Modeling landscape changes and metrics, and determining optimal resource allocation by integrating Geographic Information Systems, government policy, and economics

by

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A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

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Abstract

The main goal of this thesis is to contribute to the knowledge base of land use and land cover change dynamics in ecologically sensitive, seasonal environments with a dominant agricultural industry. Anthropogenic alteration by land-based industries currently threatens many ecosystems, including the neotropics, and agricultural belt of North America. By fusing spatial information with socioeconomics through Geographic Information Systems (GIS) and spatial modeling platforms, gaps in the understanding of the dynamics in these landscapes are addressed. Biogeophysical variables, used in conjunction with the landscape maps, were utilized to develop a baseline projection model in the Dinamica Environment for Geoprocessing Objects (EGO). Future scenarios were based on integrating legislative polices and economic factors. This makes it an effective tool for policy makers.

The second chapter outlines the impacts of current legislation, in the State of Minas Gerais, Brazil, on the remaining natural land. Recent revisions to the federal environmental policy and international agreements, of which the country is a signatory, will lead to different environmental paths. A secondary economic model indicates that incorporating the value of biodiversity into the land sale price can significantly decrease the quantity of land that is altered over the next decade. The third chapter runs a similar integrated modeling system in Alberta, Canada. Alberta, however, has sparse environmental policies and the platform served as a method of creating and predicting the effects of legislation on the landscape. If the government intervenes and deters urban sprawl that has historically been present, there are several ways to balance economic growth and environmental protection through landscape design policies.

The results of my research indicate that the Dinamica system is an effective cross-continental tool for policy makers. Future research should focus on the integration of information into a holistic system. It should also include avenues to engage in interdisciplinary studies. Communication of the research to a broader audience and engagement of these sectors in the decision-making processes are key, not only in LCC modeling, but in many aspects of environmental study.

Keywords: LUCC modeling, Dinamica EGO, government policy, economics, optimization, ecosystem services

Preface

This thesis is an original work by Kayla Dawne Stan. A version of Chapter 2 has been accepted for publication by PLOS ONE and will be published as K.D. Stan, A. Sanchez-Azofeifa, M. Espirito Santo, C. Portillo-Quintero (2015). Simulating deforestation in Minas Gerais, Brazil, under changing government policies and socioeconomic conditions, *PLOS ONE,* pone.0137911. The project was designed with the assistance of A. Sanchez-Azofeifa; however the analysis was designed and conducted by myself. Data was collected with the assistance of M. Espirito Santo and C. Portillo Quintero. They also contributed to some of the specialized information regarding Brazilian policies. The project in Chapter 3 was completed by me, as was the information compiled in Chapters 1 and 4.

Acknowledgements

I would like to acknowledge the assistance provided by my supervisor Dr. Arturo Sanchez-Azofeifa. I am grateful for having the opportunity to learn in his working group and under his mentorship. Without the support and financial assistance provided by him, I would not have been able to complete this project and grow as a student and researcher.

I would also like to thank my co-workers in the CEOS laboratory group for their advice regarding the improvement of my methodologies, and for providing the benefit of their experience. I also appreciate the advice provided throughout my program from other professors at the University of Alberta and abroad, namely, Dr. Benoit Rivard, Dr. Scott Jeffrey, Dr. Mario Marcos, and Dr. Britaldo Soares-Filho. Additional acknowledgements and funding sources for the individual projects are provided in each chapter.

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Figure 3.2: *The image is taken from the historical patch analysis and details the urban expansion in the Edmonton-Calgary corridor from 1984 to 2013. The different colours are the urban expansions for each decade. The figure zooms in on Edmonton, Calgary, and Sylvan Lake. Edmonton and Calgary show the expansion of the major towns and Sylvan Lake shows the development of small tourist towns near the lakes in Alberta.*

Figure 3.3: *The graph is divided into three different levels. On the left side, the bulk amount of change in pixels in urban areas of the three largest cities in the study area in each of the time steps analyzed. On the right is the relative growth in the urban areas in these time steps. The relative growth in all three cities decreases in the most recent decade indicating a slowing in the growth of the cities.*

Figure 3.4: *This graph is constructed the same as Figure 3.3 by city and time step with bulk change on the right and relative change on the left. The figure outlines the results from the categorical level of the intensity analysis, how much land is gained and lost in each category. Each land cover class has two bars, a gain bar and a loss bar. If the gain is longer than the loss bar, then the net change in the classification will be a gain or expansion, and if the bars are longer than the red line in each time step, then the change is active. In the three major cities, in general, there is a consistent gain in urban area for all three municipalities. The agriculture and grassland trends are not as consistent; however, on average, both categories lose land.*

Figure 3.5: *This graph is constructed the same as Figure 3.3 by city and time step with bulk change on the right and relative change on the left. In this particular case, the graph details the*

categorical level change of the intensity analysis and shows if agriculture land or natural land is preferentially altered to urban areas. The red line divides the land classes that are targeted for development (longer) versus those that are avoided (shorter). In Edmonton and Calgary, the agricultural land is targeted, while in Red Deer, historically the natural land was developed.

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Glossary of Terms

Aichi Biodiversity Targets: The Convention on Biodiversity identified strategies and targets towards curbing the loss of biodiversity from 2010 to 2020. The document consists of 5 strategies and 20 targets, and was designed with the following vision in mind:

"By 2050, biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people."

Target 5 which is explicitly referenced and used as a basis for one of the policy scenarios is as follows:

"By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced."

It is applied in this thesis as the destruction rate being brought to half by 2020.

Weights of Evidence: A Bayesian method of calculating the relationships between spatial variable and the observed land cover change. This method was originally developed in geology, specifically in mineralogy and seismic research, and has been adapted for use in the Dinamica EGO system. Input information can be categorical or continuous, and based on the combined weighting of a presence or absence of change in relation to the input variable. In the Dinamica EGO system, if there is expert knowledge that contradicts the weights found by the platform, they can be modified before projections are completed.

Externality: According to Merriam-Webster, it is the quality or state of being external. In microeconomics, the term is applied to the instances where there is a divergence between the private and social costs or gains, meaning that private gains or interest do not lead to maximum social welfare. They can be positive or negative, but in the environment, externalities are often negative. They can include things like pollution, soil erosion, global warming costs associated with carbon, or the impacts felt from biodiversity loss. The social/collective nature of the damages makes it a social problem that is not internalized even in perfectly competitive markets. Without some control or regulation to internalize these costs, private gains can lead to a loss in the collective welfare.

Intensity Analysis: A new unified approach which analyzes the amount and distribution of patterns of change in the landscape over multiple time periods. There are three levels of comparing change:

1. Interval level: Variation in the total change on the landscape while accounting for the number of years in the time period analyzed. This is used to determine if the change is fast or slow in each set of years.
2. Categorical level: Gross gain or loss in each land category which accounts for the initial amount of area and the total transitions to and from in each time step. This is used to track if the class is actively changing.
3. Transition level: Tracks the transitions between classes and how intense they are, given the amount of each class present. This is used to determine if a particular transition is more prevalent, i.e. a class is targeted or avoided for change.

1. Chapter 1 Introduction

Land cover change (LCC) and environmental monitoring have garnered significant attention since the 1990s and continue to be prevalent topics of study (1-5). The alteration of the earth's surface has become substantial enough to affect global systems, including atmospheric/oceanic fluid dynamics, soil degradation, and biodiversity loss (1-3). Population growth and land-intensive economic activities, such as agriculture, forestry, and the energy industry, are most commonly considered to be the key drivers of this change (2, 3, 6); however, this oversimplification neglects the power that government directives can have on both the protection and destruction of sensitive natural ecosystems (3).

Oversights are made in the conceptual framework and understanding of the landscape modification scheme, often because localized areas or single systems (i.e. habitat of one animal) are studied in isolation (3, 4). Environmental management strategies also follow this pattern where single resources are viewed separately and often with assumptions of a steady state or predictable pattern of growth (5). To fully develop sustainable environmental practices, interdisciplinary, multi-scale data that incorporates sociological, economic, biogeophysical, and legislative information is required (5, 7). We will be unable to effectively adapt to the constant changes and uncertainties present in the anthropogenically-influenced environment without this knowledge base (7).

Increases in the abundance and availability of satellite imagery at a variety of spatiotemporal resolutions and improvements in GIS techniques have facilitated advancements in characterizing landscapes from regional to global scales (7-10). Land cover and the modifications associated with physical properties in a region are much easier to characterize compared to land use alterations, which center on an anthropocentric view of an area (2, 11).

Historically, LCC studies and modeling have focused on biophysical parameters (12-14), with limited data fusion occurring outside of the Amazon biome or highly localized zones (8, 9, 15). This lack of socioeconomic and policy data integration is largely due to a deficiency in spatially explicit information and the inability of modeling platforms to incorporate qualitative information adequately (12).

Despite the abundance of land cover change studies, there remains a gap in the scientific knowledge, specifically when looking on a regional scale or at integrated modeling platforms that seek to track and project more complex systems (4, 7). There are many commonly utilized models, such as CLUE, IMAGE, and statistically-based modeling systems; however, these platforms focus solely on either the bulk amount of change or the landscape pattern and often not in spatially explicit terms, such as those utilized in Alberta (i.e. ALCES, GYPSY, etc.) (7). More recently, the Dinamica EGO system was developed, originally for tracking Amazonian deforestation (16), but further utilized for LCC modeling (17, 18), determining the impact of policies on the environment (17), calculating carbon balances (18), and allowing integration of spatially explicit investment models (19). This open-source, cellular automata model provides an avenue for incorporating qualitative data with spatially explicit information, creating the ability to seamlessly assimilate policies, biophysical variables, and historical change, and subsequently projecting potential futures (16-19). Dinamica also focuses on both the amount and locations of change, making it unique among modeling platforms. By utilizing this model in semi-arid systems, which has not previously been done, the platform transferability can be tested and policy tools can be built for governments.

My thesis research is designed to fill the above-mentioned gaps by producing integrative, regional-scale, full-accounting LCC models in two previously unstudied areas. Minas Gerais, Brazil, and the Edmonton-Calgary corridor in Alberta, Canada, were identified because they both have expanding economies based on land-intensive industries, sensitive ecosystems in a semi-arid climate, and rapid population growth. Both regions also have interesting situations to test the predictive power of the models for legislative changes, as Brazil recently enacted a set of new but conflicting policies (20, 21), and Alberta has no legislation for land protection (22). My research will provide an important contribution to the body of land cover modeling literature and will result in tools that cross-continental governments will be able to utilize to improve sustainable development practices. As such, my MSc thesis is divided into two main chapters:

Chapter 2 "Simulating Deforestation in Minas Gerais, Brazil, Under Changing Government Policies and Socioeconomic Conditions" The objective of this chapter is to create an integrated, regional-scale model that can track the potential effects of recently enacted legislation. There is a gap in holistic land cover change modeling in Minas Gerais, especially for incorporating policy, with research instead focusing on a single biome or highly localized areas. This study endeavours to bridge this gap in knowledge with the development of a modeling platform that combines biophysical, legislative, and socioeconomic data for tracking landscape changes in the State of Minas Gerais and projecting them into the future. Data fusion, such as that employed in this research, can be used to find the best policy options for balancing competing environmental and market interests. To further define options for sustainable growth, this chapter also presents the creation of an economic model that is utilized to test how the addition of a biodiversity value on the natural landscape can impact the amount and allocation of agricultural land in Minas Gerais in the future. These two models can be used as tools for policy makers to test how their legislation can impact the state, and provide for the development of optimized solutions towards building a sustainable future.

Chapter 3 "The Edmonton-Calgary Corridor: Simulating Future Land Cover Change Under Potential Government Intervention" In this study, I create a comprehensive land cover change history from the 1980s to present, and then project multiple future scenarios based on potential government intervention options. Despite Alberta being one of the fastest changing provinces and an economic driver in Canada, there have been no regional-scale modeling efforts on landscape alteration to date. Modeling has instead focused on local areas, specific processes, such as hydrology (15, 23, 24), or utilizing a non-spatial model environment. I attempt to fill this gap through the development of an intensity analysis to compare change during multiple time steps (25), and then project the landscape changes into the future using the Dinamica EGO modeling platform. The integrative model that is developed can be used as a tool for policy makers to test the impact of any legislative options, allowing for the balance of economic and environmental interests to be optimized and tested prior to enactment. As initial tests, I created two landscape design scenarios, implementing green belts and protecting the best agricultural lands, and projected them for the next decade.

Chapter 4 "Conclusions and Future Challenges" In this chapter, I provide a summarization of the major results and conclusions from my studies. Additionally, despite the developments made in this research, there is still work to be completed in the future and challenges to be met. I present what the future may hold for land cover change modeling and what challenges are still present in integrative modeling platforms.

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2. Chapter 2 Simulating Deforestation in Minas Gerais, Brazil, Under Changing Government Policies and Socioeconomic Conditions

Abstract: Agricultural expansion is causing deforestation in Minas Gerais, Brazil, converting savanna and tropical dry forest to farmland, and in 2012, Brazil's Forest Code was revised with the government reducing deforestation restrictions. Understanding the effects of policy change on rates and locations of natural ecosystem loss is imperative. In this paper, deforestation in Minas Gerais was simulated annually until 2020 using Dinamica Environment for Geoprocessing Objects (Dinamica EGO). This system is a state-of-the-art land use and cover change (LUCC) model which incorporates government policy, landscape maps, and other biophysical and anthropogenic datasets. Three studied scenarios: (i) Business As Usual, (ii) increased deforestation, and (iii) decreased deforestation showed more transition to agriculture from shrubland compared to forests, and consistent locations for most deforestation. The probability of conversion to agriculture is strongly tied to areas with the smallest patches of original biome remaining. Increases in agricultural revenue are projected to continue with a loss of 25% of the remaining Cerrado land in the next decade if profit is maximized. The addition of biodiversity value as a tax on land sale prices, estimated at over $750,000,000 USD using the cost of extracting and maintaining current species ex-situ, can save more than 1 million hectares of shrubland with minimal effects on the economy of the State of Minas Gerais. With environmental policy determining rates of deforestation and economics driving the location of land clearing, site-specific protection or market accounting of externalities is needed to balance economic development and conservation.

2.1 Introduction

Deforestation in tropical regions is caused by economic growth and the expansion of industries such as agriculture and mineral extraction (1-3). These drivers also commonly impact regional social and economic development by affecting natural capital, soil erosion, salinization, and carbon stock changes (4-6). Where agriculture is the primary reason for ecosystem destruction, slash-and-burn practices are often employed to clear land for crops and pastures (1, 7, 8). Fragmented, undeveloped areas of forest often dictate the landscape recovery time because higher exposure to anthropogenic activities contributes to edge degradation, stress of patch interiors, and structural changes (6, 9-11).

Landscape alteration models have focused on biophysical factors, including climatic variability, ecosystem stability, and degradation of the natural biomes (5, 12, 13). Deforestation drivers and consequences have been projected into the future with these models relying heavily on accurate land cover maps (2, 14, 15). Geoinformation, showing details about biophysical, socioeconomic, and population factors, are also important for predicting future locations of change. Field measurements of geographic information are highly accurate but often have gaps due to the time-consuming and inconsistent methods of data collection (16). Remote sensing and GIS mapping procedures have significantly improved regional landscape mapping and enhanced models by incorporating socioeconomic variables (17-19).

Spatially explicit models of Brazilian biomes which combine land cover change, policy, and economic modeling are uncommon outside of the Amazon, with an information gap specifically in semi-arid environments such as those found in the north of the State of Minas Gerais. There has also been modeling of environmental policy, by Sparovek et al (17, 18), studying the overall effects of the Forest Code in Brazil. While public opinion is favorable towards environmental policies in Brazil, with a significant positive correlation between environmental policy and higher education (20), there remains heavy deforestation and land use change. This trend is due to a lack of incentives for farmers to protect natural areas on their land, especially with reduced penalties for non-compliance with current conservation legislation (21, 22). However, even with little research into future projections, there is still the ability to model which economic drivers must be enacted to initiate conservation.

The Brazilian Forest Code is a set of federal laws which regulate the amount of original biome that must be kept intact on new farms (23), and minimum buffer zones to protect riparian areas and mountain regions from deforestation (23). The Code was recently repealed for a new law which has the potential to increase the overall degradation by reducing the restrictions on locations of deforestation and decreasing penalties for deforestation prior to 2008 (21, 24). The legislation allows landowners to pay to conserve an equivalent value of land elsewhere in the biome instead of on their own property (21, 24). The amendments made to the policy may contribute to decreased deforestation in the Amazon; however, other researchers suggest the reverse is likely to be true in the Cerrado and Caatinga (24).

In Minas Gerais, Brazil, past deforestation research focused on three primary objectives: 1) Statewide vegetation mapping (a forest inventory) to determine the distribution of natural vegetation and planted forests, as well as to estimate vegetation structure and monitor deforestation (25); 2) localized vegetation mapping (26); and 3) biome-specific modeling (5, 13, 16, 27). Research on land use/cover change mapping has taken place in different regions of the state, usually at specific parts of hydrographic basins or relief formations (26, 28-31). Biome-specific modeling focused on remnant vegetation and effects of land cover changes on the earth systems (5, 13, 16, 27). Ribeiro et al (16) and Hirota and Ponzoni (32) were interested in fragmentation and conservation prospects for the Atlantic Forest, while Rocha et al (33) and Sano et al (34) mapped land use and land cover for the Cerrado biome in different periods. Deforestation in both Cerrado and Caatinga biomes were recently estimated by Beuchle et al (35). Batlle-Bayer et al (5), Brannstrom et al (27), and Carvalho et al (13) also studied the ecosystem functions and changes in the Cerrado biome. These studies provided a holistic view of the biome using previous literature, remote sensing, government maps, and computer modeling.

Studies in Minas Gerais have not focused on how government legislation and changes in economic conditions impact the natural environment using a quantitative, spatially explicit approach. Lack of attention to the effects on land cover change produced by socioeconomic variables and legislation has been due to a deficiency in spatially explicit data and problems linking qualitative data to biophysical models (12). The Dinamica EGO platform attempts to reconcile the data differences by allowing input of biophysical and economic variables while providing an avenue for implementing policy changes (36). This integrated approach can be used to promote sustainable growth by balancing ecosystem protection and economic efficiency.

The feasibility of starting a project which may affect land cover change can be determined by cost-benefit analysis, which compares total costs with potential financial gain (37, 38). Cost-benefit analysis optimizes profit and assumes the presence of capitalism, no externalities, and that a competitive market is present in the area of study (38). Ecosystem services are externalities that are unaccounted for by this traditional analysis and, therefore, must be internalized in the markets by attaching value to the services.

Projecting economic decisions is typically completed separately from spatial models utilizing mathematical programming (4, 39), and agricultural systems are best computed using linear optimization models. These models are similar to cost-benefit analysis by attempting to optimize profit, in turn offering insight into the future financial repercussions of changing the landscapes. When integrated with projection-based spatial models, they can be used to balance both profit and conservation. Equilibrium between economic development and preservation of natural capital is needed to optimize support from government, public interest groups, and industry (6, 15).

This study aims to combine biophysical, legislative and socioeconomic data to model the changes in the Minas Gerais landscape and project them into the future. An approach focusing on data integration can be utilized to explore the policy and economic options which may be implemented for sustainable growth. This paper also explores the effect of adding the natural value of the land into an economic model to predict how full cost accounting can be used to measure the impact on rates of deforestation and the allocation of agricultural land in semi-arid regions of Brazil. Models were run annually until 2020 (spatial) and 2023 (economic) to determine the effect of policy and biodiversity value on the landscape using two different methodologies.

2.2 Materials and Methods

2.2.1 Study Region

The study area is the Brazilian State of Minas Gerais, an interior region with an area of over 586 000 km^2 and more than 20 million people. According to the Ministério do Meio Ambiente (MMA), Minas Gerais is comprised of three major biomes, namely the Mata Atlântica, Cerrado and Caatinga (40, 41). Tropical Dry Forests, a particularly sensitive vegetation type, are split between the three biomes and are prevalent in the northern part of the state (42). The Cerrado has a total area of 2.04 million square kilometres; however, less than 50% of the original ecosystems are still intact (40, 43). Mata Atlântica is located in the southeast of the state and, at most, 25% of this biome remains in extremely fragmented zones due to extensive urban development (40, 43). Between 30% and 50% of the Caatinga, found in northern Minas Gerais, has been altered by humans (43). The Mata Atlântica has just over 10% of its remaining fragments protected in natural reserves or protected areas, while only 2.2% of the Cerrado land and 1% of the Caatinga are in designated protected regions, and the remainder is allowed to be changed for anthropogenic uses (16, 43, 44). Those figures do not include the 20% of natural land that is mandated to be protected on all farming areas located in Cerrado and Caatinga (21).

The entire State of Minas Gerais was utilized for both the spatial and economic models, with the landscape divided by land cover type in the spatial model and by biome in the economic model. Land prices from 2000-2012 were derived from the north of the state (Figure 1) and then extrapolated for an average sale price for the entire state.

2.2.2 Spatial Model Data

For the model, two land cover maps were taken from 1994 and 2000, using the Global Land Cover Facility (University of Maryland) and European Commission Joint Research Centre datasets, respectively. The University of Maryland 1994 map originally had 14 vegetation categories derived from Advanced Very High Resolution Radiometer (AVHRR) satellite images (45). The European Commission Joint Research Centre classified images had information derived from SPOT 4, Along Track Scanning Radiometer (ASTR)-2, JERS-1 radar and DMSP (Defense Meteorological Satellite Program) that was divided into 22 categories, with the higher differentiation possible initially because of the data integration (46). The classification system of both maps is based on phenology not biome and the resulting designations are based on vegetation type. The methodologies for categorizing land cover were different for each organization, leading to large data errors if these different datasets were compared as they were produced. As a result, for this study, the land cover maps were reduced to forest, shrubland, and agriculture, with forest defined as any area with a majority (>50%) of trees, shrubland as all other natural landscapes including grasslands and areas with few to no trees, and agriculture as any anthropogenically altered or managed landscapes. Both maps had a 1 km spatial resolution and were consolidated to include only broad categories of forest, shrubland, and agriculture to account for the different classification methodologies and inherent data error. While this resolution may be problematic for modeling on a local scale, it is sufficient balance between accuracy and spatial filtering for a study area of this size.

All additional data used for tuning the model were acquired from the Instituto Brasileiro de Geografia e Estatística (IBGE). These included biophysical variables, climate, soil fertility and type, vegetation, and relief, derived from 2012 thematic maps (http://bitly.com/1C7UdNM), population from the 2010 census (http://bit.ly/1H0pTrn), and road maps from the Brazilian Ministry of Transport.

2.2.3 Modeling Scenarios and Parameters

The Dinamica EGO platform is utilized to complete a comprehensive land cover change model by determining the probability of each individual cell changing from one land cover to another (47). Landscape maps are input to calculate a transition matrix that outlines annual rates of change between each cover type. Variables, including any relevant spatially explicit datasets, are used to identify where change is most likely to occur. The probability is calculated by giving each variable a relative importance (weight of evidence) based on a Bayesian algorithm that identifies probabilities of transition compared to the categories on the static variable maps (47). If expert opinion disagrees with the algorithm output, the weights can be manipulated to better express current trends. Any auxiliary data can be modified if there are known or predicted correlations that are observed. In the context of this study, there were minor modifications to the soils and population dataset weights of evidence.

A probability of change map is created for each land cover, and the probability of each pixel being altered is determined through the weights of evidence. Two functions, Patcher and Expander, are used to train how continuous and connected the new islands of land cover type will be. The pixels with the highest probability of alteration, which comply with the conditions set by Patcher and Expander, will change. In this study, the model projected the landscape for the state from 1994 to 2000 and compared the results to the JRC image to validate the model performance. Following model validation, the entire state landscape was projected into the future from 2000 to 2020 using legislation to train rates of change and variable importance. Three scenarios were simulated: i) Business As Usual (BAU), ii) increased deforestation using the changes to the Forest Code, and iii) reduced deforestation using the Convention on Biological Diversity Aichi Biodiversity Targets (Figure 2).

The BAU scenario continued historical trends and accounted for the reduction in deforestation rates reported by the MMA between 2002 and 2009 (http://bit.ly/1JPGBG1). The second scenario was based on revisions to the Forest Code of 1965, where the potential increase in deforestation, due to reductions in land alteration restrictions and penalties for non-compliance in the new Code, was modeled. An increase in the rate of change was input into the model, and the weights of evidence were modified based on the reductions to the restrictions in certain zones. Any change in the amount of land altered was a function of the rate change, and differences in the spatial distribution of land cover were due to the modified weights of evidence. Brazil has also signed onto the Aichi Biodiversity Targets from the Convention on Biological Diversity, which states that signatory countries must reduce deforestation by 50% by 2020

(Target 5) (48, 49). The third model predicted the effects of this environmentally favourable initiative by reducing deforestation trends annually between 2011 and 2020 (Figure 2).

The resulting maps were regionalized into 25 km x 25 km sectors to compare the probability of change to the percentage of remaining natural ecosystem, and to compare biome loss to agricultural gain in each area. The 25 km resolution allowed for an area just over the mean size of municipalities (counties) in Minas Gerais (614 km^2), allowing whole political units to be compared overall. The standardization of size was preferable to comparing the political designations, as the ecosystems are not constrained by political boundaries. Further, fragmentation statistics, including the minimum, mean, and maximum patch sizes, were also calculated for each cover type.

2.2.4 Economic Model

The simplest way to mathematically model the economic trade-offs in a farming system is through linear programming, which maximizes a profit function subject to a set of linear constraints (47). Constraints include crop yields and maximum areal extents, labour requirements, and the capital available for investment. Some of the technologies and resources may not have linear relationships; however, assuming a well-behaved, non-linear function is present, the constraint can be approximated by a set of linear equations (47). Modeling biodiversity is not frequently completed using this simplistic system. Instead, biodiversity is typically considered through the presence or absence of individual species in a region or by the inherent uncertainty present in ecosystem management, binary and risk programming, respectively (50, 51). These two economic models require extensive data input and are difficult to interpret. As a result, based on data availability and the objectives of this study, which include deriving the area converted from the natural landscape (with and without the inclusion of a biodiversity tax) as an explicit value, a linear programming model was used instead of binary or risk programming. Linear models, although simple, result in explicit expressions of monetary values and areal extents of land bought, making them easily communicable to producers and policy makers.

A linear optimization model was used to determine the optimum area (in ha) of the five most common crops in Minas Gerais and to project the revenue generated based on historical price and yield records. Due to a lack of data and the spatially constrained nature of the information, the costs associated with technology (i.e. fertilizer, machinery, etc.) were not incorporated into the model. Profit was therefore optimized by maximizing the difference between the costs of growing each crop (labour and acquiring land) and the revenue generated from each crop (price, yield, and areal extent). The outputs of this model included the resulting profit generated, the optimal total area for each crop, the amount of labour needed, and the land bought. A linear optimization model iteratively goes through different combinations of the above output variables, and the output results are found when the profit is the highest that can possibly be derived given the cost constraints.

The maximization of profit over time derived from the crops was represented by:

$$Max\pi = \sum_{t=0}^{14} df \sum_{i=1}^{5} P_{i,t} X_{i,t} - J * L_t - K_t * R_t$$

(1)where Π = profit derived from the regional agricultural scheme in Minas Gerais (\$ USD); *df* = the discount factor which accounts for currency inflation; t = number of time steps in the model (year number), t = 2010-2023; i = crop type: 1 (beans), 2 (cane sugar), 3 (coffee), 4 (corn), and 5 (soybeans); $P_{i,t}$ = price associated with each type of crop over every time step – this is a linearly increasing function derived from historical values (\$ USD/ha); $X_{i,t}$ = the area of each crop “i” in each time step “t” (ha); J = the minimum wage associated with farming (\$ USD/day); L_t = the total amount of labour required to be hired to work the agricultural land (days); K_t = the price of buying new farmland – this is a linear function derived from land sale prices from 2000-2012 in northern Minas Gerais ($ USD/ha); R_t = total area bought for farmland conversion in a time step. The maximization problem is constrained with the following associated assumptions:

$$df = \frac{1}{(1+\text{inflation rate})} \tag{1a}$$

$$X_{i,t} = X_{i,t-1} + R_{i,t-1} \tag{1b}$$

$$X_{i,t} \leq X_{i,t-1} * G_i \tag{1c}$$

$$\sum_{i=1}^{5} R_{i,t} = R_t \tag{1d}$$

$$\sum R_t \leq \text{Total Natural Land in Minas Gerais} \tag{1e}$$

$$\sum_{i=1}^{5} L_{i,t} = L_t \tag{1f}$$

Where $X_{i,t-1}$ = the total area of each crop "i" in the previous time step, t-1; $R_{i,t-1}$ = the area bought in the previous time step "t-1" for each crop type "i"; G_i = the historical rate of expansion for each crop type "i"; and $L_{i,t}$ = the amount of land required to grow and maintain each crop "i" during time step "t."

The model was slightly modified to project the importance of natural capital by incorporating the cost of biodiversity into the price of land purchased in each biome. In this model, the same constraints and assumptions of maximizing the difference between cost and revenue still apply. The difference between this and the previous model is that the $K*R_t$ term has been expanded to include the specific biomes that could be converted – Cerrado/$Cerr_t$ (ha), Caatinga/$Caat_t$ (ha), Mata Atlântica/MA_t (ha), and the cost of buying each area if the biodiversity value from each ecosystem type was included as a tax, i.e. K_t + biodiversity cost Cerr/Caat/MA = $K_{Cerr}/K_{Caat}/K_{MA}$:

$$Max\pi = \sum_{t=0}^{14} df \sum_{i=1}^{5} P_{i,t} X_{i,t} - J * L_t - K_{Caat} * Caat_t - K_{Cerr} * Cerr_t - K_{MA} * MA_t \quad (2)$$

Crop areas, as well as yields and revenue by crop type were gathered for Minas Gerais from 2003-2010 to train the linear cost constraints and project growth rates, and were collected from the IBGE database (http://www.sidra.ibge.gov.br/). The sale price of farmland ($ USD/ha) was derived from data collected from the Banco do Nordeste do Brasil. Labour requirements (days by crop type) to grow and harvest crops were obtained through literature (52-55). Beans and corn labour data were gathered from the Latin American Studies Association (52), coffee from Vosti et al (53), cane sugar from Hermele (54), and rice from Thompson and Blank (55). The amount of free labour in the state and the minimum wage were acquired from the 2006 Agricultural Census (IBGE 2006). Both economic models include the entire state and do not regionalize results.

2.2.5 Species Value

The value of individual species was calculated by Resende et al (56), specifically for the Serra do Cipó mountain range in Minas Gerais. These values were calculated as the cost of maintaining the genetic diversity of all current species ex-situ. The price of managing species, including the costs of finding, transporting, and caring for the plants, was collected from the Zoo-Botanical Garden. The resulting value of species was between $5,148 and $7,819 for common species, and between $51,475 and $78,186 for endemic or endangered species. To extrapolate the values from Resende et al (56), the total number of known plant species in Minas Gerais was collected through the Botanical Garden of Rio de Janeiro, and their status as endemic, endangered, or common was retrieved through a combination of the Botanical Garden of Rio de Janeiro database and Biodiversitas. This methodology is useful because it provides an objective view of the biodiversity value that is not subject to changing societal values.

2.3 Results

2.3.1 Statewide Spatial Simulation Scenarios

The spatial model, which predicts land cover including forest, shrubland, or agriculture, was validated to be over 85% accurate within 1.5 pixels, and this value increased to over 90% within 3.5 pixels (Figure 3A). Larger fragments of a single cover type validated better than highly heterogeneous areas (Figure 3B). All three scenarios, Business As Usual, increased deforestation, and decreased deforestation, are most strongly impacted by deforestation in the central and northwest regions (Figure 4). Shrubland is consistently and preferentially deforested in these models, and is influenced by policy changes more strongly than the forest. The Forest Code revisions result in less natural land remaining and higher fragmentation for both natural cover types. The reduction in the amount of natural land is a function of the increased rates of deforestation implemented by the model while the spatial distribution or fragmentation statistics is a function of changes in the weights of evidence, based on the modification of restrictions of land conversion in the Forest Code. Meeting the Aichi Biodiversity Target, decreased deforestation scenario, leaves the most original ecosystems intact and preserves larger patches.

There are a large number of the small forest patches cut down entirely in the increased deforestation prediction scenario. This scenario also has a substantial reduction in the size of the largest patches over time, which, when combined with the reduced number of small patches, leads to an increased mean patch size with a smaller standard deviation (Table 1). The decreased deforestation scenario has the largest maximum patch size of all three scenarios, while the smallest reduction in maximum patch size between 2015 and 2020 occurs in the BAU scenario.

Shrubland cover shows a different trend with both the smallest mean and maximum patch sizes found in the increased deforestation scenario, and the largest mean and maximum patch sizes from the Aichi Biodiversity Target scenario.

This discrepancy may be explained by the comparison of the probability of transition and the amount of natural biome remaining in a region. The probability of change is highest when the remaining forest cover is 0-5% and exponentially decreases with increased forest cover in an area (Figure 5A). The shrubland change probability decreases linearly as its cover extent increases. It also has a higher mean probability of change with more than 5% shrubland cover in a region when compared to the equivalent extent of forest. Both forest cover and shrubland loss have a positive association with agricultural gain (Figure 5B). As these natural ecosystems decrease in size, there is a corresponding gain in cropland, with shrubland having a sharper increase when compared with forest loss (Figure 5B).

2.3.2 Statewide Economic Simulation Scenarios

Minas Gerais' landscape in the economic models is divided by biome, not land cover as in the spatial models, and my results illustrate that, if profit is maximized with no other assumptions of risk or geographic constraints, the remaining Cerrado area in 2010 decreases by 4 million hectares, leaving only 11.7 million hectares intact by 2023 (Figure 6). Profits from agriculture generated in each year increase from $4.4 billion USD in 2010 to over $8.2 billion USD in 2023 in the first resource allocation model (Figure 7B – black curve). This model, which does not account for biodiversity costs, predicted that the amount of land bought annually will increase up until 2022 and decrease in 2023 (Figure 7A – black curve). This decrease in the final year may be due to the discount factor (inflation) having sufficiently outpaced the revenue costs, making it less profitable to buy land.

The biodiversity values calculated from Resende et al (56), led to an overall natural land value in Minas Gerais of over $750 million USD (Table 2). The biodiversity values of each biome were divided by their areal extent and these values per hectare were used as the K values in the optimization model which included the biodiversity constraints.

The biodiversity scenario resulted in a cumulative net profit of $53.04 billion USD from agriculture in the 13 year period, just $2.5 billion dollars less than the first model, with only a small reduction in annual profit after 2020 when comparing the two models (Figure 7B – solid red curve). By including biodiversity in the model, through the price of land sales, there was no immediate loss in profit and only a 5% revenue decrease by 2023, a total reduction of 0.3% of the GDP growth (Figure 7B – solid red curve). In that 13 year period, over $125 million USD would be collected specifically from the biodiversity value that was added to the land sale price as a tax. This ecosystem tax would conserve over 1 million hectares of Cerrado land (Figure 7A – solid red curve), allowing for continued export of natural capital as well as other benefits, including reduced salinization and increased stability of soils. The conservation effects observed through the addition of a biodiversity tax could be further improved with increasing the taxation amount. With a larger tax, more land protection could occur and more tax revenue would be generated, but profits derived from farming would take a further and more substantial cut (Figure 7A/B – dashed red line).

Of the three biomes in Minas Gerais, the model indicated that it was most cost-effective to alter the Cerrado land. Both the Caatinga and Mata Atlântica would remain untouched if the optimal allocation of land was considered with biodiversity value. It would cost an additional $115 to $252 per hectare to buy Caatinga over Cerrado land, and an additional $22 to $136 to buy a hectare of Mata Atlântica.

2.4 Discussion

The policies included in the model scenarios are not location-specific, instead focusing on regional rates of deforestation, resulting in much alteration of the northwest in all scenarios run. The biophysical variables, therefore, dominate the calculations of probability of deforestation in each location in the model. These results agree with the optimization model and typical economic theories which assert that the benefits associated with an activity must outweigh the production costs to make the project profitable (37). There are less overhead costs associated with clearing shrubs compared to cutting forests for agriculture, which is consistent with Cerrado being preferentially deforested when allocating resources. The high probability of conversion to agriculture is correlated with the lowest percentages of remaining natural ecosystems (Figure 5). This would imply that new land alteration will be in close proximity to other farming operations, consolidating the revenue base and decreasing transportation costs between plots of land. Different government policies more strongly affect shrubland compared to forests in the Forest Code revisions and Aichi Biodiversity Target models.

The exponential decrease in forest transition with increased land cover will result in the disappearance of the smallest forest patches because they are being preferentially cut. This trend of cutting the smallest forest patches results in an increase in the mean forest ecosystem, a tendency that is exhibited in all three models between 2015 and 2020. Shrubland clearance is more uniform because this cover type has a lower gradient of mean probability of transition, resulting in a decrease in mean patch size with the BAU model and Forest Code revisions compared to the Aichi Biodiversity Target scenario. The decreased deforestation scenario shows an increase in the average patch size, possibly indicating secondary regrowth on abandoned lands.

The health and functionality of ecosystems are severely impaired with a reduction in patch size, abundance, and connectivity. Genetic diversity and re-colonization efficiency is improved and degradation is reduced in larger and more continuously connected patches (57). In the case of Minas Gerais, with few patches remaining and high rates of deforestation projected in the near future, the functionality of the original ecosystems is expected to be reduced. Connectivity is projected to decrease in the state, limiting species dispersal and migration, thereby damaging these ecosystems irreparably (57).

In Minas Gerais, there is a corresponding gain in agriculture land when natural area is lost, with a higher conversion rate when considering large losses (>40%) in shrubland (Figure 5). Less preparation for clearing is needed in Cerrado which, in addition to local climatic and soil variations, accounts for high correlation, broad scale locations of clearing, and overall crop sustainability (58).

Other studies reached similar conclusions, finding that Cerrado deforestation rates are three times those of the Amazon basin, despite the long dry season and required soil modification because of low pH and excess aluminum (44, 58, 59). Deforestation trends are related to both biophysical and economic forces, according to the studies, with location-determining factors including site conditions and proximity to anthropogenic alterations (60).

Minas Gerais has exhibited exponential increases in land sale prices in the past decade (Banco do Nordeste do Brasil), and the revenue from crops is projected to expand annually (IGBE), indicating that there is, and will continue to be, an increased ability and willingness of entrepreneurs to invest money in the farming industry. With increased investment, the threshold that limits growth rises and the optimal percentage of land to deforest can increase. This can be exacerbated by reduced costs and improved yields from technological advances, especially in soil modification and machinery. In the future, this may allow the trajectory of deforestation and fragmentation to increase beyond the model results.

Cost-benefit analysis, a foundation for the economic models in this study where the value of crops was compared to the cost of deforestation, is based on the first fundamental theory of welfare economics. This theory assumes there is the presence of capitalism, no externalities, and a competitive market in the area of study (38). If these conditions are met, then there can be a natural optimization of financial surplus or profit (38). There are flaws in applying these suppositions to agricultural scenarios, including market failure, imperfect competition and, more importantly, unaccounted for externalities (61, 62).

Externalities affect humid regions by reducing carbon stock held in the plant and soil communities, while soil erosion and salinization are more common in semi-arid ecosystems (6). In Minas Gerais, soil erosion is prominent, washing fertilizers into nearby streams and decreasing water quality (44). Slash-and-burn clearing releases large quantities of carbon into the atmosphere and often damages unintended areas (44). Other externalities in this region include alterations to nutrient and water cycling (3), biodiversity loss, and expansion of invasive species (44). As part of the Coase theorem, the producer and affected party must negotiate to come up with a financial arrangement that compensates for the impacted public goods or externalities (38).

In an attempt to account for these externalities, the value of biodiversity was characterized, estimated at $750,000,000 USD, and incorporated into one of the economic models. This amount, however, only encompasses one part of the natural capital value, while other externalities remain largely unquantified. If those rates were also determined, the value of the natural land would increase. The total Cerrado biodiversity price is the highest of all the biomes because of the large number of endangered and endemic species in the area. This value of Cerrado land is important because, according to the economic model, this biome will be preferentially cleared in the near future, given its large remaining extent compared to the other biomes, and only 2.2% is currently protected by law in Brazil (44). At least 20% of the endemic and endangered species in this biome are not found on protected territory, and public and conservation attention to the Cerrado is much lower than the Brazilian moist forests, such as the Amazon and the Atlantic Rain Forest (63).

Globalization of economies stimulates land use conversion and Brazil's emerging market makes it a strong contender to have accelerated changes on the landscape (3). Alteration is hastened by high external demand based on increased connectedness and cash flow between geographically removed consumers and producers (3). Most economic activities directly or indirectly use the land, but forestry and agriculture are some of the most involved industries (64). Monitoring how the economy impacts the land and providing incentives that make conservation more affordable and profitable for farmers are crucial in growing nations such as Brazil (65). Sustainable growth in the future relies on creating policies which balance public and social interests, conserve valuable sections of land, and increase stakeholder participation in policy development (65, 66).

Land use and cover change modeling has been useful to determine what future landscapes might look like and the economic impact of biodiversity; however, the problem remains that obtaining fine scale, reliable predictions is difficult (12). Regions are dynamic, and the factors that determine the composition of future landscapes are rarely best represented solely by a static map (66). Remote sensing data from satellites such as AVHRR, SPOT, or MODIS are commonly used, as in this study; however, coarse resolution data derived from these satellites can only track drastic changes while fine scale changes remain unknown (6). These satellites have the largest datasets and are run for the longest time frames, with higher resolution satellites only increasing in popularity in the past 5-10 years.

Integration of socioeconomic data and increasing the ability to manipulate transition matrices over the temporal scale have improved with the Dinamica EGO platform compared to previous systems (6, 12, 47). It is still extremely difficult to account for all of the variables that affect the transformation of landscapes over time; however, this system has proved to be useful in not only modeling Amazonia but also the Cerrado land and other semi-arid environments, making it a valuable transnational modeling platform.

Acknowledgements

I would like to acknowledge F. C. Anaya and R. S. Barbosa at the State University of Montes Claros for their help in obtaining the socioeconomic data required for this study. Funding for this research was provided by an NSERC Undergraduate Student Research Award, Fundação de Amparo à Pesquisa de Minas Gerais (FAPEMIG), and the Inter-American Institute for Global Change Research (IAI) Collaborative Research Network Program CRN 3 – 025 which is supported by the US National Science Foundation (Grant GEO-1128040). I acknowledge the support provided by the University of Alberta, and the National Science and Engineering Research Council of Canada (NSERC-Discovery). M. M. Espírito-Santo gratefully acknowledges a research scholarship from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq).

Tables

Table 2.1

Landscape Fragmentation – Patch Sizes

	Forest Patch Sizes (km²)				Shrubland Patch Sizes (km²)			
	Mean 2015	Mean 2020	Max 2015	Max 2020	Mean 2015	Mean 2020	Max 2015	Max 2020
Business as Usual	4.3	4.4	2,380	2,070	12.5	12.2	140,000	140,000
Increased Deforestation	5.6	5.7	1,670	820	3.6	3.4	1,370	1,360
Decreased Deforestation	4.6	4.8	3,950	2,510	14.1	16.3	183,000	159,000

Table 2.2

Value of Land – 2008

Biome	Value	Value per ha
Cerrado	364,074,657	1,743.68
Mata Atlântica	303,438,607	1,791.67
Caatinga	82,972,053	1,995.96
Total ($USD)	**750,485,317**	

Figures

Figure 2.1

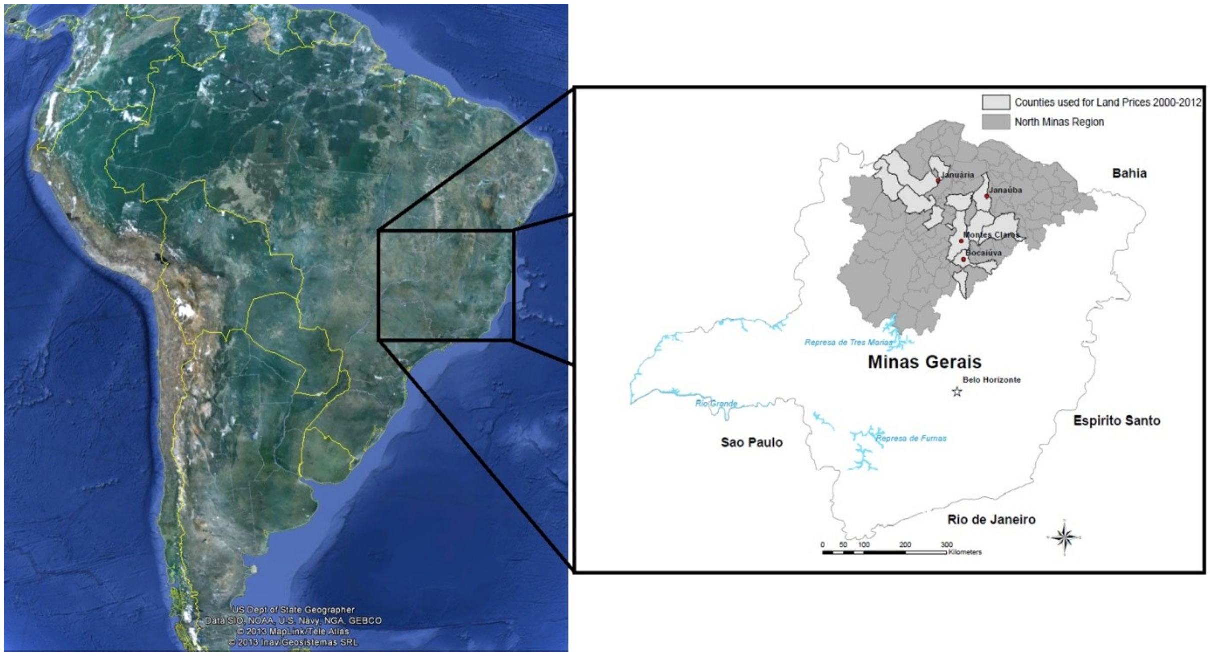
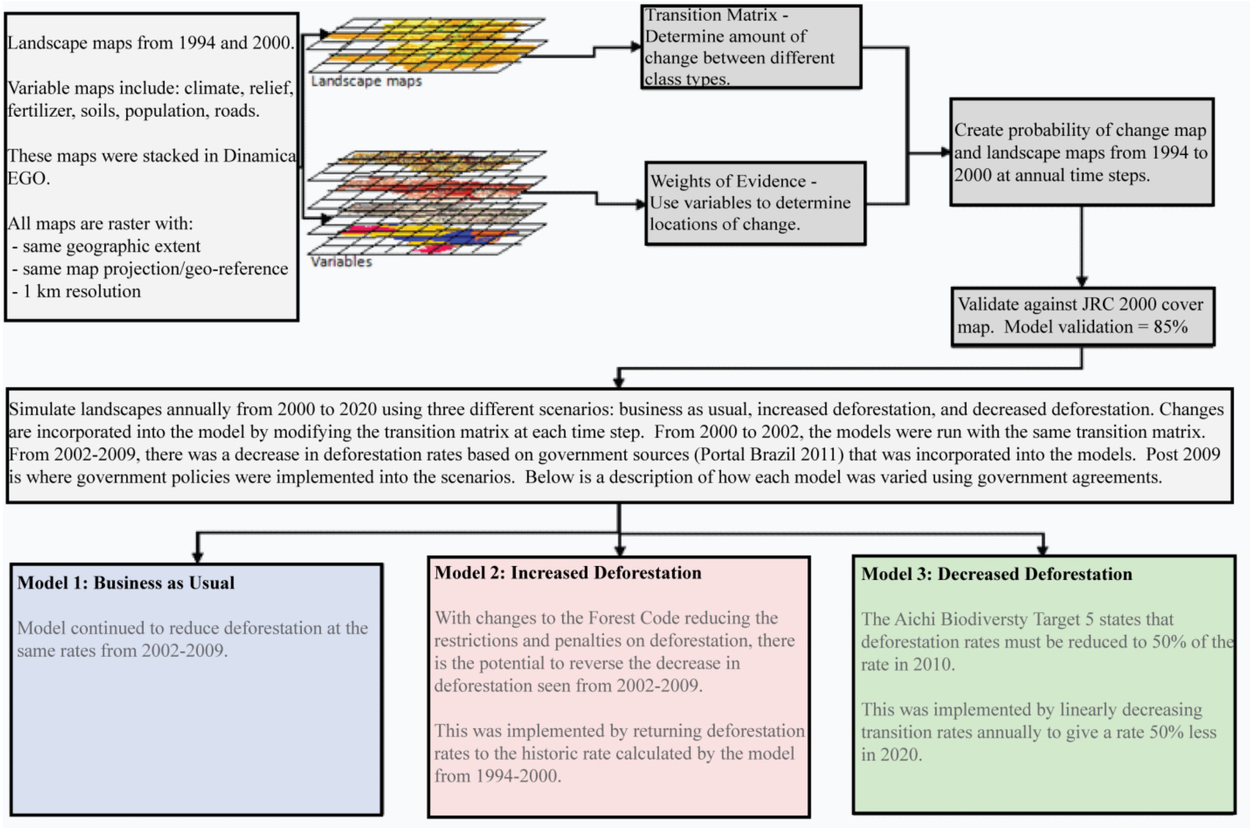


Figure 2.2



Landscape maps from 1994 and 2000.

Variable maps include: climate, relief, fertilizer, soils, population, roads.

These maps were stacked in Dinamica EGO.

All maps are raster with:

- same geographic extent
- same map projection/geo-reference
- 1 km resolution

Transition Matrix - Determine amount of change between different class types.

Weights of Evidence - Use variables to determine locations of change.

Create probability of change map and landscape maps from 1994 to 2000 at annual time steps.

Validate against JRC 2000 cover map. Model validation = 85%

Simulate landscapes annually from 2000 to 2020 using three different scenarios: business as usual, increased deforestation, and decreased deforestation. Changes are incorporated into the model by modifying the transition matrix at each time step. From 2000 to 2002, the models were run with the same transition matrix. From 2002-2009, there was a decrease in deforestation rates based on government sources (Portal Brazil 2011) that was incorporated into the models. Post 2009 is where government policies were implemented into the scenarios. Below is a description of how each model was varied using government agreements.

Model 1: Business as Usual

Model continued to reduce deforestation at the same rates from 2002-2009.

Model 2: Increased Deforestation

With changes to the Forest Code reducing the restrictions and penalties on deforestation, there is the potential to reverse the decrease in deforestation seen from 2002-2009.

This was implemented by returning deforestation rates to the historic rate calculated by the model from 1994-2000.

Model 3: Decreased Deforestation

The Aichi Biodiversty Target 5 states that deforestation rates must be reduced to 50% of the rate in 2010.

This was implemented by linearly decreasing transition rates annually to give a rate 50% less in 2020.

Figure 2.3

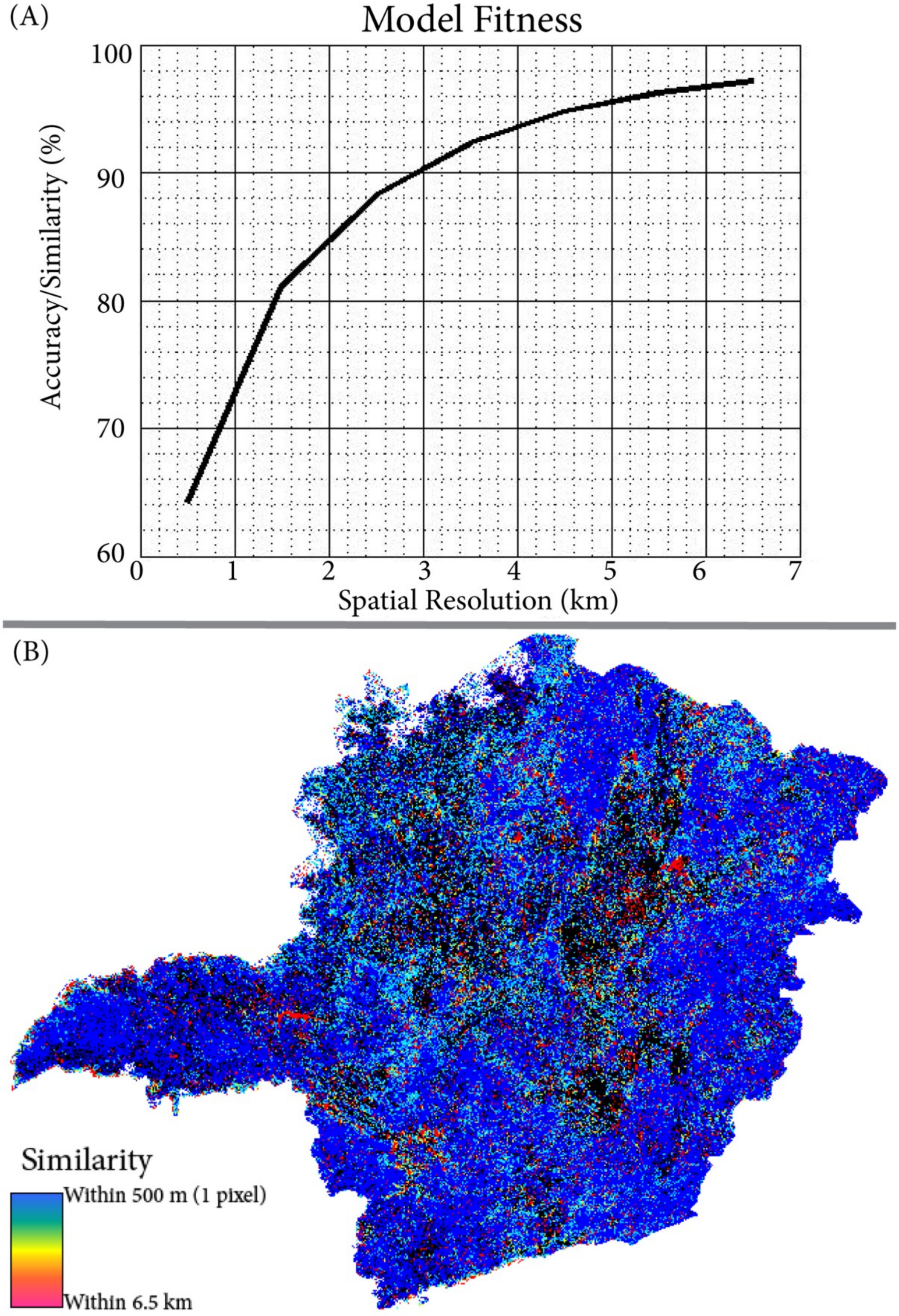

(A)
Model Fitness
Accuracy/Similarity (%)
100
90
80
70
60
0
1
2
3
4
5
6
7
Spatial Resolution (km)
(B)
Similarity
Within 500 m (1 pixel)
Within 6.5 km

Figure 2.4

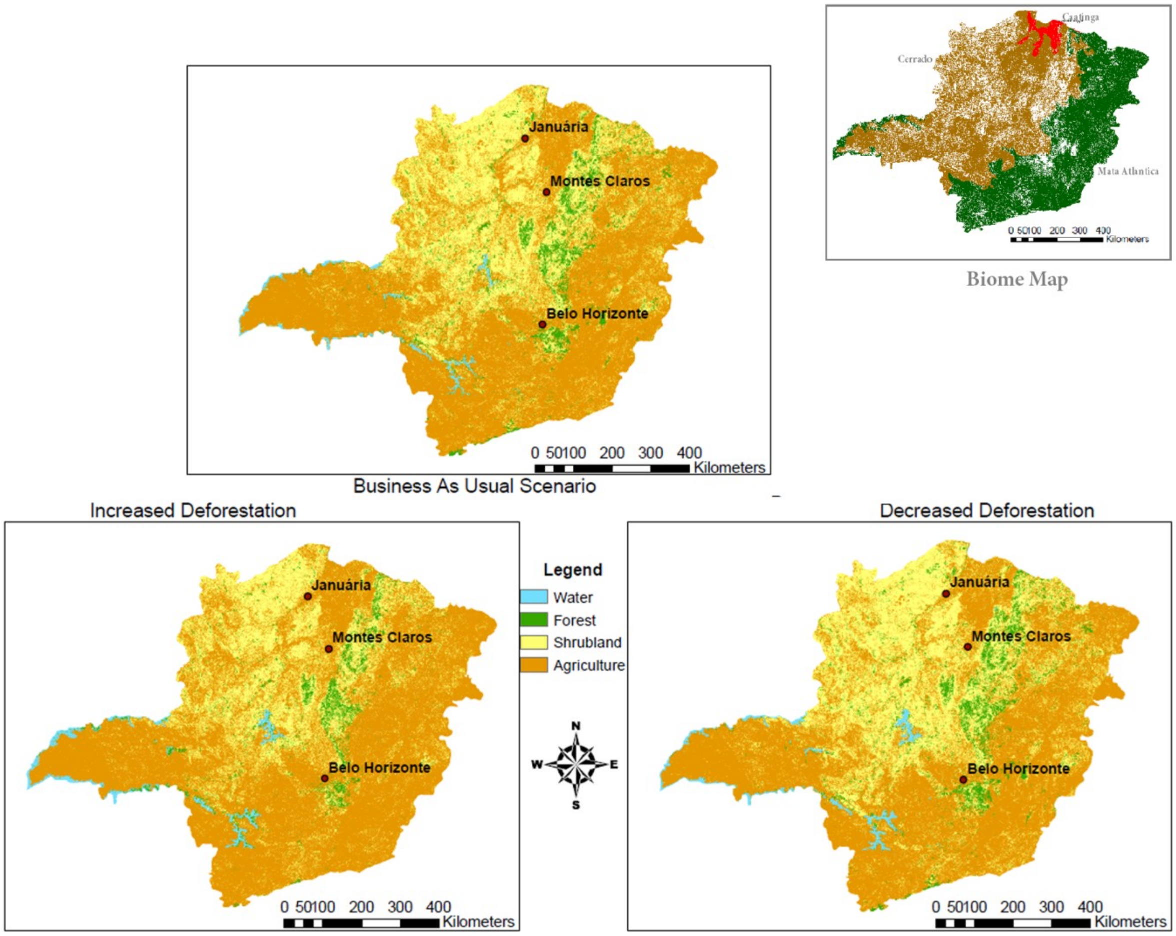

Caatinga
Cerrado
Mata Atlantica
0 50100 200 300 400 Kilometers
Biome Map
Januária
Montes Claros
Belo Horizonte
0 50100 200 300 400 Kilometers
Business As Usual Scenario
Increased Deforestation
Decreased Deforestation
Legend
Water
Forest
Shrubland
Agriculture
N
W
E
S

Figure 2.5

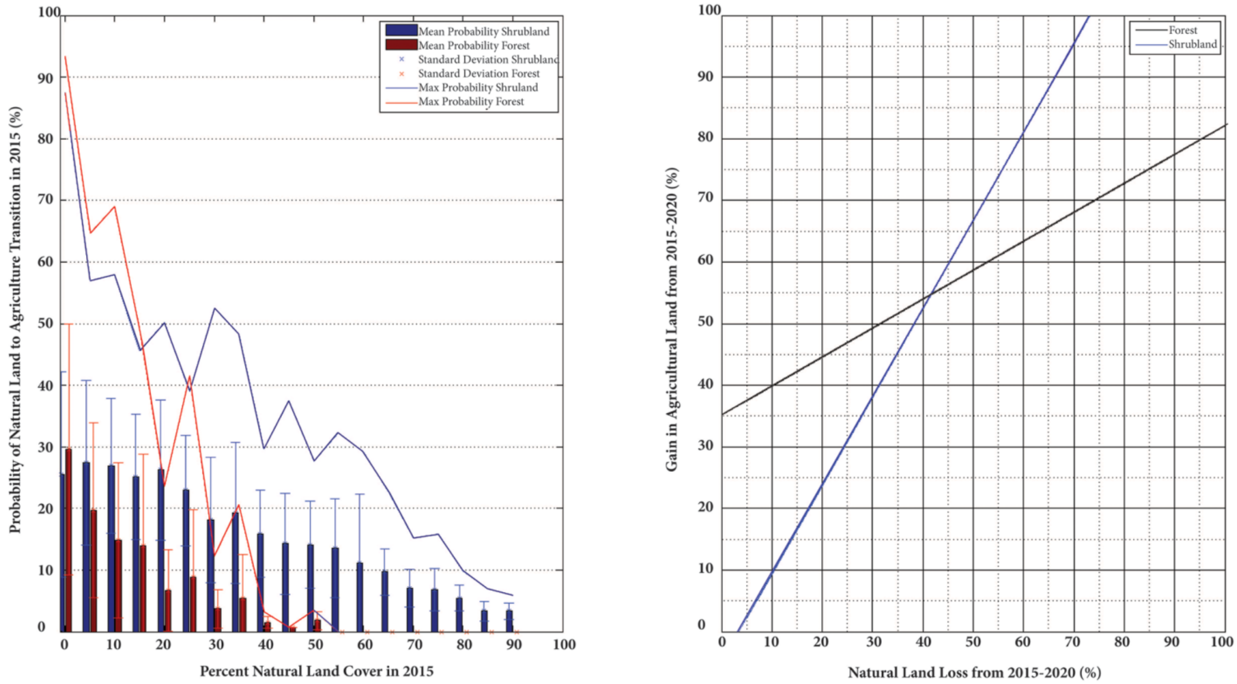

Mean Probability Shrubland
Mean Probability Forest
Standard Deviation Shrublan
Standard Deviation Forest
Max Probability Shruland
Max Probability Forest
Probability of Natural Land to Agriculture Transition in 2015 (%)
Percent Natural Land Cover in 2015
0
10
20
30
40
50
60
70
80
90
100
Forest
Shrubland
Gain in Agricultural Land from 2015-2020 (%)
Natural Land Loss from 2015-2020 (%)

Figure 2.6

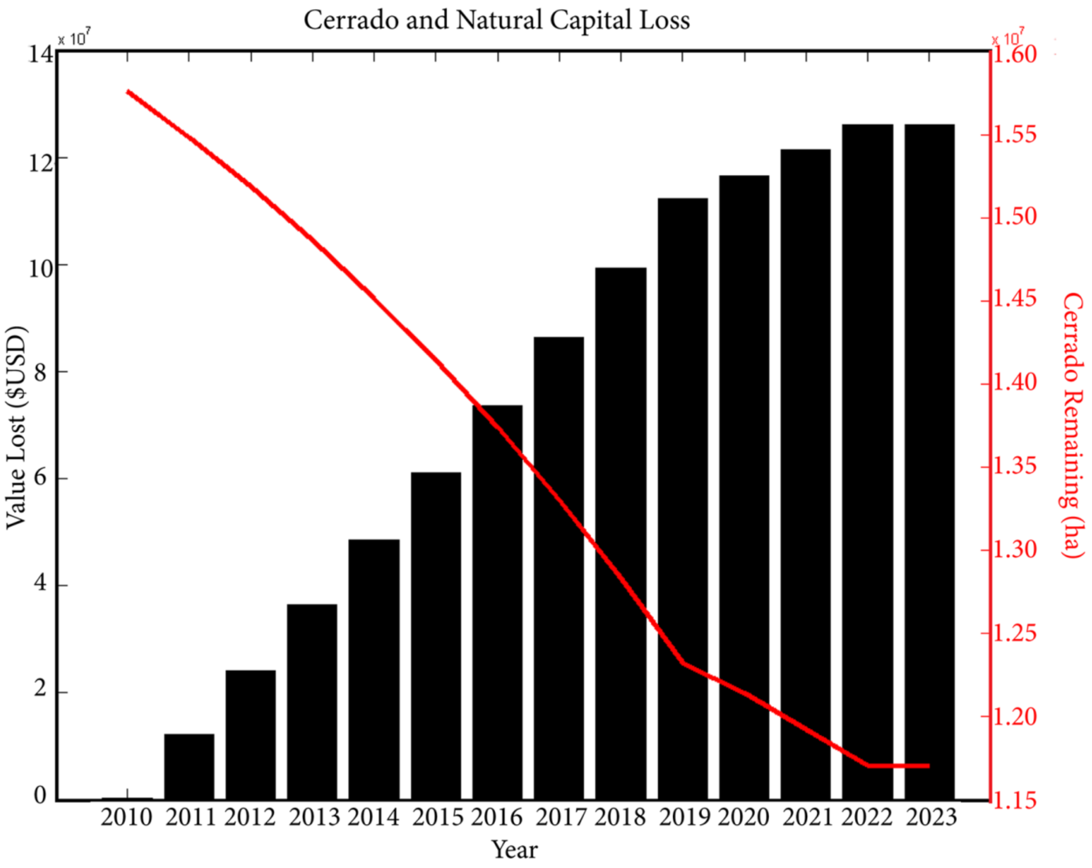
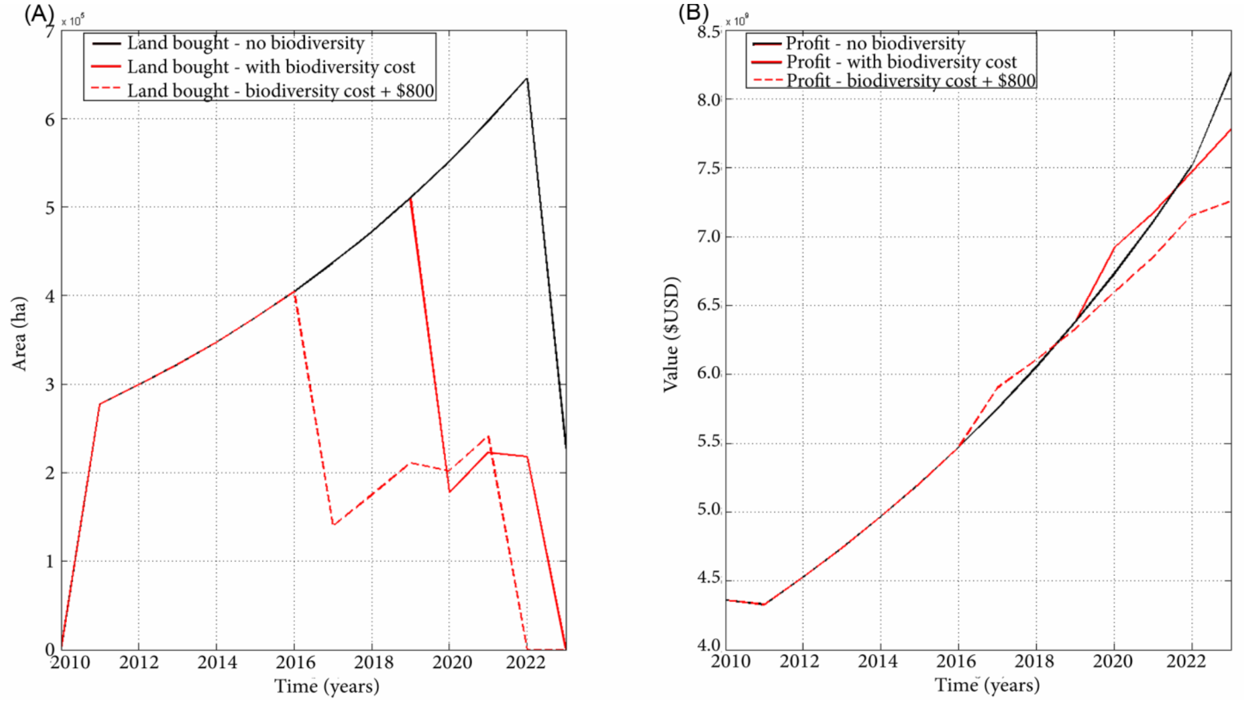

Cerrado and Natural Capital Loss
x 10^7
14
12
10
8
6
4
2
0
Value Lost ($USD)
x 10^7
1.60
1.55
1.50
1.45
1.40
1.35
1.30
1.25
1.20
1.15
Cerrado Remaining (ha)
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
Year

Figure 2.7


(A)
x 10^5
Land bought - no biodiversity
Land bought - with biodiversity cost
Land bought - biodiversity cost + $800
Area (ha)
0
1
2
3
4
5
6
7
2010
2012
2014
2016
2018
2020
2022
Time (years)
(B)
x 10^9
Profit - no biodiversity
Profit - with biodiversity cost
Profit - biodiversity cost + $800
Value ($USD)
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
2010
2012
2014
2016
2018
2020
2022
Time (years)

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3. Chapter 3 The Edmonton-Calgary Corridor: Simulating Future Land Cover Change Under Potential Government Intervention

Abstract: The Edmonton-Calgary corridor in Alberta, Canada, contains rich agricultural land and is experiencing high rates of alteration due to urban expansion. Despite this rapid change, current provincial environmental policy has few restrictions on urban expansion and subsequent fragmentation of croplands and grasslands. Additionally, long-term land cover change (LCC) assessments have not been created for the province's agricultural belt to track the distribution of regional urbanization, making it difficult to predict future alteration. As a result of these knowledge gaps, the main goals of this study are to assess historical changes in the Edmonton-Calgary corridor from the past 30 years and simulate the future LCC under potential government intervention scenarios using the Dinamica Environment for Geoprocessing Objects (EGO) platform. Satellite imagery taken from Landsat was classified to create an LCC history of the Edmonton-Calgary area. Biogeophysical variables, used in conjunction with the landscape maps, were utilized to develop a baseline projection model in Dinamica EGO. The lack of environmental legislation provides an opportunity to explore the effects of implementing policies over the next decade and resulted in five simulation scenarios being developed: i) Business As Usual (BAU); ii) two extreme scenarios assuming a) an increase in the rate of urban expansion of 7% and b) a prohibition on urban expansion; and iii) two scenarios implementing landscape design policies including a) greenbelts around cities and b) the protection of the best agricultural areas as designated by the Land Suitability Report. My results show that over the past 30 years, urban area has nearly doubled in size, especially due to an increase in rural subdivisions, and this expansion has targeted farmland. The study found that greenbelts decrease the expansion of urban land, while the Land Suitability scenario projected growth comparable to the BAU scenario but with a different spatial configuration of the resulting cities.

3.1 Introduction

Human-induced landscape alteration is a major theme in the study of regional and global earth systems due to the extensive impact that it has on environmental integrity and sustainable economic development (1-4). Large-scale studies have become increasingly prevalent given the rapid improvement of openly available aerial and satellite imagery products over a longer temporal period (1, 5). LCC models previously focused on biophysical factors, including carbon stocks, ecosystem stability, and degradation of the natural biomes (1-6), but have recently started incorporating socioeconomic data for a more holistic simulation scenario (7).

There are many LCC models that have been developed and put on the market for research and industrial use. Some of the most common platforms include CLUE and IMAGE, with statistics-based approaches recently becoming popular as well (8). These models, however, only focus on a single aspect of LCC by either recreating the spatial distribution of change or accurately assessing the total quantity of alteration on the landscape (8). In Alberta, two models that have been commonly used in environmental work are ALCES and GYPSY, but these models are extremely limited in applicability, projection capability, and transferability between different project goals.

The ALCES model, developed in the 1990s, is commonly used in industrial modeling, but is largely a numerical model, with no explicit spatial or geographic context (9, 10). Additionally, it requires extensive user input and knowledge about the direct impacts of every ecologic and biogeophysical variable that is incorporated (9, 10). The model is unable to predict or learn the impact of each variable on its own making it prone to user error and labour intensive for data collection. The lack of spatial context is also very problematic when considering a regional or provincial dataset or projection model. In contrast, GYPSY does have a spatial component attached to the platform; however, this Alberta Environment model deals exclusively with forest regeneration and cannot incorporate additional variables relating to climate, geography, human-induced alteration, or government policy (11). This severely limits the model's functionality and transferability to other industry or environmental uses beyond forestry.

The Dinamica Environment for Geoprocessing Objects is a recently developed platform that is uniquely able to focus on both the amount and location of vegetation changes (12). The model environment employs a cellular automata algorithm to simulate the land modification. Cellular automata is based on the idea that if one cell changes, the surrounding region is more likely to follow a similar pattern. This open source system improves the functionality of other models by utilizing Bayesian statistics to calculate the probability of change for each pixel while also allowing expert opinion to modify these computed values (12). A transition matrix which determines the change to and from each class is created for every time step. Dinamica EGO also has additional functions, including those which allow for basic calculations, map algebra, investment predictions, dynamic population expansion, and infrastructure growth models (12). By increasing the flexibility in functionality and model structure, the applicability of Dinamica is improved, and there is consideration for future simulation scenarios. Dinamica EGO was originally designed as a deforestation projection model for the Brazilian Amazon (12), but has since been used internationally to project the impacts of a variety of environmental concerns, including carbon stocks, urban growth, wildfires, and economic impacts of government policy (13-16). Government legislation predictions, and the incorporation of socioeconomic variables, are possible because of the loose model structure, making it an effective tool for policy makers. Dinamica EGO has not been employed in Canada, but could potentially provide an effective solution for projecting environmental change in the country on a regional scale.

Over the past few decades, Alberta has been a hub of economic development through the utilization of land-intensive industries. Over 70% of exports are linked to the extraction of oil, followed by agriculture and forestry (17, 18), with agriculture accounting for over 30% of the province's areal extent and over $6 billion in trade (18, 19). Economic advancements have resulted in rapid population growth, especially in the urban areas. Despite this use of the environment and natural capital for anthropogenic gain, there are no policies or legislation in place to effectively regulate and promote sustainable development (17). Land-use planning in the province is based on an approach called "Integrated Resource Planning." This methodology optimizes economic revenue over the short term and mainly offers environmental protection to an area if it does not interfere with industry (17, 20). Forest management is left to the market, resulting in the loss of the ecosystem services and natural habitat (13, 17, 20). Over ¾ of the protected areas in Alberta were formed by the federal government prior to 1930 and still permit industrial activity, including logging, oil, mining, agriculture, and recreational use (17). Reclamation projects post oil and mining disturbance still have 90% of sites listed as disturbed and only 0.1% as reclaimed (21). Provincial standards do not require a return to pre-disturbance conditions, only recovery of an equal land capability, leading to reduced recuperation of ecosystem services (21).

Despite the extensive demographic change, economic advancement, and few regulatory measures in place, land cover change in Alberta has only been tracked in localized areas (5, 6) or in regard to a specific process or environmental concern (i.e. carbon, hydrology) (6, 22). There is a gap in understanding the historical landscape alteration on a regional scale and predicting what may happen under different future scenarios. The current popular models, ALCES and GYPSY, are limited in their spatial functionality, transferability, and ability to project the effects of legislation (9-11), creating a need for the development of a spatially explicit, integrative modeling system. This study endeavours to fill this gap by modeling and analysing the land cover change in the Edmonton-Calgary corridor since the 1980s and projecting these changes into the future under different expansion and policy-based scenarios. The open platform Dinamica EGO, despite not being previously employed in Canada, is utilized because it is able to integrate biophysical, socioeconomic, and policy data, and project future land cover change under multiple scenarios. By creating a model which can test the impact of potential legislation, governments will have an additional tool which can optimize economic interests and environmental integrity, ultimately assisting in developing sustainable resource management policies.

3.2 Methods

3.2.1 Study Region

Alberta is the fourth largest province in Canada and has an average temperature range of -20 degrees Celsius to + 20 degrees Celsius. Days of sunshine are the highest in Alberta with over 2,300 hours of sun each year (25). The Mean Annual Precipitation is between 350 and 600 mm (26), and the southern part of the province is considered to be mainly semi-arid.

The study site is located in Alberta, encompasses the two largest cities, and accounts for roughly 8% of the province's area, over 5 million hectares (Figure 1). The region includes the parkland and grassland biomes (17) and is dominated by agricultural activity. Farming extends through much of south and central Alberta, especially within the original extent of the grassland biome (23). This area holds the majority of the population (over 75%) and is one of the most rapidly changing in the province (17, 21, 23, 24). The area encompassed by this research extends to the City of Edmonton in the north and the City of Calgary in the south. The entirety of the

Queen Elizabeth II Highway that connects these major cities was included, and the region of interest extended out approximately 100 km east and west of the highway. The alpine forest in the southeast near Calgary was not included, as it is outside of the agri-zone in Alberta, therefore falling outside of the study objectives.

Two Landsat images from path 42 and rows 23/24 cover the entire study area; however, the alpine forest and Rocky Mountains in the southeast of the image were removed from all of the analyses as they are not pertinent to the objectives of characterizing agricultural and urban changes over time. A portion of the historical analysis focused only on the three largest urban centres in the province, Edmonton, Calgary, and Red Deer. The remainder of the LCC history utilized the entire extent of both Landsat images, and the model projected change over the whole site.

3.2.2 Model Data

Two Landsat images were required to cover the area of interest and were acquired for the 1984, 1992, 2001, and 2013 growing seasons, as they provided the least cloud cover. These images were then classified using the machine learning platform See5 (27) and validated using 800 points from Google Earth, 100 of which were ground-truthed. Ground truth points were collected in the growing seasons of 2013 and 2014, with approximately equal distribution between all land cover classes. In 2013, the points were truthed in a random distribution along the QE II Highway, with a focus on the northern portion of the study area. The centre and southeastern portions of the study area were truthed in 2014, with a larger number of points in agriculture and grassland.

See5 is a data mining Machine Learning Algorithm (MLA) tool which creates classification schemes based on decision trees (28). This freeware is useful in Land Cover

Classification because it can generate multiple decision trees based on the available imagery data, and the tree results can then be combined, using the boost function, to reduce the classification error (28). For this study, all available bands from the satellite imagery were used, in addition to NDVI data, and a transformed tasselled cap dataset. The resulting classification maps have an overall accuracy between 78-82%, performing better than national datasets (29, 30) and were considered sufficient for the purpose of this study. The highest land cover classification accuracy was forests, at over 90% in all years. This was followed by bareground, urban, and agriculture. Grassland and shrubland validated the worst, typically at around 60%, and were often misclassified between themselves. Part of the classification error between these classes is similarity in their phenological and optical characteristics. The gradient and transitional zone between these regions made it difficult to separate them in the classification scheme. As a result, these two classes were consolidated into a single category.

The maps were classified separately in each time step at 120 m resolution to reduce the random error produced in the digital numbers and, given the regional study area, this was considered sufficient for the study objectives. This is a common variety of spatial filtering. The original categories of the map were Urban, Bareground/Rock, Agriculture, Grassland, Shrubland, and Forest. The Grassland and Shrubland categories were consolidated into a single class because of mis-categorization between the two. To reduce model confusion and error, all of the natural land categories were combined, resulting in 3 classes, Urban, Agriculture/Cropland, and Natural Areas, to be utilized in all parts of the Dinamica EGO analysis. Natural areas may also include unmanaged pasture, as these zones are difficult to separate from grasses and crops at an intermediate resolution (31).

Classified landscape maps were used as an initial input for the Dinamica EGO system; however, additional information was required to simulate the corridor future (32). The base model also included biogeophysical (topography, geology, soils), climatic (mean annual temperature, precipitation), and human impact variables (infrastructure, population, management units, distances to urban/agriculture). These datasets were obtained from government sources (Stats Can, AB Gov), GIS databases (Altalis, GeoBase), and climate predictions. Climate data was generated based on the methodologies by Mbogga et al (33) and Alberta Environment (34) through the ClimateAB v3.21 software from Andreas Hamann (*http://tinyurl.com/ClimateAB)*.

To allow for separate LCC drivers across the whole area to act in isolation without conflict, a water management unit dataset from the Alberta government was utilized for regionalizing the model. This allowed for each process to dominate in its respective region, a methodology which has been employed in other large-scale Dinamica EGO studies (32).

3.2.3 Modeling Scenarios and Parameters

The historical LCC was evaluated using a patch analysis and in the Dinamica EGO system using an intensity analysis. In the patch analysis, the total areal extent and patch metrics of each class type were analyzed and compared between decades for a more complete history of alteration. The intensity analysis creates a unified framework for tracking land cover change patterns over multiple time steps (35). Three levels of alteration, the interval (rate and area of change), category (losses and gains in each land cover class), and transition (the targeting or avoidance of change between classes), are combined and assessed by this methodology (35). Intensity analysis does not encompass additional statistical analysis, and it is, instead, an accounting methodology allowing for wider comparison between classes in multiple time steps

(35). A submodel add-in, implemented in Dinamica EGO by the developers (36), was used for describing comparative change between 1984 and 2013 in Edmonton, Calgary, and Red Deer.

The Dinamica EGO platform was then utilized to complete a comprehensive land cover change model by determining the probability of each individual cell changing from one land cover to another (32,37). Landscape maps were input to calculate a transition matrix which outlines annual rates of change between each cover type. Variables, including any relevant spatially explicit datasets, were used to identify where change is most likely to occur. The probability is calculated by giving each variable a relative importance (weight of evidence) based on a Bayesian algorithm which identifies the likelihood of transition compared to the categories on the static variable maps (32, 37). A probability of change map was created for each land cover, and the chance of each pixel being altered was determined through the weights of evidence.

Two functions, Patcher and Expander, are used to train how continuous and connected the new islands of land cover type will be. Patcher is used to expand and contract existing fragments of each class, and Expander is subsequently run to determine the best locations for new islands to be created (12, 32). The percentage of change allocated to each of these tools can be modified by the model user. Additionally, both functions have patch parameterization that can be modified, including the mean, standard deviation, and isometry of each fragment, to reproduce the most comparable cover distribution. The pixels with the highest probability of alteration, which comply with the conditions set by Patcher and Expander, will change.

The initial LCC model was created between the 1992 and 2001 landscape maps and validated against the 2001 and 2013 time steps. Validation is built into Dinamica EGO and runs by comparing whether pixels in the simulated map match those in the validation or training map.

The similarity is compared iteratively using a moving window size which varies from 1 to 13 pixels. Originally, the model was created for six landscape categories (Urban, Bareground/Rock, Agriculture, Grassland, Shrubland, Forest), but the categories of Grassland, Shrubland, and Forest were consolidated to reduce noise in the model and class confusion. The separation of these classifications was not pertinent to the goals of tracking urban expansion and changes in the farmland; therefore, enhanced model functionality and efficiency were optimized instead. To further improve the model, bareground was removed from the simulation as it exhibits continuity in amount and spatial distribution between multiple time steps. The model validated at over 90% accuracy within 2.5 pixels (1.5 km), a value considered sufficient for the spatial and temporal extent covered.

Due to the lack of environmental policy in Alberta (13, 17, 20), the future projections were created under three main concepts. The first was a Business As Usual (BAU) scenario that projected the continuation of the historical rates of change up until 2022. In the second, extreme upper and lower boundary conditions were created by modifying the rates of change across the whole area. Edmonton urban expansion is predicted to be the highest in the province over the next decade, outpacing Calgary in 2014 (38). This was extrapolated to all of the corridor's urban areas for the upper boundary limit. If a government was to intervene with a policy which restricted the growth of urban areas to their current extents, or if this effect was to occur due to economic problems (i.e. severe drop in oil prices), this would create the lower boundary condition.

The third and final concept targeted the design of the landscape with the inclusion of two scenarios which dealt with potential policies that could be enacted. Landscape design policies are much easier to enforce than rate-based restrictions, and the types of legislation simulated by that model have been enacted nationally and internationally.

In other parts of Canada (i.e. British Columbia), there has been a movement to protect the best agricultural land and stop the expansion of cities onto this prime real estate (39). In this model, the best agricultural lands were determined using the Land Suitability Rating system (40), and regions with a 2 rating (moisture limiting factor) or better were protected for the next decade. Moisture was used as an allowable limiting factor because of the availability of irrigation systems in Alberta and the ability to overcome this challenge except in extreme circumstances. The second landscape design policy model was based on the UK strategy of restricting urban land (41). Greenbelts that are equal in area to the city they surround were used in the model on all areas over 3 km^2. Comparison between the resulting areas of each category was completed post-modeling.

The development of these scenarios provides the possible scope of feasible growth, and the range of impact of potential legislation. If there is a pro-expansion mindset embraced by the government, then the upper boundary limit may occur, but if an environmentally conscious approach is taken, the lower limits are probable. The landscape design scenarios can be compared to the other three scenario outcomes in terms of total areal extent of each land cover classification so that any additional scenarios tested in the future can be accommodated within this overarching framework.

3.3 Results

3.3.1 Intensity Analysis and Historical Change

According to the patch and overall change analysis, urban extent has nearly doubled since 1984 from around 300,000 ha to over 500,000 ha (Figure 2). There has also been an increase in the number of urban patches, and a decrease in the mean patch size of the urban/developed class. The maximum patch size of this class is found in the City of Calgary, and it has more than tripled since 1984, from just over 16,000 ha to approximately 55,000 ha. The agricultural area has stayed relatively consistent in size at approximately 1.9 million ha; however, the spatial distribution of the cover type has changed. There have been no overarching trends in patch size change for this cover.

The first component of the intensity analysis, the interval, indicates that in all three major urban areas, Edmonton, Red Deer, and Calgary, there has been a reduction in the rate of change in the past decade (Figure 3). The rate of change in 1984-1992 and 1992-2001 is in the fast change range, while the 2001-2013 time step falls below this line. Red Deer has the fastest average rate of change at 5.0% uniform intensity, while Calgary is at 4.8% and Edmonton is at 4.4%. In the 1984-1992 time step, all three municipalities have very similar rates of change. Edmonton has the fastest rate of change in the 1992-2001 time period, at just over 6%, but has the smallest rate of change at 1.8% in the most recent decade. In the 2001-2013 time period, both Red Deer and Calgary are also below their uniform intensity rates, with a rate of change of ~3.4%.

The second component of the intensity analysis shows a consistent gain in the built-up areas in all time steps in all three municipalities, with the exception of 1992-2001 in Red Deer (Figure 4). The loss and gain are both so slight in the number of pixels, however, that this could be an artifact in the land cover maps. Grassland or Natural areas show a predominant, but not universal, loss in this component, and the results for agriculture are mixed in this case. The greatest loss of agricultural land occurs in the 1992-2001 time period in Edmonton, with a net loss of over 5,500 ha; however, much of this land was reclassified as grassland (over 4,500 ha), potentially indicating a change from crop to pastureland.

Edmonton consistently gains the most urban area (always > 2300 ha) and Red Deer consistently has the smallest expansion (<1000 ha). Red Deer, however, is smaller so the relative percent change is highest at 10%, 6.5% and 4.2% in the 1984, 1992, and 2001 time periods, respectively.

The third and final part of the intensity analysis, which looks at target and avoidance for change, results in interesting trends. Agricultural land has been targeted over natural areas in the greater Edmonton and Calgary regions since the 1980s. In Red Deer, originally natural land was targeted, but in the past decade this has shifted to cropland (Figure 5).

In Edmonton, there is at least a 0.5% difference between the grassland and agriculture changed to urban area. The threshold between target and avoidance is highest in Edmonton at 2.1% and 2.4% in 1984 and 1992, respectively, but then falls to 1.2% in the most recent decade. With the threshold for targeted change reducing to 1.2%, both grassland and agriculture are considered optimal targets for additional urban development. In 1984, Red Deer development originally targeted grasslands, with the relative change over 0.5% higher than the targeting threshold. In 1992, and the most recent decade, the change has drawn, relatively equally, from farmland and natural lands with <0.1% difference in both years (1.3% and 0.95% targeted in 1992 and 2001, respectively). Calgary exhibits similar trends as Edmonton, with agriculture targeted by a large margin (> 0.5%) in 1984 and 2001.

3.3.2 Future Modeling Scenarios

The five scenarios present a range of future possibilities for southcentral Alberta (Figure 6). The BAU results in the further expansion of urban areas, increasing the number of small islands and the area of the major cities. Edmonton and its surrounding towns consolidate into an area larger than Calgary. East of the Queen Elizabeth II (QE II) Highway, which connects Edmonton and Calgary, has more development than the western part of the study region.

In the extreme upper boundary, cities and subdivisions accrue 300,000 ha more than the BAU scenario, with both agricultural and natural areas being used equally. The lower boundary results in a reduction of urban area compared to 2013. In this scenario, the urban sector is consolidated into well-established cities, and there are the greatest agricultural and natural extents remaining.

In the Land Suitability model (LS) and the Greenbelt scenario (GB), there are differences in both the amount of land converted and the spatial distribution of the changes. The LS scenario follows most closely with the BAU scenario, with only 10,000 ha less urban area and an increase in the remaining natural land. There is less development on the east side of the QE II Highway. The development is, instead, much more continuous on the areas proximal to the highway. Edmonton does not expand as much as in the Business As Usual scenario, but Calgary has additional land alteration nearby. The Greenbelt scenario follows more closely with the No Expansion model, resulting in only 400,000 ha of urban land in southcentral Alberta. The cities do not expand, but there is some smaller development that occurs across the region. Edmonton and its surrounding communities do not consolidate in this scenario, which is unique among the 5 models. There is expansion in agricultural area and a larger remaining extent of natural land.

3.4 Discussion

Farmers in Alberta have indicated that their land has increasingly been taken over by developers due to increased popularity of country-urban, or peri-urban living (42, 43). Many people have become interested in the comforts of urban living within the charm of a country setting, and this has resulted in subdivisions or acreage developments that are largely unconnected to a major urban centre (42). These trends are reflected in both the intensity and the patch analysis results presented in this study. Mean patch size decreases over the past few decades, while the number of patches and maximum patch size increases. This indicates that, despite the continued growth of the largest cities, there is an increase in the number of small isolated islands in the province. This is consistent with the peri-urban living trend (42). Agricultural land is found to be targeted in two of the three major urban centres from 1984-2001, and targeted in all three for the most recent decade. The trend experienced by farmers, where proximal cropland is being sold to developers and subdivided, supports this result.

The consistency in the amount of agricultural land found both in the model and in the historical land cover change supports government reports that state the area of farmland has not significantly changed in recent years (44, 45); however, this is problematic because urban growth is targeting agricultural land. If cropland amount is to stay consistent then it must take over other lands, fragmenting the remaining grasslands and shrublands. Fragmentation and reduced connectivity of these areas is concerning, not only for loss of natural capital, but also because of the large fauna they house. Thorton and Quinn (43) and Chetkiewicz and Boyce (46) have shown that there is a correlation between the fragmentation and increased isolation of islands of forest and the amount of human contact with large animals, including, but not limited to, bears, cougars, and moose (43, 46). This is dangerous both for these species and for the human populations with whom they will interact.

My results also indicate that the rate of urban expansion in the major areas is decreasing, or slowing down. This is despite the predictions that both Edmonton and Calgary will be two of the fastest growing cities in Canada (48); however, these two growth predictions are not mutually exclusive. Growth rate reduction may be due to development encroaching on designated city limits and the inability to annex the surrounding counties, infrastructure design changes favouring condominiums and apartments, and infill projects such as the development of the City Centre Airport in Edmonton (49, 47). Additionally, the City of Edmonton has attempted to tackle urban expansion with residential infill development. They have completed 11 of 23 actions that were set out to improve infill development, and have made a commitment to increase density (50, 51). There have been some concerns with this sort of infill, especially in mature neighbourhoods, where exceptions to zoning have increased, community consultation is extremely limited, and the price point of new houses is outside the range of many individuals (50, 51). The population increase of both cities is still of concern, however, as it has been found to be one of the major drivers of sprawl in Albertan municipalities (52).

The results from my intensity analysis are very comparable to results from an intensity analysis run on the newest national dataset (Figure 7). Agriculture Canada classified maps using a voting system of all other LCC datasets that have been created for the country, and the LCC from each year validates at over 90%. When compared with the intensity analysis results from the southcentral Alberta LCC maps, similar trends emerge, with agriculture predominantly targeted, reduced urban expansion in the last decade, urban growth actively changing, and a large loss of rangelands (Figure 7). These similar results further validate my Land Cover Classification System, and Dinamica EGO model. This can improve policy makers' confidence in the future scenarios and modeling results.

The future land cover change model allows for the development and implementation of potential policies. The Dinamica EGO system has been previously utilized to predict the overall effects of legislation changes in Brazil and the impact on specific economic investments (13, 15), but has not previously been employed in Canada. In this case, both the rates of change and the probability of individual pixels altering are modified in at least one of the four prediction scenarios. In general, landscape design legislation that does not directly place a restriction on growth is easier to implement and enforce, which is why this type of policy can be found across Canada (B.C., Ontario, and Quebec), Europe (U.K.), and even in Brazil (53). Brazil was recently a great example of the difficulty in enforcing rates of change. The 2012 Forest Code revisions in the country forgave farmers for not maintaining the required 20% of their land in its natural state prior to 2008 (13, 53). The conservation policy was also relaxed to allow natural areas to be preserved elsewhere in the same watershed, instead of on a farmer's property. Sections of the legislation directly related to geographic areas that cannot be modified, i.e. on slopes or in riparian zones, were left largely untouched (53).

The two models implementing landscape design legislation include the Greenbelt and the Land Suitability (LS) scenarios. Protection of the most suitable agricultural land, based on other Canadian legislation, leads to similar urban growth rates as in the BAU model (Figure 6). The main difference between the LS and BAU scenarios is the resulting spatial distribution of urban area. The QE II Highway exhibits much more development along its entire route, and the eastern portion of the province has less development in the LS scenario. Much of the best agricultural land is east of the major highway. Additionally, while Edmonton and its surrounding communities still consolidate into a single city, there is much less development, especially along the northern border. The Edmonton area is considered to be a region with prime cropland, and this can be protected from destruction by a landscape design policy similar to the one modeled in the LS scenario. Other areas, including Calgary and its surrounding land, have expanded urban development when compared to the BAU and upper boundary future projections.

An LS policy would provide a conservative solution that would have minimal impact on the economic and urban development of the study area. There would be no drop in the areal extent of cities or farmland; however, this would reduce the remaining grasslands and shrublands, decreasing its effectiveness as an environmental conservation solution.

A more stringent environmental policy would follow the Greenbelt simulation, which results in a spatial distribution that is more similar to the lower boundary limit. With no ability for the main towns and cities to expand, there is some growth in the rural-urban areas. One notable feature is that Edmonton and its surrounding communities do not consolidate in this case, which is unique among all of the scenarios. Agricultural and natural areal extents are much larger than in the LS scenario, indicating that this would be a more environmentally sustainable model. Implementation of this policy would require innovation in Canadian infrastructure, and likely restrictions and restructuring of the bylaws relating to zoning and infill developments.

In the UK, the greenbelt policy has become problematic to maintain, and every year more regions are rezoned to allow some development (41). If such legislation was passed in Alberta, rezoning issues would be unlikely immediately as there is still land that could be modified; however, it could become a future concern. Other countries have attempted to control expansion of their cities via strict population regulations (54). The two boundary conditions from this study follow this variety of control, utilizing either expansion of populations and city growth, or placing strict controls on development and population. Given the difficulty enforcing this legislation on a macro scale (55), these scenarios are unlikely to occur but provide constraints for policy application and feasibility checks on other model designs.

One component that remains unstudied in this particular context, due to lack of available data, is the impact of economic forcing as a method of controlling sprawl. In other locations, economics has been found to be an important driving factor (55). In Israel, for example, political measures alone could not outstrip the importance of the economic growth found in expanding the cities (55). In Brazil, models have projected that attaching a value to natural land to account for biodiversity value can have an impact on reducing the destruction of ecosystems (see Chapter 2), showing again the importance of proper land valuation working in conjunction with policy. This is largely due to the unaccounted for externalities in natural lands and even farmland.

The models in this study predict that, without government intervention, cities will continue to expand beyond their borders in Alberta, and will result in the destruction of natural land by pushing the farmland frontiers beyond their current boundaries. Urban sprawl is problematic in today's society for a number of reasons (54, 55). In China, there are concerns about the country no longer being a self-sustaining food source (54). In general, expansion also puts pressure on the ability of governments to provide services and infrastructure to all citizens, social disparity, and pressures on travel time and traffic (55). All of these things are of concern in Canada.

It is important to have an idea of what the future landscape might look like and how it can impact what drives the economy. The results from this study show that the Dinamica EGO platform is an efficient way to test how effective a policy will be before it is enacted in Canada. Despite extensive work in Brazil, this is the first time that the Dinamica system has been used in Canada, and it has proven to be equally effective in a completely different country. With this base model, policy makers now have a tool that is spatial in nature, can account for legislation and future predictive scenarios, and provides an integrated, holistic view of the changes occurring at a regional scale. These are improvements on the ALCES and GYPSY models (9-11), because the Dinamica system can determine where information is available and where there are data gaps. The results from simulations can be used to balance local, regional, and provincial interests and concerns in an explicit way, because the geographic context is available in the Dinamica system. Overall, these improvements can lead to enhanced land use planning frameworks, present optimal solutions, and provide an avenue for sustainable growth. With the correct data, it can also be extended into an investment or economic feedback model, such as the ones that have been created for Brazil (13, 15). This holistic approach will provide an effective avenue for building a balanced future in Alberta.

3.5 Conclusion

Landscape alteration has been occurring at a rapid and unsustainable pace in Alberta over the past 30 years and is unlikely to stop unless governments take action. Without intervention, land degradation and overuse of major resources that drive the economic growth will continue, leading to an uncertain future. Based on the scenarios tested, this study found that landscape design policy can also impact the rates of change. The Greenbelt scenario would be the most sustainable environmentally-friendly policy, as it falls closely to the lower boundary condition, but without the unrealistic expectation of no urban growth in the corridor. The most development-heavy scenario is the urban expansion model, with more than 200,000 more hectares of land than the BAU scenario at the expense of both croplands and natural land.

With the development of a model that incorporates biophysical, socioeconomic, and legislation variables, the future can be simulated and policies can be tested before they are implemented. This study indicates that policies which have worked in other parts of Canada and Europe can have an impact on preserving the best agricultural land and stemming the unchecked growth of cities. Regional and provincial models are essential in understanding the effect that humans are having on the province of Alberta and the future of this landscape.

Acknowledgements

I would like to acknowledge Dr. Britaldo Soares-Filho and his laboratory for their assistance with the Dinamica EGO program and conceptualization of the scenario implementation. Funding for this research was provided by an NSERC CGS-M and the Alberta Land Institute. Additional funding for presenting this study was contributed through a J. Gordin Kaplan Graduate Student Award. I acknowledge the support provided by the University of Alberta, and the National Science and Engineering Research Council of Canada (NSERC-Discovery).

Figures

Figure 3.1

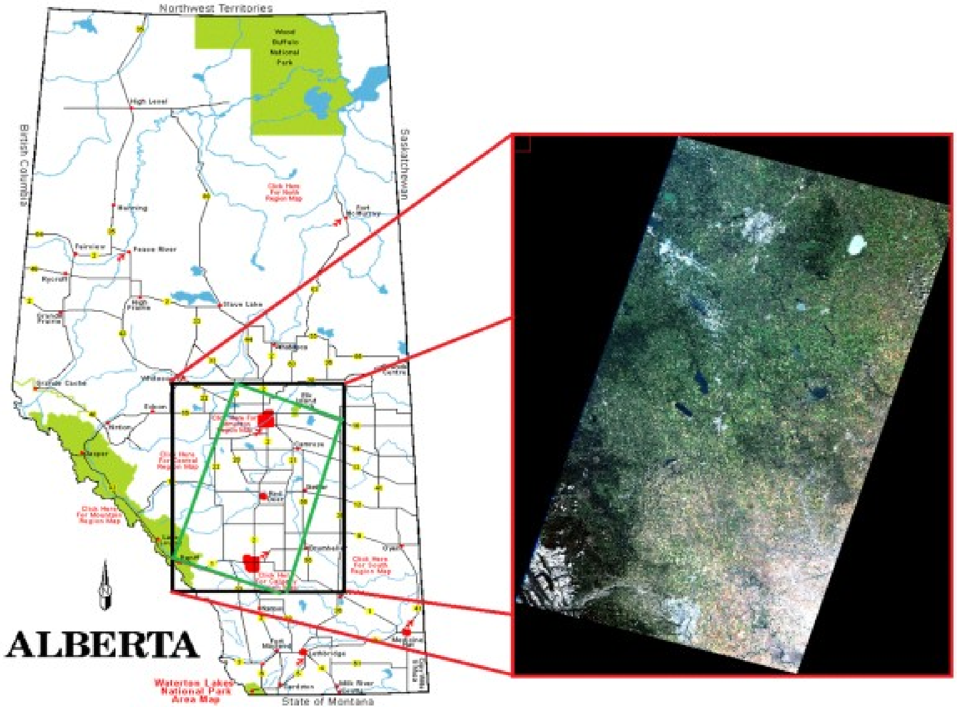


Figure 3.2

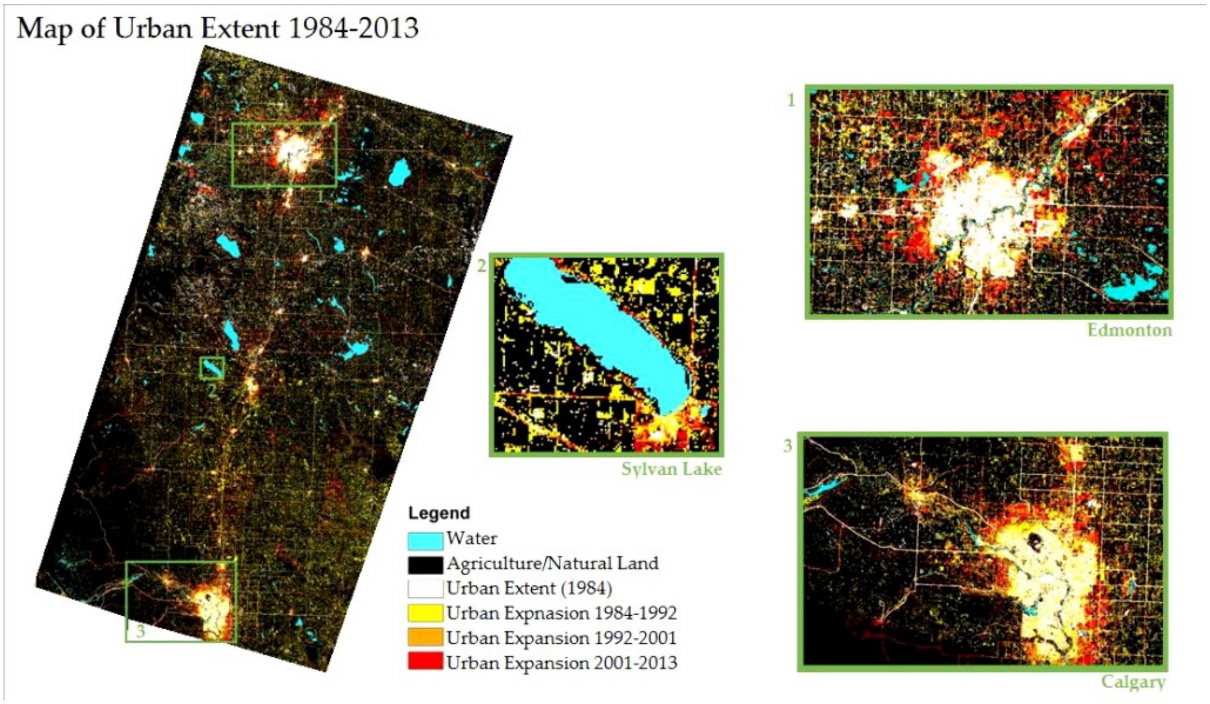

Map of Urban Extent 1984-2013
1
2
3
Legend
Water
Agriculture/Natural Land
Urban Extent (1984)
Urban Expnasion 1984-1992
Urban Expansion 1992-2001
Urban Expansion 2001-2013
Sylvan Lake
Edmonton
Calgary

Figure 3.3

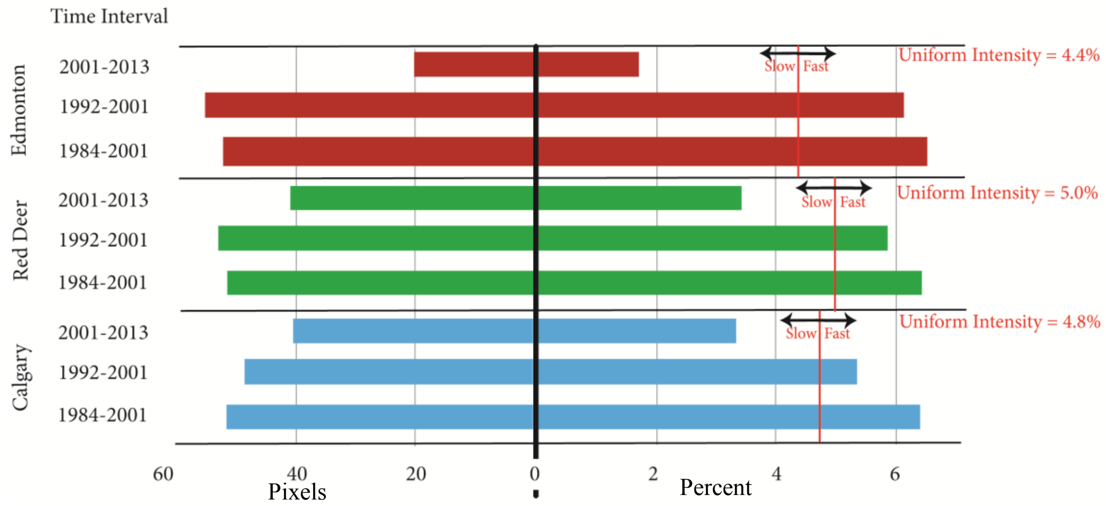

Time Interval
Edmonton
2001-2013
1992-2001
1984-2001
Red Deer
2001-2013
1992-2001
1984-2001
Calgary
2001-2013
1992-2001
1984-2001
Uniform Intensity = 4.4%
Uniform Intensity = 5.0%
Uniform Intensity = 4.8%
Slow
Fast
Slow
Fast
Slow
Fast
60
40
20
0
2
4
6
Pixels
Percent

Figure 3.4

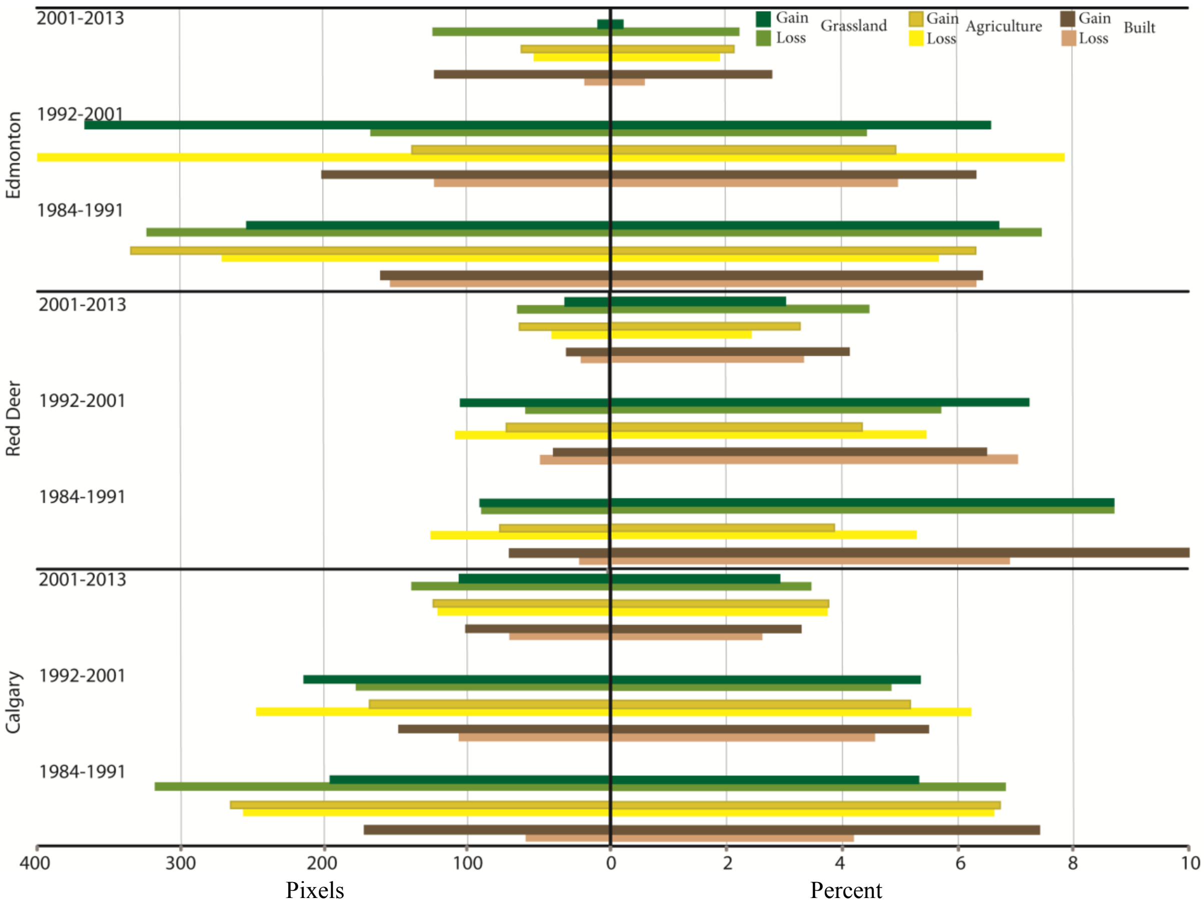

Gain
Loss
Grassland
Gain
Loss
Agriculture
Gain
Loss
Built
Edmonton
2001-2013
1992-2001
1984-1991
Red Deer
2001-2013
1992-2001
1984-1991
Calgary
2001-2013
1992-2001
1984-1991
400
300
200
100
0
2
4
6
8
10
Pixels
Percent

Figure 3.5

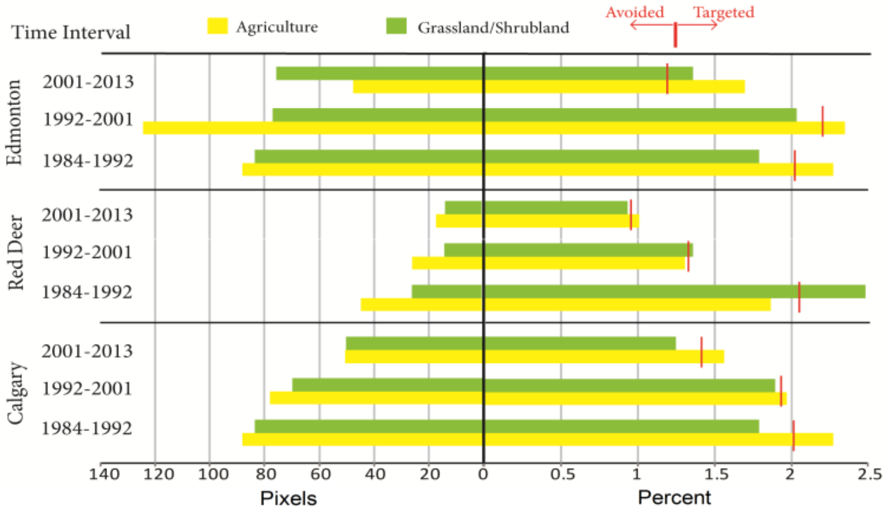

Time Interval
Agriculture
Grassland/Shrubland
Avoided
Targeted
Edmonton
2001-2013
1992-2001
1984-1992
Red Deer
2001-2013
1992-2001
1984-1992
Calgary
2001-2013
1992-2001
1984-1992
140 120 100 80 60 40 20 0
0.5 1 1.5 2 2.5
Pixels
Percent

Figure 3.6

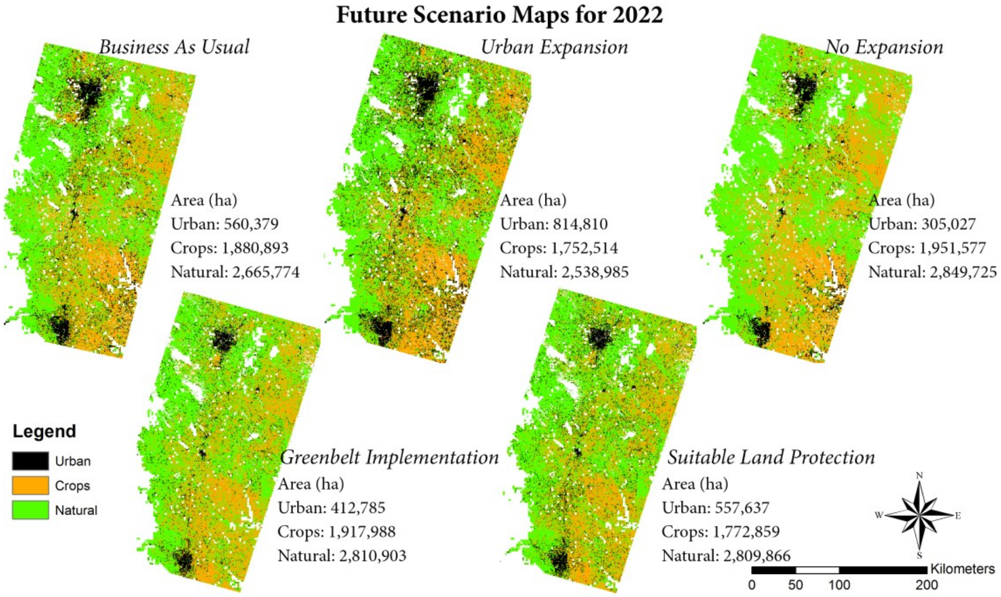
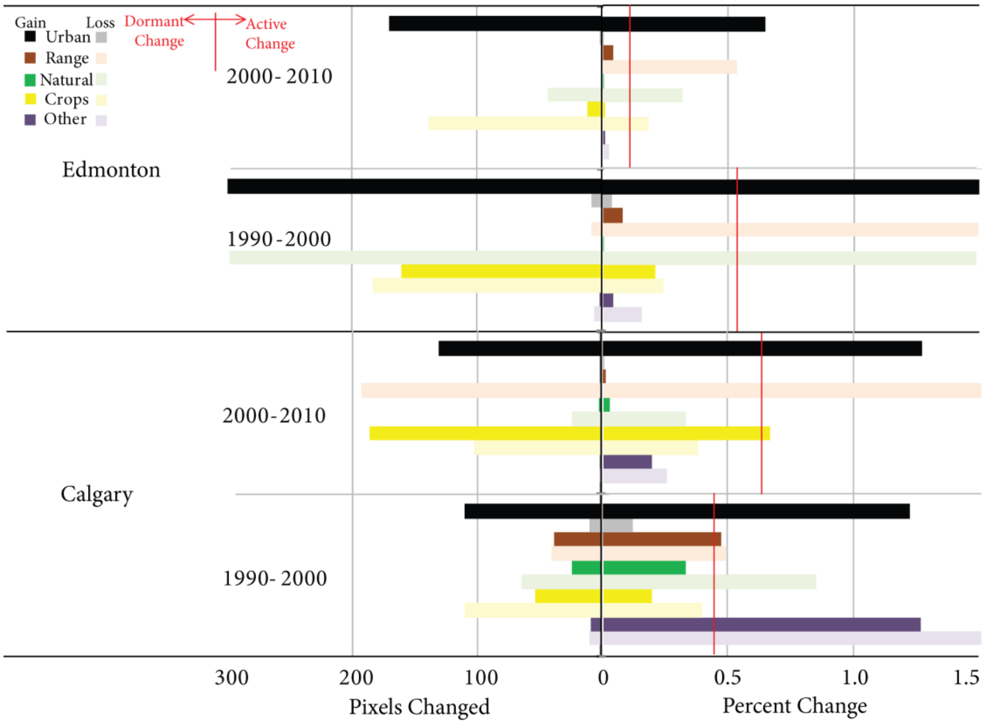

Future Scenario Maps for 2022
Business As Usual
Area (ha)
Urban: 560,379
Crops: 1,880,893
Natural: 2,665,774
Urban Expansion
Area (ha)
Urban: 814,810
Crops: 1,752,514
Natural: 2,538,985
No Expansion
Area (ha)
Urban: 305,027
Crops: 1,951,577
Natural: 2,849,725
Greenbelt Implementation
Area (ha)
Urban: 412,785
Crops: 1,917,988
Natural: 2,810,903
Suitable Land Protection
Area (ha)
Urban: 557,637
Crops: 1,772,859
Natural: 2,809,866
Legend
Urban
Crops
Natural
N
W
E
S
Kilometers
0
50
100
200

Figure 3.7


Gain
Loss
Urban
Range
Natural
Crops
Other
Dormant Change
Active Change
Edmonton
2000- 2010
1990-2000
Calgary
2000-2010
1990- 2000
300
200
100
0
0.5
1.0
1.5
Pixels Changed
Percent Change

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4. Chapter 4 Conclusions and Future Directions

The objective of my thesis work was to create a tool for decision makers that allows them to have a full assessment of the impacts of potential environmental policies on land use and cover change in two different regions: Minas Gerais, Brazil and Alberta, Canada. This project evolved from the lack of integrated modeling approaches that could provide sound scientific information to the decision-making process. In my thesis, I created Land Cover Change (LCC) scenarios for the aforementioned regions and projected these changes into the future, utilizing potential government policies. This improved both the knowledge base of integrative modeling systems in semi-arid biomes, and provided optimized scenario solutions that balance competing environmental and economic interests in these two locations.

4.1 Synthesis of significant contributions

The results from Chapter 2 ***"Simulating Deforestation in Minas Gerais, Brazil, Under Changing Government Policies and Socioeconomic Conditions"*** show divergent possibilities for deforestation in Minas Gerais, Brazil, but the potential to protect large amounts of Cerrado land through market forcing.

The spatial LCC projections indicate that shrubland is preferentially converted to agricultural land over forests in all scenarios, with the greatest areas of destruction found in the northwest of the state. I determined that there is little alteration in the south of Minas Gerais, largely due to the protection of the remaining Mata Atlântica, with any further conversion likely resulting from illegal deforestation. The model scenario which projected the recently implemented Forest Code sees increased fragmentation and less remaining natural land than the Business As Usual model. On the other side, the Aichi Biodiversity Targets, which Brazil has pledged to follow, could result in more shrubland remaining than with a continuation of current trends. This poses an interesting question as to which policy will be followed in the next decade.

If environmental conservation and the Aichi Biodiversity Targets is the goal of the State of Minas Gerais, it is possible to steer the agricultural development through market forcing. This was shown in the economic modeling system. The economic model optimized the profit and compared the impact on the amount of area bought and converted every year by including the price of biodiversity as a tax on land sale prices. With the inclusion of this tax, over 1 million hectares of Cerrado land would be saved with a minimal impact on the GDP expansion (less than 0.3% reduction to the rate of increase). This is a significant saving in the areal extent of biodiversity-rich savannah, and provides a potential sustainable option which will not hinder the growth and development of the Minas Gerais economy.

My model results indicate that the legislation (Forest Code and Aichi Biodiversity Targets) implemented in Minas Gerais may not be location specific, as all scenarios converted areas in the northeast, but they can have a substantial impact on the rates of change if they are enforced. One way to implement these policies effectively might be through economic drivers, by adding a tax onto the sale price of lands. Not only can this reduce the amount of land that is bought for agricultural development, but the value recouped by the government can be put back into environmental conservation through park maintenance or restoration of damaged/abandoned lands. Without an integrated modeling approach, there would be no way of testing the impact of policies, and there would be limited information about possible solutions, both conventional and innovative. The Dinamica EGO system has previously provided insight about challenges and successes in Amazonian protection, and this functionality can now be applied to the sensitive, semi-arid biomes, including the Cerrado, Tropical Dry Forest, and Caatinga.

The results of **Chapter 3** ***"The Edmonton-Calgary Corridor: Simulating Future Land Cover Change Under Potential Government Intervention"*** are equally important but are applied in a different location and opposite legislative spectrum. The government in Alberta has not historically implemented laws restricting land conversion, instead leaving it to market drivers. My research in this area provided the opportunity to fully characterize the land cover change history, something which has not been done in the Edmonton-Calgary corridor, and project how government intervention may impact the region in the future.

Urban area has nearly doubled since the mid-1980s and agricultural area has stayed approximately the same size. The problem, however, is that the growth of towns and cities targets the surrounding farmland for conversion, pushing the frontiers of the cropland into the adjacent natural areas. My analysis shows that, in the past decade, urban sprawl has slowed; however, recent predictions from government indicate that Calgary and Edmonton will be two of the fastest growing municipalities in the next few years.

This background provided the basis for creating upper and lower boundary conditions where rates increase beyond the Business as Usual (BAU) scenario and where a moratorium of growth is implemented, respectively. Two additional scenarios that focus on landscape design rather than rate changes were also created as potential policies to be implemented. The first, a Land Suitability model, was created using the British Columbia policy of protecting the best agricultural land (1), and the second was adapted from the English greenbelt legislation (2). Greenbelts performed better for reducing rates of change as well as directing growth away from farmland. The Land Suitability model projected similar rates of change to the BAU scenario, but focused growth along the Queen Elizabeth II Highway. These two scenarios can be translated into relevant policies; they also show that the model can predict legislative outcomes and governments can have a tangible impact on balancing economic and environmental interests. Results indicate that the integrative modeling system is a very powerful tool for policy analysts, and should be further developed to become commonplace in governmental institutions.

4.2 Challenges and Future Directions

Despite the past 30 years of work on land cover change and the abundance of literature, there is still a lack of knowledge about the effects that land modification will have in the future (3), the relevance of spatial, spectral, and temporal scales in affecting results (4, 5), the causal relationships between society and LCC (5), and integrating the entire system in a modeling platform (6). There has been a focus on developing technology that can increase spatial and spectral resolutions; however, modeling platforms that effectively handle these datasets are still largely underdeveloped. Consistent definitions for individual land cover classes and a universal system of identifying landscapes still do not exist, making comparability between models and studies difficult (3, 7).

In a modeling system, auxiliary data is equally important to accurate landscape maps (8) and can include biogeophysical, climatic, sociological, economic, and governmental information. While there has been some effort to put this data into a spatially explicit format, this is still largely in its infancy, resulting in the need for models to handle qualitative data or for additional research in relating pixels and people, a concept defined in the late 1990s as socializing the pixel (5). The data that has been transformed into a spatiotemporal format typically is at a much lower resolution than the landscape maps, such as the broadly generalized thematic maps from the IBGE in Brazil (9). Other problems exist for obtaining data, as many locales still have proprietary information which is difficult to get from companies and often at a very high cost, including the common Alberta database AltaLIS, which has maps costing upwards of $90,000 (10).

Beyond the data constrictions, there are also challenges in engaging governments and policy makers to effect actual change. The literature has indicated that there are problems occurring as we know land modification does affect global systems (11, 12), but there remains the belief in some places that passive protection is sufficient (12), or worse, governments implement policies that may unintentionally increase rates of change (13). It is my belief that one of the greatest challenges in this branch of research is, in fact, not the science at all. The technology and methodology are all present, even if in scattered areas. Instead, the task that poses the biggest challenge to the community is to provide relevant, applicable tools and information to the stakeholders to gain their support for balancing the environment and the economy. Without buy-in from industry, government, and the public, a sustainable future is largely unattainable, and the global environment will continue to be modified at unprecedented rates.

Future research should focus on the integration of information into a holistic system. It should also include avenues to engage in interdisciplinary studies. Communication of the research to a broader audience and engagement of these sectors in the decision-making processes are key, not only in LCC modeling, but in many aspects of environmental study.

4.2 References

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