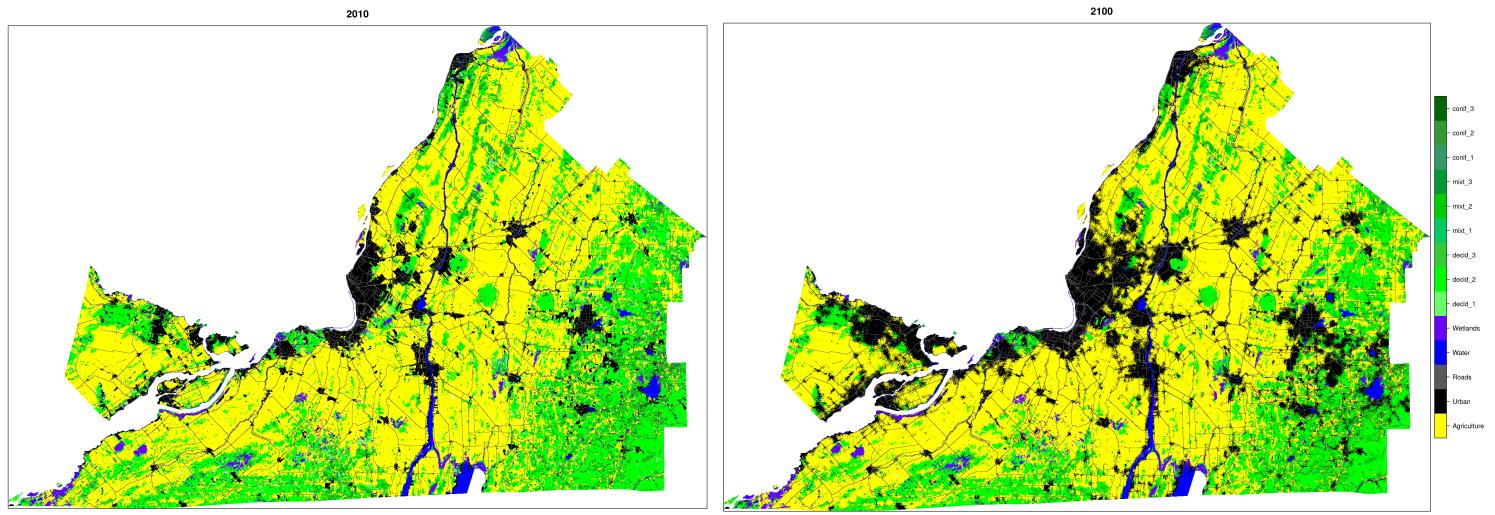


Figure 3–6: Comparison of Montréal at the beginning of the BAU simulation in 2010, and at the end in 2100 (BAU-Baseline scenario).

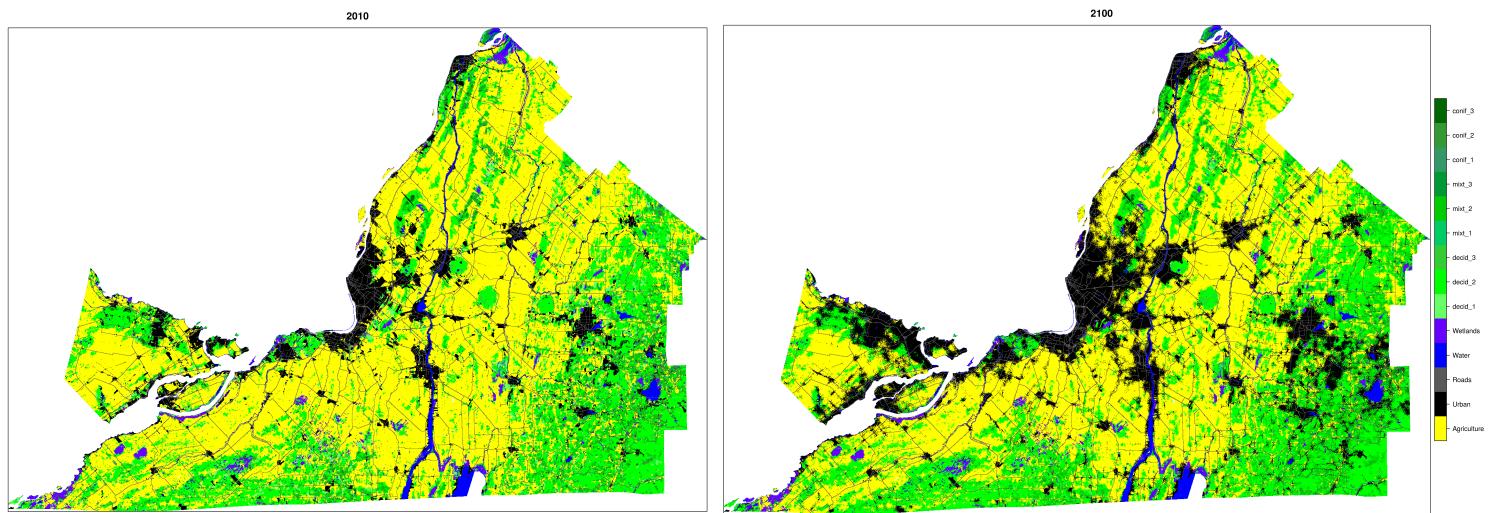


Figure 3–7: Comparison of Montréal at the beginning of the Reforestation simulation in 2010, and at the end in 2100 (BAU-Reforestation-Baseline scenario).

## Chapter II Supplementary Material

Table 3–9: 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 3–10: 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

Table 3–11: 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)

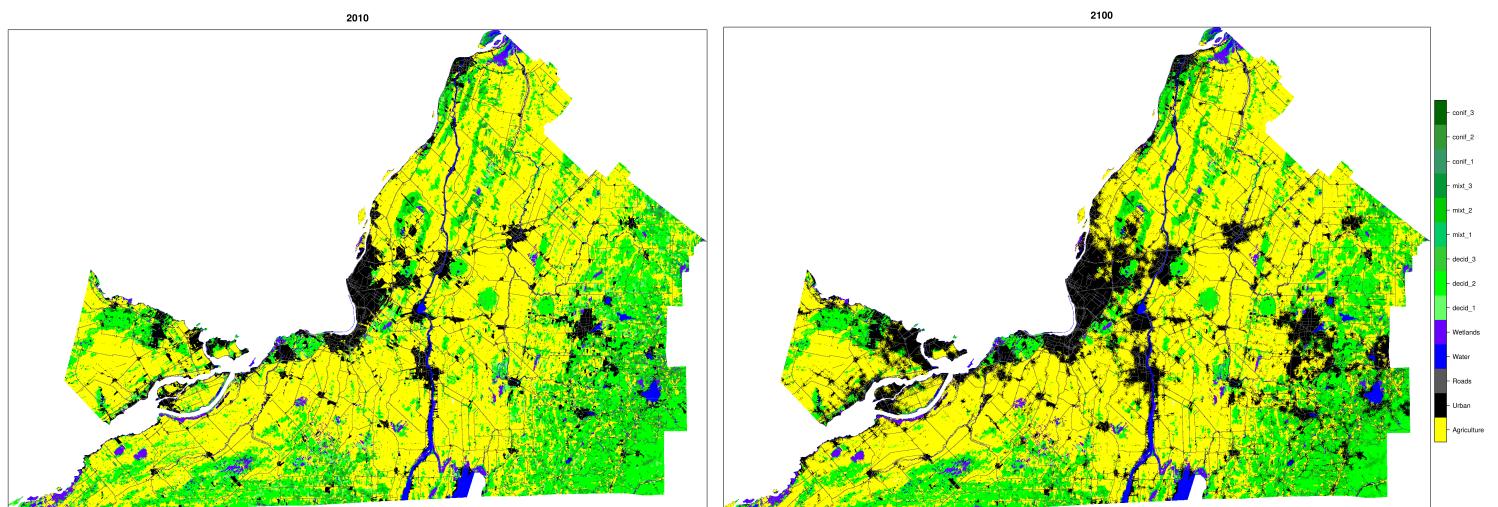


Figure 3–8: Corr).

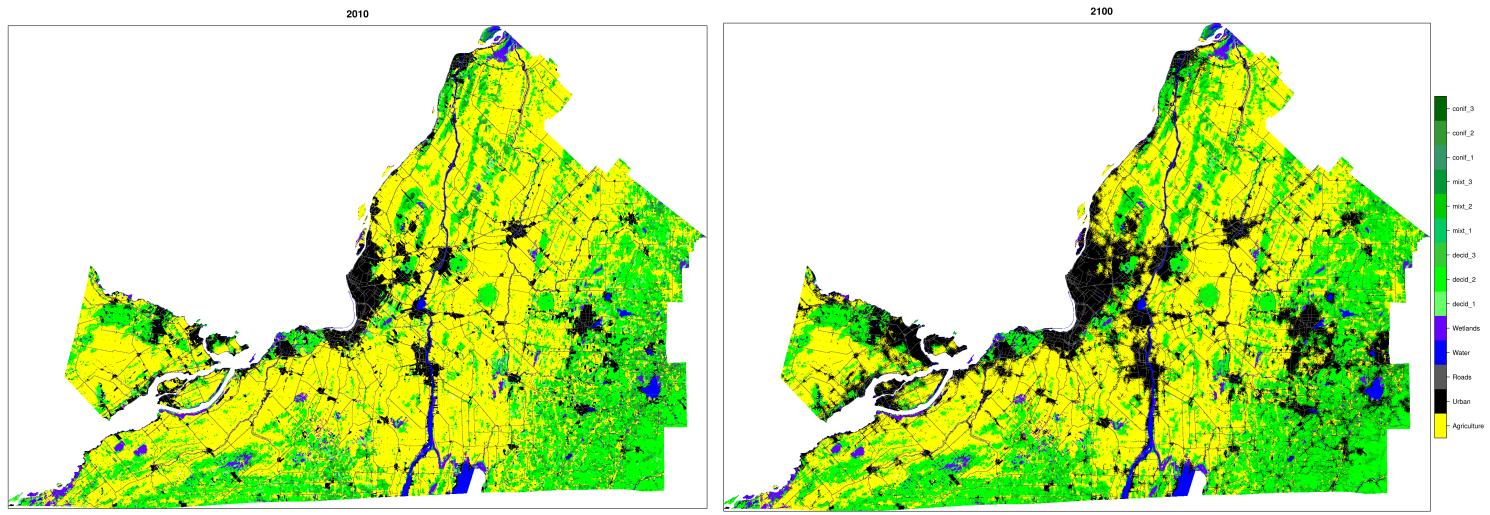


Figure 3–9: CorrRef).

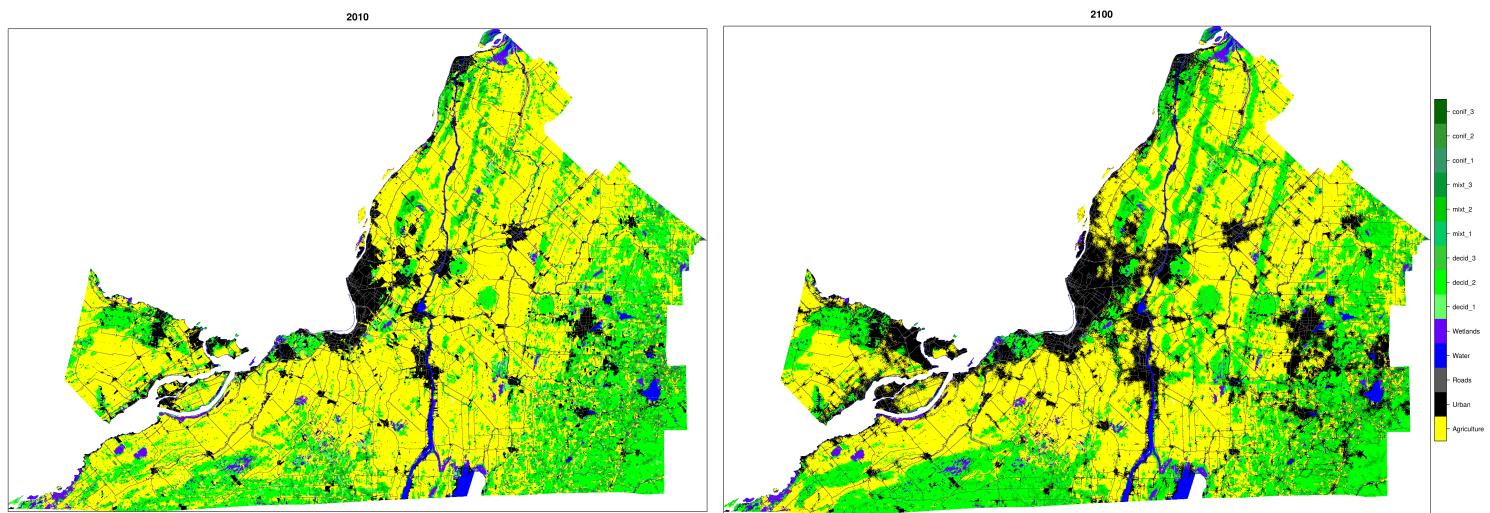


Figure 3–10: CorrRefTar.

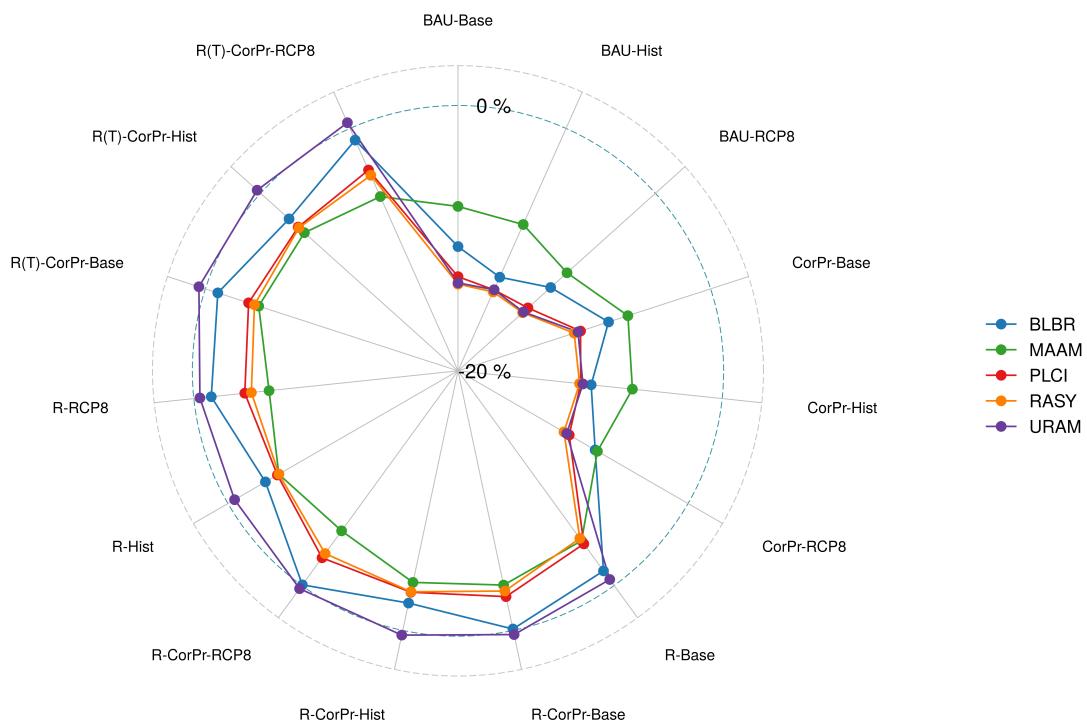


Figure 3–11: Change in mean flow (in % of the the 2010 flow) between 2010 and 2100, contrasting BAU scenario (solid line) with both other land use change and conservation scenarios.

## **Appendix 2: Workshop Materials**

## Feuille de route du participant

### 1. Plan de la journée:

**9h25** - Activité Brise-glace

**9h30** - Présentation: notions de bases en connectivité et son enjeu en Montérégie

**9h50** - Echanges

**10h05 - 10h55** - Activité 1

*Pause (15 minutes)*

**11h10 - 12h25** - Activité 1

1. Milieux importants (à connecter)

2. Facteurs qui font qu'un lien soit prioritaire

3. Milieux à connecter en priorité

**12h25 - 13h25** - Pause Repas (1h)

**13h25 - 15h05** - Activité 2

*Pause (15 minutes)*

**15h20 - 16h10** - Activité 2

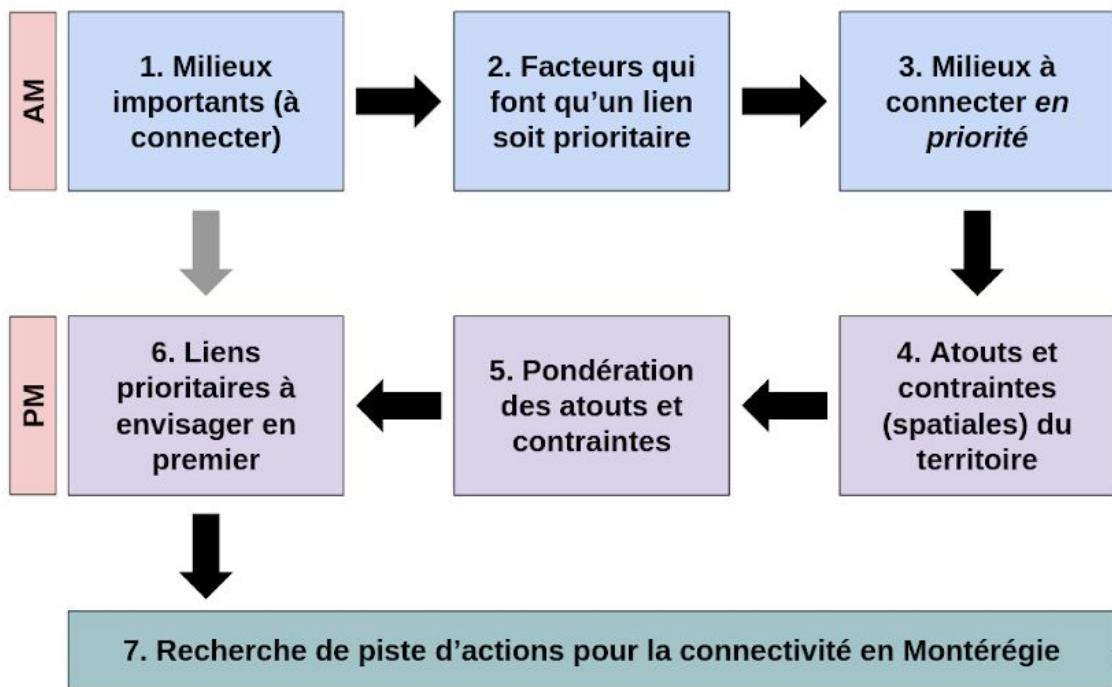
4. Atouts et contraintes (spatiales) du territoire

5. Pondération des atouts et contraintes

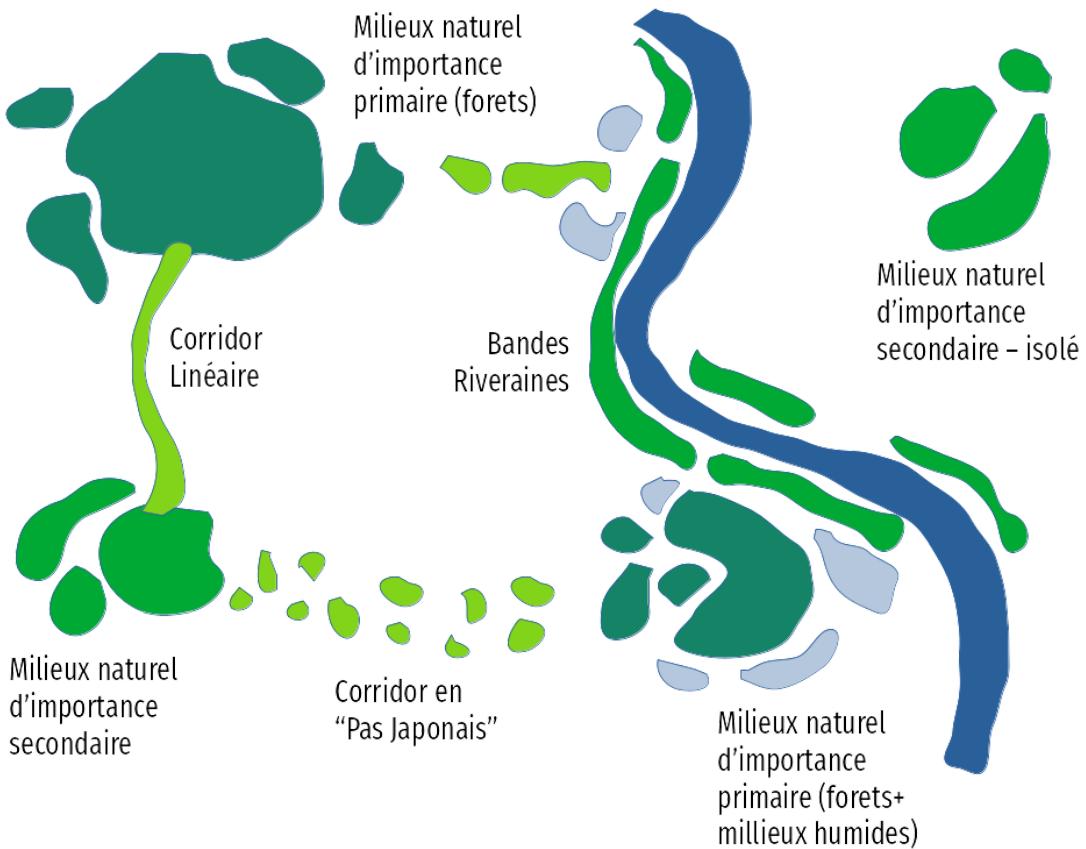
6. Liens prioritaires à envisager en premier

*Mots de la fin à 16h30.*

### 2. Étapes de la journée



### 3. Rappel des formes de connectivité:



### 4. Exemples d'atouts et de contraintes

Ces exemples sont fournis à titre indicatif uniquement. Ils ne représentent peut être pas la réalité de votre territoire.

<b>Atouts</b>	<b>Contraintes</b>
<ul style="list-style-type: none"> <li>- Usage des sols favorables au couvert forestier (vergers, haie brise-vents, etc...)</li> <li>- Règlements municipaux spécifiques</li> <li>- Bandes riveraines</li> <li>- ...</li> </ul>	<ul style="list-style-type: none"> <li>- Usage des sols non favorables au couvert forestier</li> <li>- Projets de développements urbains (en cours ou en préparation)</li> <li>- Route achalandée</li> <li>- ...</li> </ul>

## DOCUMENT DU (DE LA) FACILITATEUR/FACILITATRICE - à remettre à la fin de la journée

**RAPPEL:** En tant que facilitateur.trice, votre rôle est de (1) **guider** les discussions à votre table, (2) **s'assurer** que tout le monde ait l'occasion de s'exprimer librement, et (3) **prendre en notes** certains résultats clés.

**RAPPEL AUX PARTICIPANTS:** *N'échangez pas le matériel de votre cahier de participant avec celui de vos voisins.*

### (1) Identifier les ensembles de milieux naturels d'importance sur vos territoires

1. **Chacun:** Sur votre carte, dessinez ces ensembles de milieux naturels d'importance individuellement, sur vos **transparents**.

Facilitateur.trice (F): Assurez vous que tout le monde a bien compris les consignes. Le terme milieux naturels est volontairement vague: cela peut être des noyaux forestiers, des milieux humides, ou des milieux forestiers avec des milieux humides

2. **Tour de table:** Déposez, chacun à votre tour, vos transparents sur la **carte centrale et expliquez vos choix**

F: Assurez-vous que tout le monde a pris le temps de s'exprimer (**3 minutes par personne**). Ne laissez personne monopoliser le temps de parole. Si certains ne parlent pas beaucoup quand leur tour vient, tenter de revenir vers eux à la fin du tour de table

3. **Chacun:** Observez les résultats et **réfléchissez** aux ensembles à connecter en priorité

4. **Tour de table:** On fait un tour de table et chacun choisit **3 ensembles prioritaires**.

F: Assurez vous que tout le monde liste au plus 3 ensembles. Faites la liste dans l'encadré ci-dessous. Rappeler que si les ensembles ne font pas consensus, ça ne veut pas dire que les autres ensembles de milieux naturels seront évacués de toute la réflexion.

Nom de l'ensemble	# de mentions

## (2) Identifier les facteurs de priorités pour les ensembles

1. Chacun, avec post-its: Ecrivez sur vos post-its (contenus dans **otre** cahier de participant), notez les facteurs qui rendent un ensemble prioritaire.

F: Assurez vous que tout le monde a bien compris les consignes. Les facteurs peuvent être variés, on cherche ici tout ce qui peut influencer la désignation qu'un ensemble soit à connecter en priorité.

## (3) Identifier les ensembles à connecter en priorité

1. En groupe, à chaque table: On essaye de dégager un **consensus sur les ensembles prioritaires**.

F: Pour dégager un consensus, quelques conseils:

- *Tenez compte de la liste des facteurs que vous venez d'identifier*
- *Reprenez la liste et comptez le nombre de mentions obtenues par chacun d'eux*
  - *Annoncez la liste et le nombre de mentions aux membres de la table*
- *Evaluez le consensus (y-a-t-il des ensembles qui ressortent clairement comme majoritaire? Y-a-t-il beaucoup d'ensembles avec peu de mentions?)*
  - *Demandez aux participants s'ils considèrent qu'un consensus est évident ou non*
  - *S'il y a des "non", permettez aux participants de développer leur idées*
  - *Demandez à la table s'il est nécessaire de grouper certains ensembles*

À la fin, ENTOUREZ sur la carte les ensembles qui sont retenus par le groupe

2. En plénière: Une personne du groupe partage les résultats avec la salle

## (4) Atouts et contraintes spatiales du territoire

1. Chacun, avec post-its: Ecrivez sur vos post-its (contenus dans **otre** cahier de participant), notez les atouts (**A**) et contraintes (**C**) spatiales du territoire. Placez-les sur la carte.

F: Assurez-vous que tout le monde a bien compris les consignes. Les atouts et contraintes peuvent être: projets (présents ou futurs), règlements, politiques qui peuvent représenter soit des forces, soit des freins pour travailler sur les liens de connectivité identifiés.

Questions pour guider la discussion:

- Qu'est-ce qui peut faciliter ou freiner le développement d'une connexion?
- Au regard des ensembles de milieux naturels à connecter en priorité, quels seraient les atouts et contraintes du territoire pour imaginer des actions de maintien ou de restauration de la connectivité à ces endroits ?

Important: Concentrez-vous sur des éléments qui peuvent être spatialisés, i.e. qui peuvent être mis directement sur la carte ou dont la localisation des effets peuvent être directement mis sur la table (carte ?).

### (5) Pondération des atouts et des contraintes

1. Chacun, avec des collants de couleurs: chacun distribue ses collants sur les atouts et contraintes identifiés sur les *Post-its*. Rouge = atout ou contrainte majeur.e — Jaune = atout ou contrainte intermédiaire — Bleu = atout ou contrainte mineur.e.

F: Assurez vous que tout le monde a bien compris les consignes. Assurez vous que chacun vote au moins pour un atout et une contrainte, et que chacun ait pu placer ses gommettes.

2. En plénière: Une personne du groupe partage les résultats avec la salle

### (6) Identification des liens à envisager en premier

1. En groupe, en tour de table: On essaye de dégager un **consensus sur les ensembles prioritaires**. Chacun dessine les liens qu'il considère prioritaires: chaque participant, un par un, dessine les liens de connectivité qui lui semblent prioritaires.

F: On veut savoir quels sont les liens de connectivité entre les ensembles naturels à travailler en priorité.

- Le tracé n'a pas besoin d'être précis. On veut juste une idée du passage du lien
- Lorsqu'un participant identifie un lien déjà dessiné, il fait son trait à côté pour que l'on puisse juger du nombre de fois où ce lien a été choisi grâce au nombre de traits ou à l'épaisseur du trait.

### (7) Brainstorming des pistes d'action

1. En groupe, à chaque table: On discute des pistes d'actions potentielles

F: Une question pour mener la discussion: Au regard des résultats des contraintes identifiées, quelles pistes d'action seraient indispensables pour contourner les contraintes les plus importantes ?

2. En plénière: Une personne du groupe partage les résultats avec la salle



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**Research Ethics Board 1**  
**Certificate of Ethical Acceptability of Research Involving Humans**

**REB File #:** 19-12-011

**Project Title:** Consensual mapping of the conservation of ecological connectivity in Montérégie: identifying stakeholder's perceptions of the obstacles and opportunities of connectivity conservation in the context of land use planning

**Principal Investigator:** Valentin Lucet

**Status:** Master's Student

**Department:** Biology

**Faculty Supervisor:** Prof. Andrew Gonzalez

**Approval Period:** January 21, 2020- January 20, 2021

The REB-1 reviewed and approved this project by delegated review in accordance with the requirements of the McGill University Policy on the Ethical Conduct of Research Involving Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

Deanna Collin  
Senior Ethics Review Administrator

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- \* Approval is granted only for the research and purposes described.
  - \* Modifications to the approved research must be reviewed and approved by the REB before they can be implemented.
  - \* A Request for Renewal form must be submitted before the above expiry date. Research cannot be conducted without a current ethics approval. Submit 2-3 weeks ahead of the expiry date.
  - \* When a project has been completed or terminated, a Study Closure form must be submitted.
  - \* Unanticipated issues that may increase the risk level to participants or that may have other ethical implications must be promptly reported to the REB. Serious adverse events experienced by a participant in conjunction with the research must be reported to the REB without delay.
  - \* The REB must be promptly notified of any new information that may affect the welfare or consent of participants.
  - \* The REB must be notified of any suspension or cancellation imposed by a funding agency or regulatory body that is related to this study.
  - \* The REB must be notified of any findings that may have ethical implications or may affect the decision of the REB.

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