VEGETATION RESPONSE TO CLIMATE CHANGE IN NORTH AMERICAN NATIONAL PARKS: POLICY & MANAGEMENT IMPLICATIONS

by

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I hereby declare that I am the sole author of this thesis.

This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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ABSTRACT

Climate change is no longer debated in the context of whether or not it is occurring, but rather in the context of how rapid and extensive that change will be. This is the global situation to which the biomes of national parks in Canada and the United States must adapt. Through the use of the MC1 Dynamic Global Vegetation Model (DGVM) this thesis constructs projections of possible vegetation response of ten biome classifications to the impacts of continental-scale climate change in seven regions: Atlantic, Great Lakes, Mountain, Northern, Pacific, Prairie, and Southern. It then analyzes the potential ways in which DGVMs can be utilized by park management schemes in accommodating for future climate change in the selection, creation, and maintenance of national parks.

As the latest generation of vegetation modelling systems, the advantages of Dynamic Global Vegetation Models over pre-existing equilibrium biogeography models are examined in this thesis. DGVMs highlight the degree to which ecosystems are interconnected, and are able to provide continental-scale data necessary in coordinating an integrated planning approach for national parks in North America. They are utilized in this study for generating projections of future biome distribution, based on climate information from three General Circulation Models: CGCM2, CSIRO Mk2, and HadCM3. Following the generation of possible climate scenarios, the impact of changes to biome distribution within national parks is discussed. The thesis findings provide valuable modelling analysis and scenarios for use in future planning by the US National Park System and Parks Canada. Utilization of DGVMs will help in creating flexible, coordinated management strategies that take into account projected vegetation responses to climate shifts that lie ahead.

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TABLE OF CONTENTS

PAGE

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: RESEARCH CONTEXT & APPROACH

1.0 INTRODUCTION

Earth’s global climate is in a constant state of flux. Ice cores, extracted from Greenland and the Antarctic, indicate that the earth has regularly undergone rapid climate changes and during some interglacial periods over the last 250,000 years has been warmer than present day. However, it is now recognized that the trajectory of present day anthropogenic warming is likely to push Earth’s climate beyond this natural variability (Overpeck, Cole & Bartlein, 2005). A general consensus has been reached by the international climate research community that while natural warming has been occurring over the last century, most warming observed within the last 50 years is attributable to anthropogenic activities (IPCC, 2007).

The United Nations’ science authority on climate change, the Intergovernmental Panel on Climate Change (IPCC), estimated in its Fourth Assessment Report that global surface temperatures are likely to increase between 1.8 to 4.0°C by the year 2090-2999 (IPCC, 2007). This figure however, represents the global average and does not adequately reflect the magnitude of change in nations at higher latitudes, such as Canada and the United States. Members of the US National Assessment Synthesis Team found that the conterminous United States will likely experience a 3° to 5°C increase in mean temperature (NAST, 2000). The Canadian Climate Impacts Scenarios project found that mean temperature increases of 2° to 8.5°C could be expected (CICS, 2006). These projections only represent the average within North America and warming is projected to be much more pronounced in the Arctic (CICS, 2006; IPCC, 2001).

Just as Earth’s climate has always varied considerably, so too have the distributions of vegetation/flora and fauna species in the past. Climate plays a large role in determining the physiological stresses directly acting on a species at any time (such as temperature and precipitation) as well as indirect stresses (through changes in disturbance frequency and magnitude, like fire cycles). Consequently, the biological associations observed in natural areas today are largely the result of, and are heavily impacted by the climate of an area (Hannah, Lovejoy & Schneider, 2005). Responding to future climate change will not be as simple as in the past, however. Indeed, what makes contemporary climate change unique, in terms of biological response, is not only the magnitude and relatively short time frame at which it is expected to take place (IPCC, 2007), but also the disruption that human development will play in hampering species' responses (Peters & Darling, 1985). As species attempt to adapt to changes in their environment, they will encounter towns, cities, agriculture, highways and other obstacles that were not present during any previous period of climate change. This fragmented landscape will isolate them and impede their ability to respond (Hannah et al., 2005). The Technical Report of the IPCC entitled *Climate Change and Biodiversity* (IPCC, 2002) elaborates that fragmentation will contribute to ecosystem stress as species are unable to cross barriers in order to shift poleward or upward in response to change. Additionally, individualistic responses of species will contribute to the disruption of current assemblages and subsequent replacement by "weedier" assemblages that are poor in biological diversity (Malcolm, Markham, Neilson & Garaci, 2005).

As a result of projected climate change impacts, serious concern has been raised about the ability of global protected areas to preserve biodiversity in the future. The stresses induced by climate change will have widespread impacts, altering population dynamics and geographical distributions of species world-wide (Halpin, 1997). It is thought by many that the combination of changing conditions and increasing isolation of habitats will lead to the loss of many species and could significantly deteriorate protected natural areas on a global scale (Bush, Silman & Urrego, 2004; Groves et al., 2002; Halpin, 1997; Hannah et al., 2002; Leemans & Eickhout, 2004; Martin, 1996). The dangers presented to species confined to isolated protected areas will likely prove more drastic as they would be subjected to limited ranges in order to track climatic changes. Small populations which are more prone to random events and extirpation, and are susceptible to genetic impoverishment. In response to these risks, it will be increasingly important in the future to incorporate long and short term projections of climate change and potential responses of biota into protected area management strategies (Bruner et al., 2001; Fonseca, Sechrest & Oglethorpe, 2005; Graham, 1988; Hannah & Salm, 2005; Lemieux & Scott, 2005; Lovejoy, 2005; Scott, 2005; Scott & Lemieux, 2005; Bruner et al., 2001).

Efforts within Canadian and American national parks have been made in order to determine the risks that may present themselves with continued climate change; however, despite the risks associated with climate change there continues to be a relatively limited inclusion of climate change into park management and creation strategies in North American national parks (Parks Canada, 1997; NPS, 2006; Welch, 2005; Scott & Lemieux, 2005; Scott, Malcolm & Lemieux, 2002). Beyond commissioning reports and developing climate change scenarios it will be important to incorporate these projections into management actions within parks and into the process of park establishment. Scott and Lemieux (2005), have compiled a detailed list of the policy and planning implications that national parks within Canada will have to grapple with in the future because of climate change (and are applicable in most cases to national parks in the United States). The first aspect that Scott and Lemieux state will need to be addressed is protected area system planning. This includes revising park selection criteria and system goals to incorporate climate change. Park management bodies should also be aware that steady-state planning disregards the possibility of biological communities that have no current analogue. The second aspect addressed is the management of individual parks. Many park mission statements do not accommodate for climate change and the impacts that may take place because of those changes. Essentially park managers will be attempting to “hit a moving target” with regards to preserving biodiversity as species ranges respond to climatic change. The third aspect is active management plans; park managers will have to decide how management schemes will need to be adjusted to respond to climate change. Fire suppression, visitation rates, and the management of invasive species, for example, will become factors that require more scrutiny as climate impact changes take place.

It is in this regard that the utilization of dynamic global vegetation models (DGVMs) can play a potential role in the management of existing parks and the selection of new ones. Conservation managers can use the information provided by these models in order to assess which biomes may be the most threatened and where vegetation types are likely to persist in the long term. Additionally, by providing scenarios with and without fire suppression actions, disturbance management policies within parks can also be examined and compared to system-wide goals to ensure that management strategies within parks are consistent with greater objectives.

1.1 SIGNIFICANCE OF THE RESEARCH

The effects of projected climate change will not respect international borders, nor will the responses of ecosystems in adjusting to these changes. In spite of this, data limitations have forced many studies modelling the responses of ecosystems to climate change to focus on national, or smaller, scales. Capturing the context in which these changes are going to occur requires a continental focus, which this study provides. The study will include national parks from both Canada and the United States and will provide information on vegetation response to climate change that could be considered in management practice as well as new park selection criteria. It will also provide projections which could potentially be used by both countries in a collaborative effort to coordinate large-scale conservation management strategies.

The projections used in this study are created using transient vegetation responses to climate change. Past studies have relied on equilibrium biogeography models which are unable to assign temporal values to simulations and whose projections may take centuries to be fully realized (Cramer et al., 2001). This "lag-time" has led to a hesitance on the part of conservation managers to consider their results, as no clear indication of when responses might occur were provided. The newest generation of biogeography models incorporates transient responses which allow projections of the approximate time period during which changes are likely to take place. Projections can be made for any time period ranging from years to centuries, but medium- and long-term decadal projections are generally deemed the most appropriate. Here the time frames of 2045-2055 and 2075-2085 are used. The medium-term projection carries a higher degree of certainty and provides a useful time period for future management planning, while the long-term projection is useful to identify eventual implications of climate change for biodiversity and protected areas. In particular, these projections will likely prove very useful for future decisions concerning network establishment, invasive species management, and wildfires. Detailed examples will be included in this thesis showing how future projections can be integrated into present day fire management within a protected area.

Further improvements to the field of climate and biogeography modelling have taken place which improve their effectiveness. First, climate models made the advancement which soon followed in biogeography models, shifting from equilibrium-constrained models to transient models. Rather than assuming an instantaneous change in atmospheric composition, transient models use emissions scenarios to simulate annual changes in atmospheric composition – thus providing a more rational simulation of Earth's climate (Bachelet, Neilson et al., 2001). Second, vegetation simulations produced using transient models can be compared with older simulations in order to spot areas of agreement, and identify areas where there is disagreement that could stimulate more study.

1.2 RESEARCH OBJECTIVES

The primary goal of this study is to assess the extent to which terrestrial vegetation is likely to change at the biome level within Canadian and American national parks under projected climate change, and to examine the possible management and planning implications. In order to accomplish this goal, the following objectives have been established:

- Review the literature relevant to climate change, vegetation response, the models projecting these responses, and park management and policy;

- Assess how climate change is likely to affect biome level vegetation distribution within North America using the MC1 dynamic global vegetation model under HadCM3, CGCM2 and CSIRO Mk2 climate change scenarios;

- Explain how these vegetation changes are likely to impact protected areas in North America – investigating policy and management sensitivities that exist within the current system and illustrating how this relates to preserving ecological integrity;

- Explain how decision makers could utilize DGVM model outputs to develop and refine current management decisions and policy;

- Demonstrate how modelling results from DGVMs can be utilized by park managers in the implementation of disturbance management decisions. This will include a case study of how fire management can alter projected future biome representation within a protected area.

1.3 CHAPTER OUTLINE

This study is divided into six chapters. The second chapter provides a review of current literature pertaining to climate change, and terrestrial vegetation response. The literature review also provides an overview of the implications of climate change for protected areas policy and management and biodiversity conservation more broadly, including contemporary management and planning adaptation strategies (adaptation in this case, and when mentioned in reference to management actions, refers to response strategies that can be taken to address to climate change). Chapter three describes the methods employed to assess the magnitude of vegetation change in North American parks, with a particular emphasis on the selection criteria for parks included in this study. It details the climate and vegetation scenarios utilized, and the procedures used to determine the extent of expected vegetation change in each park. The fourth chapter presents the vegetation change results for both Canadian and American national parks. Particular emphasis is placed on analyzing the regional distribution and magnitude of expected change. Chapter five will then comment on the potential implications of terrestrial vegetation change for park management and policy. Detailed examples will illustrate how the management of fire regimes may have pronounced influences on future biome representation within certain parks, and how the results of this study can be applied to management strategies. The final chapter will conclude by summarizing the findings of this study and by proposing future research directions.

CHAPTER TWO: LITERATURE REVIEW

2.0 INTRODUCTION

Climate change in combination with habitat loss and fragmentation has long been stressed as a paramount threat to biodiversity, (Lovejoy & Hannah, 2005) but it has been difficult to generate scenarios which have the temporal resolution and spatial extent necessary for use in conservation policy formation and planning. Dynamic Global Vegetation Models (DGVMs), however, include time-dependent inputs which make them able to generate projections for both short- and long-term time frames while maintaining the ability to cover large geographical extents, thus fulfilling the requirements that past modelling had failed to achieve (Betts & Shugart, 2005).

The intent of this chapter is to introduce theories from past and current literature and how this research fits into that body of knowledge. Further, this thesis aims to illustrate the importance of incorporating climate change into the policy and management of protected areas. Four areas of study that have been utilized for setting the foundation for this analysis are reviewed. The first section describes both past and recent climate change and explains how projected future climate change varies across North America. Sections two and three outline past, current and future vegetation responses to climate change and introduce the models which have been used to describe these changes and project future responses. Lastly section four seeks to review possible responses in park planning and management to adapt to the impacts of changes expected to occur in an era of climate change. Through examining the literature that has developed in these areas of study, an understanding of how the research relates to past works, and how it builds upon them, will be established.

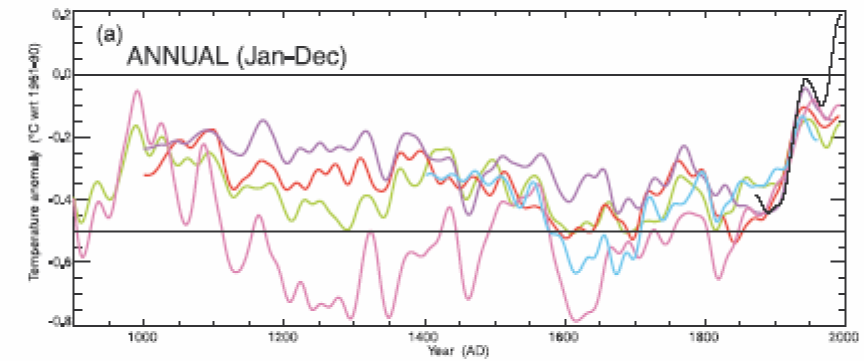
2.1 PATTERNS OF CHANGE IN EARTH’S CLIMATE

It is valuable to view the changes that have occurred in Earth’s climate in the past before moving on to recent changes. In this manner, past climates are able to provide a starting point from which to place modern observations into context. Past studies provide us with two important conclusions about past climate change, the first being that rapid climate changes, 10°C over 10 years over the North Atlantic, have occurred repeatedly in the past 80,000 years

(Alley et al., 1993; Broecker, 1987; Overpeck et al., 2005; Labeyrie, Cole, Alverson & Stocker, 2002). The second observation is that despite this variable nature of Earth's climate, these past changes have almost always fallen within an "envelope of natural climate variability," which takes into consideration magnitude and rate of past changes (Overpeck et al., 2005, see Fig. 7.4; Overpeck, Whitlock & Huntley, 2002). The authors go on to note that the projections of numerous studies modelling anthropogenic warming project that it will exceed the bounds of this past envelope of natural variability (Briffa & Osbourne, 2002; Hulme, 2005; IPCC, 2001; Robertson et al., 2001).

Hulme (2005) focuses on a closer time frame when comparing today's climate with that of the past and states a similar observation that the increases in average temperatures observed in the Northern Hemisphere over the last two decades have been warmer than any observed in the last 1000 years In **Figure 2.1** coloured lines indicate various paleological temperature reconstructions, while black lines indicate average temperatures derived from instrumental records.

FIGURE 2.1 - Reconstructions of Temperature Variations in Areas North of 20°N since 1000 AD

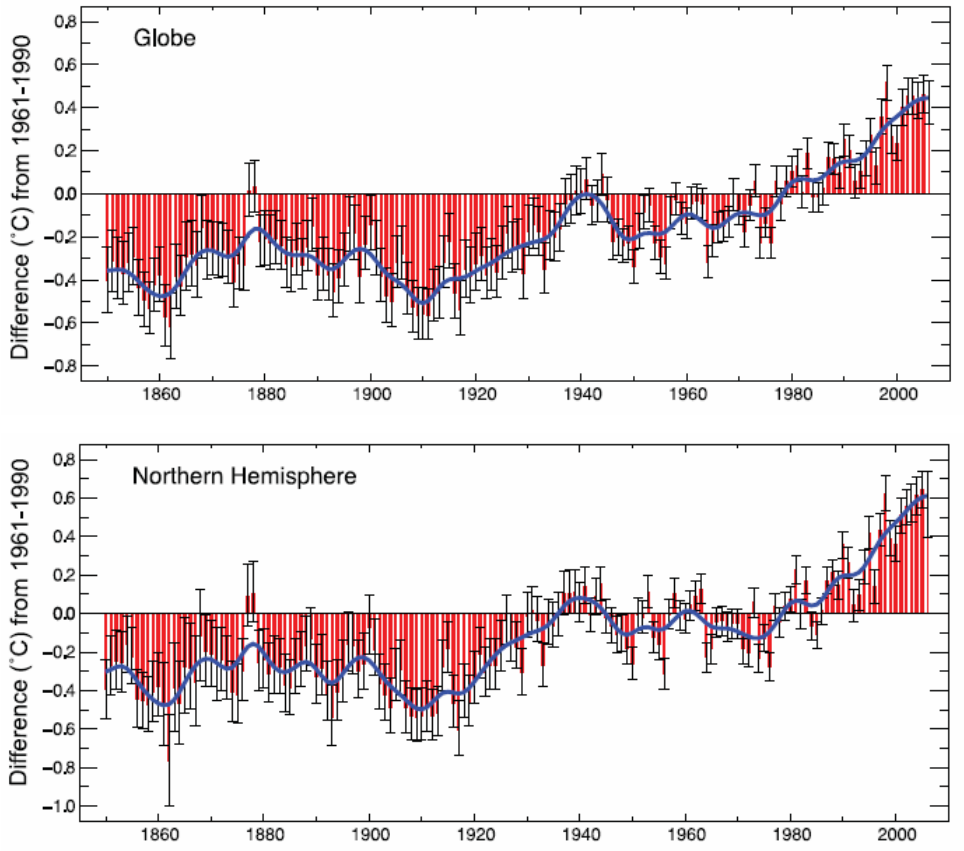


Source: Briffa, Osborn & Schweingruber, 2004

This observation agrees with findings made by Overpeck et al. (2005), where evidence is provided that Earth's climate is being pushed beyond the natural envelope of variability which has been observed over the last 450,000 years. Hulme makes a further observation which is critical to climate change impact research; while climate change is often measured using the global increase in average temperature these changes are not distributed in a spatially equivalent manner (Hulme, 2005). The continental mid- to high-latitudes will bear the brunt of global temperature increases, and are expected to warm at a significantly greater rate than the global mean (IPCC, 2007).

The following two charts in **Figure 2.2** illustrate the temperature change differences between global average temperatures, and those experienced in the Northern Hemisphere that have occurred over the last 150 years. These figures represent the average temperature difference for each year from the 1961-1990 mean which is used in most contemporary climate studies to represent the current period with minimal inter-annual variation. It can be seen from the two diagrams that the observed temperatures for the Northern Hemisphere in 2006 are 0.6°C above the 1961-1990 mean, while globally the average temperature is 0.45°C above the same mean. This difference becomes even greater in the mid- to high-latitudes (IPCC, 2007).

FIGURE 2.2 – Warming Differences Between Northern Hemisphere and Global Averages



Source: IPCC, 2007

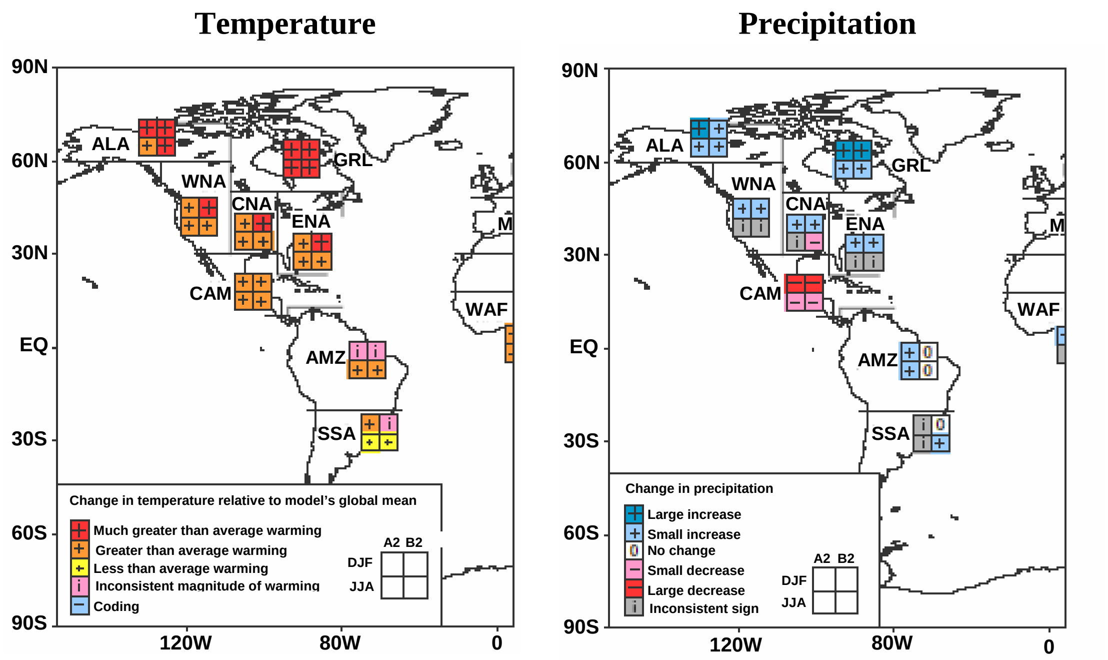
Because climate changes will not have a uniform distribution, it becomes important to take into particular consideration the regional variations that are expected for North America. Several General Circulation Models (GCMs) that are able to accomplish this task have been developed, and will permit improved estimates of climate change that take into account the different processes at work across the continent.

2.1.1 PROJECTED CLIMATE CHANGE IN NORTH AMERICA

Concentrating on global patterns alone will significantly understate climatic change likely to take place in North America due to its large landmass and the positive feedbacks associated with snow and ice retreat (IPCC, 2007; Karl & Trenberth, 2005; Raper & Giorgi, 2005). Through employing multiple GCMs it becomes possible to examine the plausible range of future climate change and to establish common trends in the distribution of temperature and precipitation patterns. There is a greater degree of agreement between GCMs concerning changes in temperature, while precipitation poses more difficulties in the modelling process, as rainfall rates and distribution often occur on a sub-grid scale. As a consequence, significantly less agreement between models has been achieved with regard to precipitation (IPCC, 2007).

Working Group I of the Intergovernmental Panel on Climate Change (2001) produced two maps, included below in **Figure 2.3**, dividing the continent of North America into five regions in order to show the agreement between GCMs and the magnitude of change projected. Wherever change is expected, four out of five models agree on the approximate magnitude of change. For instance, four out of five GCMs agree that temperatures would warm at least 40% more than the global average in the Greenland region for both summer and winter months. Discernable patterns were not as prevalent in the precipitation map, where it can be seen that the sign of projected change can even be inconsistent.

FIGURE 2.3 – GCM Agreement of Projected Regional Climate Change



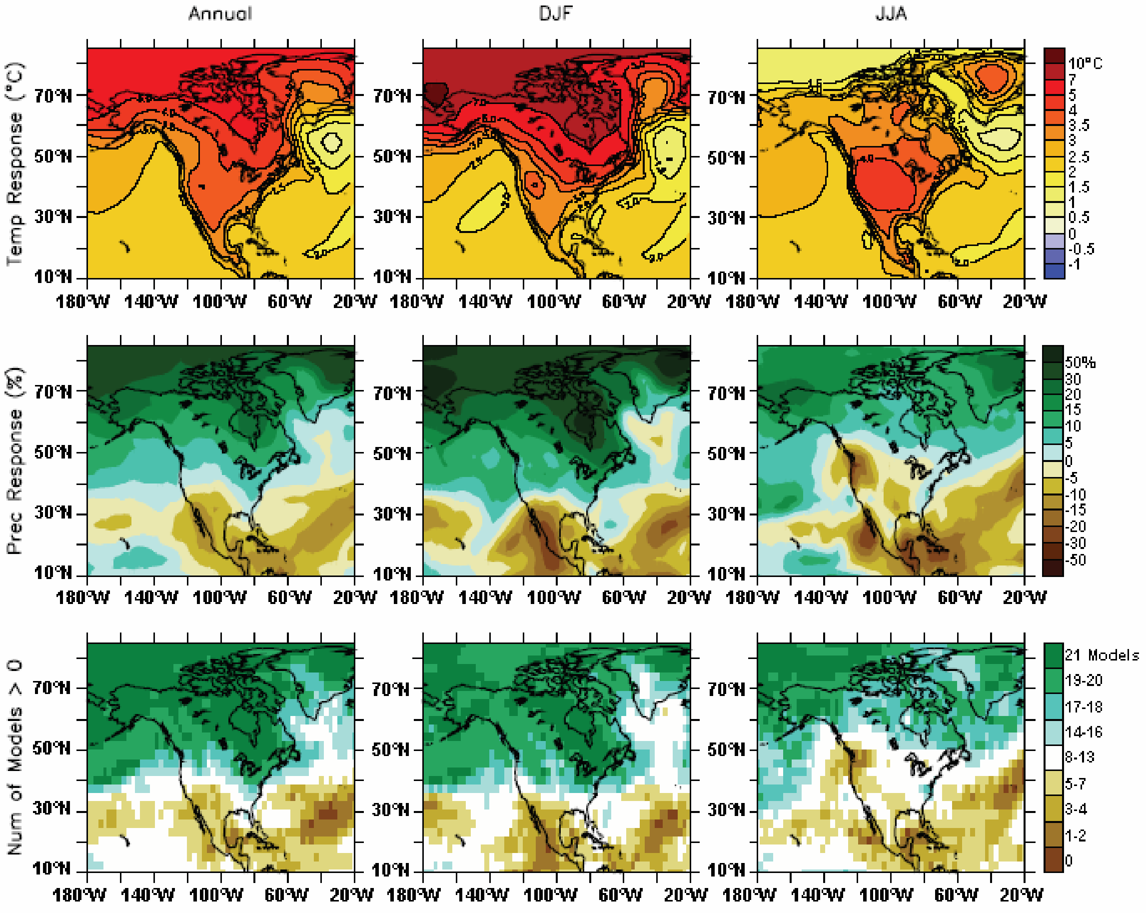
Temperature

Precipitation

Source: IPCC, 2001

In 2007, the same working group produced a similar set of maps that are included in **Figure 2.4**, showing projected surface temperature and precipitation rate changes, as well as model agreement for precipitation. Many of the trends modelled in the maps produced in 2001 persist in the maps generated in 2007. Precipitation continues to be less consistent between models than temperature, which is reflected in the additional set of maps showing model agreement for precipitation in the 2007 maps where none are included for temperature.

FIGURE 2.4 – Multi-Model Data Showing Projected Regional Climate Change and Model Agreement (2080-2099)



Source: IPCC, 2007

From these maps valuable information about regional change in North America is acquired and it is possible to describe the changes that future climates will likely bring to specific regions of the continent. There is a strong agreement between models that warming will be much greater than the global average in the northern latitudes of Canada and Alaska, in both winter and summer months. The mid-latitudes are also likely to warm significantly, but not to the same extent as the northern latitudes. Precipitation, as mentioned, shows a greater degree of variability between models, but there is agreement that the northern latitudes will experience larger increases in precipitation and decreases are expected in the southwest in areas near Texas and Mexico. The summer months are less certain, with many areas of the mid- and lower-latitudes displaying inconsistent results. However, there is a chance of reduced summer precipitation in central North America which could lead to increased droughts.

2.2 VEGETATION RESPONSE TO CLIMATE CHANGE

Using a broad collection of literature and GCM projections, Scott and Suffling (2000) conducted a study of the potential impacts that climate change could have on Canada's protected area network. This analysis included a broad spectrum of impacts, from abiotic features, individual species and ecosystems to visitor activities. A key finding of this study is that climate change will play a very significant role in shaping the vegetation communities within these parks in the future. Other studies (Halpin, 1997; Malcolm & Markham, 2000; Peters & Lovejoy, 1992; Rizzo & Wikken, 1992) have also offered supporting evidence that climate change will have a large, mostly negative, impact on the biodiversity supported within protected areas. However, essential to this conclusion, and critical in its formation, is the development of an understanding of how plant communities have responded, are responding, and likely will respond to climate change.

A fundamental understanding of what responses are available to plants in order to cope with a changing climate is attained from the work of Holt (1990). In this framework, three possible options exist: (1) changing distribution and abundance, without evolving; (2) evolving, perhaps coupled with an altered distribution or abundance; or (3) extinction (Holt, 1990, p. 311). Numerous studies have addressed each of these possible responses, and particularly relevant studies will be included in the following section which has been divided into three segments corresponding to Holt's framework – movement, evolution and extinction. The importance of understanding the methods by which plant species respond to change is twofold: first, understanding the processes which encourage species range shifting will improve modelling efforts; and second, being able to project how plants are likely to respond to change will increase the effectiveness of proactive management actions in protected areas. These actions will be especially important for those species that are already under stress (Halpin, 1997; Leemans & Eickhout, 2004; Scott, Malcolm & Lemieux, 2002).

2.2.1 MOVEMENT

Climate has long been observed as closely correlated with species distribution (Holdridge, 1947). More recent studies have also observed that as climate is changing, many species are keeping pace with this change and have adjusted the geographical range they inhabit accordingly (Chapin, Shaver, Giblin, Nadelhoffer & Laundre, 1995; Hughes, 2000; Innes, 1991; Parmesan & Yohe, 2003; Root et al., 2003). Parmesan (2005) provides a valuable meta-study of papers that document changes already taking place within species' ranges in response to climate change. Other studies have sought to explain why these changes take place and to identify the underlying processes. Many, including the work of Bachelet et al. (2000), have identified that it is not only climate change, but alterations in disturbance cycles occurring as a result of climate change, that trigger the largest responses. This study explained that future plant species may shift in range as a response to altered fire cycles that result from decreased precipitation and increased temperatures. This interaction, it was stated, would likely lead to decreased tree growth in woodlands as frequent fires would kill slow-growing trees, to be replaced by faster growing grasses. In a subsequent study by Bachelet, Neilson, Lenihan and Drapek (2001), a Dynamic Global Vegetation Model was used to explain that shifts in vegetation distribution would be slow expansion processes which follow potentially very rapid decline, as a result of changes in climate and episodic disturbances. A number of past studies (Easterling et al., 2000; Inouye, 2000; Kirilenko, Belotelov & Bogatyrev, 2000; Parmesan, Root & Willig, 2000) support this observation, each of which uses empirical evidence to show that it is not changes in yearly climate means that influence vegetation distributions most; rather it is climate extremes that are associated with these changes.

Many scholars agree that what makes the understanding of potential future vegetation range shifts important is the realization that the time frame in which anthropogenic climate change is expected to occur will likely limit the adaptive response ability of most plant communities (Huntley, 2005; Thomas, 2005). Grinnell, as early as 1917, stated that the ecological niche of a species remains relatively stable over the course of time. Parmesan (2005) adds to this by stating, the response of most plants to changing environmental conditions, is to alter their range rather than change their ecological niche (Parmesan, 2005). This indicates that park managers should be first and foremost concerned that plant communities within protected areas are likely to move rather than adapt. The tendency towards movement is particularly important as species which need the most protection are likely to have the fewest competitive advantages in a changed climate and are therefore more likely to shift their range out of a protected area in order to remain within suitable climatic conditions (Parmesan, 2005).

Research examining how plant communities are likely to change in distribution cannot be viewed as simply projecting the movement of contemporary ecosystems. Ecosystems will not pick up and move with each constituent species progressing northward in unison with its contemporary neighbours (Lovejoy, 2005, p. 326). Instead, responses will vary between individual species, and between individuals within that species (Graham & Grimm, 1990; Overpeck, Webb & Webb, 1992). Authors writing on the topic stress that a vegetation community should not be perceived as anything more than a transient assemblage of plant species that are able to "tolerate the prevailing conditions" (West, 1961; Huntley, 1996). An immense variety of responses would require a likewise massive research effort in order to form projections about individual species' responses. Instead, researchers must limit their studies either to a concentration on already-threatened species or to grouping plants which share similar physiognomy, leaf habit and form, and photosynthetic characteristics into groups (referred to as Plant Functional Types – PFTs) in order to create generalized response projections (Foley, Levis, Prentice, Pollard & Thompson, 1998).

Keeping in mind that individual species respond to climate change, "migration" rates of 100 to 200 metres per year appears to be the maximum for many modern tree taxa (Betts & Shugart, 2005). The degree to which plants will need to disperse in order to respond to future anthropogenic climate change is not well known, but was estimated by Malcolm et al. (2005) to be above 1000 metres per year in many areas of North America. There is, however, a large degree of uncertainty both in projecting what climate changes are to be expected and also how individual species are going to respond (Huntley, 2005) thus making it possible that rates could be above or below this. Therefore, it is feasible that many species will not be able to keep pace with changes, and in cases where entire biomes are vulnerable, a decline in biodiversity is fairly certain (Kirilenko et al., 2000; Malcolm, Martin, Neilson & Garaci, 2005; Martin, 1996). Such a decline would most likely take the form of extinction of specialist species that are associated with the jeopardized biome (Huntley, 2005). It is also important to note that vegetation is not limited only by its biological ability to respond to change but also by extraneous factors, such as impermeable human land-use (Huntley, 2005).

The challenges created by the concurrence of climate change alongside increasing land-use demands is a concern that has been gaining attention since the early 1990s (Lovejoy & Hannah, 2005; Sanderson et al., 2002). Authors have recognized that not only is human land-use itself causing problems for dynamic plant response, it is also exacerbating challenges for plants to disperse effectively by limiting accessibility to potential habitats (Halpin, 1997; Malcolm, Martin, Neilson & Garaci, 2005; Martin, 1996). Important decisions face conservation planners concerning how to manage landscapes in order to allow natural range shifts to occur and how best to incorporate highly fragmented landscapes into these plans (Hannah & Hansen, 2005). If management attempts are not successful and plant species are not able to migrate properly, either because climate change is too rapid or human interference too great, then biological diversity, whether at the species or individual level will continue to be lost (Thomas, 2005). By developing a plausible estimation of which future distributions may take place, it is the intention of researchers to provide a source of information concerning likely distribution shifts, which will subsequently aid in developing park system plans that incorporate vegetation response into management decisions.

2.2.2 ADAPTATION

Simultaneous to range shifting, evolutionary adaptations within plant species will play a secondary role in plant response (Huntley, 2005). These adaptations[1] will range from pre-existing resiliency which has developed as an inherent safeguard against extreme weather, to phenological change within individuals, including seasonal timing of leaf development, flowering and leaf drop, to true adaptation resulting from the recombination of genes (Root & Hughes, 2005; Thomas, 2005). The development of new genetic traits is unlikely to be a significant response given the rapid climate change projected to occur and the tendency for such adaptations to take place only during persistent conditions (Huntley, 2005).

Huntley’s view is supported by many works which state that for the most part ecological niche will remain constant; instead the primary reaction of plants to climate change

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[1] Adaptation in this section refers to the natural adaptation of organisms to changing conditions, as opposed to management adaptation mentioned earlier which refers to response strategies that can be taken to address to climate change

will be niche tracking – changing location to stay within the same set of prevailing conditions (Holt & Gaines, 1992; Holt & Gomulkiewicz, 1997; Peterson, 2003). Paleological evidence also has provided many instances in which niche tracking is observed due to insufficient time for adaptive or genetic responses to take place (Rousseau, 1997). To elaborate on this point, Rousseau argues that in the past, genetic response to rapid changes has been limited to *micro-evolution*, the process in which recombination of the species' genetic material takes place, limiting the adaptive response to the envelope of environmental conditions in which the species' genetic diversity already enables it to adapt (Rousseau, 1997).

Resiliency, plasticity and phenological change all hamper the necessity, and thus the likelihood, of genetic adaptation. Plants that demonstrate high levels of *plastic response* to environmental changes are able to put themselves closer to the ideal in terms of natural selection, and thus without changing any genetic adaptation are able to pass along their genetic traits (Price et al., 2003). This likewise eliminates the necessity for genetic change in order to survive and persist in new environments. Many seasonal botanic phenomena; for example, flowering, leaf development and leaf drop, rely on accumulated temperature-days and thus are able to respond to rapid climate change by advancing or postponing these events (Penuelas & Filella, 2001). As temperatures increase, flowering and leaf development will occur earlier in the spring and similarly leaf drop will take place later in the autumn in order to take the greatest advantage from changing conditions (Root & Hughes, 2005). In the mid-to-high northern latitudes climate change is likely to take place faster than in other locations and is also likely to be more pronounced as snow-free periods become lengthened, allowing a longer growing season. In this situation of pronounced change, plastic responses and resiliency will be more important as genetic adaptation is generally limited to persistent conditions (Huntley, 2005).

Faster adaptive responses, for instance plastic and phenotypic change, in combination with micro-evolution, will occur as future climate changes take place. The temporal scale of climate change, however, will likely be significantly shorter than the rate at which genetic adaptation (the creation of unique genotypes through the process of mutation) will operate, thus limiting its effectiveness as an adaptive response (Hewitt & Nichols, 2005; Holling, 2001). If this theory is correct and natural adaptation to conditions is effectively limited to recombining pre-existing capabilities, then the three principal responses of vegetation communities will be limited to two: movement or extinction (Thomas, 2005). Resilient and dispersive genotypes will prosper at both the individual and species levels (Hewitt & Nichols, 2005).

Given that there will be little opportunity for genetic adaptive response of plants to climate change, the importance of maintaining a wide variety of existing variation will make projected changes easier to endure. For this reason large, connected, protected areas will be important to providing grounds on which existing genetic variation can flow between individuals to allow recombination of genotypes. Isolated populations are prevented from diversifying as they are limited to a smaller degree of initial variation and the inability to acquire more from adjacent populations (Markgraf & McGlone, 2005). Premoli et al., (2001) follow on this note, stating that in past climate changes species confined to small populations have been more prone to random extinction from such causes as fire and disease, and to go through "cycles of extreme abundance and contraction, purging them of variation though allele losses during contractive phases" (Markgraf & McGlone, 2005, p. 158).

While genetic adaptation is not likely to be the *primary* response of plant species to climate change, current literature emphasizes that this does not imply that climate change will not have genetic repercussions on plant communities. Overall, a loss of genetic variation both between and within species is expected (Descimon, Zimmerman, Cosson, Barascud & Nève, 2001). Hewitt (1999) argues that within their current range, most species have a zone where their glacial and interglacial distributions overlap and that zone is located at the lower-latitude extents of their current range. Should this prove to be true, as temperatures begin to rise the areas which have the greatest genetic diversity would be lost as the zone of overlap recedes, and expansion into the higher latitudes would include only those subspecies predisposed to dispersion (Thomas, 2005). For those populations which remain stationary, changing abiotic factors such as altered temperature, precipitation, and disturbance cycles – as well as biotic factors, for instance altered community compositions and competition, will likely result in an evolutionary response (Thomas, 2005).

Due to the individualistic nature of response to climate change, there very likely will be disparities between the successes of different species in responding. In general, species with expansive ranges, high climatic tolerances, and a predisposition towards dispersal appear more likely to be successful. This gives rise to the projection that "climate change has [the] potential to lead to a ‘weedier’ future dominated by fast moving and climatically tolerant species,” leaving slow moving specialists in a position of apparent risk (Malcolm, Markham, Neilson & Garaci, 2005, p. 253).

2.2.3 EXTINCTION

By definition, a species that fails to disperse or adapt to changing conditions, will “find itself outside of the conditions that constitute its niche, and extinction [will] occur” (Peterson et al., 2005, p. 211). Likewise, in the instance that an entire biome becomes threatened in a region, for example if warming leads to a replacement of tundra by boreal forest, then the extinction of specialist species associated with that biome will likely face extinction (Huntley, 2005). By extension of this statement, developing projections of likely vegetation distribution change will allow for anticipatory planning on the part of park managers – an increasingly important aspect of planning as the global climate continues to change (Scott et al., 2002).

The danger of extinction is magnified during periods of rapid climate change when species are simply unable adapt to new circumstances and even find themselves unable to dynamically adjust their ranges to track climate change. During periods of rapid, large-scale climatic change in Earth’s history, substantial extinction events have been observed in fossil pollen data (Parmesan, 2005). It is theorized that those extinctions stemmed from the inability of some species to match the rate of change with a similar rate of response. A simple relationship formula has been derived from the observation of such extinction events: if the required rate of dispersion is greater than the rate achieved, biodiversity will be lost due to population constrictions, extirpation and possibly extinction for slow responding species (Huntley, 2005; Martin, 1996; Webb, 1997).

While the risk to species possessing slow response rates is evident, current research emphasizes that observations of past changes alone will underestimate these risks. The literature has reached a consensus on at least two factors which make the risks posed by modern climate change more severe than in the past; the first, discussed in detail under Section 2.1, is that climate change is projected to exceed the envelope of natural climatic variability (Overpeck et al., 2002). The second factor is the degree to which humans have altered their surroundings (Lovejoy & Hannah, 2005; Peters & Darling, 1985). The stresses created by human population growth and corresponding environmental degradation destroys suitable habitats, limits access to others, and decimates species populations (Martin, 1996). It is for this reason that the extent of habitat fragmentation should be considered when examining the impacts of climate change; (McCarty, 2001). Numerous authors have incorporated this concern into their research, and the resounding conclusion is that population growth, (Markham, 1996) habitat fragmentation, (Halpin, 1997) and impermeability of developed landscapes (Collingham & Huntley, 2000; Hill et al., 2001) have hampered the ability of many vegetation species to respond to climate change today and will extrinsically challenge future responses to climatic changes.

Global climate change is expected to be one of the most significant threats facing protected areas and is projected to display the largest change in the Northern latitudes (Hannah, Lovejoy & Schneider, 2005). Since the late 1980s authors have shown concern over these changes and the impacts that might follow. Many authors have stressed that the geographically-isolated protected areas of both Canada and the United States are in particular danger and may be unable to preserve the ecological communities they are charged to protect (Peters & Darling, 1985; Graham, 1988; Halpin, 1997; Peters & Lovejoy, 1992; Scott & Lemieux, 2005; Scott et al., 2002). Thomas (2005) notes that many population-level extinctions and receding species ranges have occurred at the southern portions of past distributions. Subsequently, the effectiveness of current management park goals and management objectives should to be reassessed with climate change impacts as a central focus to this re-examination. Thomas (2005) also notes that climate change is likely to prove even more threatening than habitat loss, not to mention that the two stressors will be affecting protected areas concurrently. Given the uncertain and potentially devastating impacts that global climate change presents, it will become increasingly important to take these changes into account when managing protected area systems. In order to assure that our protected areas are managed to their greatest effectiveness it is necessary to better understand the ecological impacts that can be expected to accompany climate change, along with the capability of current conservation systems to adjust to these impacts (Scott & Lemieux, 2005; Scott et al., 2002).

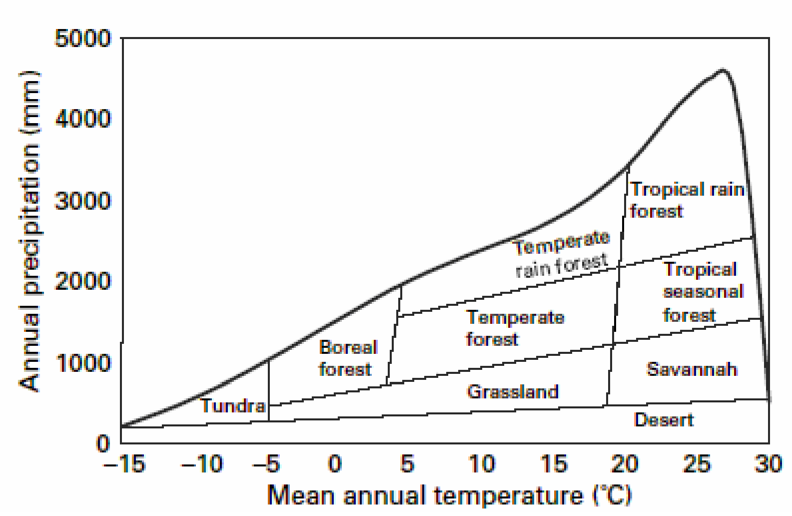
2.3 VEGETATION MODELLING

Climate change is expected to have dramatic results on the vegetation of North America. The majority of researchers agree that North America as with other northern continental areas worldwide, is likely to face the largest impacts. Plant communities are expected to display a variety of responses ranging from shifting distribution to facing extinction. Biogeography models are necessary in order to project the potential impacts of future climate change on natural vegetation distributions (Peng, 2000). Efforts to produce such models have been taking place since at least 1947 when the Holdridge Life Zone Model was developed. This popular correlative model is still in use today but has limited predictive ability compared to modern mechanistic models which incorporate vegetative processes in the projection of future plant function type (PFT) distributions. Currently, models are continuing to grow in size and complexity due to increases in information availability, computational power, and improved knowledge of vegetation responses based on field research. Consequently, the accuracy to which these models can describe vegetation dynamics also continues to grow, increasing their predictive value to future conservation efforts.

2.3.1 VEGETATION DISTRIBUTION MODELLING

Early distribution modelling was limited to making correlational observations between present distributions and climatic conditions. Using this information, environmental envelopes were developed which detailed the environmental conditions in which a species was able to successfully maintain a viable population. Holdridge (1947) utilized these observations in order to project what vegetation types would be dominant under a prescribed set of environmental conditions (shown in **Figure 2.5**). Further progress was made when Emanuel, Shugart and Stevenson (1985) first used correlational models to project how climate change would affect future vegetation distributions. The most evident limitation of these earlier models is the exclusion of biological processes or underlying dynamics (Woodward & Lomas, 2004).

FIGURE 2.5 – Climatic Envelopes of Global Vegetation Types



Adapted from: Woodward & Lomas, 2004

Due to this omission, it is impossible to answer questions concerning the rate at which these changes might occur, or regarding successional changes (e.g. would a temperate rainforest expected to become grassland make the transition in one swift, unlikely change, or would it be a gradual process?). Additionally, this type of model is exceedingly subjective in its biome classification (Yates, Kittel & Cannon, 2000) and is predicated on climate means determining vegetation distribution, when there is strong evidence which shows that it is climate *extremes* that have the largest influence over vegetation dynamics (Kirilenko et al., 2000).

Box (1981) improved upon the correlational framework by introducing plant functional types which organized species into groups based on physiognomic, morphological, and climate response traits. However, this model still relies on correlation climate envelopes to determine responses for each PFT.

The rule-based biome model (RBBM) from Neilson, King and Koerper (1992) began a new trend in vegetation modelling: the process-based or mechanistic model. This model was composed of a number of "If-Then-Else" rules which used climate and vegetation characteristics to develop a primitive mechanistic approach to vegetation modelling. What followed after a series of step-wise improvements was an equilibrium biogeography model named the Ecophysiological-based Biome Model (BIOME), developed by Prentice et al.

(1992). This model eliminated many of the past constrictions which limited early vegetation modelling. The climatic envelopes which prescribed the maximum boundaries of PFTs were now based on phenomenological constraints rather than on correlative observations. Biomes were no longer considered a single entity and allowed individualistic responses of PFTs whose relative dominance determined the biome present in any location; factors such as growing degree days, annual accumulated temperature, plant height and moisture availability were included in interactions between plant types (Peng, 2000).

Equilibrium biogeography models (EBM) underwent many transformations; BIOME was replaced by BIOME3 (Haxeltine & Prentice, 1996) and other biogeography models such as MAPSS (Neilson, 1995) and DOLY (Woodward & Smith, 1994) also were developed. This generation of models included complex processes represented in the form of ecophysiological rules such as: canopy densities; maximum leaf areas; energy, nutrient, and water constraints, and introduced rudimentary disturbance models (Yates et al., 2000). Two significant limitations, however, still remained with the introduction of equilibrium biogeography models. First, they were unable to replicate the *time course* of vegetation changes. Instead, a new climate state was defined, (e.g. the climatic conditions that are projected to follow a doubling of atmospheric CO_2) and the future *potential* natural land cover was determined after the vegetation ceased to respond to this change, having reached equilibrium with the new climatic conditions. This process gives no indication about how responses are likely to take place, instead providing only a *snapshot* of future distributions (Neilson et al., 1998). The second most often cited limitation of EBMs is the need for inclusion of more processes, particularly the feedback of biogeochemical processes, growth, competition, and mortality (Neilson & Running, 1996).

2.3.2 DYNAMIC VEGETATION MODELS

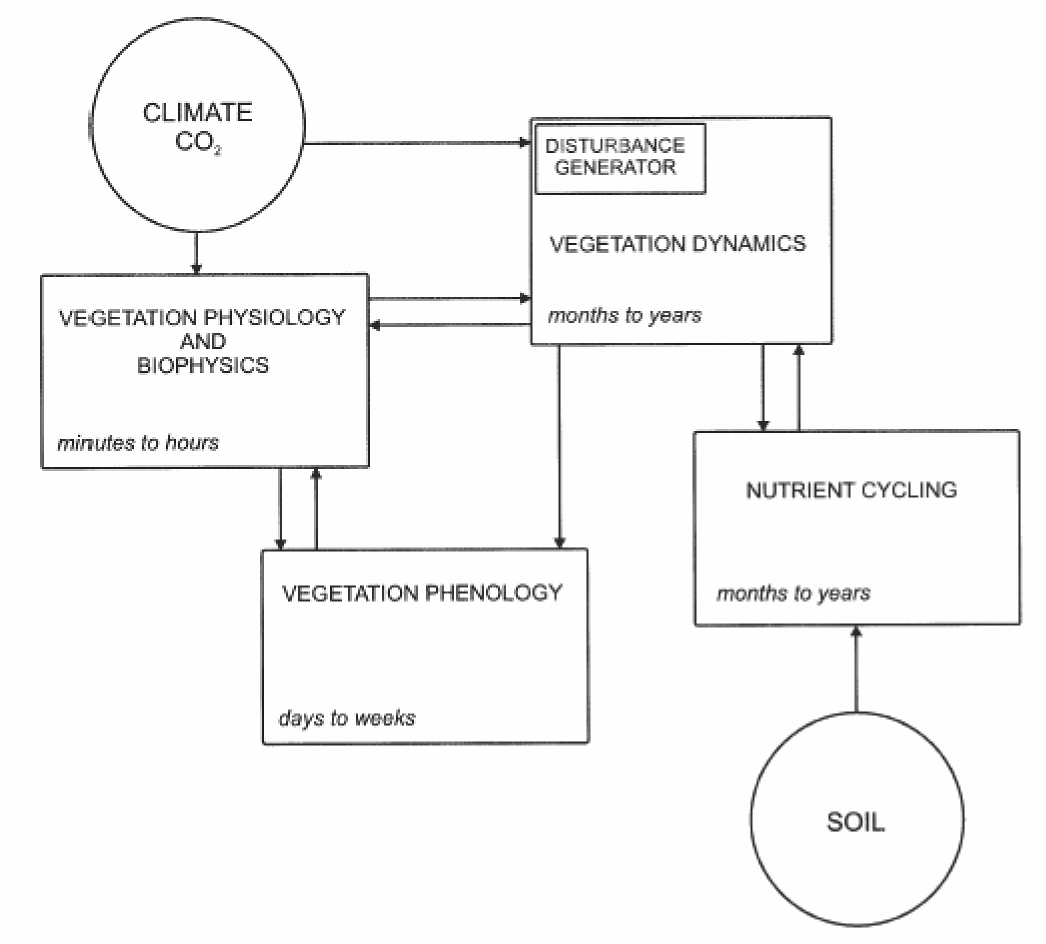
The problems associated with equilibrium biogeography models spurred the development of the most recent generation of vegetation models, dynamic global vegetation models (DGVM). Cramer and colleagues (2001) simulated global vegetation responses to a climate change scenario using six DGVMs and concluded that these models were able to simulate many of the processes which the previous EBMs could not. DGVMs also operate in a time-dependent manner, which allows for the observation of transient responses to change (Betts & Shugart, 2005).

In order to produce vegetation response simulations, DGVMs first require a map detailing initial vegetation to be used. This usually is acquired using one of two methods: a pre-existing potential vegetation map may be used to represent initial distribution or, more commonly, it can be constructed using the model. The latter process is referred to as *spin-up* which involves generating a vegetation map using observed climate data and soil information in order to produce an initial map where vegetation is in equilibrium with present conditions (Daly et al., 2000). In some, but not all, DGVMs another spin-up period is required in order to establish realistic disturbance cycles. This is necessary as the dynamic patterns of these disturbances do not lend themselves to equilibrium-constrained modelling which is used to create the initial vegetation map (Bachelet et al., 2000).

After the initial spin-up period where equilibrium distributions are established a DGVM is then switched to a transient mode where the future climate conditions can be inputted. This information is often acquired by coupling a DGVM with a general circulation model (GCM) which provides projections of future climatic conditions (Foley et al., 1998). Employing projected climate information, it is then possible to observe transient responses of vegetation distributions along a regular set of 'time-slices' (often 1- year periods, but varying from hours to decades). This ability is one of the key features which distinguishes the outputs of DGVMs, which allow for the observation of transient responses to changing conditions and temporal estimations of responses, as opposed to the snapshots provided by equilibrium-constrained models (Betts & Shugart, 2005). The responses that are being observed in each time slice are the fractional changes of PFTs in each individual cell.

The processes responsible for determining the responses of individual PFTs and the time steps at which they operate vary greatly among individual models. Cramer and colleagues (2001) compare the structure of six DGVMs and have generated a generalized diagram detailing the modular components included in most models and time steps which are commonly associated with them (See **Figure 2.6**).

FIGURE 2.6 – Structure of a Generic DGVM



Source: Cramer et al., 2001, p. 359

By coupling a DGVM to a General Circulation Model which provides dynamic climate inputs, it has become feasible to model the transient vegetation responses within each of these modules to changing climatic conditions and atmospheric compositions (Foley et al., 1998).

The processes modelling vegetation physiology and biophysics operate on the smallest time scale. The Integrated Biosphere Simulator (IBIS) DGVM uses climatic variables such as temperature, precipitation, humidity, and sunshine hours in order to simulate changes in photosynthesis, respiration, stomatal behaviour, and nutrient and water balances using thirty-minute time steps (Foley et al., 1998). This module is critical to the process of mechanistically modelling dynamic responses of vegetation as changes observed at these time scales serve as input variables to other modules with the DGVM. The uptake of carbon in photosynthesis, the release of carbon in respiration, and water cycling involved in photosynthesis and transpiration help to determine the primary productivity, competition and carbon used for growth in the vegetation dynamics (Betts & Shugart, 2005). Vegetation phenology is also influenced by the responses of vegetation physiology. Growing-degree days, light and water availability, as well as photosynthesis, act as controls on plant phenological changes such as budburst, senescence and dormancy (Foley et al., 1998).

Moving in scale from minutes-and-hours to days-and-weeks, the phenological changes of plant functional type represent the stages of growth which are strongly tied to bioclimatic factors. The timing of phenological changes is largely dependent on accumulated temperature, productivity and photoperiod and to a lesser degree, moisture availability (Penuelas & Filella, 2001). DGVMs incorporate these changes in order to model the growth cycle responses of individual PFTs not only to changing conditions which occur in the vegetation physiology module, but also to changes occurring in vegetation dynamics within each cell. Vegetation structure, resource allocation and the growth of stems, leaves and roots influence how plants will adjust the timing of growth events according to changing conditions (Foley et al., 1998). Vegetation phenology will influence the daily biophysics of plant function types differently. Phenological responses play a large role in determining the Leaf Area Index (LAI) of each PFT, as each will have different leaf characteristics, thermal thresholds, and therefore different phenological responses to ambient climate conditions (Bachelet, Neilson et al., 2001). As LAI is influenced by phenological responses, so too are many plant physiological variables, such as photosynthesis, leaf respiration and stomatal conductance.

Vegetation dynamics represent the vegetation processes which take place over longer periods, from months to years. Data from individual PFT physiology concerning daily gross photosynthesis and respiration, as well as climate and nutrient information are all utilized in order to project larger scale vegetation dynamics. The vegetation dynamics module simulates processes of competition, natural disturbance – such as fire and general mortality – and succession. Because individual species are not included in the model, succession represents the transition from one plant functional type to another (Bonan, Levis, Sitch, Vertenstein & Oleson, 2003), usually following some sort of disturbance or long term change in climate trends (Foley et al., 1998). Of key importance in this module is the disturbance created by fire. This phenomenon has large impacts on modelling outputs (Bachelet, Neilson et al., 2001; Betts

& Shugart, 2005) and has been criticized as being oversimplified for the importance it plays in determining vegetation dynamics (Steffen, Cramer, Plochl, Bugmann, 1996; Peng, 2000). After competition, disturbance and succession have been simulated, the new values for PFT dominance, plant height, soil carbon and plant carbon will alter processes encompassed within the vegetation physiology module (Foley et al., 1998; Cramer et al., 2001).

The last component commonly included in DGVMs is one that simulates nutrient cycling. The PFTs which occupy a site provide the inputs to this module. Plants are assumed to accumulate biomass in the form of growth, but a portion of that accumulation is assumed to be dropped to the soil in the form of leaf litter. Additionally, as plants die from disturbances, bouts of extreme weather and senescence, above ground biomass continues to accumulate (Bonan et al., 2003). Within the module, leaf litter and other accumulated biomass are involved in various nutrient cycling processes, including decomposition, soil respiration and nitrogen allocation. After cycling through these processes, nutrients become available within the soil and play a critical role in the plant biophysics and physiology modules as well as vegetation dynamics. These modules use new values of nutrient availability in order to determine growth rates and competition between plant functional types over limited resources (Bonan et al., 2003).

2.3.3 ASSESSMENT OF DYNAMIC GLOBAL VEGETATION MODELS

Woodward and Lomas (2004) argue that the best method of modelling vegetation distributions is to develop models of the processes responsible for those distributions, rather than of the distributions themselves. This supposition leaves dynamic global vegetation models as the most ideal method of vegetation modelling due to a number of strengths unmatched by previous models. DGVMs address the major processes in vegetation response which have either been ignored or accounted for through correlation in the past (Woodward & Lomas, 2004).

The single most important feature which distinguishes DGVMs from their precursors is the removal of equilibrium constraints (Steffen et al., 1996). By combining equilibrium global vegetation models with smaller-scale ecosystem modules which simulate the reactions of plants to changing climate inputs it is possible to model the transient responses of plants to changing climatic conditions (Peng, 2000). This ability to track plant responses in regular time-steps removes many questions which plagued equilibrium models; for example, will the transition between one dominant plant structure to another be a gradual transition or quite sudden? As Neilson et al. (1998) note, it is only possible to make inferential estimations about how the biosphere will shift from one condition to another. The inclusion of time-steps also allows for detailed, mechanistic simulation of processes which were left to parameterized approximations in the past. The importance of this progression is that in the case of altered disturbance cycles, it may be impossible for vegetation to reach its potential land cover, and instead "be 'locked into' a different state (particularly early successional states)" (Steffen et al., 1996, p. 327).

Process modelling improvements of DGVMs over equilibrium/static biogeography models come in two broad classes: plant physiological processes and plant relationship processes. As equilibrium-constrained models provide only a snapshot of the future, processes involved within modelled plants must be parameterized; alternatively, transient vegetation models allow for plant growth processes like photosynthesis, respiration, and transpiration to be explicitly incorporated into the modelling process. Similarly, changes in plant phenology, i.e. bud-burst, leaf burst, and leaf drop, are also included as explicit, dynamic processes (Bachelet, Neilson et al., 2001).

Bonan et al. (2003) emphasize that the importance of including plant growth, and respiration in vegetation models as carbon assimilation associated with this growth will play an important role in determining the feedback of vegetation dynamics on the global atmosphere. This assertion agrees with a study conducted by Foley et al., (1998) who concluded that vegetation has significant feedback (with a 95% confidence level) not only on global atmospheric composition, but also on global temperatures and precipitation levels. Both works stress that increased understanding of the role of vegetation-climate feedback will be important to the production of accurate simulations of future potential vegetation distributions – a conclusion which further exemplifies the advantages of transient vegetation models over their predecessors.

The second broad class of processes which distinguish dynamic vegetation models from their predecessors concerns plant relationship rules. These processes focus on how plants from different PFTs interact with one another in response to their environment. This class includes such processes as competition over resources, successional growth, responses to disturbances such as fire, and rates of dispersion. These processes are especially important in transitional areas such as savannah, where the ratio of trees to grass will depend largely on climatic and disturbance events (Daly et al., 2000), and in other ecotonal areas where even small climatic variations could alter the dominant plant functional type at a particular location (Bachelet et al., 2000).

Being able to simulate vegetation processes mechanistically and produce more sophisticated simulations of eventual distributions are not the only strengths which DGVMs possess that could potentially prove useful in conservation policy development. By projecting changes within a definite time-frame it becomes more feasible to use these in a management or decision-making context. Past studies have noted that vegetation responses to climate change lag considerably behind the climate changes themselves, often taking centuries in order to equilibrate to a novel set of climatic conditions (MacDonald, Edwards, Moser, Peinitz & Smol, 1993; Cramer et al., 2001). This lag-time limits the usefulness of equilibrium vegetation models, and highlights the ability of DGVMs to simulate vegetation responses in time frames which could be more appropriate for protected area management, (i.e. yearly to decadal simulations).

While dynamic vegetation models possess many strengths which set them apart from past modelling efforts, they share in common with equilibrium models one significant limitation. Mechanistic models, dynamic or otherwise, entail an enormous degree of complexity in order to model small-scale physiological processes. This level of complexity leads to three main obstacles: one is the large demand for computational resources required for running the models, the second is the necessity of grouping species into simplified functional types, and the third is poor spatial and/or temporal resolution. These drawbacks will continue to diminish as computational power increases, however, allowing the inclusion of more specific PFTs, better resolution, and more accessibility (Woodward & Lomas, 2004; Betts & Shugart, 2005). There have also been numerous remarks concerning the simplistic representation of natural disturbances, in particular fire and human disturbance (Steffen et al., 1996; Foley et al., 1998; Peng, 2000; Betts & Shugart, 2005). In recognition of this limitation many studies incorporate improved fire disturbance models (Bachelet et al., 2000; Bachelet, Neilson et al., 2001; Daly et al., 2000; Woodward & Lomas, 2004), while most have chosen to exclude human disturbance and land-use modelling.

Possibly the largest caveat that accompanies vegetation modelling on a continental scale is the ubiquitous influence that human beings have on their environment. It is impossible to predict how humans are going to act in the future. This leads to difficulties starting with developing emissions scenarios and climate modelling (IPCC, 2000), to land-use changes and vegetation modelling (Peng, 2000). For this reason, most works suggest that modelling outputs should not be taken as *predictions*, but rather as *projections* of a range of potential, plausible outcomes (Bachelet et al., 2000; Scott et al., 2002; Raper & Giorgi, 2005; IPCC 2007). In order to compensate for the uncertainty that is inherent within climate and vegetation modelling, a general consensus has been reached that the most appropriate action to manage this uncertainty is to integrate simulations from numerous models in order to produce a multi-model ensemble (IPCC, 2007; Raper & Giorgi, 2005). The Inter-Governmental Panel on Climate Change explains that no model can be chosen as the *best* model from a group that are all considered plausible. Rather, the projections realized by each model should be compared in order to identify features which are common to most, if not all, models (IPCC, 2007). By examining similar features from multiple models by way of a multi-model ensemble, better estimations of future responses can be developed by reducing the amount of "noise" created by natural variability, simulation forcings, and varying process representations between models (Raper & Giorgi, 2005).

2.3.4 VALIDATION OF DYNAMIC MODEL PROJECTIONS

Due to the large degree of uncertainty that is incorporated into modelling vegetation response to future climate change, attention must be turned to the efforts that have been undertaken in order to validate model projections. While validation of any model is critical, Peterson and colleagues maintain that "compared to the effort expended in *building* biogeography models, relatively little effort has been put into *validating or verifying* results derived from them." (2005, p. 220, my emphasis) This lack of effort has been prompted by three significant difficulties: the lack of data at appropriate time scales, uncertainty surrounding the effects of human activity, and the long time-scale involved in vegetation dynamics (Steffen et al., 1996). In spite of the perceived lack of attention that has been extended to verifying model projections, numerous attempts can be found within the existing literature.

These efforts focus on four primary methods. The first is comparing simulations of global PFT distributions to modern, observed distributions. Ideally, if dynamic vegetation models are able to produce a vegetation distribution, using contemporary climate information, that resembles biogeographical distributions observed from remote sensing platforms, then it would follow that the processes being modelled have been captured satisfactorily and that the models' outputs adequately represent real-world processes. Assuming, then, that the processes used in producing the contemporary distribution remain the same, it can therefore be more easily believed that projections of future distributions will also hold true (Steffen et al., 1996; Foley et al., 1998; Cramer et al., 2001; Bonan et al., 2003; Woodward & Lomas, 2004).

The next most common method focuses on small-scale processes rather than on large-scale distributions; by comparing simulated processes such as leaf gas exchange and net primary productivity, it can be argued that if small-scale processes are suitably captured then they will also hold true when applied at a global scale (Steffen et al., 1996; Beerling, Woodward, Lomas & Jenkins, 1997; Foley et al., 1998; Peng, 2000; Bachelet, Neilson et al., 2001; Woodward & Lomas, 2004).

Thirdly, Prentice and Webb (1998) have argued that because vegetation models have been tuned into the climate that is prevalent at the time of development it is necessary to test whether their results are robust to climatic change. Since the future climate is unavailable for observation, this only leaves the past. Thus, in order to confidently say that a model will be able to successfully simulate vegetation dynamics in the future, it should be able to reasonably simulate vegetation dynamics of the past (Prentice and Webb, 1998). In order to test models using this method, simulations of past vegetation distributions are compared against paleological pollen records to note similarities and differences.

Finally, it has also been suggested that large-scale global vegetation models can be tested for plausibility by comparing their projections to models which operate at a smaller scale (Steffen et al., 1996). The authors stress that this, indeed, would not be true *validation* but rather *agreement* between a "bottom-up" patch model specifically developed for a particular area and "top-down" DGVMs. The dynamics projected by a patch model would serve to increase confidence levels in the performance of the DGVM. By necessity, patch models used to compare DGVM projections must be excluded from the patch module of the DGVM if the intention is to provide any sort of verification or assurance. While Steffen et al. (1996) suggest that this practice would be useful, no references are made to studies which have conducted such comparisons.

2.4 PROTECTED AREA MANAGEMENT IN AN ERA OF CLIMATE CHANGE

Parks and protected areas serve to protect fundamental biological integrity and diversity within North American ecosystems. Bruner, Gullison, Rice and Fonseca (2001) contend that beyond providing this basic service, protected areas are the most effective and most important conservation strategy in use today. However, most parks have been designed with an underlying assumption of climatic and biogeographical permanence (Scott, 2005) and face an uncertain future in the face of global climate change. Efforts should be taken to incorporate projected climate change impacts into protected area management and to prepare appropriate responses to assist in mitigating them.

2.4.1 CLIMATE CHANGE IMPACTS ON PROTECTED AREAS

Martin (1996) was among the first researchers to simulate the biodiversity impacts that might be expected to follow greenhouse-induced climatic changes. In order to produce a preliminary estimation of future biodiversity, Martin (1996) employed the Ecological Module version 1.0 with the Woodward-Rochefort biodiversity index and five equilibrium based General Circulation Models including GFDL, GFDLQ, GISS, the Oregon State University (OSU) GCM and the UKMO GCM. The results from this simulation were used to compare areas of “no change” or a “decrease” in biodiversity based on the assumption that if a change in vegetation coverage occurs, biomes will move too slowly across the landscape to track changing conditions. The simulation projected that within World Heritage Sites, under a doubling of CO_2 levels, many are expected to experience a reduction in biodiversity within 50 years (GFDL 46%; GFDLQ 17%; GISS 47%; OSU 48%; UKMO 54% - with a median of 47%). Martin concluded that there is relative agreement between all models and it is unlikely that reserves will be able to protect biodiversity from climate change. Instead, reserves should only be viewed as a safeguard from short term destruction caused by habitat destruction on the part of humans.

Leemans and Eickhout (2004) conducted a similar simulation concerning global biodiversity. In this study, distributional shifts of ecosystems were examined in order to locate positive, neutral, and negative shifts based on the new carbon storage capacity of an ecosystem compared to its original capacity. The authors utilized IPCC-SRES scenarios to drive IMAGE, an integrated assessment model used in combination with BIOME, in order to simulate current ecosystem distribution and projected future distributions based on three Global Mean Temperature Increases (GMTI), +1 to +3°C over 100 years. Their results indicate that even small increases in global temperature will lead to pronounced ecosystem impacts. The highest magnitude of change was observed in tundra, wooded tundra and cool conifer forests, where high latitude is correlated with magnified climatic change. The authors also note that because protected areas are distributed throughout sensitive and exposed biomes they are likely to face the most accentuated impacts, even without taking into consideration the fragmented nature of many protected areas.

In 1997 Parks Canada officially acknowledged climate change as a significant threat and growing concern in the *State of the Parks Report*. Using a survey sent to each of the national parks within Canada (36 at the time) expert panels reported stressors which were significant to each individual park. Before being considered a significant threat three conditions had to have occurred: i) the stress had to be causing ecological impacts, ii) impacts occurred on a spatial scale greater than 1 square kilometre, and iii) impacts had to be stable or increasing. Seven parks answered that climate change was already having significant, observable impacts.

In recognition of the growing threat posed by climate change on Canadian parks, a screening level assessment of projected climate change impacts on Canadian national parks was conducted by Scott and Suffling (2000). Using one equilibrium (CCCma GCM II) and three transient GCMs (GFDL; GISS; CGCM I) seasonal temperature and precipitation change profiles were developed for each national park. A checklist was also developed containing biophysical and socioeconomic variables that would likely be influenced by climate change. Using the checklist as a guideline, each park was reviewed to examine resource inventories, management plans and existing regional and climate change research in order to determine which impacts could affect parks most dramatically. The authors noted that numerous problems were likely to be associated with climate change in every region of Canada, from glacier and permafrost retreat, rising sea levels and altered hydrology to disturbed habitats, exotic species invasions, vegetation change and loss, as well as altered fire, storm, and pest disturbance cycles. Scott and Suffling (2000) concluded that numerous steps could be taken in order to mitigate these impacts. Suggested actions included a reassessment of the Parks Canada *National Park System Plan* as a whole, undertaking vulnerability analyses within individual parks, monitoring impacts, and increased collaboration and coordination between both agencies and countries.

Work concerning the impacts of climate change on Canadian protected areas was continued by Scott, Malcolm and Lemieux (2002). Employing two equilibrium-process based vegetation models (BIOME3 and MAPSS), three equilibrium doubled-CO_2 GCM scenarios (UKMO, GFDL-R30 and GISS) and two transient GCM scenarios, (HadCM2-ghg and MP1-T106) this study simulated the vegetation response expected to occur within Canada as a result of a doubling in atmospheric CO_2. Park boundaries were then superimposed on top of the altered vegetation distribution in order to produce an estimation of biome representation change within Canadian national parks. The study observed that in five of six scenarios, "a novel biome type appeared in more than half of the national parks and greater than 50% of all vegetation grid boxes changed biome type." (Scott et al., 2002, p. 478) The authors concluded that climate change is likely to present unprecedented challenges to Canadian parks and that a reassessment of existing policy and planning frameworks is called for. Additionally, further research should be conducted concerning not only the ability of ecosystems to adapt to change, but also "the capacity of conservation systems and agencies to adapt to climate change." (Scott et al., 2002, p. 475)

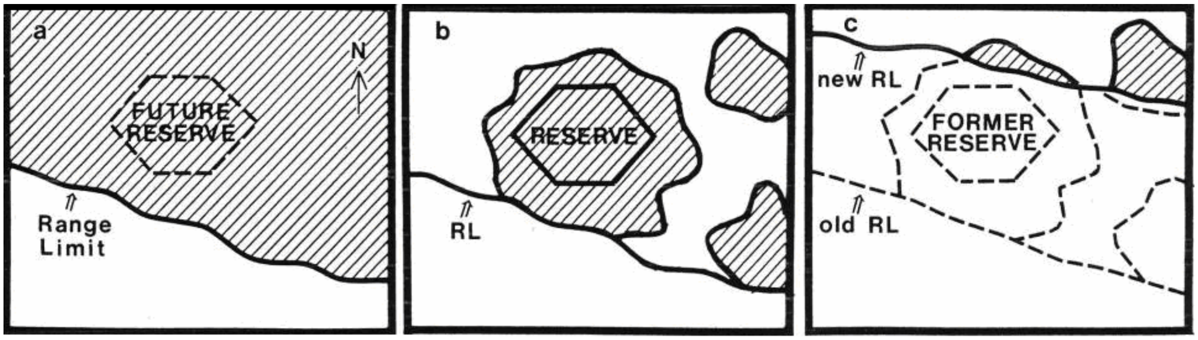
The impacts of vegetation distribution change within US national parks have received less attention in the literature compared to Canadian parks. The National Park Service (NPS) Management Policies (2006) acknowledge that climate change is occurring but provide no course of action for responding to these changes other than to suggest climatological monitoring in order to establish baseline conditions, and to state that no weather modification strategies will be adopted by the NPS in the attempt to mitigate climate change impacts.

A recent publication by the National Parks Conservation Association goes into more detail concerning the impacts that have been forecast to occur in American national parks. This report does not provide the level of detail that Scott and Suffling's (2000) report on Canadian parks does. However, it supplies a useful overview of climate-related impacts forecast to influence US national parks. It does so from a regional standpoint, identifying potential climate change-related impacts in the Appalachians, South Florida, Alaska, Pacific Coastal Mountains, and Historic Coastal regions. The report also lists a number of ways in which climate change impacts can be mitigated – or adapted to – referencing the importance for increased funding to protected areas, developing "climate friendly" parks, and the importance of inter-agency and authority cooperation.

2.4.2 MANAGEMENT RESPONSES

In a paper by Peters and Darling (1985), the authors indicate that the consequences of climate change would be greatest for species confined to protected areas. Peters and Darling argue that protected areas effectively become "islands" after having been isolated from other wilderness areas because of habitat fragmentation. **Figure 2.7** displays how the authors theorize that climate change, in combination with habitat fragmentation could transform current biological reserves into former reserves.

FIGURE 2.7 – How Climatic Warming May Deteriorate Reserves



Source: Peters & Darling, 1985

The authors point out first that as viable reserve sites within a particular species' range (diagram a) become isolated after human habitation causes fragmentation (diagram b) it will not be easy for colonization of new areas to occur and the once viable site may no longer lie within the species range limit – as represented by "RL" (diagram c). Peters and Darling show that the challenges which are believed to face future populations are both physiological stresses from living in a changed environment, as well as altered interspecific relationships, such as new competitors, invasive species, and the possibility of increased predation. They also predict that protected areas will increasingly function as islands – isolated from sources of genetic input, and left with the inability to colonize new habitats (1985, p. 709). Species thought by the authors to be most endangered by climate change are peripheral populations near the extent of their range limit, geographically localized species, small genetically impoverished populations, and poor dispersers. The corresponding suggestions for conservation efforts include more intensive management of disturbance cycles and invasive species, site selection which incorporates climate change, flexible zoning around protected areas, and a proactive approach to management. In the authors' view, if management efforts are delayed until impacts are observed it will be too late to mitigate them.

Many of the conclusions which Peters and Darling (1985) suggest in their work are supported by Graham's findings (1988). In this study paleological distributions of Pleistocene populations were compared with distributions observed in the present. After observing the range changes which occurred subsequent to climatic change Graham argued that while modern-day protected areas effectively function under island biogeography rules because of habitat fragmentation, this theory erroneously depends on the assumption of environmental stability. Protected area managers should recognize not only that climate conditions are unstable, but so too are current species assemblages. Species response to climate change will be individualistic and it is therefore necessary to ensure that they are able to respond to changing conditions by providing large, connected and heterogeneous habitats to support them. Graham also agrees with Peters and Darling (1985) in the speculation that marginal populations and those with limited connectivity will face genetic bottlenecks and possibly localized extinction. His work concludes with the novel suggestion that protected areas should be viewed as "merely holding stations for species through time" and that "their survival will be dependent upon mobility and dispersal" (Graham, 1988, p. 392). It is therefore imperative for protected areas management to include the possibility of climatic change and corresponding species distribution tracking.

In 1992, Peters built upon earlier work conducted with Darling (Peters & Darling, 1985) in order to further explain the management challenges and responses that would be necessary in the face of climatic change. He observed that protected area management would have many practical, but also many philosophical hurdles to consider. Should managers strive to protect all species within a reserve even if climate change will likely cause them to disappear? Should representativeness be a goal when species assemblages are transient? Also, should nature be left to run its course at the expense of possible extinctions? Peters stresses that regardless of the answers given to the preceding questions, it is recommended that climate change be given a high priority in park management, beginning with improvements in monitoring to better understand species response to climate change. This should be followed by the development of contingency plans that incorporate projected precipitation and temperature changes. Additionally, a partnership should ideally be forged between protected areas and surrounding management units as regional plans that transcend park boundaries will be important to ensuring connectivity and allowing dispersion. Lastly, more reserve lands should be created as each refuge provides additional chances for species and populations to successfully respond to changes, and existing lands should be expanded in order to mitigate the effects of human habitat fragmentation. If these precautions do not come to pass, Peters concludes that artificial translocation of species and other interventionist efforts may be the only way in which natural systems can keep up with climate change.

Halpin (1997) sympathizes with previous studies, agreeing that climate change in combination with habitat loss raises many questions about the vulnerability of protected areas. He stresses that future management will necessitate dynamic and flexible planning, beginning with casting off assumptions of static conditions that, despite past literature, are still prevalent. However, the author also moves on to say that the universal, generalized prescriptive measures that have been raised in the past, such as connective corridors, altitudinal heterogeneity, and redundancy have assumptive errors of their own. He argues that “While large, well-placed, well-managed, and interconnected nature-reserve systems are ideal solutions, such solutions may not be easily implemented in a world of diverse environmental situations and increasingly scarce resources” (p. 831). Halpin continues by explaining that as well as proper management, the location of protected areas is important, as polar areas are expected to be impacted 120-140% more heavily than the global average (p. 832). Halpin acknowledges potential vegetation-cover mapping, but advises against this method until dynamic models become available, as managers would require knowledge about what time frame changes would likely occur on. His work concludes by listing numerous areas of research that would assist park managers in adapting management plans to changing conditions.

Lovejoy's work (2005) echoes the sentiment that while current conservation efforts retain great value, they need to be thought out and reassessed in the context of climate change. This is especially true when habitat fragmentation limits the ability of species to respond naturally by adjusting their range to changing conditions. Conventional measures to preserve biodiversity – protected areas, corridors, landscape conservation, ecosystem management and others – will continue to play critical roles but to date most have operated on the assumption of a static world. "Ecosystems will not pick up and move like Birnham Wood with all constituent species in concert," (Lovejoy, 2005, p. 326) meaning that flexible management strategies need to be put into place for a changing and uncertain future. Lovejoy posits that institutional collaboration and coordination is necessary, as is a change in the scale of planning – from short term to longer terms of 50 to 100 years and from local to national and international scales. Additionally, a more active stance is necessary in management efforts, including a shift in disturbance management paradigms and active involvement within the matrix – the landscapes surrounding and in-between protected areas.

Critiques of current conservation efforts and their underlying assumptions of biogeographical and environmental stability have continued into the 21st century. Hannah et al. (2002) question contemporary conservation practices, arguing that present efforts may soon become obsolete as a consequence of climate change. They continue to stress the necessity of new, dynamic strategies which explicitly incorporate changing conditions. The authors refer to this new generation of strategies as Climate Change-Integrated Conservation Strategies (CCS). In order to be most effective CCS must be individualized to particular localities, and must include: regional biodiversity response modelling; systematic site selection of protected areas with explicit regard to climate change; management across regional landscapes; mechanisms to support cross-boundary management collaboration; and the provision of resources by those responsible for generating climate change to those who are most highly impacted. Through the incorporation of CCS the authors theorize that a natural response should be possible and a scenario of artificial species translocation, such as that mentioned by Peters (1992), or other such measures could be avoided.

Hannah and Hansen (2005) expand initial desires presented by Hannah et al. (2002) for new dynamic strategies to be included in a framework for developing Dynamic Landscape Conservation Plans (DLCP). Unlike past works which prescribe universal management goals such as habitat protection or species protection, Hannah and Hansen suggest the development of landscape-level targets which range from genetic intra-specific targets to entire ecosystem targets, such as facilitating migration. In order to most effectively meet these targets, fixed elements must be designed which safeguard areas projected to either remain within target range limits, or to assist with tracking responses of species to new conditions. Subsequent to this, the dynamic elements of a DLCP should be designed while putting extensive effort into considering connectivity and surrounding land uses. The authors state that conservation managers should work in cooperation with surrounding land management units in an effort to mitigate external land-use pressures. Lastly, in order to maximize the benefit of flexible management, it is suggested that regular monitoring efforts be put into effect to observe changes and that targets set in the DLCP be constantly updated to reflect these changes. These recommendations of Hannah and Hansen (2005) adhere closely to the rationale of other contemporary works that emphasize the importance of not viewing protected areas in isolation but rather as a part of the surrounding matrix of land uses.

Beyond park management, Fonseca, Sechrest and Oglethorpe (2005) argue that with just over 10 percent of the globe protected in some form of conservation area, management of the intervening matrix is essential. The authors re-emphasize the goal of establishing protected areas, ensuring connectivity, and minimizing land use stressors, thus echoing the position held by Hannah and Hansen (2005). Fonseca and colleagues (2005) however, delve into greater detail concerning management strategies that might be employed to limit these stressors. The authors specify that current practices of segregating natural and human landscapes are inappropriate in a management context; rather, partnerships should be created. These would not only integrate protected and non-protected areas, but would also entail cooperation between different levels of management and sectoral jurisdictions such as agriculture, water, energy and transport. This cooperation would extend both to planning and management efforts as many landscapes under management do not fall neatly into one management unit. Consequently, planning efforts should avoid technical desk studies in favour of stakeholder participation. The authors argue that management will also have to make a transition, from primarily regulatory measures to a mixture of regulatory and incentive-based options with two significant goals: to slow degradation of managed landscapes and to improve relinquished land that has been degraded. The shift to incentive-based alternatives is deemed necessary by the increased need for voluntary cooperation. The authors conclude that effective, flexible management will not be possible without accurate scenarios of future change and increased monitoring efforts, inside and outside park boundaries, to confirm expected impacts, identify unforeseen impacts, and to suggest refinements to current change projections.

A study by Scott (2005) introduces the philosophical and practical intricacies that are involved with incorporating climate change into existing park systems. Canada's *National Park System Plan*, (Parks Canada, 1997) like many other park systems such as the United States' National Park System (NPS, 2006), was developed with "assumptions of climatic and biogeographic stability" (Scott, 2005, p. 342). While Parks Canada recognizes that ecosystems are dynamic and that ecosystem changes must "occur within *acceptable limits*, [to ensure ecological integrity]" (Parks Canada, 1998, p. 24, their emphasis) the National Plan does little to clarify what changes will be deemed unacceptable, especially in the context of climate change that is likely to exceed the envelope of natural climatic variability of some regions (Overpeck et al., 2002). In response to this ambiguity Scott (2005) calls for a re-assessment of Parks Canada's management goals, especially in the context of climate change, and also suggests that in the meantime short- term responses should include improved park establishment criteria that incorporate climate change explicitly. In the long term, Parks Canada should consider its management philosophy – whether to continue protecting current ecological assemblages or to facilitate species responses to changing conditions, and which will best serve their mandate of ensuring ecological integrity. Further confounding the situation, as Scott points out, is the difficulty that would be inherent in shifting management paradigms from maintaining current distributions to facilitating change; Parks Canada cannot unilaterally develop climate change contingency plans without ministerial approval and possibly legislative action. While Scott's article only addresses management issues within Canada, the issues within it also pertain to the National Park System of the United States, which will have similar philosophical questions to struggle with in the future.

Park managers in both countries should also consider the management issues surrounding novel assemblages as climate change continues to alter species distributions.

Hobbs et al. (2006) argue that as humankind transforms more area at a faster pace, directly and indirectly, these novel ecosystems will increase in number and importance. The authors state that creation of these novel systems may stem from degradation of natural areas as a result of changing abiotic conditions or the abandonment and subsequent reclamation of developed areas. Of particular importance to park managers is the observation that it will likely be very difficult and costly to return such systems to their previous state, thus increasing the need for developing innovative management approaches to deal with their growing presence. Additionally, positive feedback loops frequently exist within novel ecosystems that not only assist in their maintenance and expansion but also simultaneously inhibit the regeneration of previous ecosystems. Hobbs et al. pose questions such as: how do we develop management schemes that maximize beneficial changes and reduce the less beneficial aspects? and what is defined as (and who decides what is) beneficial (2006, p. 4)? In order to respond to the growing concern over novel ecosystems and the difficulty in returning them to a *more natural* state the authors postulate: 1) that conservation efforts should be focused on areas that have not been significantly impacted 2) resources should not be "wasted" on a futile effort to restore systems that have been significantly impacted and have limited prospects of being restored and 3) management philosophy should dispose of the natural/human dichotomy in favour of a more appropriate depiction of how humans interact with their environment (2006, p. 5).

The dominant approach of viewing undisturbed habitats as islands (Markham, 1996) surrounded by dichotomic human-altered landscapes that act as barriers is also criticized by Kupfer, Malanson, and Franklin who argue that it is important not to lose sight of "the ocean for the islands" (2006, p. 8). It is argued that an effort should be made to transcend the habitat/non-habitat notion and instead focus on how processes within altered landscapes can contribute to species persistence and dispersal. Altered landscapes need to be viewed not only as sinks and impermeable barriers but also as semi-permeable barriers, conduits for dispersal, and even as potential population sources. Further, many studies erroneously assume that areas within the matrix are static, ignoring the possibility of future succession, and enforcing the need to view not only the extent and degree of modifications but also their permanence. The study concludes that while some habitat remnants may essentially function as habitat islands (Markham, 1996) in many, or even most, instances this is not the case and processes within the matrix have a remarkable potential to mitigate the negative impacts of change within forest areas.

2.4.3 SCIENTIFIC AND RESEARCH NEEDS

If one management response has reached a consensus throughout the literature, not surprisingly it is that more research is required. Almost all information concerning climate change, species response, and management alternatives is based on a degree of uncertainty. In order to better adapt protected area management to a host of uncertainties, authors have commonly proposed five research themes:

- Climate projection improvement
- Understanding species responses
- Collection of spatial data
- Increased monitoring
- Evaluation of management response effectiveness

Climate projection improvement: It is often argued that in order to prepare for changing conditions (and assuming that management resources will be limited – thus ruling out universally robust management solutions), model scenarios must be as accurate as possible. Particularly, this means not only improved representation of the climate system but also refining these results to a resolution that is usable by individual conservation units (Peters & Darling, 1985; Lovejoy, 2005).

Understanding species responses: Just as it will be important to develop an understanding of how the climate system is going to be behave in the future; similar understandings should be sought concerning how species are likely to respond to these changes (Peters, 1992), and how vegetation species cause feedback into the climate system through responding to changes (Foley et al., 1998). Current works emphasize the need to represent dynamic responses rather than those constrained by equilibrium conditions (Woodward & Lomas, 2004) and to better understand the dispersal biology that underlies these responses (Lovejoy, 2005).

Collection of spatial data: In order for projections to work to the best of their ability, detailed knowledge of baseline conditions is necessary. Data concerning species distributions, abundance and sensitivity to change are important for any conservation effort (Peters, 1992) alongside information concerning the distribution and size of suitable habitats and human land use, including economic value and potential of undeveloped lands (Fonseca et al., 2005). Social information is important, and will increasingly be so, as protected areas come into closer contact with the matrix of human land uses as development spreads (Fonseca et al., 2005).

Increased monitoring: Lovejoy (2005) contends that monitoring will play a critical role in identifying impacts caused by climate change and developing subsequent management responses. Many past works agree about the necessity of monitoring efforts, from identifying impacts – expected or otherwise – (Scott & Suffling, 2000; Fonseca et al., 2005) and confirming projections (Bachelet, Neilson et al., 2001; Lovejoy, 2005) to evaluating management responses (Halpin, 1997; Lovejoy, 2005) and guiding future adaptive management responses (Hannah & Hansen, 2005). Additionally, as the matrix begins to play a larger role in influencing protected areas, monitoring efforts will have to become broader-ranging, less intensive in detail, and be conducted both inside and outside of protected areas (Fonseca et al., 2005).

Evaluation of management response effectiveness: Halpin (1997) criticizes prescriptive management alternatives for protected areas concerning climate change. He argues that before connective corridors are touted as the universal solution, field testing should be employed to measure the effectiveness of blindly recommended alternatives. In particular, he suggests numerous study topics including: the effectiveness of redundant reserves over the addition of complementary reserves which add new protection targets; the effectiveness of corridors and our ability to project species dispersion; heterogeneity of habitat as site selection criteria; the opportunity costs of buffer-zone maintenance; and maintaining stable conditions within parks rather than letting nature take its course. None of these options are directly criticized, but Halpin (1997) stresses that before they are recommended, their effectiveness should be analyzed. By asking similar questions, such as whether to choose redundancy over complementarity, or irreplaceability over representativeness, the work of Hannah and Hansen (2005) implicitly demonstrates that many of these questions remain unanswered. Hobbs et al. (2006) also state that further assessment of management policies is required regarding novel ecosystems; many studies have made it explicitly clear that species response will be individualistic. However, Hobbs and colleagues ask two important questions: “What do [novel ecosystems] mean for our attempts to protect ‘natural’ ecosystems?” and “Do we need special concepts and methods to approach today's novel ecosystems or do they simply represent one quite typical example of ecosystem dynamics that have always occurred?" (2006, p. 5).

2.5 CHAPTER SUMMARY

This chapter has provided a review of contemporary literature pertaining to climate change expected across North America and vegetation responses anticipated to follow these changes. The latest generation of vegetation modelling has also been analyzed as well as the most recent works concerning possible response alternatives available to protected area managers in an era of climate change. In investigating these areas, this chapter has examined antecedent studies and provided a context from which the remaining portions of the thesis are based.

All things considered, it is important to note that impending climate change is projected to have profound impacts, some positive – many not – on both the extent and composition of ecosystems in North American parks. This will present a new variety of challenges to park managers, who will likely find vegetation distribution projections invaluable in preparing for change. While projections have been produced concerning Canada's national parks the same cannot be said for the national park system of the United States. Additionally, past scenarios for Canada were based on now-outdated equilibrium biogeography models which cannot provide accurate timeframes to park management, thus limiting their utility. New transient vegetation models overcome this obstacle and thus are appropriate and beneficial to park managers from both Canada and the Unites States. Dynamic Global Vegetation Models are the most advanced methods available to produce projections of future vegetation distributions at the continental scale of this study. While park agencies are beginning to acknowledge the threats that climate change may present in the future, more effort implementing this knowledge into park management strategies can help minimize the increasingly difficult challenges that are expected in the future.

CHAPTER THREE: METHODOLOGY

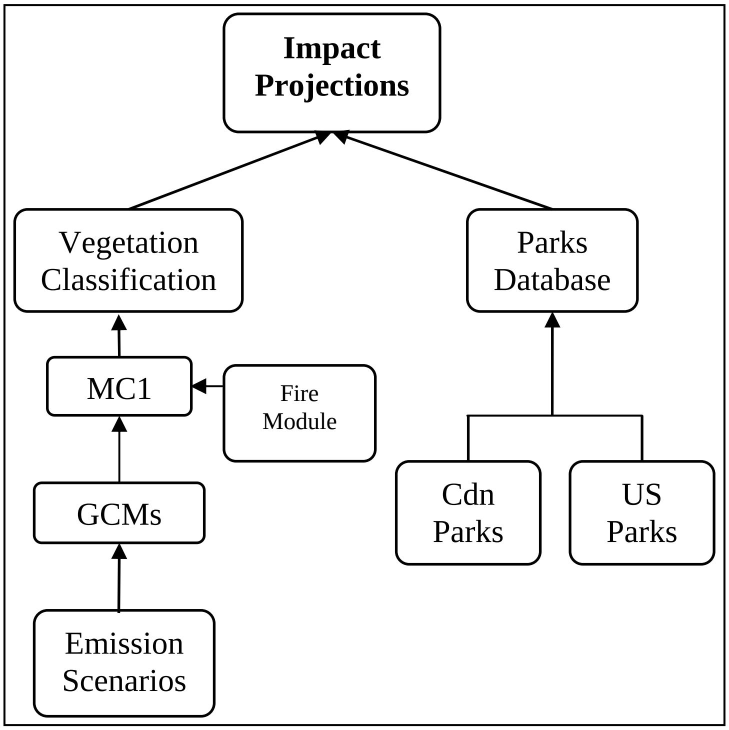
3.0 INTRODUCTION

In order to assess the possible impacts that global warming and altered precipitation patterns will have on the vegetation distribution within North America's national parks, this study used projections developed by the MAPSS CENTURY v.1 vegetation model (Bachelet, Lenihan et al., 2001; Price & Scott, 2006). MC1 is a new-generation dynamic vegetation model which was created "to assess potential impacts of global climate change on ecosystem structure and function at a wide range of scales from landscapes to global" (Bachelet, Lenihan et al., 2001). The MC1 model was run at the continental scale for this study, and likewise projected future vegetation change in 0.5° latitude by 0.5° longitude grid boxes. This resolution allows for an analysis of change that spans both Canada and the United States while keeping computational demands at a manageable level. The limitation of doing analysis of such a broad scope is that fine-scale detail is lost. Instead, the intent of this study is to identify broad-scale patterns and potential risks which would be a starting point for future more detailed regional studies that could employ both more regional-specific PFTs and better spatial resolution.

The MC1 model was chosen for a number of reasons, the foremost being that, unlike earlier models, MC1 incorporates biogeography, biogeochemistry and disturbance processes into one integrated model. The second deciding factor is that it explicitly models ecosystem structure in a transient manner which allows for the creation of projections of exact time periods when transitions are expected to occur. Lastly, the model was created, tested and calibrated in the United States and thus is expected to result in projections that are more accurate than other DGVMs within this study's area of interest, North America.

The purpose of this chapter is to present the decisions that were made in developing the methodology for the study. Strengths, assumptions, and limitations behind all of these choices will be closely examined while detailing the processes and transformations that took place in devising a Geographic Information System framework which converts raw data supplied by the multiple partners, **V**ulnerability and **I**mpacts of **N**orth American Forests to **C**limate Change: **E**cosystem **R**esponses and **A**daptation – "VINCERA" – project (Price & Scott, 2006) into projections of future plant responses to a changing climate and the subsequent management implications for Parks Canada and the (US) National Park Service. **Figure 3.1** below illustrates the data and processes used in this study to produce the vegetation impact projections of future climate change on North America's national parks.

FIGURE 3.1 – Flowchart of Impact Projection Development

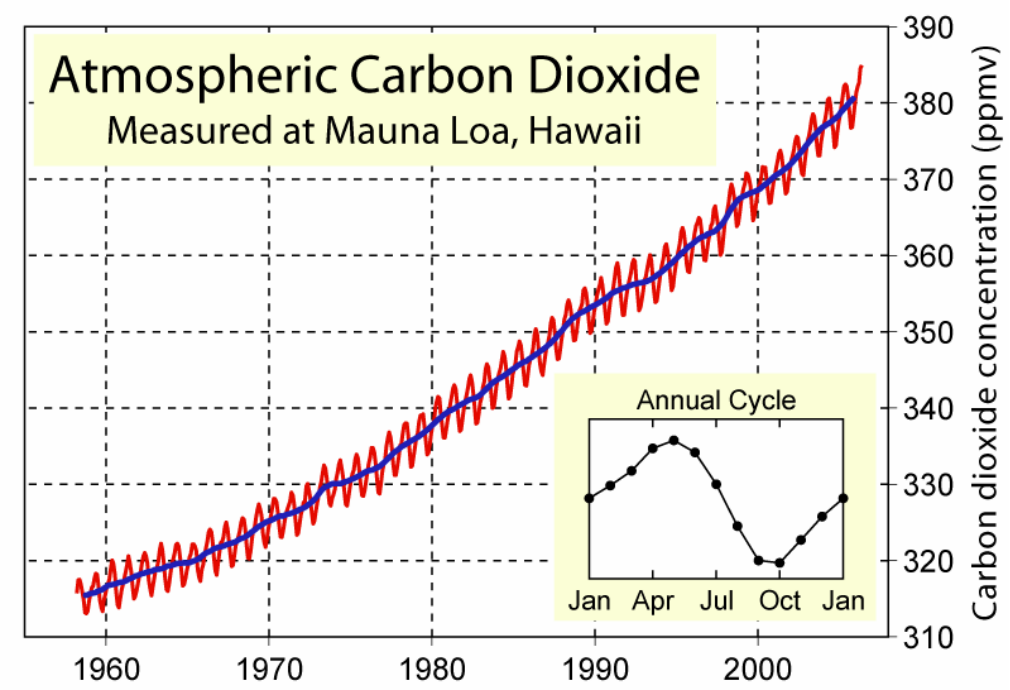


3.1 EMISSION SCENARIOS

Long before vegetation, temperature or precipitation changes can be projected into the future it is first necessary to estimate the future global concentrations of anthropogenic greenhouse gas (GHG) emissions. These levels exert a high degree of influence over temperature and precipitation projections that are the products of GCMs. The daunting task of predicting atmospheric emissions was by-passed in past studies because equilibrium projections required only an arbitrary level, such as double pre-industrial levels. Thus future projections would be based on a climate that in effect, instantly climbed to a level of 560ppm CO_2 (twice the pre-industrial level of 280) and remained stable at that level.

Now that dynamic modeling of climatic changes exists, it is possible to represent a transient atmosphere with a constantly changing composition. With this comes the challenge of developing reasonable scenarios of what future concentrations will be and how they will change. **Figure 3.2** shows how the atmospheric levels of CO_2 have changed from 1960 to 2006.

FIGURE 3.2 – Recent Changes in Atmospheric CO_2 Concentrations



Source: NOAA, 2006

The first attempt to project future concentrations of atmospheric carbon dioxide was made by the IPCC with its IS92 scenarios, followed by the more advanced IPCC Special Report on Emissions Scenarios, (SRES) which incorporated a broader range of assumptions concerning the driving forces behind emission increases (IPCC, 2000). The SRES scenarios include four "families," which are based on assumptions concerning societal objectives and regional integration and make plausible estimates as to how the composition of the atmosphere might change in the coming decades.

The progression from equilibrium to transient modelling of atmospheric processes has resulted in a shift of emphasis in contemporary studies from atmospheric criteria independent of time references, such as a doubling of atmospheric CO_2, to an emphasis on particular time periods. While emissions levels of the past can be represented with reasonable accuracy and confidence, setting a numeric value to future conditions cannot be done by simply taking and correcting measurements. In order to develop a scenario – or a number of scenarios – of the future, the Special Report on Emissions Scenarios was prepared by the IPCC for the Third Assessment Report containing four broad families of emissions storylines. In **Table 3.1** the four families of emissions scenarios are listed, along with the assumptions they make about future society. In **Figure 3.3** a description is provided in order to further distinguish the four storylines.

TABLE 3.1 – Storyline Descriptions

	Global Integration	Regionalism
Economic Emphasis	A1B Balanced Energy	A2
	A1FI Fossil-Fuel Intensive	
	A1T High-Tech Renewables	
Environmental Emphasis	B1	B2

Source: IPCC, 2000

The storylines include many social, demographic, and technological variables, but can be broadly generalized according to their underlying assumptions concerning two aspects of global society – the level of global integration of social and cultural interactions and the orientation towards which these interactions align themselves: an economic or an environmental emphasis.

FIGURE 3.3 – Storyline Elaboration

The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

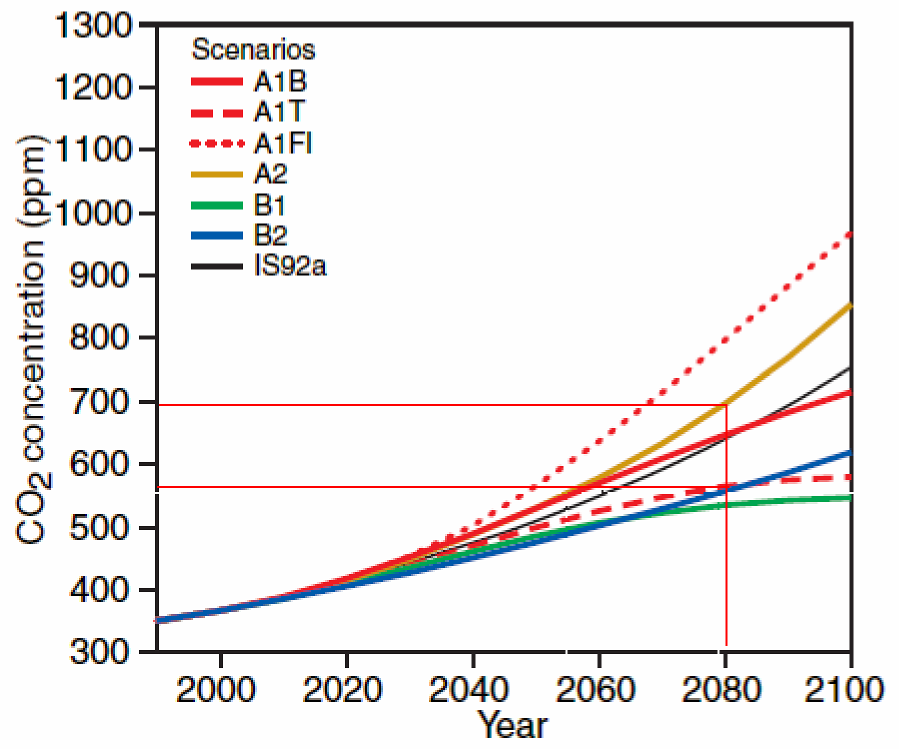
The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Source: IPCC, 2000, p. 532

These storylines are critical in shaping emissions scenarios, as they provide guidance in what values to assign to unknown variables. Values that represent future population, technologies, and material dependencies are all based on these stories and consequently become more divergent as time passes under different assumptions. Below, in **Figure 3.4** the impact that these assumptions make on modelled atmospheric composition can be seen. At year ~2020 all scenarios are still reasonably similar and it is not until ~2040 that notable differences can be observed; and by ~2080 to ~2100 the differences become readily apparent.

FIGURE 3.4 – Projected Future CO_2 Concentrations



Adapted from: IPCC, 2001

The VINCERA project employs two of the above emissions storylines in order to force the General Circulation Models that provide the future climate information for the MC1 vegetation model. The A2 and B2 scenarios were selected partly because of availability of other scenarios, but also their use provides a full range of future emissions (from low to high) and corresponding atmospheric compositions. This in turn provides a wider range of projections when these emissions scenarios are used as inputs into the DGVM. When all of the emissions scenarios are made available it would be best to incorporate as much variability as possible, but the variability included in these two scenarios is sufficient to draw valuable comparisons.

3.2 GENERAL CIRCULATION MODELS

The emission levels projected by the scenarios described above are fundamental to developing future projections of climatic conditions. GCMs are complex three-dimensional models which attempt to simulate anthropogenic climate change. As highly complex computer models they represent the most advanced efforts to simulate future climates. Older generations of GCMs were dependent on equilibrated atmospheric conditions, such as a doubling of atmospheric CO_2, but newer-generation models employ dynamic emissions estimates in order to produce time-dependent estimates of climatic change. Each of the models included in this study use three dimensional representations of Earth's atmosphere, oceans and land surfaces, coupling the interactions among all three. Thus, they are properly referred to as Coupled Atmospheric and Oceanic GCMs (AOGCM).

In 2001, the IPCC evaluated the performance of AOGCMs against contemporary climate observations and compared their results to other methods of projecting climate change. Included in this comparison were analogues, incremental or threshold models, climate scenario generators and weather generators. It was found that AOGCMs were the most realistic and comprehensive representations of climatic responses to increased greenhouse gas emissions. It was also found that the models in general were able "to provide credible simulations of climate, at least down to sub-continental scales and over temporal scales from seasonal to decadal" (Raper & Giorgi, 2005, p. 202). With this success, however, comes the caveat that no single model should be considered "best" and usually it is ensemble projections from the combination of multiple model inputs that produce the best correlations to observed patterns (IPCC, 2001).

While General Circulation Models are currently the best available method of producing future climate projections, they are not without relative disadvantages. Foremost among these weaknesses is poor resolution. GCMs have a poor spatial resolution, with each cell representing 1.25 to 3.8 degrees latitude by the same longitude. Generalization can lead to increasing inaccuracies, especially in mountainous regions. This poor spatial resolution helps to explain the scope of this study; as the spatial resolution of a GCM is too coarse to conduct in-depth analysis of individual parks. Instead, a screening level analysis is used to examine climate change impacts on the park systems of Canada and the USA as a whole. The poor spatial resolution of GCMs also limits this study to identifying long-term generalized patterns best characterized by a decadal time frame. Finally, despite the complexity and comprehensiveness of GCMs compared to other methods of climate projection development, it must not be overlooked that certain physical processes by necessity have been excluded or generalized and that regional biases may be introduced in the construction and tuning of these models (IPCC, 2001; Raper & Giorgi, 2005).

The GCMs used in the VINCERA project are all newer generation models that produce time-dependent projections. In order to reduce individual model biases three GCMs were used, all of which were developed in different regions of the globe. The GCMs included in this study were CGCM2, developed by the Canadian Centre for Climate Modelling and Analysis (Flato & Boer, 2001), CSIRO Mk2, developed by Australia's Commonwealth Scientific and Industrial Research Organization (Gordon & O'Farrell, 1997), and HadCM3, developed by the United Kingdom's Hadley Centre for Climate Prediction and Research (Gordon et al., 2000). **Table 3.2**, below, details the atmospheric and oceanic resolution of the three included models as well as providing their expected temperature increases from the 1961-1990 climate normal.

TABLE 3.2 – GCMs Utilized in this Study

Model Name	Atmospheric Resolution	Oceanic Resolution	A2 Projected ~2080 Global Temperature	B2 Projected ~2080 Global Temperature
CGCM2	3.8 x 3.8 (T32) L10	1.8 x 1.8 L29	+3.39°C	+2.42°C
CSIRO Mk2	3.2 x 5.6 (R21) L9	3.2 x 5.6 L21	+3.28°C	+2.61°C
HadCM3	2.5 x 3.75 L19	1.25 x 1.25 L20	+2.97°C	+2.39°C

Adapted from: IPCC, 2001, p. 478 & 541

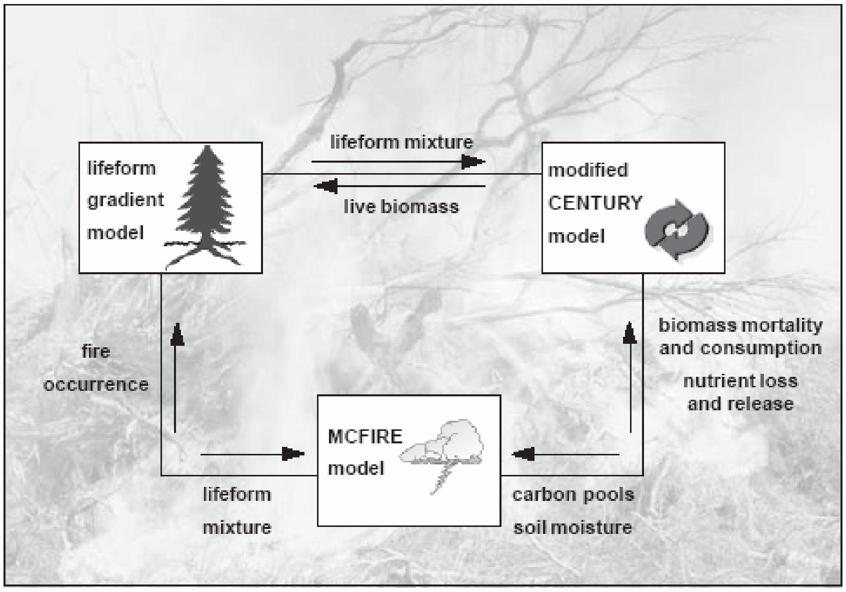
Notes:
Atmospheric Resolution – Horizontal and vertical resolution. Expressed as degrees latitude x longitude with spectral truncation noted in brackets. Vertical resolution is expressed as "Lxx" where xx represents the number of vertical levels
Oceanic Resolution – Horizontal and vertical resolution. Expressed as degrees latitude x longitude. Vertical resolution is expressed as "Lxx" where xx represents the number of vertical levels
Projected ~2080 Temp – Increase from Normal climate (1961-1990) to ~2080

Through the inclusion of multiple GCMs, developed in very different regions of the world, and which cover a spectrum of expected climate impacts and temperature increases, it is hoped that multi-model ensembles will "increase confidence in [model] results by providing an improved representation of model uncertainty" (IPCC, 2007, p. 58). Later on, further modelling efforts can use these projected climates as an input to determine future vegetation responses to changing conditions.

3.3 MC1 – DYNAMIC GLOBAL VEGETATION MODEL

What separates MC1 and other DGVMs from their predecessors are not only their ability to produce mechanistic, time-dependent projections, but also the components or modules included within them. Past equilibrium vegetation models came in two classes, biogeography models and biogeochemistry models. Biogeochemistry models attempted to simulate carbon cycling and nutrient movements within ecosystems. Biogeography models, on the other hand, attempted to determine what sorts of vegetation could persist in an area based on climate, surrounding vegetation, and hydrology. Newer dynamic vegetation models have successfully coupled biogeography and biogeochemistry models into one synchronous model which utilizes the information from one component to feed the other. Add to this a fire modelling module and a basic picture of the MC1 model can be envisioned. **Figure 3.5** provides further illustration of the interaction between modules contained within the MC1 model.

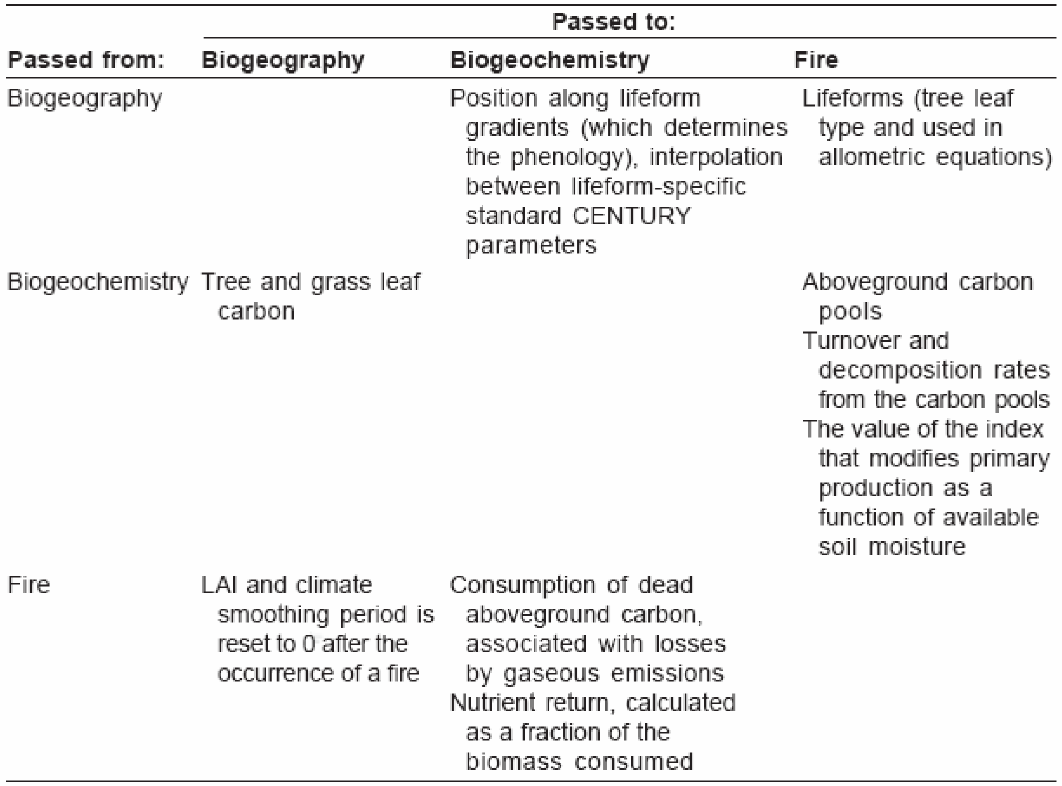
FIGURE 3.5 – Schematic Diagram of the MC1 DGVM



Source: Bachelet, Lenihan et al., 2001, p. 1

Acting in unison, the biogeography, biogeochemistry, and fire modules are able to produce a generalized mechanistic representation of the growth, mortality and structure of a number of vegetation biomes. The biogeography model is responsible for two main functions, the first being to project the "lifeform" or composition of a biome including the mixture of deciduous and coniferous trees as well as the mixture of C3 and C4 grasses (See Glossary for definition). The second function is to classify those mixtures and their biomass information into distinct vegetation classes using a climate-based set of rules. The biogeochemistry module simulates carbon and nutrient cycling through each ecosystem. Processes included within the module are: "plant production, soil organic matter decomposition, water and nutrient cycling" (Bachelet, Lenihan et al., 2001). Finally, the fire module simulates wild-fire events within MC1 by creating events with distinct occurrence triggers, extents and intensities. It does so using aboveground biomass as a fuel source and climate-based probability rules as a catalyst. **Table 3.3** describes the way in which information is passed between each module within MC1 in order to produce a simulated vegetative environment.

TABLE 3.3 – Module Interaction within MC1



	Passed to:		
Passed from:	**Biogeography**	**Biogeochemistry**	**Fire**
Biogeography		Position along lifeform gradients (which determines the phenology), interpolation between lifeform-specific standard CENTURY parameters	Lifeforms (tree leaf type and used in allometric equations)
Biogeochemistry	Tree and grass leaf carbon		Aboveground carbon pools Turnover and decomposition rates from the carbon pools The value of the index that modifies primary production as a function of available soil moisture
Fire	LAI and climate smoothing period is reset to 0 after the occurrence of a fire	Consumption of dead aboveground carbon, associated with losses by gaseous emissions Nutrient return, calculated as a fraction of the biomass consumed	

Source: Bachelet, Lenihan et al., 2001, p. 2

Before any dynamic interactions, such as those described above, can take place it is first necessary to run the model in equilibrium mode in order to establish initial conditions, such as soil type, as well as carbon and nutrient storage, which are used by the biogeochemistry module once a transition is made to the second, dynamic mode. Perhaps the most important product of the initialization period is the original vegetation-type map which is produced. The vegetation-type map plays a key role once the model transitions to dynamic mode. This study employs historical climate data from 1901 to 1915. First the mean monthly values from each of these years are used to generate one year of mean monthly values that would serve as the "normal" conditions for the initialization period. In order to incorporate natural climatic variability, the anomalies from this period are added each month after going through a de-trending process. By assorting the anomalies into a random order, any inherent trends which occurred from 1901 to 1915 are not repeated in a cyclical fashion throughout the initialization phase (Price & Scott, 2006).

Once the random weather conditions are created for the initialization period, the model is left to repeat its annual cycle year after year until a steady state is reached within the soil carbon pool. This process can take hundreds to thousands of model-years; during this period vegetation class distributions find their optimal locations under the static climate conditions and nutrient and water cycles slowly establish themselves (Bachelet, Neilson et al., 2001). It should be noted that in reality fire activity cycles would be playing an important role in shaping vegetation distributions, however, representing fire cycles during this process is not easily accomplished, and thus requires special treatment using monthly climatic data.

Since the mean monthly climate does not incorporate extreme values – only the anomalies present within the 15 sample years – and also does not include daily extremes, the fire module, MCFIRE within MC1 cannot operate effectively. To compensate for this, a schedule of events dictates fire occurrence until the model can transition to its dynamic mode. For each different plant functional type (PFT) a prescribed schedule of fire events takes the place of a true mechanistic fire module. Intervals can be as short as 5 to 30 years for grasslands and savannahs and exceeding 400 years for some forest types (Bachelet, Lenihan et al., 2001). These periods reflect average return intervals that are derived from empirical fire event data from historical fire records in both Canada and the United States.

Subsequent to establishing a steady-state carbon pool, and an initial vegetation-type map during the initialization process, conditions are assumed to adequately represent the equilibrated vegetation distribution and carbon pool conditions of 1901. From this point MC1 is run in transient mode. Observed historical daily weather data can now be used in the place of a monthly mean and in temporally-explicit monthly time-steps the model supplies estimations of vegetation structure and function, carbon storage, and fire events. A contemporary soil database provides the soil conditions that are incorporated into the biogeochemistry module and fire is modelled mechanistically as a response to fuel loading and extreme weather events. This process will be described in more detail in the subsequent sub-section. MC1 continues to run in this manner until its simulations exhaust available weather data, leaving it in the year 2006.

From this point onwards climate data from the selected GCMs and emission scenarios are used. Starting at the end of available climate data and projecting nearly one hundred years into the future, the climate information generated by the three GCMs and two emission scenarios drives the model until its termination in 2100. These climate projections take the place of observational data in determining such factors as plant phenology, mortality and growth, fire events, biomass production and soil moisture contents. Using these and other pieces of information, MC1 produces estimates of how vegetation form, structure and distribution will respond to projected climatic changes of the future.

3.3.1 BIOGEOGRAPHY MODULE

The primary instruments by which MC1 determines the temporal and spatial shifting of vegetation dominance patterns are the life-form interpreter and the classification rule-base within the biogeography module. Vegetation life-forms are initially sub-divided into four classes of trees: deciduous-needleleaf trees, deciduous-broadleaf trees, evergreen-needleleaf trees, and evergreen-broadleaf trees, as well as two classes of grasses – C3 grasses and C4 grasses. Initially, the life-form interpreter assigns a class of tree to each cell based on ambient environmental conditions. Temperature plays a pivotal role in this classification; if the mean monthly temperature (MMT) value associated with a particular cell is below -15°C, plants are assumed to be exclusively needleleaf. They are considered to be evergreen if the growing season precipitation – the amount of precipitation occurring during the three warmest months of the year – is below 75mm, or deciduous if above 95mm. Anywhere in between will result in a mixture of the two types along a gradient. Meanwhile a MMT over 18°C will result in evergreen broadleaf trees while anything between -14°C and 17°C will possess a mixture of evergreen and deciduous plants that are also a mixture of broadleaf and needleleaf trees. The decision- making process is discussed in further detail in Bachelet, Lenihan et al. (2001), but will depend on the three variables of mean monthly temperature, growing season precipitation, and growing degree days (GDD). The last is used only in the high-latitudes where <50 GDD indicates the presence of permanent ice, 50<GDD<735 indicates tundra, and 735<GDD<1330 indicates taiga. Anywhere it is possible for two different life forms to exist the exact composition is determined using a process of linear interpolation along both the temperature and precipitation gradients.

Beyond the life-form interpreter (LFI), there is an additional rule base which modifies the original classification provided by the LFI. The Leaf Area Index of a particular cell –

information provided by the biogeochemistry module – will determine whether the plants present are in fact trees (LAI > 3.75), savannah (3.75>LAI>2), shrubs (2>LAI>1), grasses (LAI<1), or desert for extremely low values measured in grams of carbon, which must be below 600g. With the life form mixture indicated by the LFI and its structure by the classification rule-base, a final classification of vegetation type is produced. This result is then used by the fire and biogeochemistry modules, and by the maps generated in the results of this study.

3.3.2 BIOGEOCHEMISTRY MODULE

The biogeochemistry module works as the "invisible-clockwork" that drives numerous processes within MC1. In isolation it does not cause any shifts in vegetation type, but the information it passes along to both the biogeography and fire modules are extremely vital to the functioning of MC1. For the purpose of this study, what is most important to understand about the biogeochemistry module is that it determines both the carbon available for growth and the leaf area index, which are used by the biogeography module in order to classify which type of vegetation is dominant. It also passes information to the fire module which will be described in further detail in the subsequent sub-section. For the fire module, the primary production of a pixel is determined by the biogeochemistry module and it is this production that determines how above-ground carbon accumulates as a result of growth (and subsequent litter and mortality). Decomposition rates also determine how much of this above-ground litter biodegrades and how much remains available as a fuel source.

The MC1 technical guide describes in detail the processes by which these pieces of information are developed (Bachelet, Lenihan et al., 2001), including: i. Net Primary Production which determines plant growth, allocation of resources to roots, leaves and stems, as well as litter and mortality; ii. decomposition which determines the amount of above ground litter that is converted to soil; iii. competition between present life forms over available light, nitrogen and water; and iv. hydrology which determines the water available within soils for competition and production.

3.3.3 FIRE MODULE

The fire module within MC1 plays two vital functions in this study; the first is its integral role within the vegetation modelling process and the second, unique to this study, is its importance in demonstrating the sensitivity of ecosystem structure to fire cycles and the management of fire processes within protected areas. Along with the biogeochemistry and biogeography modules, the fire module governs the dynamics which occur during each monthly time-step of the vegetation model. During the equilibrium-constrained initialization period the fire module is limited to a prescribed schedule of events, but its true strength and complexity becomes apparent when MC1 transitions to transient mode. Once daily temperature, humidity and precipitation become available to the fire module, MCFIRE is able to mechanistically simulate the chances of occurrence, behaviour and ecosystem effects of fire events.

As plants grow through the process of Primary Production a by-product of this growth is the deposition of above-ground litter which translates into the addition of fuel for MCFIRE. Before a fire is able to take place, however, there must first be sufficient drought conditions to exceed a fire-likelihood threshold and then it is a matter of probability until a fire event takes place. Fuel sources, behaviour of the fire – both on the surface and in the crown – and the effects of the fire are all dependent on information supplied from the biogeography and biogeochemistry modules. Biogeography determines the structure of the ecosystem where the fire occurs, and subsequently also determines the behaviour of the fire: whether it is an intense boreal fire or a creeping grass fire depends on the surrounding vegetation structure.

The behaviour characteristics of fire events are also important in simulating the ecosystem effects which result as a consequence of the fires. Fire intensity, height, and extent determine the extent to which vegetation mortality will occur, how much above-ground carbon is burnt, and the atmospheric emissions that will be released. Fire behaviour also resolves the amount of nutrient and biomass loss that occurs within affected soils and the ensuing changes in vegetation cover. Complete vegetation mortality could leave an area open to successive growth, or surviving large trees could out-compete new growth leaving a temporary savannah biome until shrubs and small trees are able to establish themselves.

As noted previously, the treatment of fire modelling also has a unique role in this study. The biome distribution changes that are to be projected will operate under one of two different assumptions within the dynamic vegetation model. Both concern how disturbance events caused by wildfires are treated. One method of handling fire disturbances is using the static, predetermined rate which is also used during the initialization process and continued afterwards. This method establishes a control scenario from which to compare the sensitivity of biome distribution to fire events.

The other fire modelling method that will be simulated utilizes the MCFIRE module included in the MC1 DGVM. This module attempts to mechanistically model the occurrence of fire. By comparing static and dynamic fire modelling methods it is hoped that some insight can be gleaned into the influence fire disturbance has over the distribution of ecosystems in different climates. This comparison may also provide insight into how fire management decisions made by park managers could affect the park system as a whole. Depending on the desired biome representation and future park system mandates, fire events either could be managed within parks or left to take their natural course.

3.4 VEGETATION CLASSIFICATION

In their initial form, vegetation distribution maps are generated by MC1 to follow the classification scheme provided by Vegetation/Ecosystem Modeling and Analysis Project definitions (VEMAP members, 1995). While the VEMAP classification provides a greater degree of precision in distinguishing between vegetation types, such precision might also lead to an increased perception of future change. For example, a national park which observed a change from cool temperate mixed forest to warm temperate mixed forest would indicate as great a magnitude of change in the analysis calculations as a change from boreal forest to grasslands even though some species would regard these two habitats as equivalent. Thus, in order to highlight only the more significant changes, the 23 vegetation classes used by MC1 were reduced into a more generalized 10-class scheme. Using a more generalized classification means that only large-scale biome level vegetation change will be represented in the analysis statistics, and a more conservative estimate of change will be achieved. Additionally, a generalized re-classification will allow comparison of results of this study with previous work that uses a similar classification scheme. **Figure 3.6** outlines the reclassification method used in this study to generate the new classification.

FIGURE 3.6 - Vegetation Re-Classification Scheme

Ice Tundra	Tundra
Taiga	Taiga
Boreal Conifer Forest	Boreal Conifer Forest
Maritime Temperate Conifer Forest Continental Temperate Conifer Forest	Temperate Evergreen Forest
Cool Temperate Mixed Forest Warm Temperate/Subtropical Mixed Forest Temperate Deciduous Forest	Temperate Mixed Forest
Tropical Mixed Forest Tropical Evergreen Forest	Tropical Mixed Forest
Temperate Mixed Xeromorphic Woodland Temperate Conifer Xeromorphic Woodland Tropical Thorn Woodland	Arid Woodlands
Temperate Deciduous Savannah Warm Temperate/Subtropical Mixed Savannah Temperate Conifer Savannah Tropical Deciduous Savannah	Savannah/Woodlands
C3 Grasslands C4 Grasslands	Grasslands
Mediterranean Shrubland Temperate Arid Shrubland Subtropical Arid Shrubland	Shrubs/Woodlands

It is significant to note that the initial maps generated from MC1 in the VINCERA project, and consequently the maps presented later in this study, represent only "potential" land cover. Neither historical/current nor future land-use patterns are incorporated into the modelling process. As Peng (2000) states, the primary issue with including human land use in modelling efforts is the issue of scaling – "Because of the large area involved, DGVMs must rely on pixel sizes of a few square kilometres or more; but land-use management frequently occurs on a much smaller scale, making the interactions among land-use drivers, topography, and climate change difficult to simulate" (p. 47). In spite of this exclusion, it is argued that an accurate representation of land cover potential is still attained as vegetation is bound by climatic, hydrological and physiological constraints which limit what vegetation could possibly be found in any given location (Neilson et al., 1998). Additionally, as national parks are inherently among the least influenced areas in North America, it follows that if any areas can be accurately represented by potential vegetation cover it would be these.

In addition to creating a more suitable representation of expected change, the vegetation class generalization was conducted in order to facilitate its comparison to previous studies. In particular, the generalized classification scheme, shown in **Table 3.4**, almost exactly duplicates the schemes used by Malcolm and Markham (2000) and Lemieux (2002). The primary exceptions are that both studies possessed a Taiga/Tundra class representing the "ecotonal region of open woodland, which occurs at higher latitudes or elevations beyond the 'closed' Boreal forest" (Lemieux, 2002). In this study the Taiga/Tundra class is now segregated into: Tundra, which represents the open, barren plains of northern Canada and Alaska; Taiga, which represents the ecotonal region described previously, and Boreal forest, which possesses a closed canopy rather than open woodland. Detailed descriptions of the remaining vegetation classes can be acquired from Lemieux (2002; see pp. 49 – 51).

TABLE 3.4 – Vegetation Types (Biomes) Used in this Analysis

Tundra
Tundra is defined as the treeless vegetation which extends beyond the treeline at high latitudes and altitudes regardless of whether it is dominated by dwarf shrubs or herbaceous plants.
BIOME3: Arctic/alpine tundra, Polar desert
MAPSS: Tundra, Ice
Taiga/Tundra
Taiga/Tundra is the broad "ecotonal" region of open woodland, which occurs at higher latitudes or elevations beyond the "closed" Boreal Forest. This type of vegetation classification is not explicitly simulated by BIOME3, but rather is included in Boreal Conifer Forest.
BIOME3: Boreal deciduous forest/woodland
MAPSS: Taiga/Tundra
Boreal Conifer Forest
Boreal Conifer Forest is the Taiga proper, i.e., relatively dense forest composed mainly of needle-leaved trees and occurring in cold-winter climates.
BIOME3: Boreal evergreen forest/woodland
MAPSS: Forest Evergreen Needle Taiga
Temperate Evergreen Forest
Temperate Evergreen Forest encompasses the wet temperate and subtropical conifer forests of the Northwest in North America.
BIOME3: Temperate/boreal mixed forest

MAPSS: Forest Mixed Warm, Forest Evergreen Needle Maritime, Forest Evergreen Needle Continental
Temperate Mixed Forest
Temperate Mixed Forest includes pure temperate broadleaf forests, such as oak, hickory, or beech-maple. It also includes mixtures of broadleaf and temperate evergreen types, such as the cool-mixed pine/fir and hardwood forests of the Northeast or the warm-mixed pine/hardwood forests of the Southeastern US.
BIOME3: Temperate conifer forest, Temperate deciduous forest
MAPSS: Forest Deciduous Broadleaf, Forest Mixed Warm, Forest Mixed Cool, Forest Hardwood Cool
Savannah/Woodlands
Savannah/Woodlands encompass all “open” tree vegetation from high to low latitudes and elevations. The tropical dry savannahs and drought deciduous forests are contained within this classification. So too are the temperate pine savannahs and “pygmy” forests and the aspen woodlands adjacent to the Boreal Forest. Fire can play an important role in maintaining the open nature of these woodlands, while grazing can increase the density of woody vegetation at the expense of grass.
BIOME3: Temperate broad-leaved evergreen forest, Tropical deciduous forest, Moist savannahs, Tall grassland, Xeric woodlands/scrub
MAPSS: Forest Seasonal Tropical, Forest Savannah Dry Tropical, Tree Savannah Deciduous Broadleaf, Tree Savannah Mixed Warm, Tree Savannah Mixed Cool, Tree Savannah Evergreen Needle Maritime, Tree Savannah Evergreen Continental, Tree Savannah PJ Continental, Tree Savannah PJ Maritime, Tree Savannah PJ Xeric Continental
Shrub/Woodlands
Shrub/Woodlands are distinguished from Savannah/Woodlands by their lower biomass and shorter stature. This is a drier vegetation type than the Savannah/Woodlands and encompasses most semi-arid vegetation types from Chaparral to mesquite woodlands to cold, semi-desert sage shrublands. The actual vegetation associated with this type is very susceptible to variation depending on soils, topography, fire, grazing and land-use history. Distinctions between shrub, steppe and grassland are sometimes difficult to quantify, given that each usually contains elements of both grass and woody vegetation. The relative abundance of the two functional types is considerable in determining the classification, but there are no generally accepted rules to indicate how much woody vegetation is sufficient to label a region a shrubland, or conversely, how much grass is required to label it a grassland.
BIOME3: Short Grassland
MAPSS: Chaparral, Open Shrubland No Grass, Broadleaf, Shrub Savannah Mixed Warm, Shrub Savannah Mixed Cool, Shrub Savannah Evergreen Micro, Shrub Savannah SubTropical Mixed, Shrubland SubTropical, (Mediterranean: Shrubland Temperate Conifer, Shrubland Temperate Xeromorphic Conifer, Grass Semi-desert C3, Grass Semi-desert C3/C4
Grasslands
Grasslands include both C3 and C4 grassland types in both temperate and tropical regions. Much of the grassland type is a “fire climax” type that would be populated by shrubs either with the absence of fire, or with extensive grazing.
BIOME3: Dry savannahs, Arid shrubland/steppe

MAPSS: Grassland Semi Desert, Grass Northern Mixed Tall C3, Grass Prairie Tall C4, Grass Northern Mixed Mid C3, Grass Southern Mixed Mid C4, Grass Dry Mixed Short C3, Grass Prairie Short C4, Grass Northern Tall C3, Grass Northern Mid C3, Grass Dry Short C3, Grass Tall C3, Grass Mid C3, Grass Short C3, Grass Tall C3/C4, Grass Mid C3/C4, Grass Short C3/C4, Grass Tall C4, Grass Mid C4, Grass Short C4
Arid Lands
Arid Lands encompass all regions drier than Grasslands, from hyper-arid to semiarid.
The regions could be more or less “grassy” or “shrubby” depending on disturbance and land-use history.
BIOME3: Desert
MAPSS: Shrub Savannah Tropical, Shrub Savannah Mixed Warm, Grass Semi-desert C4, Desert Boreal, Desert Temperate, Desert Subtropical, Desert Tropical, Desert Extreme

Source: Lemieux, 2002

In the analysis chapter to follow, one section will be dedicated to comparing forecasts produced by MC1 to previous projections using equilibrium vegetation models BIOME3 and MAPSS. From this comparison it will be determined whether comparable climate impacts are projected and whether future vegetation distributions are similar in nature. Optimistically, conclusions can be drawn from both sets of models, showing how they differ, and determining when a degree of change can be seen in MC1 that is comparable to the simulations of previous models that did not incorporate temporal projections.

3.5 PARKS DATABASE

The intention of this study is to examine how climate change is expected to affect the biome distribution of North America and thus change the composition of the park systems for both Canada and the United States. As it was deemed most appropriate to concentrate on the *national* park systems of both countries, provincial, state and territorial parks were excluded from the study during the park database construction, as were municipal or other parks. It is hoped that studying the national park systems of North America will provide a number of indicators, showing which regions are estimated to experience the largest degree of change. This knowledge could subsequently be applied in more detailed regional studies.

In order to construct the database of protected areas which were to be included in this study it was first necessary to obtain relevant information pertaining to the national park systems of Canada and the United States. This included two spatial databases containing park boundaries in the form of shape files, proper park names, and their classifications. The two geo-databases employed, ArcCanada and ArcUSA, were supplied by ESRI and represent North America’s parks at a scale of 1:2 million. ArcUSA included a park classification system which was useful as it allowed for the exclusion of many protected areas which are not suitable for a study of this nature. The same information was collected for Canada by manually removing parks which are not included on the Parks Canada list of national parks. The following section details the selection framework that was employed to narrow down the available parks to the subset used in this study.

First, the park database only includes protected areas that are national *parks*. A number of protected and managed areas which are under federal jurisdiction in both Canada and the United States have been excluded from this study. Marine parks and conservation areas, historical sites and trails, monuments, battlefields and cemeteries are all examples of areas which have not been included. The reason for this lies in their management objectives and mandates. Historical areas, even trails which traverse wilderness areas, are not explicitly managed to preserve ecological integrity or diversity, but instead focus on cultural heritage or providing outdoor recreation opportunities. Alternatively, while mandates of marine parks often mirror, or at least closely resemble, the management objectives of their terrestrial counterparts, marine ecosystems are not modelled by the MC1 DGVM and therefore are not included in this study.

Finally, a number of different wilderness areas and sanctuaries were not used. Of particular note are migratory bird sanctuaries, bison sanctuaries of northern Canada and the USA, as well as areas set aside for scientific preservation. These would be well suited for future study but were not included in this work, as doing so would have required information resources which were not available or beyond the scope of this study.

After completing the park selection procedure and having produced a final database of parks that were to be used in the study, they were divided into regions. Doing this helped to accomplish one of the study’s goals to identify particular areas in North America that are estimated to experience greater amounts of change, which could then direct future studies. The continent was partitioned into seven regions that loosely resemble the regions first utilized by Thoman (1978) and based on pre-existing census regions. The Northern region includes Alaska and the northern Territories of Canada, including Yukon, Northwest Territories, and

Nunavut. The Pacific region includes BC and the American states situated along the shore of the Pacific Ocean. The Mountain region includes the mountainous western states and provinces. Included in the Prairie region are the central, flatland provinces and states. Ontario, Michigan, New York and the other states surrounding the Great Lakes are appropriately referred to as the Great Lakes region. The Southern region includes the southern states which are not included in the mountain region, extending from Texas to Florida and as far north as Tennessee and North Carolina. The Atlantic region includes Quebec and the Maritime Provinces and the states in close proximity to the Atlantic Ocean, including the New England states down to Virginia. A series of maps illustrating the regions described above and the parks they contain are provided in **Appendix A**.

3.6 CLIMATE CHANGE IMPACT ASSESSMENT

The initial step in translating both the vegetation maps from MC1 and the park boundaries into a vegetation impact assessment was to produce vegetation maps for a select number of time slices, and subsequently to compare these in order to identify areas where vegetation is anticipated to change. In this study four decade-long time slices were chosen to represent present and future conditions. The decade surrounding 1975, i.e. 1970 to 1980, was chosen to represent baseline or “current” conditions as this time slice represents the decade in which pronounced late 20th century warming became apparent. Similarly, this time period also coincides with the establishment of many conservation objectives and park system plans – such as the Parks Canada National System Plan in the early 1970s, and the NPS General Authorities Act in 1970. Near-future conditions are represented by the decade 2015 to 2025, encompassing the year 2020. In order to represent mid-future conditions, the years 2045 to 2055 (2050) were chosen as a moderate future scenario and 2075 to 2085 (2080) were selected to serve as a long-term future scenario. After choosing the ten year time slices, each annual layer within that time slice was overlaid in a GIS and the most frequently occurring vegetation cover was selected as being representative for those ten years. A large set of vegetation distribution maps was created: one for every GCM, emission and fire scenario combination, for each time slice (See **Appendix B**).

Utilizing the vegetation maps for each time slice it was possible to begin identifying regions experiencing change. By overlaying two time slices it was possible to identify those areas which did not remain the same over the course of time. A binary map was produced from this overlay, showing those areas that changed and those which did not. This map was then converted into a shapefile in order to increase the functionality of ArcView. Using a selection method which identified those parks which intersected with the change polygons, a tally was produced that counted those parks which experienced any degree of change.

Three methods were devised to characterize the change that was modelled. First, a continental-scale analysis was completed in order to explore the extent to which modelled vegetation change occurred within the North American national park systems. Second, a regional analysis examined how many parks within each region were projected to change in biome type. For the continental and regional-scale analyses any change present within the park, regardless of its extent, was recorded as a park that experienced change. Finally, a change-analysis was completed examining the extent to which park representation of each type of biome changed. The number of parks present within a biome at $time_1$ was subtracted from the number present in $time_2$ in order to derive a percentage-change in the number of parks representing each biome. For the biome change-analysis, if any portion of the park was represented by a particular biome it was added towards the sum of parks that were present within a biome during that time slice. Thus a park containing three boreal cells and one temperate mixed-forest cell contributed to both the boreal and the temperate mixed-forest tallies. Through separating continent-wide change into regions and biomes it is possible to characterize expected vegetation change in national park systems. In the next chapter the results of these analyses are presented.

3.7 CHAPTER SUMMARY

This chapter has described the steps that were required in the production of numerous impact projections for North America’s national park systems. Crucial to the process are the initial models chosen to represent the complex processes involved in shaping continental vegetation distribution. General Circulation Models, forced with GHG Emissions Scenarios generate a key input into the modelling process – the projected future climate. After generating a number of possible climate futures, each was run through a Dynamic Global Vegetation

Model in order to project future plant distributions. This study uses the results generated from the VINCERA project where the MC1 DGVM (Bachelet, Lenihan et al., 2001) was driven using three climatic GCMs – CGCM2 (Flato & Boer, 2001), CSIRO Mk2 (Gordon & O'Farrell, 1997), and HadCM3 (Gordon et al., 2000) in order to generate future plant distribution projections for each year from 1900 to 2100.

ArcMap 9, a GIS platform, was employed in order to produce aggregated time slices which displayed the dominant vegetation cover over each individual period, as well as to spatially reference North America's national parks in the context of vegetation change. By draping park boundaries over polygons of expected change, three different analyses were conducted: one to illustrate the encompassing vegetation change to be expected as a result of a changing climate, another to illustrate how biome representation is expected to change through the course of time, and the last to display regions where changes are expected to be particularly extensive.

As Malcolm and Markham (2000) explain, the scenarios produced from a modelling exercise such as this should not be viewed as precise predictions of future change, but rather as a "range of possible outcomes." As different models have different methods of representing (and generalizing) complex processes, it is impossible to say that one model is the "best" model to use (IPCC, 2001). For this reason, future studies should strive to include additional DGVMs in order to increase the robustness of studies such as this. In the near future two models in particular, the Sheffield DGVM (SDGVM) and the IBIS DGVM would make valuable contributions, and are expected to be available shortly after the publication of this work. By including other DGVMs it would be possible to eliminate some of the biases that are present within MC1, or any other DGVM for that matter. Having said this, DGVMs are among the most advanced and scientifically thorough methods of projecting future vegetation distributions, and they currently represent our best scientific understanding of future vegetation distributions.

CHAPTER FOUR: ANALYSIS

4.0 INTRODUCTION

The purpose of this chapter is to discuss the quantitative results that were generated by the methodological framework described in the previous chapter. Analysis of this information will be applied to three areas of focus critical to evaluating the potential impact of climate change on vegetation distribution within North America's parks. First, a system-wide analysis will examine potential impacts in the broadest scope of this study, looking for pervasive effects which reach beyond regional and political barriers. The results generated will also display how sensitive projected distributions are to such factors as changing emissions levels, climatic conditions, and fire behaviour – as modelled by the use of different emissions scenarios, GCMs and fire modules within MC1.

Analysis of the system as a whole will provide a benchmark from which to compare individual regions within North America. Therefore, as a second focal point of analysis, this study divides North America into seven broad regions and analyzes the extent of change that is projected for each region. The seven regions -- including Atlantic, Great Lakes, Mountain, Northern, Pacific, Prairie, and Southern -- will be examined individually and a profile developed for each. The regional analysis will include the percentage of change projected to occur within that region over the time frame of the study (up to ~2080) and show how extensive future regional change is likely to be in comparison with system-wide changes. Each regional profile will investigate the extent to which the different models and scenarios agree with one another (which can be interpreted as a proxy for the degree of uncertainty concerning future changes) and the estimated trajectory of future change. The purpose of developing these regional profiles is to refine the patterns discovered in the continental/North American analysis, providing a better understanding of projected changes and their spatial distribution.

Thirdly, this study aims to examine/assess the changes which are expected to take place with respect to biome representation in National Park systems. Parks Canada in particular has placed a strong mandate on preserving the ecological integrity of Canada's parks and completing a park system that represents each of Canada's 39 representative natural regions (Parks Canada, 2000). While the United States National Park Service does not explicitly outline the importance of ecological integrity within its park system to the same degree as Parks Canada, there can be little doubt that the prospect of changing biome distributions is of great concern for the American national park system. In this section, each of the ten biomes will be analyzed to identify its susceptibility to change as a response to variables such as climate and fire. Additionally, the trajectory of projected change throughout the study period will be examined. Breaking down change into its potential impact on component biomes will highlight those biomes that are likely to experience greater-than-average change or are likely to remain stable.

Before proceeding in the presentation of the results, a few important points must be considered. The first has to do with time slices and park boundaries; it should be noted that the most current park boundary layers available (2004) have been used for this study. These boundary layers were used for all of the time slices, including 1970-1980 when many of the current national parks did not yet exist. The intention is to show how the land where the parks are situated will likely change, so that comparisons can be drawn. As previously mentioned, the time slice from 1970 to 1980 will be referred to as "current" because this is the era that represents the beginning of distinct anthropogenic climate change and serves as a baseline from which to examine potential future vegetation change. The second is that two new terms have been developed to present the results of this study; first, Park Change Rate indicates the number of parks which will experience some degree of change, whether partial or complete, from their simulated dominant 1970-1980 state. The second term is Biome Representation Change Rate; this indicates a change in the number of parks in which a particular biome can be found, as compared to the 1970-1980 value. Both of these change rates are expressed as either percentages or whole numbers.

4.1 SYSTEM-WIDE PATTERNS

The first observation that was made from the continental scale analysis displays the projected park change rate for each time period. The table below shows the number of parks which are projected to experience any degree of biome representation in a particular time period. To include the full range of plausible futures, results from all three GCMs forced using both A2 and B2 emissions scenarios were considered. Only vegetation futures generated using the dynamic fire module were included. Other than in one section, where they are specifically included, static fire vegetation futures were excluded from the following tables as they artificially simplify the DGVM results and are not theoretically valid. The complete results of the system-wide analysis can be seen in **Appendix C** of this thesis.

TABLE 4.1 – System-Wide Park Change Rate by Time Slice

Time Period	Park Change Rate (#)	Percentage Change (%)
1970 – 1980	Baseline	Baseline
2015 - 2025	37 - 44	40.2 – 47.8%
2045 - 2055	42 - 49	45.7 – 53.3%
2075 - 2085	49 - 59	53.3 – 64.1%

The numbers shown in **Table 4.1**, above, are interesting for a couple of reasons, the first being that there is notable agreement between the vegetation futures developed by MC1. The second is that under three GCMs, using two very different emissions scenarios, there is a general agreement between the vegetation futures. This indicates that a significant amount of change can be expected within North America’s national parks. As the DGVM projects vegetation distributions further into the future the variance between scenarios increases as might be expected – from a difference of seven parks (37 to 44) in the near future (2015-2025) to ten near the end of the century (2075-2085). Despite the variance between vegetation futures, however, it is important to note that every one of them projects a change in the majority (greater than 50%) of parks some time between the mid- and end of century time period (2045 to 2085).

As mentioned, the differences between vegetation futures based on emissions levels were not significant enough to alter the general trajectory of changes to be expected within national parks. Included below is a table showing the different park change rates associated with vegetation futures that were generated using the two different SRES emissions scenarios described previously. The results listed in **Table 4.2** show the range of park change rates from the three GCMs used in this study.

TABLE 4.2 – System-Wide Emissions Scenario Sensitivity

Emissions Scenario	2015 – 2025 Park Change Rates	2045 – 2055 Park Change Rates	2075 – 2085 Park Change Rates
A2 Scenario	38 – 41	48 – 49	53 – 59
B2 Scenario	37 – 44	42 – 48	49 – 52

When the results were collected the park change rates follow a pattern that might be expected: the A2 scenario, which assumes a greater degree of anthropogenic emissions contributions, also generates vegetation futures that possess larger park change rates. B2 vegetation futures project smaller park change rates, except for in the near-future time period where the atmospheric composition in the B2 emissions scenario is still relatively similar to the A2 scenario. Once again it is worthwhile to note that there is a strong agreement between the two sets of vegetation futures, which both forecast a large degree of change within North American national parks, .

Figure 3.4 illustrates that by ~2080 the A2 scenario expects approximately 25% higher levels of atmospheric carbon dioxide than the B2 scenario. Just as a growing difference can be observed between the two scenarios, it can also be noted that there is a corresponding difference between eventual biome distributions within parks based on emissions levels. This difference may, however, be overshadowed by the large number of parks that are projected to change even under the more conservative scenario. Corroboration by other vegetation models would be beneficial to add robustness to this projection, but supposing that this conclusion is backed by future modelling efforts, it will be important to adjust park management plans for changing park conditions whether or not future emissions levels are successfully curbed.

The projected park change rate, as in the case with emissions scenarios, also proved to be sensitive to the fire modelling method employed. **Table 4.3** below shows the range of park change rates of those vegetation futures that were generated using dynamic fire versus those using static fire conditions. In order to extract further information from the results, they were also divided by the emission scenario that drove the GCM for each vegetation future.

TABLE 4.3 – System-Wide Fire Modelling Sensitivity

Time Period	A2 Emissions		B2 Emissions	
	Dyn. Fire (#)	Stat. Fire (#)	Dyn. Fire (#)	Stat. Fire (#)
2015 – 2025	38 – 41	41 – 43	37 – 44	41 – 45
2045 – 2055	48 – 49	46 – 48	42 – 48	46 – 50
2075 – 2085	53 – 59	51 – 55	49 – 52	49 – 56

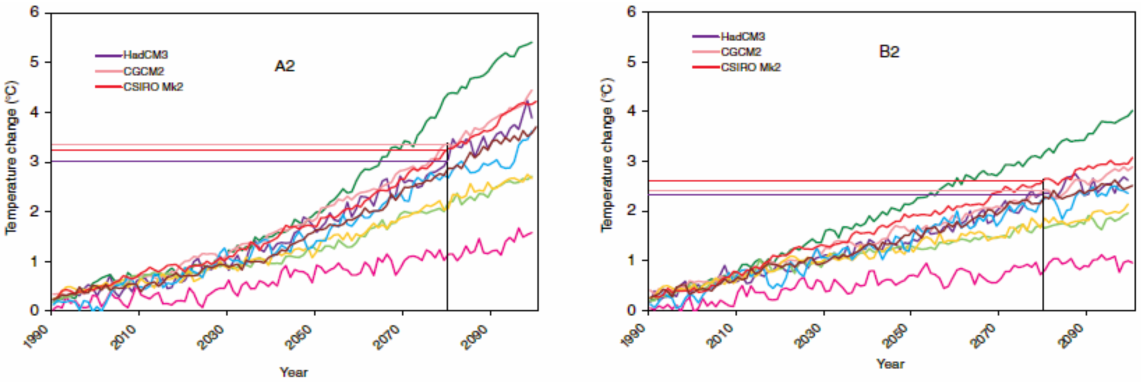
One noticeable pattern can be observed from **Table 4.3**. Under the A2 emissions scenario, where climate change is more pronounced, the dynamic fire vegetation futures have a higher incidence of biome change in parks than do the static fire vegetation futures. On the other hand, under the B2 emissions scenario, where climate change is less pronounced, the dynamic fire vegetation futures have a somewhat lower incidence of parks changing biome than those using static fire modelling.

There is evidence to suggest that in both Canada (Gillett, Weaver, Zwiers & Flannigan, 2004) and the United States (Westerling, Hidalgo, Cayan & Swetnam, 2006), forest fire frequency has been increasing with climate change and this would help explain the increased park change rate in A2 dynamic fire vegetation futures. As previously mentioned fire is a great agent of change. It would also help explain why the B2 dynamic fire vegetation futures have a lower park change rate than the A2 dynamic fire vegetation futures, but does not explain why they would have lower change rates than B2 static fire vegetation futures. There is no clear explanation available from the data to explain this at a system-wide level. Hopefully, a pattern will become more evident when analyzing park change rates on a regional level; fire will likely play varying roles in landscape change from region to region.

The unexplained sensitivity could also be an artifact of the method in which this study was conducted. No attempt was made to determine the magnitude of change within areas experiencing change. It is certainly possible that landscapes currently experiencing a significant degree of fire dynamics will experience only faster, more intense changes in the future – rather than the role of fire as an agent of change being to transform areas where it does not already have a large influence. One conclusion that can be drawn from **Table 4.3** is that the influence of fire as an agent of change for the park system will vary and will depend on which climate projection turns out to be closer to reality. More important though, the role that fire plays in shaping the landscape will likely be both more evident and more dramatic at the regional scale. Fire-based impacts will also be addressed in the Regional Analysis section.

Possibly the most anticipated result was that the climate model scenario utilized in each vegetation future proved to have significant impacts on the projected park change rate at a system-wide level. In **Figure 4.1** the temperature increases that are projected by each GCM are plotted by year. HadCM3 is always the most conservative of the three models and CGCM2 and CSIRO Mk2 alternate as to which projects the greatest temperature increase. The average of the A2 temperature and B2 temperatures are slightly higher for CSIRO Mk2 and likewise, vegetation futures generated using CSIRO Mk2 climates produce minutely greater park change rates than CGCM2. HadCM3 vegetation futures consistently project the least change of all three GCMs. **Table 4.4** provides a detailed breakdown of projected park change rates by time slice for each of the GCMs.

FIGURE 4.1 – GCM Projected Global Temperature Increases



Adapted from: IPCC, 2001

The left hand figure displays projected temperature increases under A2 conditions while the figure on the right displays projected temperature increases under B2 conditions

TABLE 4.4 – Climate Model Sensitivity

GCM	2015 – 2025 Park Change Rate	2045 – 2055 Park Change Rate	2075 – 2085 Park Change Rate
CGCM2	37 – 40	48 – 49	52 – 59
CSIRO2	41 – 44	48 – 49	52 – 53
HadCM3	38 – 38	42 – 48	49 – 53

As seen above in **Table 4.4**, among the three climate scenarios there is a wide range of park change rates projected for the 2075 to 2085 time slice. Despite the range of possible futures, however, it is also important to note that even the most conservative projection estimated that 46% of 92 parks would experience biome change by the 2045 – 2055 time period, and this would rise to 53% by the 2075 to 2085. From this perspective, despite the range of possibilities, the future will very likely be one of extensive change throughout the national park systems of North America.

Many of the scenarios even forecast that in as little as 50 years, the majority of parks throughout the continent may be expected to experience the early stages of biome change. There is a startling agreement between the outcomes projected by the MC1 model despite the use of a variety of climate and emissions scenarios. In the most extreme case there is only a 10.9% (between 49 and 59 parks) disagreement between model scenarios by 2075 – 2085. Using the Hadley GCM3, SRES B2 emissions scenario, the lowest projection of 53.3% change was estimated (49 parks). This can be compared with the CGCM2-A2-dynamic fire scenario which estimates that as many as 59 parks within North America will experience a biome transition of some sort by 2075 to 2085. As can be seen by examining both the best and worst case scenarios, as far as conservation efforts are concerned, dramatic changes can be expected over the next 80 to 100 years and management goals should be adapted to incorporate, or at minimum acknowledge, this change.

Further, previous studies have noted that vegetation communities often take extensive periods of time to equilibrate to new conditions; thus, it is likely not only that extensive changes within North American national parks will occur in coordination with warming conditions, but also that these changes will continue even if warming patterns are stabilized, thus increasing the importance of the changes from a park management standpoint. Having said this, it also can be noted that of all the future variables included in this study (fire rates, emissions levels and climatic conditions), it will likely be future climatic conditions that exercise the greatest influence on future distributions. These changes will not be distributed in a spatially uniform manner, and thus it is important to not only analyze how climate change is expected to influence the national parks of North America, but also how these changes are expected to be distributed from region to region. In the next section of this chapter, the influence that climate change is expected to exert on individual regions within North America will be examined.

4.2 REGIONAL PATTERNS

The purpose of this section is to describe in further detail the regional distribution of projected changes, as well as to compare changes in each region to the continental average. For the complete results of the regional patterns analysis, please see **Appendix C** of this thesis. Each region is projected to have unique responses to future climate change, some being much more sensitive than others, and still others being more variable. Differences were noted according to the GCM and emissions scenarios that were used to drive the vegetation model.

TABLE 4.5 – Regional Park Change Rate Summary

Region	Parks (#)	B2 2075 - 2085 Park Change Rate			A2 2075 – 2085 Park Change Rate		
		CGCM2	CSIRO2	HadCM3	CGCM2	CSIRO2	HadCM3
Atlantic	12	4	5	4	6	5	5
Great Lakes	6	4	3	2	3	3	2
Mountain	20	14	14	13	15	14	15
Northern	17	13	14	13	13	14	13
Pacific	17	11	11	12	12	11	11
Prairie	9	4	4	3	5	5	4
Southern	11	2	1	2	5	1	3
Total	92	52	52	49	59	53	53

Table 4.5 above possesses significant detail helpful in describing the regional distribution of changes projected to occur in North America's national parks. It is immediately evident that the extent of change expected to occur is not distributed evenly among these regions. Looking at the Mountain, Northern and Pacific regions it should be noted that every single vegetation future produced forecasts projecting that more than half of the parks situated in these regions will change biomes by 2075 to 2085. On the other hand, the Southern region experiences change in less than half of its parks in every vegetation future, and most often this number is below one-quarter. This illustrates the regional patterns that shape the system-wide patterns, and the importance for park management of examining change at multiple scales in order to achieve a better understanding of projected change. Effective management responses will

likewise need to reflect the spatially variable nature of climate change and its impacts, placing significance on providing the ability of national parks to respond individualistically to changing conditions.

In order to analyze the regional distribution of projected change three simple comparisons were made. The first was to compare the projected park change rate of each region to the national average to see which areas are expected to experience greatest or least amount of change. The next two comparisons involved agreement, or disagreement, between scenarios for each region in order to understand the consistency of projected change between models. It will be shown that the park change rate for any region can change quite dramatically, depending on which climate and emissions scenarios are used to develop a vegetation future.

When the park change rate from each region's national parks is compared to the system-wide average it quickly becomes apparent that there are three regions that will likely bear the brunt of future vegetation change. The Northern region is projected to experience a large northward surge of Boreal Conifer Forest into the western mainland portions of the Northwest Territories, Yukon Territory, and Alaska where Taiga used to be present. Similarly, the northward advancement of Taiga-dominated cells in those same provinces and states displaces many cells within the Northern parks that were previously Tundra. The large redistribution of Boreal Conifer Forest, Taiga and Tundra leads to projections of between 76% and 82% of parks within the Northern region experiencing a change in biomes by the 2075 to 2085 time period.

Parks are likewise projected to be dominated by changing biomes in the Pacific region. The projected changes are slightly more complex for this region, including conversions from mountainous Taiga to Boreal Conifer and Temperate Evergreen Forest. Shrub/Woodlands is also projected to recede for the Pacific region, to be substituted instead with a mixture of Savannah/Woodlands, Grasslands, and Arid Woodlands. The projected park change rate for this region ranges from 65% to 71%, any of which exceeds the average park change rate projected for the continent as a whole (53% to 64%).

Lastly, the Mountain region is projected to experience change in 65% to 75% of its parks. This is characterized by northward advancing Boreal Conifer Forest into both the northern and western portions of Alberta, and the subsequent displacement of Taiga-dominated cells. In southern Alberta, Montana, Idaho and Wyoming many parks which are currently modelled to be dominated by Boreal and Temperate Evergreen Forest have new biomes represented in 2075 - 2085 distributions including Grasslands, Temperate Evergreen Forest (where Boreal Conifer once dominated), Temperate Mixed Forest, and Arid Woodlands.

While the Northern, Mountain and Pacific regions all displayed above average change compared to other regions examined in this study, others displayed a pattern of remaining distinctly stable compared to other regions. The Atlantic, Prairie and Southern regions all ranked below the average park change rate for the continent-wide system of national parks. Regardless of which GCM or emissions scenario was used to generate the vegetation futures, all six possible combinations agreed that these regions would experience below-average change. This stability can also be noted in the Modelled Biome Extents found in **Appendix B**. It is interesting to note that while some of this stability is due to a smaller biome distribution change in the regions themselves, another significant reason for the stability is due to the location of projected change within each region. As an example, the Southern region is projected to experience a fair amount of biome change throughout the study period, yet of 11 parks only 1 to 3 are projected to change in most vegetation futures. As it happens, this region's parks are located in what are projected to be the most stable portions of that region. The spatial distribution of change must again be taken into account when analyzing the extent of change occurring within a region's parks, for even if considerable change occurs within the region it may not be occurring with those parks.

It has been shown that the degree of change projected for the national park systems of North America varies significantly depending on the emissions scenario that is used to drive the vegetation model's climate. The change that is projected for individual regions often follows the same pattern, but it can be seen that in some regions change appears to be inevitable regardless of which emissions scenario is employed. Three regions displayed almost identical park change rates regardless of emission scenario; they are the Northern region, which had identical park change rates when comparing A2 results to B2 results, and the Great Lakes region. The latter also had identical park change rates except using the CGCM2 climate model, which projected one more park to change in the B2 scenario than in the A2 scenario. To demonstrate that other regions are projected to be especially variable in response to future emissions one can look to the Southern region. Here park change rates are projected to be as low as 1-2 parks under B2 conditions, or as high as 1-5 parks under A2 conditions.

Park change rates also varied depending on the GCM which drove the climate component of the modelling process. As shown in **Figure 4.1** each of the GCMs responds differently to different climate forcings and likewise projects different climatic conditions in future time periods. CGCM2 and CSIRO Mk2 model the greatest increase in temperature resulting from changing atmospheric compositions, and as might be expected, vegetation futures developed using these GCMs project greater degrees of biome change within North American national parks than do the vegetation futures that are developed using HadCM3. Biome representation rates vary most by GCM in the Southern region where CSIRO Mk2 projects a change of only one park using both A2 and B2 emissions scenarios. This is strongly contrasted by the vegetation futures generated using CGCM2 which projects either 2 or 5 parks to change by the 2075 – 2085 time period.

Other regions' projections are less impacted by choice of GCM. In particular the Pacific, Mountain and Atlantic regions project differences of only 0.5 parks when comparing the average projected change of each different GCM. For example, in the Mountain region CGCM2 projects biome change to occur within 14.5 parks (14 under B2 and 15 under A2 emissions), whereas both HadCM3 and CSIRO Mk2 project this change rate to be 14. For some regions park change rates appear consistent between the vegetation futures developed using each of the three GCMs while others vary considerably. A combination of two factors explain the sensitivity of a region's parks to different climate scenarios: the responsiveness of the biomes located within a particular region to climate change and the location of the parks within a region. For some biomes the MC1 results project consistent range distribution changes, whether that be significant but consistent change or little-to-no change. Biome specific patterns will be discussed in more detail in the following section. Park location also plays a large role; biomes may experience significant distribution changes between the various climate futures, but unless those changes occur within the boundaries of one of the included parks this change will not be recorded.

4.3 BIOME SPECIFIC PATTERNS

Whereas the previous section concentrated on the geographical distribution of biome change within national parks, this section focuses on the quantification of biome representation change within the two national park systems. The following figures were determined by tabulating the number of parks within which a particular biome appears during each time slice. It is important to note that large parks will often possess more than one type of biome and therefore totals for each time slice will be greater than, not equal to, the number of parks used in the study.

TABLE 4.6 – Biome Representation Change Summary

Biome	Presence (# Parks)	B2 2075 – 2085 Biome Representation Change Rate % (# Parks)			A2 2075 – 2085 Biome Representation Change Rate % (# Parks)		
		CGCM2	CSIRO2	HadCM3	CGCM2	CSIRO2	HadCM3
Arid Woodlands	4	+75% (7)	+125% (9)	+150% (10)	+200% (12)	+200% (12)	+125% (9)
Boreal Conifer Forest	33	-24% (25)	-30% (23)	-21% (26)	- 42% (19)	-36% (21)	-27% (24)
Grasslands	16	-6% (15)	+31% (21)	±0% (16)	+44% (23)	+56% (26)	+38% (22)
Savannah/Woodlands	3	+333% (13)	+100% (6)	+267% (11)	+233% (10)	+133% (7)	+267% (11)
Shrubs/Woodlands	10	-50% (5)	-60% (4)	-60% (4)	-30% (7)	-30% (7)	-50% (5)
Taiga	20	-30% (14)	-30% (14)	-25% (15)	-30% (14)	-55% (9)	-45% (11)
Temperate Evergreen Forest	13	+69% (22)	+62% (21)	+62% (21)	+69% (22)	+54% (20)	+54% (20)
Temperate Mixed Forest	18	+22% (22)	+117% (39)	+33% (24)	+67% (30)	+106% (37)	+33% (24)
Tropical Mixed Forest	3	±0% (3)	±0% (3)	±0% (3)	±0% (3)	±0% (3)	±0% (3)
Tundra	15	-40% (9)	-67% (5)	-40% (9)	-53% (7)	-67% (5)	-47% (8)

Table 4.6 shows how the presence of biomes within North American national parks is projected by MC1 to change by 2075 – 2085. Like regions, the potential impacts that are projected for each biome differ significantly depending both on the physiology of the dominant PFTs in that biome, and on the climate conditions that drive the DGVM. In these results it will be shown how some biomes are expected to better adapt to future climate conditions than others, and how this might impact their distribution in Canadian and American national parks.

Temperate Mixed Forest and Temperate Evergreen Forest are among those biomes which are expected to either be aptly suited to the changing conditions brought about by climate change or situated in areas densely populated by national parks. The former is projected to recede in actual spatial extent, yet is also expected to rise from being present in 18 parks to 22-39 by 2075-2085. The latter is both expanding in range, and in representation resulting in a dramatic projected increase from 13 parks to between 20 and 22 by the same time period. This expansion does not occur in a vacuum though, and just as many biomes are expected to see large increases both in distribution and in representation, others must be displaced by this growth. Tundra is expected to both recede in range and drop from being present in 15 parks, down to somewhere in the neighbourhood of 5 to 9. Boreal Conifer Forest is also expected to show declining representation, despite showing a greater range in most scenarios, which in a similar distribution contraction is expected to drop between 21% and 42% of its current representation – a reduction of seven to fourteen parks.

Boreal Conifer Forest loss is one of the more variable biome representation figures, as the average loss between the A2 scenarios and B2 scenarios is 3.33 parks. For many individual biomes this figure is between zero and one park. As might be expected with increased warming, the colder Boreal Conifer Forest is replaced more frequently by warmer forest biomes (Temperate Evergreen and Temperate Mixed Forest) in the A2 scenarios. Other biomes which showed a larger variability between emissions scenarios were the Grasslands biome which on average varied by six parks. This is likely due to changes in fire disturbance cycles which are expected in many places to become more frequent as a warming climate creates more ideal fire conditions. More frequent fires favour those plants which are able to recover quickly, giving the competitive advantage to grasses over trees. The distribution maps in the **Appendix B** show that in many areas the Grasslands biome replaces cells which used to be dominated by forests. The maps also show that the future range of this biome is just as variable as its park representation rates. Lastly, the representation of Taiga also depends on atmospheric composition more heavily than most other biomes. This variability is directly related with the redistribution of the Boreal Conifer Forest biome in most projections. As the Boreal Conifer Forest biome expands northward into areas once dominated by Taiga, Taiga in turn makes a smaller advancement northward into what is currently modelled as Tundra.

The Savannah and Temperate Evergreen Forest displayed quite the opposite variability within the results. The average A2 versus B2 distributions in both cases was less than one park. The distribution maps suggest that neither of the emissions scenarios used to drive the climate module of MC1 significantly altered the expansion of the two biomes. In the 2075 – 2085 time slices, there is a fair amount of disagreement between all of the vegetation futures regarding the distribution of these two biomes. However, if comparisons are made between the A2 and B2 scenarios of one particular GCM it can be seen that the projected distributions will agree rather closely concerning eventual distributions for these two biomes. This would indicate that it is in fact the GCM that explains more of the variability in Savannah and Temperate Evergreen Forest than emissions levels.

The GCM used to develop vegetation futures introduces another source of variability in vegetation futures and biome change within parks. As mentioned above, both the Savannah and Temperate Evergreen Forest biomes show consistent change dependent on the GCM used in MC1, but Temperate Mixed Forest shows even more dependency. Both HadCM3 vegetation futures agree that in 2075 to 2085 there will be 24 parks which possess Temperate Mixed Forest. In comparison to this, CSIRO Mk2 vegetation futures show that this number should either be 37 or 38 depending on the emissions scenario. Each GCM portrays climate dynamics in unique ways and each will project different reactions to forcing mechanisms such as atmospheric composition or solar insolation. Using multiple GCMs displays the range of plausible climate futures and the results suggest the response of vegetation communities to changing climates will depend largely on which GCM projection most accurately reflects future climatic conditions. There are, of course, errors introduced in the modelling of vegetation responses to these changes, but (assuming that the modelling accurately reflects actual vegetation responses) this suggests that for some biomes future distributions will depend heavily on how successful humankind is at mitigating anthropogenic climate change.

For some biomes, the current modelling would suggest that future presences within the current set of national parks is more or less sealed. Temperate Evergreen Forest and Tropical Mixed Forest illustrate this point very clearly. The latter observed absolutely no biome change, for any vegetation future. Only minimal distribution changes occurred for this biome, ranging from no movement at all to slight expansion into the Florida panhandle and the northern shore of the Gulf of Mexico. All of the parks in this region are located in the southern half of Florida, thus explaining the stability observed in park representation for this biome.

Temperate Evergreen Forest likewise had very consistent park representation in each vegetation future, showing expanding ranges and a consistent increase in park representation that only varied by one or two parks depending on the driving emissions scenario. This expansion occurred primarily in the American half of the Pacific and Mountain regions where it is interspersed with Shrubs/Woodlands, Grasslands, Arid Woodlands, and Savannah/Woodlands. Both HadCM3 and CSIRO Mk2 GCMs projected an increase for Temperate Evergreen Forest from 13 parks to 20-21 parks, and CGCM2 projected 22 parks under either emissions scenario. While the future distributions are not as consistent for Temperate Evergreen Forest as they are for Tropical Mixed Forest, examination of the Modelled Biome Extents in **Appendix B** displays that expansion is consistently projected in the same general areas. The coastal mountains of the Pacific and Mountain regions, particularly the in the northern states and southern British Columbia possess the majority of parks that could experience this change. Distributions also occur at the southern extent of the Boreal Conifer Forest across the continent but these changes do not explain changes found in park representation.

As was mentioned previously, range expansion or contraction explains some of the changes seen in the park representation rates projected for the future, but park locations themselves also play a large role. While for the most part expanding biomes are projected to experience increased representation in future parks and receding biomes will have decreased representation, a few examples are immediately visible where this is not the case. When comparing the distribution maps included in Appendix B with projected park representation many instances can be seen where the location of protected areas plays an equally strong role as the redistribution of the biome in response to climate change. Boreal Conifer Forest for example expands in range in virtually all of the scenarios, yet because of the locations of existing national parks, it loses in overall representation. The opposite is true for Temperate Mixed Forest which increases in representation despite being projected to face range contractions. Tropical Mixed Forest remains stable despite increasing in spatial range in most scenarios. The location of protected areas is thus demonstrated to be of great importance in determining their ability to protect representative samples of biomes seen today, a point that will be elaborated on in the following chapter.

4.4 CHAPTER SUMMARY

In this chapter the results generated from the MC1 DGVM using a number of climatological and emissions scenarios were examined. This was done at the system-level as well as by region and biome type. Regardless of the scenarios utilized, it became readily apparent that change is projected to occur in a significant number of parks across both Canada and the United States, and that there is not a vast difference between scenarios. Park representation change rates rise to an average of over 50% by 2075 - 2085 in all cases, ranging from 53% (of 92 parks) in the most conservative vegetation future to 64% in the most extreme.

Regionally, transitions are expected to concentrate in the Northern provinces and states as well as in mountainous states and provinces located in the western half of the continent. While there is a large degree of variability in the Mountain region's parks the conversion of biome types within the Northern region seems more absolute as there is significantly less variation between scenarios. On the other end of the spectrum, both the Atlantic and Southern regions are projected to remain relatively stable compared to other regions. The Atlantic region possesses the added benefit of low variability between scenarios, thus increasing the confidence that can be held in this projection of limited change. The Southern region alternatively is characterized by significant variance between scenarios, thus making its future much less certain.

Future change is not distributed evenly among the regions, nor is it between the various biomes of North America. Bearing the brunt of projected losses will be the Taiga, Tundra and Shrubs/Woodlands. This is expected to be balanced by dramatic increases in Savannah/Woodlands, Arid Woodlands, Temperate Mixed and Evergreen Forests. The most uncertain future lies with the Grasslands biome which in some scenarios is estimated to lose up to 50% of its presence within parks, all the way to gaining 86% in others. Tropical Mixed

Forest appears to be quite the opposite of such biomes, as not one of the scenarios projected any change from what is modelled for the present.

Having thus presented the results from the MC1 projections, the next chapter endeavours to explain management and policy implications of such changes. Discussion will focus on the necessity of adopting new management objectives for existing parks, and revising park selection and creation guidelines in order to incorporate a landscape in transition, rather than one that will be static in perpetuity.

CHAPTER FIVE: DISCUSSION

5.0 INTRODUCTION

The potential impacts of climate change have caught the attention of those who have an interest in the long-term future of protected areas (Graham, 1988; Peters, 1992; Scott & Suffling, 2000; Hannah et al., 2002). One of the primary concerns is the rapid rate at which the climate is projected to change, compared to the gradual response rate of plants to these changes. Previous studies from simple correlations to complex modelling experiments have reinforced this concern with an array of quantitative results that may diverge on the projected rate and outcome of change, but have come to a relatively universal agreement concerning the widespread extent of expected changes (Box, 1981; Emanuel, Shugart & Stevenson, 1985; Neilson et al., 1992; Beerling et al., 1997; Bachelet et al., 2000; Scott, Malcolm & Lemieux, 2002; Woodward & Lomas, 2004). The findings of this study support the assumption that widespread disruption of current species distributions and assemblages is to be expected, but furthermore, provide temporal estimates of when such changes could be expected – thus also offering a trajectory of expected change.

Subsequent to using a new set of projections in order to develop future estimates of change, and before incorporating these projections into future management decisions it is necessary to place the results of this study into context. As has been stressed throughout this work, the projections developed are not predictions; too many assumptions lay in the formulation of these estimates to feasibly consider them as a future which is expected to occur. Instead, they represent a range of futures which could plausibly occur. Having said this, they are also our best estimation of what the future holds in store, thus a dilemma arises as to how much confidence should be placed on these *projections*. The intention of this chapter is first to identify challenges to the national park systems of the United States and Canada that have been identified as a result of analyzing future projections of vegetation and secondly, to comment on how these projections fit into the context of protected areas management. Before hastily accepting the projected futures, it is important to consider the uncertainties that are inherent in the modelling process and to evaluate how the derived projections can be used to shape future decision-making processes, management strategies, philosophies, and park creation criteria while leaving suitable flexibility to adapt to situations where projections could be inaccurate.

5.1 FOCUS OF SYSTEM GOALS

Numerous studies in the past have indicated both the importance that climate plays in the shaping of our national parks and the importance of addressing this change in our future planning efforts (Halpin, 1997; Hannah et al., 2002; Scott, 2005). Very similar to the findings of Lemieux (2002) which examined Canadian parks in isolation, this study observes that the large majority, between 53 and 64%, of national parks in both Canada and the United States are expected to experience a significant degree of vegetation change by 2075 - 2085. Climate and vegetation modelling inherently possess a large degree of uncertainty and thus their results can only be viewed as plausible outcomes which could occur. However, despite a large body of literature on the subject of climate change appearing in the early 1980s (Box, 1981; Emanuel et al., 1985; Peters & Darling, 1985) it was not until ten years later, in the *State of the Parks* publication (Parks Canada, 1998), that climate change was acknowledged as a significant stressor in seven of 36 national parks. Despite this lag, there is significantly more recognition within Parks Canada publications than has been produced by the United States National Park Service.

The National Parks Service has produced an even smaller body of literature concerning climate change as a threat to American national parks and towards preserving ecological health that could be compromised because of it. In its current draft of *Management Policies* (NPS, 2006) there are several references to leaving resources unimpaired for future generations with very little in the way explaining what "impairment" is. Also within its *Management Policies* the NPS mission statement does little more than to ensure the preservation of resources so that they may inspire, teach, and entertain those who would use the parks (2006). Other publications by the NPS regarding climate change include little more than a small number of "Outreach Materials" for interpretive tours and classroom use. Little has been published in the way of environment screening or scientific assessment of the potential impacts of climate change or on the adaptation of park management to such changes. This lack of attention illustrates that more recognition should be given to the threats of climate change both in Canada, and the United States – the same could be said on a global scale. It will be important for the conservation of our natural systems to shift the focus of the management of our parks toward a greater emphasis on the dynamics of our natural systems and their reactions to changing climatic conditions.

Even in the instances where climate change has been acknowledged as a significant threat to natural systems within national parks, considerable difficulty lies in taking explicit action at the park system level and the slow movement of other sectors certainly has not encouraged proactive measures. Climate change has made its way into the park system plans of either country (Parks Canada, 1997; NPS, 2006); instead responses to climate-induced dynamics within parks has largely been piecemeal, and in reaction to changing conditions rather than in anticipation of them. As more examples of climate-induced stresses on natural systems manifest themselves, such as polar bear mortalities in Wapusk National Park, it becomes more evident that reactions to climate change will ideally transcend the individualistic responses that characterize today’s actions. Instead, effective park management will require well planned system-wide (or even inter-system) efforts based on a foundation of new management foci that explicitly include climate-induced dynamics.

Unintentional conflicts between management goals and management actions have also occurred because of the omission of climate change from park management plans. Species re-introductions and fire restoration projects have occurred in many parks (Parks Canada, 2000), but there is no clear explanation of how these activities are incorporating the possibility of both climate and biome change into management objectives. As an example, forest fire suppression has been cited by Parks Canada as having a significant ecological impact in Pukaskwa National Park on the north shore of Lake Superior (Parks Canada, 1998). In 2005 the prescribed burn policy within Pukaskwa National Park was revisited (Parks Canada, 2006), and while re-introducing fires is expected to assist in re-establishing natural disturbance cycles that have been suppressed, it may also increase the rate at which plants from warmer ecoregions will have the opportunity to colonize the area. Biome distributions from eight of twelve scenarios developed from the MC1 model project that by the decade of 2075 - 2085 this park will no longer possess boreal forest. Equilibrium-constrained modelling studies conducted by Lemieux and Scott, using multiple EGVMs reach a similar conclusion that boreal forest is not expected to persist in Pukaskwa National Park (2005). This process of transition will most likely be hastened as more fires are both allowed to take place and are lit as part of the current fire management protocol for the park. This limits the likelihood that the park will function for all time a representative sample of the current Natural Region it currently preserving (Parks Canada, 1997), as the park will no longer possess the boreal conifer forest that it was originally established to protect. From this example it becomes clear that climate change will need to receive more attention in the formation of management policies if an effective response to climate change is to occur.

The Pukaskwa National Park example is only one of many such instances, however, where Parks Canada will soon have to address the growing disparity between many of its static future goals and the dynamic nature of the impact of climate change upon national parks. Ensuring the maintenance of a representative park system will involve a battle of increasing intensity against the transient character of natural systems, as species that would naturally be displaced need re-introduction and natural cycles which are bound to occur, such as fire, need to be controlled in order to preserve contemporary conditions. Alternatively, if forces of natural change are left unaltered and parks are left as arenas in which natural change can occur unhindered by the actions of humankind, there is similarly large potential for undesirable natural changes to occur. Regardless of how Parks Canada approaches the changes that are projected to occur, it will be to the benefit of the system as a whole if a concerted effort is made to ensure that the actions of one park will act to complement the actions taken by others within the system, and between national systems.

The National Park Service of the United States likewise fails to mention climate change within its management policies (NPS, 2006). Rather, the closest semblance to recognition of climate change impact derives from ambiguous statements such as: “We preserve unimpaired the natural and cultural resources and values of the national park system for the enjoyment, education, and inspiration of this and future generations” (NPS, 2006, p. 2). This leaves a great deal to interpretation: such as, what is considered to be a resource? This word carries with it the connotation that an ecosystem function may not be considered a resource because it is not immediately useful to humankind, and this is exacerbated by the second half of the statement which indicates that the primary reason resources are to be preserved is to entertain, enlighten or inspire people, rather than to promote ecological health, integrity or well-being. Further examination of management policies yields no more information as to how the United States National Park System is to respond to climate change. Additionally, rather than focusing on the health, integrity - or any other such word for well-being - of the biotic components within the park system, preservation of resources for human utility is emphasized. Thus in a response context, this would also imply that the most suitable management response to climate change would be the one that produces the most desirable outcome for human utility. It is difficult to say what different park managers will deem “desirable”.

Paradoxically, this same vagueness could be valuable for the integration of climate change response into management policies of the United States National Park System. With no strong definition of what “impairment” relates to it could be argued that any anthropogenic climate change is a form of impairment, or similarly, it could be argued that only aspects of climate change that are deemed as “negative” are impairments. Notably this creates the desire for conclusive policies concerning which aspects of climate change are indeed impairments and which are not. This vagueness, however, also allows for an adaptive approach that offers a large degree of flexibility in order to formulate responses to climate change based on evolving scientific knowledge and predictive abilities. Having a large degree of flexibility in this interpretation will optimistically allow dynamic management responses to upcoming challenges, but it cannot be overlooked that this same freedom in interpretation could allow the issues accompanying future change to be effectively ignored.

Both Parks Canada and the National Park System, in addition to maintaining as much flexibility as possible to deal with unforeseen circumstance, would best serve their goals of resource preservation by continuing examination of alternative foci suggested in the literature. Two principles which have experienced both past and current consideration include seeking to increase connectivity between protected areas, along with a more recent and complementary principle: seeking to incorporate areas outside of protected areas into planning efforts. These areas, commonly referred to as the “matrix,” will play an increasing role in allowing biotic systems to respond naturally to climate change as the proportion of developed lands in North America continues to intensify.

Increasing understanding of climate processes, and the ways in which they are projected to change, emphasizes the importance of allowing natural systems to have unimpaired *responses*. The current practice of assuming biogeographical stability is theoretically faulty and attempting to maintain current vegetation distributions within existing parks, or striving to complete a system based on these assumptions, would not only involve tremendous effort but would have questionable benefits and uncertain impacts (Hannah & Hansen, 2005; Scott, 2005; Scott, Malcolm & Lemieux, 2002). Instead of focusing on managing for – or with the assumption of – stability, seeking to ensure that future parks are situated so as to facilitate species movement between them would provide the benefit of allowing natural systems to respond to changing conditions as they have so many times in the past (Overpeck et al., 2002). The knowledge acquired from modelling efforts such as those found in this study will improve our ability to plan for such changes. Employing a number of projections from MC1 and other DGVMs as such systems become available will allow for estimates to be made for future plant distributions and the creation of planned "pathways" for natural adjustment to take place. Further research is necessary both for the improvement of our predictive ability concerning future distributions, as well as in planning for implementation of such networks. Further, it will enhance the ability to respond if all does not go according to plan. This will entail both scientific and social research into the policy tools and incentives which will allow for flexible management plans in the future.

Among others, Fonseca et al. (2005) and Hannah and Salm (2005) suggest that the successful management of tomorrow's parks will also depend on management of the areas between protected areas. Recent additions to the literature have stressed that beyond situating new parks and planning existing parks for increased connectivity, it is important to discard the view that parks are "islands" in a sea of developed areas and acknowledge that there is in fact a "matrix" of land uses and corresponding development intensity. Areas such as tree plantations will most certainly be more conducive to allowing natural species to occupy the area than residential or commercial developments. Following on this line of reasoning, if it is possible to identify biomes that are expected to be negatively impacted by climate change using projective models, it might also be feasible to use this knowledge in order to target management efforts to threatened parks and their surroundings in order to facilitate dispersion. Incorporating surrounding land uses into the management plans of national parks will be an important next step in ensuring that the conservation efforts of today continue to play a valuable role in the future.

The concepts mentioned above – allowing unimpaired responses and managing areas between protected areas – stress the importance of connectivity and of natural response to changing conditions. However, as noted, neither the Canadian nor the American national park systems have *explicitly* included climate change in their system plans. Instead, they have avoided the issue in the American context and have been slow to adapt in the Canadian context. Passive management may allow for ecosystems to respond naturally, but it does little to protect those species that are endangered or threatened. Actively working to maintain static conditions thus may be a lost cause and a terrible expense of limited resources and capital that could be better allocated. If climate changes continue to occur as projected, the glaring deficiencies in today's park system policies and goals will continue to manifest themselves in more obvious and harmful ways, and will put into question the effectiveness of contemporary conservation efforts. In summary, both national systems will hopefully invest time and resources into examining the probable impacts of climate change and determining alternative foci in their policies and goals to help to address future changes.

5.2 SITE SELECTION REFINEMENT

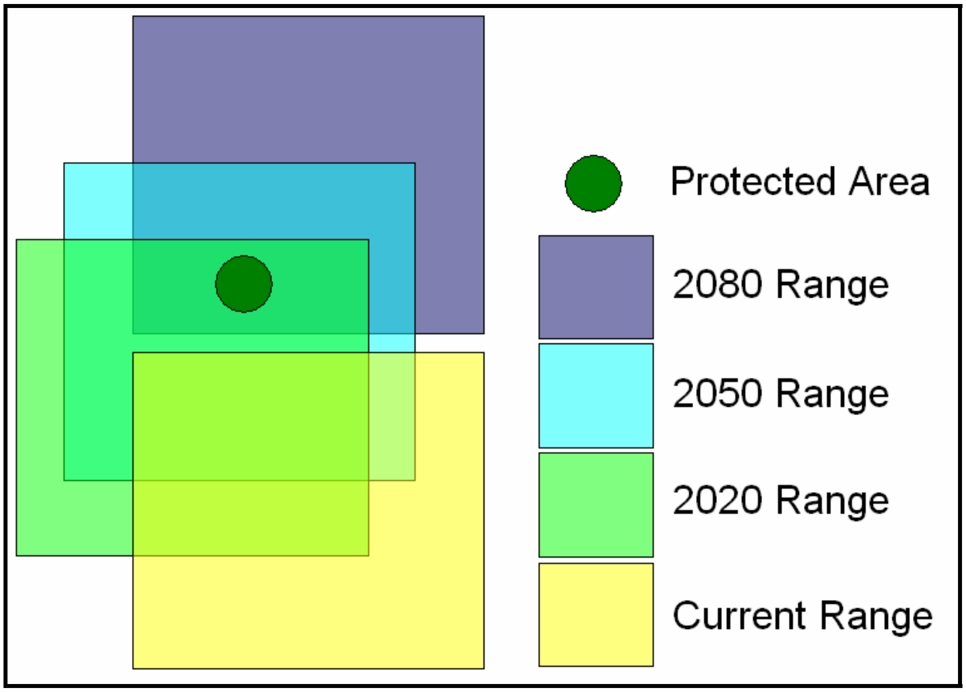
Intrinsic to any park system are criteria and procedures which detail the process by which locations for new parks are selected. The selection processes in place today will be critical to the future success of North America's park systems. Currently large expanses of undeveloped land can still be found in western and northern portions of Canada and the United States, a luxury not found in many other industrialized countries. However, as populations and the demand for resources and energy increases, this pool of available lands is rapidly diminishing. Despite how complicated the selection process may seem today, with multiple stakeholders and conflicting views of land use priorities, the process will only become more difficult as available lands are appropriated for other uses. In order to maximize the efficacy of North American park systems in the future it has been stated by many that it is thereby highly recommended to have a concise vision of what our parks are to accomplish in the future, to make sure that site selections today reflect these future goals, and ensure that selection processes explicitly include climate change as a consideration.

While Parks Canada has made observable progress in recognizing and responding to risks and impacts of climate change throughout the park system – see *Report of the Panel on the Ecological Integrity of Canada's National Parks* (2000), where climate change is officially recognized as a significant threat in many parks – neither Parks Canada nor the National Park Service have explicitly included climate change into the park selection and creation process.

This leaves both park systems in a dangerous position where assumptions of biogeographical stability have been made – consciously or not – which will likely result in inadequate park systems that are unable to provide important territory for the natural response of vegetation species. This problem is compounded by two factors which make the projected climate change of the future more hazardous than previous changes: unprecedented rates of change and a continually decreasing amount of undeveloped land available where natural responses can occur. It is thereby crucial not only that national park systems adopt climate change considerations into a refined set of site selection processes for the future, but to use these refined processes to establish parks which will protect future natural responses in the best way possible with the knowledge available. It will not be possible to go back and "re-select" areas which are to become parks, so decisions should be made soon and they must be made to the best of our current ability.

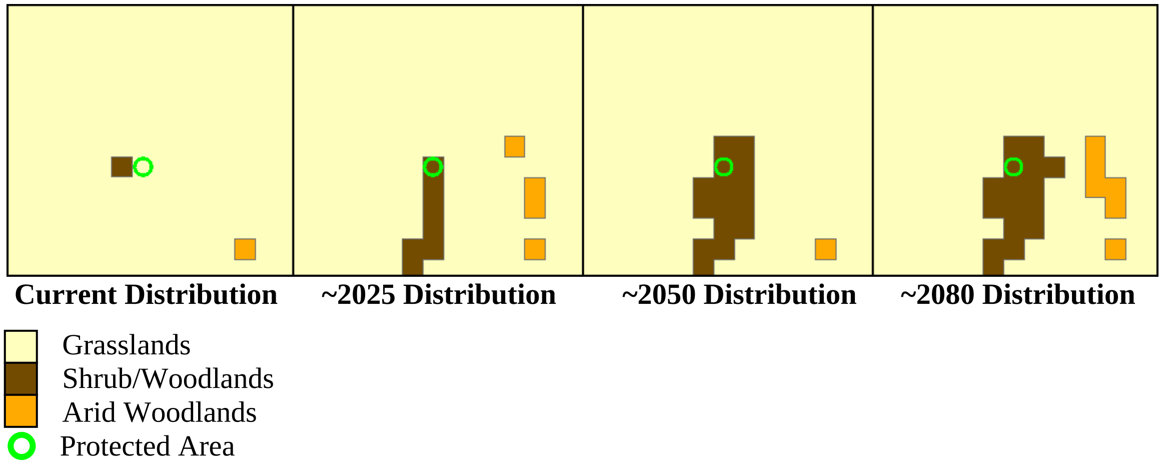
The insights gleaned from the MC1 simulations of vegetation response to projected climate change occupy an advantageous position from which to assist in the selection of new protected areas. Using just one DGVM, it is possible to make estimates as to which areas are likely to remain stable, which are likely to change, and how those areas are likely to change. This ability will be complemented in the very near future with further availability of additional DGVM simulations. Two distinct possibilities - assisted transition and selected refugia – will be discussed in terms of using projected distribution due to climate change for locating future parks and integration into other management objectives. Assisted transition, as seen below in **Figure 5.1**, illustrates how park locations can be situated in order to facilitate the transition from one biome to another. This is a preliminary framework for selecting future protected areas. It is derived from DGVM vegetation projections and would identify locations where transitional processes could facilitate the protection of small segments of a contracting biome.

FIGURE 5.1 – Assisted Transition



In this figure, a segment of a biome is projected to drift in a general northward direction. While the protected area in the diagram is not situated in the sample biome's current range, the segment is expected to occupy that area soon (by 2015-2025 according to projections) and to persist in this location until 2075 - 2085 or later. The intention of placing the park in this location is to provide an area within which natural transitions can be protected, or augmented using active management if desired. This strategy could be used to preserve healthy populations of a biome projected to lose representation as a result of climate change. From the analysis chapter above, it can be seen that the Shrub/Woodlands biome is expected to suffer from such a loss. **Figure 5.2** illustrates how the assisted transition method of park selection could prove beneficial to the preservation of a Shrubs/Woodlands assemblage of species. This example was taken from a sample distribution found in one of the MC1 vegetation futures and is located in northern Texas.

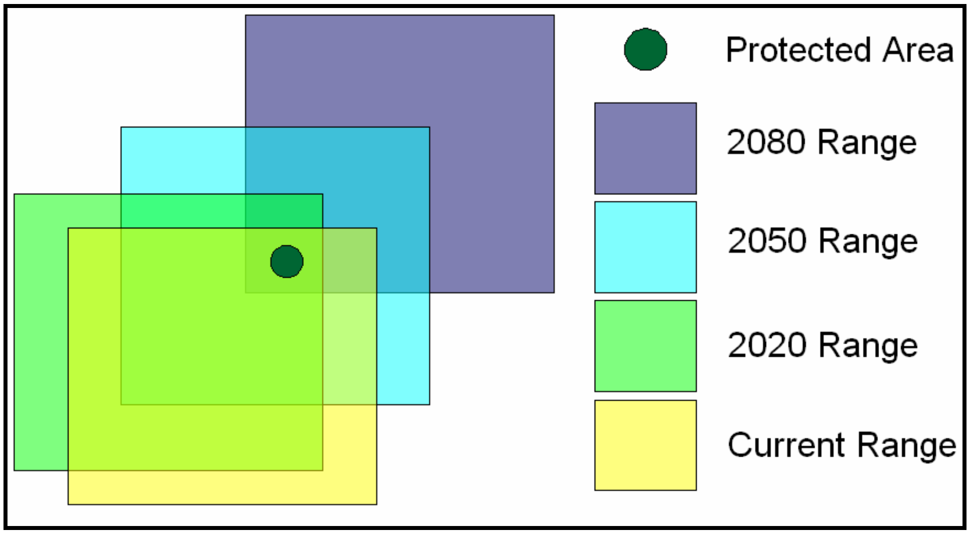
FIGURE 5.2 – Assisted Transition Example



In this scenario, the brown squares represent Shrubs/Woodlands areas found to be decreasing in representation throughout North American parks as time progresses. As can be seen, the park is situated to encourage the transition from Grasslands (which are expected to increase in representation) to Shrub/Woodlands. This location could be passively managed to allow a natural transition, or be actively assisted if such action is deemed necessary or desirable. This site selection strategy is most likely suited to moderate or warm temperature biomes which are expected to experience range contractions due to other more competitive species moving in. Thus the intention is to preserve one desired biome at the expense of another expanding biome.

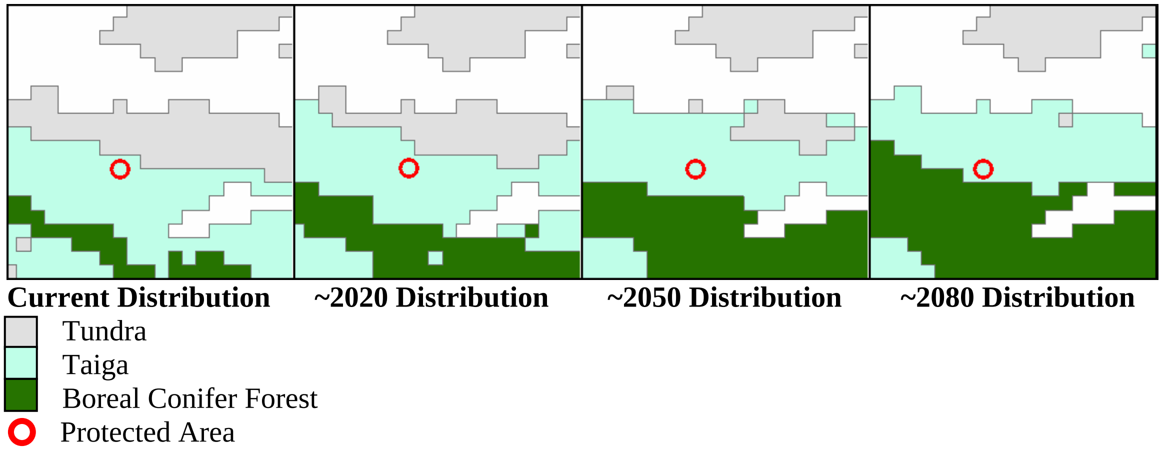
In colder biomes, a different scenario will likely prove more useful, as both the advancing and retreating biomes are declining in overall representation. As an example, Taiga may expand its northern boundaries into what was previously Tundra area, but this expansion is not expected to match the rate at which Boreal Conifer Forest is causing its southern boundaries to recede. In a situation where assisting one biome’s natural responses is projected to occur at the expense of another receding biome, it will be more useful to concentrate on preserving areas of stability. The areas referred to commonly in biogeography literature as “refugia” are those likely to remain – and most often have remained – relatively stable compared to other regions. By selecting stable refugia areas for the placement of parks, the goal of preserving representative samples of contemporary ecosystems within a nation or continent likely will be more tenable, if only temporarily. **Figure 5.3** provides an illustrated example of such a placement strategy for selecting future national parks.

FIGURE 5.3 – Selected Refugia



It would be accepted that refugia may eventually change, but situating the protected area within a zone that is projected to remain stable for the extent of the modelled period would maximize the potential time available to make such a transition. **Figure 5.4**, below, is an actual example of how this strategy might be applied in the Northwest Territories of Canada.

FIGURE 5.4 – Selected Refugia Example



Maximizing response time reduces the stress placed upon a threatened biome. Many have pointed out that the problem is not in fact that a response has to be made as species are constantly responding to changing conditions. Rather, it is the rate at which anthropogenic climate change is forcing the responses to take place that is problematic (Huntley, 2005; Malcolm et al., 2005; Thomas, 2005). Extra time may be what is necessary in order for a) receding species to respond naturally, b) for society to curb its greenhouse gas emissions or c) for park managers to undertake active management solutions such as relocation. It would also provide time to evaluate which management alternatives would likely have the most desirable effects.

One benefit of revising site selection methods to incorporate climate change is that site selection methods, for the most part, do not dictate corresponding management styles and thus can be more easily incorporated into any system plan. For example, using the selected refugia method does not dictate whether park managers take a passive, active or resistant management approach in regards to climate change impacts. Once the park is situated it can be managed just as other parks are; following the selected refugia example, a park could be placed in an area expected to remain Taiga for a prolonged period of time. During this time natural processes could be allowed to take place freely, be enhanced, or restrained. All three management styles, originally proposed by Suffling and Scott, 2002, would benefit from having the extra time made available by wise park placement. The same holds true for the assisted transition method: natural phenomena may be allowed to take place, they may be enhanced, or they can be restrained. In the latter case, natural processes may be slowed using suppressive measures in order to provide an adequate response time for involved species.

Given the lack of imposed management requirements that accompany the incorporation of climate change into park selection criteria, there is little reason not to explicitly include it in the process. It can be argued that the accuracy of the models comes into question over extended periods of time. This is easily countered, however, with the argument that climate change is occurring – whether or not it is anthropogenic or not is irrelevant to this discussion – and we may either proceed blindly or we can use the best available estimate which, as it happens, has been generated from years of scientific observation and research. The cost of revising current park selection criteria will no doubt be smaller than the future cost of responding to changes in a park system where climate change was ignored.

5.3 INTENSITY OF PARK MANAGEMENT

The maps shown in the analysis chapter demonstrate that a significant portion of the current Plant Functional Type (PFT) distributions are expected to change as a result of climate change. This is consistently observed regardless of which emissions scenario is used, which indicates that park management decisions will have to react to these changes whether they are officially addressed in management plans or not. Scott, Malcolm and Lemieux (2002) situate management responses within two typified response strategies. The first is passive management – where natural phenomena are left to take their course unaltered, as much as possible, by human influence. The second is active management – where management actions are undertaken which attempt to actively assist species in their response to change events. Such strategies include "wildfire management strategies, individual species management plans, contingencies for species at risk, non-native species management programmes and species reintroduction programmes" (Scott, Malcolm & Lemieux, 2002, p. 482) A third additional strategy fits into this framework; static management would also take an active role in manipulating natural processes using the previously described tools, but with the intention of resisting changes instead of encouraging them. Any mixture of all of the above strategies could be taking place within individual park management plans at present. This raises important questions such as how current management actions are addressing these changes, whether park managers are willing to interfere with natural processes, and the degree of time, resources, and knowledge necessary to generate the desirable effects.

The answers to these questions will vary among individual parks as each faces a unique combination of species, threats, changes, resources and staff. Consequently, it would be inappropriate to prescribe one universal response strategy to all parks within any given system. Rather, the variables within each park will need to be assessed at the regional or, more likely, individual park level. In order to evoke some sort of effective change strategy, careful consideration must first be made about what approach will be taken towards changes – active, passive, static, or a mixture – and secondly about the resources and staff available to a park in order evoke some sort of effective change strategy. In many parks facing limited resources or expansive areas of land, active management solutions may be untenable, thus allowing only responses that are passive or near-passive in nature. For those parks with the resources and staff to mount an effective, active management programme there are still considerations that have to be made concerning *which* programmes would be appropriate or desirable in all aspects, or which alternatives would produce the best results while requiring the least amount of a limited set of resources.

Dynamic vegetation models are a valuable resource which can be drawn upon to help answer such questions. Increasingly, management literature is showing that changes outside of park boundaries have a significant impact on the decisions being made within park boundaries (Fonseca et al., 2005; Kupfer et al., 2006). DGVM outputs can provide a general context to park managers of not only of the changes to be expected for the park itself, but also changes expected to occur within their region. As each region, and ultimately each park, will respond in varying ways to a climate characterized by continuing change, it follows that individual parks should ideally have the freedom to adapt individually to these spatially variable changes. Provided with knowledge concerning the potential composition of their park by an ensemble of modelling projections, more informed decisions could be made by individual park managers concerning the management of disturbances and the way in which the park will interact with its surroundings – either passively allowing natural disturbance cycles to take place, or manipulating them in order to further the protection of threatened species.

The individual response of parks to changing conditions should not be mistaken for an each-to-their-own approach. Just as no universal solution can be appropriate for every park, isolationist solutions are equally inappropriate. As Hannah and Salm (2005) point out, a corridor connecting two protected areas will only function if one area is managing species in order to facilitate dispersal while the other is managing to encourage suitable habitat changes. If neither is providing the dispersing species, or alternatively, if both are suppressing climate-induced change, then protected areas will truly just be islands of wilderness. Fonseca, Sechrest and Oglethorpe (2005) contribute to this argument, adding that the most effective park management systems will be those which are precise enough for each actor within the system to know what role they play, yet are flexible enough for each to react individually within this role. As can be seen, a fine balance must be drawn in order to avoid park management becoming either too constrictive or too liberal. Additionally, both system and individual park managers will benefit from access to vegetation response projections – where further decisions can be made as to whether to resist, embrace, or simply monitor natural disturbances and change.

In this study it has been demonstrated how the method in which fire is addressed within a DGVM will significantly influence the subsequent projections that are produced. This information could be effectively integrated into a management context by generating managed fire scenarios. For example, three park management response schemes developed by Suffling and Scott (2002): passive, active or static could be used as a guideline in order to develop possible fire management schemes. A passive management strategy, would allow for fires to take place as they naturally occur. This method has been included in this study in all dynamic fire scenarios; these scenarios include a process-based representation of fire behaviour which responds to changing climate conditions. Alternatively, in an active management context where controlled burns are taking place on a regular basis, fires could, for example, be modelled to recur every five years. Another management strategy option could be complete suppression of any fire, and in this scenario no fire would be included in the modelling process.. Any of the three disturbance response strategies could be readily integrated into DGVM simulations, thus supplying estimations of how park vegetation might respond to various fire management schemes.

The benefits that would be provided by the development of these fire management schemes in a parks administration context are immediately clear. Having an estimation of how different fire management schemes would impact on a park's vegetation would assist park managers in deciding the level of management intensity likely to be required in order to attain park goals, or even whether any action is appropriate. For example, a park currently dominated by savannah, and projected to remain stable, might deem that its current fire suppression program is not the most appropriate course of action as it would cause the eventual replacement of savannah by woodland or forest. The various projections may also serve to suggest more appropriate courses of action. Ideally, the projected impacts of various DGVM scenarios could be used beyond advising disturbance management policies and be extended to evaluation and possible restructuring of park objectives and the methods by which these goals are pursued.

When examining the results of DGVM projections, care should be taken by the management bodies of individual parks to carefully weigh the projections both against one another and against the knowledge of local specialists. Their findings could indicate that current goals are likely to be too resource-intensive to sustain and call for a re-evaluation. As mentioned, active management requires intensive capital and labour expenditures, but it also necessitates a strong scientific understanding of natural processes at work within a park. This may not be available – or feasible to acquire within a reasonable timeframe. Alternatively, adopting a passive approach may result in the loss of culturally-valuable species – such as the polar bear or elk. Such an approach may be difficult to support both from an ecological and a political/public involvement perspective (Scott, Malcolm & Lemieux, 2002). In summary, DGVM projections should be viewed as one of many tools available to park managers in guiding future decision-making processes, with the potential to estimate what changes lie ahead and to show how these changes can be influenced by today's management decisions. It will be up to park managers to decide how intensive management actions must be in order to accomplish their goals, and to determine whether these goals are in fact tenable over the long run.

5.4 SCALE OF MANAGEMENT

Climate change has been observed to have had dramatic impacts on species distributions in the 20th century. Among other studies, Parmesan (2005) provides a significant review of many studies which have documented these changes and concludes that there is already strong evidence of the persistent and widespread impacts of climate change. The findings of this thesis indicate that expansive changes are expected to continue, with more than half of North America's national parks likely to experience significant changes in dominant vegetation forms. Previous modelling studies also support the belief that the 21st century will be one dominated by ecological dynamicism (Bachelet, Neilson et al., 2001; Bonan et al., 2003; Lemieux, 2002). Management responses should reflect the scale of projected changes – changes that will range from local to international.

The most drastic impacts of climate change are expected to occur in the high latitudes of the northern hemisphere. This leads to the assumption that the national, state, or provincial parks of North America will all be in a similar situation of having to adapt management policies to a set of constantly changing conditions. The far-reaching impacts of climate change on vegetation communities will subsequently call for an integrated management response which coordinates the efforts of North America's protected areas (Peters, 1992; Lovejoy, 2005). This integration will be most beneficial if it includes not only the cooperation of individual parks within a region but a large scale planning and coordination of management efforts between parks and at the national and international levels. The most vital aspects of management response to climate change is the adoption of long-term planning efforts by park system managers which reflect the time scales in which climate changes occur: coordinate management responses on a larger spatial scale; and increase the degree of institutional cooperation between park systems at the local, provincial/state, and national levels.

Short term management plans which focus on time periods of a decade or less will not sufficiently ensure the long-term protection of North America's park systems. Short term management plans alone are prone to omitting long term patterns of change from the planning process, and are more apt to respond only to short term, dramatic events such as epidemics or other disturbances. Hannah and Salm (2005) suggest that longer time frame outlooks (such as 30-50 years and 80-100 years) will provide the necessary foresight for plans which will operate on a scale closer to that in which climate change occurs, in addition to having the benefit of incorporating GCM projections which are produced at this scale. The addition of long term plans should contribute to, not be taken to replace, short term management plans which provide needed flexibility in responding to more immediate concerns. By including short term response strategies into park management, it is possible to react to new conditions and events which could be a consequence of climate change or might simply be due to annual variability (Hannah & Salm, 2005). By looking further into the future park managers can adapt to long term changes, but one park acting in isolation does not necessarily ensure the best protection of today's resources. Park managers should also monitor the changes which are happening in neighbouring parks.

Just as park management operations should match the temporal extent of climate change, collaboration on a grander spatial scale will also contribute greatly to the resiliency of North America's parks. In order to facilitate the response of natural systems to changing conditions, park management should strive to provide an environment where such reactions can occur. This will occur when a coordinated effort between parks exists where each park has a role to play. Park management plans at this scale should ideally possess:

> [the] precision for all conservation actors to understand their respective roles in managing, monitoring, and adapting to dynamic change [but must also be] sufficiently open to permit individual actors to design dynamic responses specific to their site or management mandate (Hannah & Hansen, 2005, p. 338).

If collaboration fails to occur, neighbouring parks will be much more likely to produce gaps that would otherwise be minimized. The seeds of collaboration are visible; Parks Canada already has a strong, explicit, focus on providing a representative park system that will no doubt serve as a strong foundation from which the coordination of a system-wide response strategy can be developed. However, the system includes only Canadian national parks, and does not address other Canadian protected areas, such as provincial parks, nor those of the United States.

Thus the benefits of collaboration not only between parks within a system, but also between systems should not be overlooked. In an effort to match the scale at which impacts will be felt from climate change, it is important to coordinate efforts on a biological scale rather than a political one. The natural systems within which species are included do not respect the arbitrary borders of states, provinces or nations and so, as much as possible, these boundaries should not be the primary influence behind park planning and management. Through the inclusion of all parks (from municipal to national) within a biological region, and a set of coordinated goals and objectives, aspects such as: planned redundancy in landscape representation; connectivity; migration and dispersal could be optimized to provide ideal conditions for affected species to respond to climatic change. Groves (2002) supports this opinion by arguing that the “targets” or goals of protected areas will vary depending on what species are present and their general condition. Since the distribution of these species varies, those protected areas that share species should likewise have similar targets for conservation. By proxy this leads to a regional collection of associated parks based on the presence of biological species, rather than political boundaries.

However ideal, the unrestricted collaboration of protected areas based on ecoregions is not likely to occur in the near future. As Scott (2005) points out, Parks Canada is not able to develop a complete contingency response to climate change without legislative changes – so to imagine a protected area system that transcends political boundaries would require considerable transformation of the current national park systems of North America. Because the jurisdiction of protected areas in North America lies with two countries, each possessing many levels of government, the closest foreseeable scenario is one of close cooperation. To begin with, both systems should start explicitly addressing climate change within their own policy frameworks. Then methods of fostering close working relationships between parks at different jurisdictional levels and between countries will be crucial for mounting an effective response to climate change and its impacts for protected areas. Finally, the creation of regional steering committees (based on ecoregions) could serve as a vehicle by which common goals and objectives can be identified and integrated responses developed.

The impacts and natural responses of species pose a great problem both now and to the future of North America's national park systems. Due to the scale of the problem, an unprecedented degree of collaboration between different park systems will become more important to an integrated response. DGVM models are situated to greatly aid this cause by providing both spatial and temporal information about the projected responses of major plant functional types. This information can assist park managers in deciding what species might become threatened in the future and those which are likely to prosper – leading in turn to better choices in the establishment of new protected areas, and the management of existing ones. It must be remembered that projections are merely plausible outcomes of an unpredictable future, but by looking at several possible outcomes it is possible to identify those that are most likely. Consequently, while the projections of DGVMs can play a valuable role in any large protected areas network, it is also important that parks and park managers retain the flexibility to adapt to new estimates as errors become evident and as better information becomes available.

5.5 MANAGEMENT FLEXIBILITY & THE UTILIZATION OF DGVM PROJECTIONS

Based on the information that has been presented in this study, it is already evident that the mission statements of many protected areas may be compromised by future climatic change. The example of Pukaskwa National Park has demonstrated the issues that may arise with fixed biogeographical goals. On the other hand, mission statements of many American national parks closely reflect the sentiment of the National Park Service itself; "preserv[ing] unimpaired the natural and cultural resources and values of the national park system for the enjoyment, education, and inspiration of this and future generations" (NPS, 2006). While the omission of a specific ecological goal might lead to questions concerning how ecological challenges are to be confronted, abstaining from setting specific goals ironically has also left a larger degree of freedom necessary to react to unforeseen changes. This study has shown that the majority of national parks will experience significant changes in biome representations, and assuming that this comes to pass, this freedom will be valuable in the development of management responses in individual parks.

Results from MC1 analysis show that there can be dramatic differences between emissions scenarios and the corresponding response of vegetation distribution. No matter how well biological or disturbance events are modelled, the amount of climate change which is to be experienced will vary dramatically based on human emissions (IPCC, 2001). To this end, even with the accurate modelling of biological processes, constant re-calibration of models will produce more reliable results – and almost certainly, different projections. This will also likely ensure the need for individual parks and park systems alike to reconsider goals and objectives on a continual basis, but also will require the freedom to act on new information, change management directives, or even reverse past actions. As Scott and Lemieux (2005) point out, this will likely entail legislative action in the case of Canadian national parks, along with correspondingly altering goals and mission statements within the United States.

They also report that, at present there are a number of cases where Canadian national parks have chosen to pursue goals which are, according to projections, not likely to be tenable in a future of climate change – citing Pukaskwa National Park once again as a specific example. Puskaskwa is dedicated to preserving a representative sample of the central boreal uplands while being projected to represent something closer to Temperate Mixed Forest in the future. MC1 projects that in the majority of emissions and climate scenarios, the park will no longer possess such a species assemblage. This example further illustrates the importance of using new information for more efficient management responses and the necessity of adapting park goals to new information.

The projections produced by MC1 and discussed in this work demonstrate that DGVMs have met with relative success in modelling the mechanistic relationships that affect vegetation distribution. This can be seen in the representation of modern biome distributions which are produced in the modelling process, and the strong resemblance that these distributions have to actual distributions. This agreement has been quantified in the past with other DGVMs (Bonan et al., 2003; Cramer et al., 2001) and using the DISCovery dataset – derived from satellite observations – similar comparisons could be made to the projections of this study. There are, of course, discrepancies between the modelled distributions and those recorded in the DISCovery dataset, which emphasizes that projected distributions must be viewed as what is "likely" rather than what will definitely come to be.

By their very nature DGVM projections are simplifications of the complex processes and relationships which form biological dynamics, many of which are beyond contemporary modelling ability. For this reason, it can be questioned how useful it is to employ model projections, which are saturated with uncertainties, or even argued that such models should not play a significant role in reshaping park mission statements and decision-making processes. Betts and Shugart (2005) point out that disturbance events play a large role in shaping the dominant vegetation type in many habitats, yet the modelling of such events is debatably less advanced than other physiological and ecological processes and are in need of improvement. Such refinement of the models which provide input to DGVMs, such as GCMs and emissions scenarios, is critical to the incorporation of DGVM projections into policy management guidelines. Computer-based modelling must not come to embody the decision-making process, but rather support those who are involved in the decision-making process. Projections must also be tested and viewed with skepticism in order to detect oversights, but this skepticism must be checked before the value of these projections is dismissed.

Dynamic Global Vegetation Models currently represent the state-of-the-science understanding of how different plant-function groups will respond to climate change. A great deal of beneficial information can now be provided to park stakeholders who are willing to utilize what is available. Decisions made with a limited vision of the future will be of much greater value than those which are made in the absence of such vision. Hannah et al. (2002) explain that particularly in the areas of reserve site selection and planning for connectivity between parks, those protected area systems which formulate plans with explicit regard to climate change will perform with much greater effect than those planned using other criteria.

Along with DGVMs, there are many additional modelling methods which simulate vegetation dynamics (such as GAP models) which will complement the projections of DGVMs. The Inter-governmental Panel on Climate Change supports their use, stating that employing the results of many model scenarios (and by extension many different modelling methods) will result in the best use of the included models. This provides not only an estimation of the future conditions most likely to occur, but also the range of conditions that might be expected. Strong agreement between models developed independently will provide a strong argument for accepting projected conditions as likely to occur. It will be the professional judgment of those who are responsible for interpreting this information to choose whether the projected outcomes are likely, whether they are feasible, and how well they represent probable future conditions – and subsequently to judge how this knowledge will be best utilized in planning for the future efficacy of affected parks and park systems.

Further to the uncertainties intrinsic to DGVMs, there is the matter of data resolution to consider in their usage. While there is no limit to which they may be scaled – from global to localized sites – the data used for their inputs heavily affects the scale to which they are accurate and to which they should be used. As an example, this study employed a 0.5 decimal degree grid in order to model the continental response of various Plant Function Types to future climate conditions. Spatial constraints for temperature, precipitation and soil data as well as "species resolution," limited to 22 Plant Functional Types, hamper the effectiveness to which these projections could be used for individual park planning. At the scale used in this study, the intent is to demonstrate how this information can be used in a park system planning context. Conversely, for those parks with access to local soil and climatological data, the MC1 model is quite capable of modelling processes within parks and has been used in a number of studies at Wind Cave National Park in the United States (Bachelet et al., 2000; Bachelet, Neilson et al., 2001). Without access to this data, however, the results of this study are likely too coarse for direct use with individual parks. Instead it is recommended that local experts and park managers view this information as a general trend for their region. They will have access to both local knowledge and resources required to interpret how model projections will likely correspond with site-specific responses. Local experts can, however, use these results in order to estimate the vegetation responses likely to take place in the regions surrounding individual parks.

As discussed above in the Literature Review chapter, both fixed and transient elements will be vital components of complete protected areas systems in the future. As an alternative to using DGVM projections as guides to the management of the fixed elements of a park system, projections have another possible function in assisting the management of a system's transient elements. Fonseca et al. (2005) discuss the use of incentive-based approaches in order to manage the “grey” areas of a conservation system – such as managed forests and sylviculture – in order to increase connectivity between fixed elements. Projections of PFT spatial trajectories would play a valuable role in determining where such incentives could be applied while maintaining the flexibility to adjust the location of application based on continually updated information. Such use of DGVM projections would suffer far fewer consequences when projections need correcting compared with those of an ill-situated national park. As once isolated national parks begin to cope with encroaching neighbours, it will be become increasingly vital to incorporate these neighbouring land uses into the protected areas system. An incentive-based approach, such as that suggested by Fonseca et al. (2005), is an alternative which has currently been gaining attention in recent literature (Hannah & Salm, 2005; Kupfer et al., 2006). When or if, “matrix-management” makes its way into national park system budgets it will be necessary to target the distribution of incentives to provide the greatest ecological value for each dollar spent. Just as DGVM projections can assist in the management of parks or fixed elements, they similarly have great potential in managing those transient elements which are integrated into the system.

The initial step to utilizing DGVM projections, for fixed and transient elements alike, will be to explicitly recognize climate change as a significant threat along with the necessity of its inclusion into protected area system planning. This will provide the political atmosphere necessary for utilizing DGVM projections. If stakeholders involved in the planning of park systems are unwilling to acknowledge that anthropogenic factors are influencing the climate, due to the uncertainty in the science, it is doubtful that the uncertainty inherent in DGVM projections will be given the attention they warrant. With this acceptance, however, insightful park management staff will find that these projections provide information valuable for almost every aspect of park management: devising/revising park mission statements and goals; revising site selection methods; distribution of management efforts and resources; inter-system collaboration and the allocation of power and autonomy within the park system. With appropriate use and scrutiny, those who are required to plan proactively for an uncertain future will find that Dynamic Global Vegetation Models provide an exceptional contribution to the suite of models and tools which will help to make such preparations.

5.6 CHAPTER SUMMARY

This chapter has outlined many potential ways in which projections from Dynamic Global Vegetation Models could be utilized in order to accommodate for climate change in the management and creation of national parks. The initial stepping stone to adopting such models is accepting that climate change is occurring and that it will have potentially dramatic impacts on the distribution and composition of North America's ecosystems. These changes will correspondingly require a large-scale reassessment of many procedures conducted in the management of national parks, including how the locations of future parks are selected as well as the reconsidering the goals of today's parks. Depending on how park management objectives adjust to address future change, there may also be the need to alter the intensity in which the parks should be managed; slowing the infusion of new species in some areas or introducing new species in others will require the wise expenditures of limited resources and reasonably strong understanding of what potential developments lie ahead. Beyond the refocusing of park system goals, selection of new parks, and intensity of management within existing parks, the efficacy of tomorrow's protected areas will hinge on the coordinated actions among several parks rather than on the actions of any individual park.

DGVMs are able provide continental-scale information necessary in coordinating a continental system of integrated park planning. Complete integration will require extensive legislative action along with precious time, energy and resources. International cooperation will have to substitute until such integration becomes possible; if indeed it does. In Canada, there already is a framework developed where each park is playing a fundamental role in completing the "National System." Its objectives for representativeness may call for revising but this demonstrates the sort of coordination necessary to accommodate for climate change. Yet, as vital as cooperation will be, both parks and the system as a whole should also retain the flexibility to alter goals and objectives as better information becomes available concerning species' temporal dynamics. Additionally, the role that unprotected areas play in the conservation of biodiversity within North America will dramatically continue to dramatically increase as land use becomes more intense and widespread. DGVMs will assist in identifying areas that will be most important to the enduring effectiveness of our protected areas. The most important step for North America's national parks concerning climate change is to explicitly include it in the planning and management of protected area networks. The second is to have a sound understanding of the impacts this change is likely to herald. It is in this respect that DGVMs will serve as valuable tools for conserving the biodiversity of tomorrow’s park systems.

CHAPTER SIX: CONCLUSION

6.0 INTRODUCTION

The IPCC recently released the executive summary of its Fourth Annual Report (2007) on climate change. It is concluded in this summary that the observed climate change of the 20th and 21st centuries is very likely (> 90%) to be anthropogenic in origin and the global rate of temperature increase is very likely to be unprecedented within the last 10,000 years. What this means for North American national parks is that there are going to be substantial changes in Earth's climate and corresponding responses in North America's biogeography. Indicator species around the world have been shown to be adapting their behaviours and geographical ranges in response to changing climatic conditions, and this change is projected to manifest itself in the future biome distribution of North America. Consequently, the assumption of biogeographical stability, which is central to many of North America's park management and planning processes, will likely need to be adjusted to avoid losing the biological diversity which they seek to protect. The results of this thesis display projections from the MC1 DGVM using three different GCMs and two emissions scenarios for each. The overwhelming observation drawn from these results is that the contemporary biome distribution is far from stable and there is likely to be a significant change in vegetation representation in more than 50% of North America's national parks by 2075 - 2085.

6.1 REVIEW OF KEY FINDINGS

This study observed the vegetation distribution changes that are projected for 12 climate change scenarios developed using various GCMs, emissions scenarios, and fire modules. Each scenario showed a unique distribution but the common elements that were observed throughout all scenarios are cause for concern.

FIGURE 6.1 – System Wide 2075 - 2085 Park Change Rates

		Projected ~2080 Change	
Scenario Details		# of Parks	% of Parks
CGCM2	A2 - Dynamic	59	64.1%
	A2 - Static	55	59.8%
	B2 - Dynamic	52	56.5%
	B2 - Static	51	55.4%
CSIRO Mk2	A2 - Dynamic	53	57.6%
	A2 - Static	51	55.4%
	B2 - Dynamic	52	56.5%
	B2 - Static	56	60.9%
HadGCM	A2 - Dynamic	53	57.6%
	A2 - Static	52	56.5%
	B2 - Dynamic	49	53.3%
	B2 - Static	49	53.3%

As can be seen in **Figure 6.1** it was projected in all 12 scenarios that at least 53% of parks will undergo a transition in biome type. There was not a very wide range of projected change between scenarios (between 53% and 64% of current parks) indicating that a large degree of change should be expected over the next century. Sensitivity analysis was conducted in order to see how different variables; such as, GCM, emission scenario, or fire module influence projected park change rates. It was found that the GCM utilized had the largest influence over the final projected distribution, and led to a difference of approximately 5% when comparing the average park change rates projected when different GCMs were used. This small difference indicates that there is a fairly strong agreement between models as to the extent of change which can be expected. The results, despite small differences, show a general agreement in the number of parks that are projected to experience some degree of biome representation change by 2075 – 2085. Regardless of driving climate models, emissions scenarios or fire modelling, for the majority of parks in the current national park systems of North America the evidence suggests that park managers should be ready for significant change.

Examining North America as a whole fails to observe the variety which exists between various regions of the continent. The impacts of climate change, responses of vegetation to such change, and the distribution of national parks are unique to each region and as such it is important to observe regional disparities. Seven regions were identified to isolate patterns of projected change. The Mountain and Northern regions observed the largest estimated 2075 - 2085 Park Change Rates which, at 70.8% and 78.4% respectively, were 13% to 21% above than the national average (57.6%). The Southern and Atlantic regions lay well below the national average at 21.2% and 40.2% respectively. Further analysis also discovered that each of the regions displayed unique levels of agreement between modelled scenarios. A relative comparison of each region found that the Southern region showed the most variability between scenarios while the Northern and Pacific regions demonstrated the least variability. Comparing the projected rates of change and the agreement between scenarios highlights three notable observations; first, the Northern region is expected to have the greatest degree of change within its parks and also, unfortunately, has the highest degree of certainty between scenarios. Quite the opposite, the Atlantic region is projected to have the second lowest Park Change Rate, and also has the second highest degree of agreement between scenarios. Lastly, it is important to mention that while the Southern region is currently projected to have the lowest Park Change Rate there also is a fairly high disagreement between scenarios, lending to an uncertain future.

Projected vegetation change within North America’s national parks also varies by biome. Unlike national parks, the boundaries of biomes are not permanent and thus it was observed how many parks were expected to represent each biome type during each time slice of the study. Temperate Mixed Forest, Temperate Evergreen Forest, and Savannah/Woodlands each showed increases in representation ranging from 12.8 and 9.9 to 7.2 parks respectively. Alternatively, colder biomes Tundra and Boreal Conifer Forest both observed projected declines in representation within parks, ranging from a loss of 7.3 to 9.3 respectively. The forecast loss of representation in Boreal Conifer Forest is made worse by the fact that this figure shows very low variability between scenarios. The representation of Tundra varied moderately between scenarios as did Savannah/Woodlands which is expected to increase in representation by 2075 - 2085. Tropical Mixed Forest showed no variability between scenarios while Grasslands appeared to be the most dependant on variables such as climate model, emission scenario and fire modelling processes. Lastly, the expansion of Temperate Evergreen Forest is complemented by a relatively low degree of variability between scenarios, indicating a higher degree of confidence that its representation in national parks in Canada and the United States is going to increase with time. For some biomes the impending climate change that has been projected will be a benefit, creating ideal growing conditions where they did not exist previously. For others however, particularly in Northern Canada and the United States, changing climates will mean the loss of competitive advantage for colder-climate plants, and will necessitate proactive management to ensure that sufficient action is taken now to ensure their continued existence in the future.

A comparison was also drawn between the extent of change that was projected in the previous work of Lemieux, using equilibrium-constrained global vegetation models, and the results that were generated using the MC1 dynamic global vegetation model. Despite many methodological differences between the two studies it is worthy to note the general agreement that was found in conducting this comparison. In both studies, the average number of parks expected to experience change was observed under a number of different scenarios. Both concluded that more than 50% of parks within Canada are expected to experience a significant shift in biome distribution under the condition of doubled atmospheric CO_2 concentrations. In addition to demonstrating a general agreement across Canada, when the expected change within particular regions of Canada or within particular biome types is ranked, there are still many strong patterns of agreement between the two studies. Due to the methodological variations between them, it was expected that there would be many deviations between the two studies with regard to precise numbers, but the patterns that were consistent between both provide a good sense of where park managers can expect to see the greatest changes within North America's parks in times to come.

That a new generation of models and scenarios, developed independently by researchers around the world, with improved representations of climate, emissions, biogeography and biogeochemistry, and incorporating temporal dynamics, come to the same conclusion as past studies demonstrates that projections seen in this study cannot be overlooked by park systems which hold the preservation of biodiversity as a high priority. If the climate changes that we are experiencing today continue to follow modelled trajectories, national park systems in Canada and the United States will be very different from what is seen today, and it will be up to those same national park systems to decide whether to act now in preparation by revising management objectives and site selection processes, or to react later when impacts have already occurred and the potential of reversing such impacts is limited.

6.2 METHODOLOGICAL STRENGTHS

One strength of this study lies in the way it is contextualized within previous works. It draws on work from many fields of research in order to describe the dynamics that are expected to occur within North America's national parks. Research into Earth's climate is utilized to project future changes of environmental conditions; our understanding of biology helps to inform our estimations of how plant communities are expected to adapt to these changes, and geomatics explains how the spatial distribution of these changes will influence our current and future protected areas. This study also builds on a very similar study, conducted by Lemieux (2002), which used equilibrium-constrained models to project how climate change will influence Canada's protected areas. By following closely the study framework developed in Lemieux's study it is possible to examine how the addition of temporal dynamics and improved modelling processes has changed the future projections of plant responses to climate change and the corresponding change observed within Canada's national parks. This study also works to address many of the concerns that were raised by Lemieux.

Lemieux (2002) concluded his study with a number of suggestions which would improve the analysis of impacts of climate change on protected areas. This thesis addresses a number of those suggestions. First, temporal processes were included which show the trajectory of changes within national parks rather than the fully equilibrated response of plant communities to an instantaneous change in atmospheric composition. Second, soil dynamics, succession and fire contribute to a more realistic representation of vegetation response to climate change than would be possible to include in a modelling process that does not include temporal dynamics. Third, three GCMs and two emissions scenarios, which themselves are transient in nature rather than equilibrium-constrained, provide a large variety of change scenarios to develop a range of plausible outcomes in addition to forming an estimate as to the extent of change most likely to occur. As well, the inclusion of a number of scenarios provides the opportunity to the variability that exists between different scenarios – and between different studies – as seen in Chapter 4. Lastly, the study utilizes park boundaries rather than geocentroids to represent parks. This allows a more spatially accurate analysis of expected change to be conducted as many of the larger national parks within North America extend beyond 0.5 degrees latitude by 0.5 degrees longitude.

6.3 METHODOLOGICAL LIMITATIONS

Despite having made many improvements on previous modelling exercises, the methods employed in this study still possess several limitations. A large caveat that has been mentioned is that the projections made in this study are just that – projections. There remain many processes which are poorly understood, poorly modelled, or absent from the modelling process at this time which prevent claims of “prediction” from being made. As an example, while fire disturbances have continued to receive attention and are explicitly included in the MC1, there is no inclusion of disease, insect disturbance, or human land use. MC1 also suffers from the same limitation which is common to all DGVMs - the use of Plant Functional Groups generalizes plant responses to broad families of plants, thus not allowing for individual species dynamics. This limitation exists both because of our incomplete knowledge as well as current limitations with computing resources. Canada and the United States together possess approximately 22,000 species of vascular plants (Berhardt, 2007; USDoI, 2006), which would make individual species modelling impossible at the present time.

DGVMs are also limited by the availability of spatial information and the computational resources required for finer-scale resolution. In order to use a finer resolution there must be a corresponding availability of data; work is currently underway using a 10 km grid rather than 0.5 degrees (Price & Scott, 2006), but is unavailable for this study. Additionally, with finer resolutions come increased demands for computational power which limit the ease with which finer-scale resolutions can be utilized. What was observed in this study is that many national parks are smaller than the grid used to conduct the study. While this would constitute a problem for analysis of an individual park, it does not pose a problem for conducting continent-wide analysis of vegetation distribution responses. With regions of interest that were identified in this study other viable options are to focus on those areas and use fine resolution data from local sources, or to use a regional climate model to enable more detailed DGVM studies.

As a final note, just as it is preferable to utilize multiple GCMs in order to best characterize the possible variability within Earth’s climate system, it would have also been preferable to employ more than one DGVM to characterize possible plant responses to climate change. Currently MC1 is the only DGVM which explicitly records future plant distributions and is available for this study. The inclusion of other DGVMs in future studies will serve to improve the robustness of projections that are derived.

6.4 RECOMMENDED AREAS OF FURTHER RESEARCH

The methods used and results generated by this study have exposed a number of facets which could prove useful in future research. They can be grouped into four general areas: 1) expand research beyond the park set used in this study 2) focus on regions which displayed the greatest amounts of change 3) validate projections using field and remotely sensed observations 4) improvements to the modelling process. Each area will be discussed in further detail.

6.4.1 EXPANDED PARK SET

Concentrating solely on national parks has been useful to demonstrate how the projections of vegetation models can be used in order to help shape park selection and management processes for a body of parks that share a common set of mandates. Vegetation models have further potential, however, to assist in the development of shared goals and objectives between park management bodies. As was seen in this study, there are decided benefits to integrating park management strategies where common goals exist between different park agencies and this should be further reflected in future studies. Expanding the study set to provincial, state and municipal parks as well as other protected areas could demonstrate how goals such as the preservation of biodiversity can be shared and improved by associated but independent park systems. Additionally, the inclusion of Mexico and its national and state parks would make a natural and logical contribution to further studies of this nature.

6.4.2 REGIONS OF CONCERN

In Chapter 4 three regions in North America - Mountain, Northern and Pacific - were projected to experience significant amounts of change as a result of climate change. This initial identification should act as a basis to prioritize further investigation into the likely impacts of climate change on protected areas within those regions. Scaled-down versions of the methodology used in this study could be applied on an individual park basis provided that significant data exists. A good example of a DGVM being used to model climate change responses within one park can be found in the work of Bachelet, Neilson et al. (2000, 2001). This would provide a refined outlook for areas of concern. Additionally, research could be pointed towards identifying new potential areas for protection using site selection criteria that incorporate considerations for changing climatic conditions, whether or not that involves the use of vegetation modelling. Lastly, areas which are not, and for what ever reason are not likely to become, protected should be examined to identify those areas which might serve as the dynamic portions of protected area systems in regions of concern. As Hannah and Hansen (2005) point out, protected areas are just the fixed portion of a dynamic landscape conservation plan. Further research also should be conducted into how vegetation models can be used to identify areas that have high value for connectivity between protected areas.

6.4.3 PROJECTION VALIDATION

Analyzing areas outside of current park boundaries would be helpful to future studies of this nature. This study examines the potential change within the national park system. This estimate would be enhanced with similar knowledge of what may happen in the surrounding landscape. It would help establish whether the high rates of change observed within this study are indicative of the change likely to face the entire continent, or whether the placement of today’s national parks has situated them in locations more prone to change. Increased awareness of the relationship between these two patterns would have a number of planning benefits, both for existing parks and for the selection process of creating new ones.

Due to the complex nature of modelling future vegetation responses to climate change, an understanding of how well current projections are performing compared to observed responses is necessary. Peterson et al. (2005) identify the lack of testing that has occurred concerning the accuracy of projections made by models such as DGVMs. Sufficient data is now publicly available online (Loveland, Reed, Brown, Ohlen, Zhu, Yang et al., 2001) to conduct initial comparisons between projections and observed distributions, but long-term continuation of such an effort to note developing trends would be valuable. A second benefit of using these data sets would be the inclusion of current human land use into the end-analysis product. Using current human land uses would provide a more realistic illustration of the difficulties that might challenge the development of dynamic landscape plans and would also assist in the identification of areas which have both suitable potential habitat, and a suitable land use today – either undeveloped, or with the potential to revert to an undeveloped state. Finally a regular, consistent monitoring protocol for the performance of DGVMs would be helpful to both national park systems, hopefully providing confirmation that projections hold a good deal of value for park management and planning, and if not, providing feedback which would allow for recalibration of modelling efforts and improved modelling processes.

6.4.4 MODELLING PROCESS IMPROVEMENTS

As was detailed in Chapter 2 and 3, the literature review and methodology, there still exist many opportunities for improving the modelling process for DGVMs. Disturbance events, such as disease and insect infestation, have been identified as areas for improvement with these models. Fire modelling parameters have received a lot of attention, especially in the MC1 model used in this study, but other processes need to experience a similar improvement. Modelling human land use patterns would also prove to be a valuable contribution, but as with disturbance events, this is particularly difficult and in need of development.

With constantly improving computational resources, more short term goals should include models which incorporate better resolution, such as models with 10 km grids which are currently either in development or have just recently become available. Continuing along this path of thought would be the inclusion of more Plant Functional Types; each additional PFT provides a classification that reflects its members more effectively. Also, as more DGVMs become available for academic use it would be beneficial to conduct ensemble projections using multiple vegetation models as was done by Cramer et al., 2001. Just as ensemble forecasts are utilized in climate modelling, the vegetation aspect of this study also illustrate the benefit of drawing from multiple models in order to develop ranges of alternative futures and to identify which of those appear to be most likely.

As a last note, when the resolution of new vegetation models is sufficiently increased so as to represent the majority of protected areas with multiple cells, it would be valuable to begin measuring the amount of projected change within a park rather than simply noting the presence of change or the lack thereof. Providing an areal estimate of change would be most helpful to existing parks and their park managers. Where projected change in the majority of a park might illicit one response, minor changes in a portion of a large park might not cause the same reaction. Until this becomes possible it will be necessary to rely on the observation of whether a park lies close to a boundary between two biomes, or is completely contained, and interpret the results accordingly.

6.5 CHAPTER SUMMARY

When this study commenced, the IPCC had stated that the changes observed in today's climate were *likely* (> 66%) caused by anthropogenic factors (2001). They have now strengthened their standpoint, claiming that the changes observed in today's climate are *very likely* (> 90%) caused by anthropogenic factors (2007). Climate change is no longer debated in the context of whether or not it is occurring or whether or not humans are a source of the problem but rather in the context of how much change is going to occur. Flora and fauna in North America are reacting to this change, each adapting to these changes at a different rate in a different way, and can be classified simply as adaptation, movement, or extinction.

Species have responded in this manner to many cycles of heating and cooling throughout their existence on this planet, but there has never before been the large obstacle of human development and land use to hinder these responses or fracture their habitats. This is the global situation which national park systems in North America must adapt to. Park management bodies are increasingly coming to grips with the reality that the assumption of biogeographical stability which has permeated the park system planning process is no longer valid. Park management and selection in the future will be dynamic in nature – acting to preserve species which are constantly moving. This adaptation has been slowed, if not crippled, by our uncertainty and indecision regarding climate change and its causes, but it needs to occur.

National park systems, especially those which aim to protect representative samples of the natural diversity of their nation, will find that this goal will become increasingly difficult as these "representative" samples continue to move into, out of, and between protected areas. Park systems will benefit from projections of these movements provided by Dynamic Global Vegetation Models. Providing an estimation of what range of possibilities lie in the future, and which scenarios seem to be most likely, allows for park management bodies to embrace the dynamic nature of the species which they aim to protect.

This thesis has demonstrated a multitude of ways in which the incorporation of dynamic vegetation models into both selection criteria for the creation of new parks and the management of existing ones can be beneficial. Having an estimate of what is likely to come raises important questions such as how parks will aim to preserve the species they are charged with protecting, as well as other management goals. Site selection criteria can be expanded to include the potential of future park sites to contribute to system-wide goals of reaction to climate change. Park managers receiving this information may also wish to alter the management strategies which are currently practised in order to better reflect park and system goals – for example, they may wish to cease, decrease, increase or introduce controlled burns depending on what response is desired, and what response is expected under current management practices.

Dynamic vegetation models also highlight areas where large shifts in management philosophy are necessary. They highlight the degree to which ecosystems are interconnected with each other, how little those ecosystems respect political borders, and how important inter-jurisdictional and international cooperation will become as species responses progress. Vegetation response scenarios also highlight the flexibility which park managers and planners will need in order to alter management strategies to address unexpected change. Simultaneously, these scenarios will also expose how little flexibility there is within current protected areas and their boundaries.

Dynamic Global Vegetation Models are one tool, of many, from which park management bodies could greatly benefit in the future. Especially in the context of today’s human land-use expansion, the benefit of having some degree of foresight into future vegetation responses is apparent. Competing land uses essentially eliminate the luxury of being able to “wait and see” what changes will take place in our ecosystems as they respond to climate change. Instead, national park agencies will need to acquire land for protected areas which they estimate will be most valuable to the future protection of today’s resources and similarly, park managers will face the increasing difficulty of trying to accomplish more with a limited set of park resources. The desire for efficient, and coordinated management responses in pursuit of a unified goal is apparent, and dynamic vegetation models are one of the tools to help provide this.

GLOSSARY / LIST OF ACRONYMS

AOGCM:
Atmosphere-Ocean General Circulation Model; these are the product of coupling Atmospheric GCMs and Oceanic GCMs.

BIOME3:
The third version of the Ecophysiological-based Biome Model, an equilibrium-constrained terrestrial biosphere model

C3 Pathway:
Photosynthetic pathway where a 3-C molecule is passed through the Calvin-Benson cycle to produce a 5-C molecule and glucose. This cycle takes place in the mesophyll cells of the leaf (Emslie, 2007).

C3 Grass:
Plants that use C3 fixation tend to prosper in areas where sunlight intensity is moderate, temperatures are moderate, carbon dioxide concentrations are moderate or high, and ground water is freely available.

C4 Pathway:
Photosynthetic pathway where CO_2 is initially converted to a 4-C molecule (malic or aspartic acid) in the mesophyll cells, then transported to the bundle sheath cells where it is resynthesized to produce glucose using the C3 pathway (Emslie, 2007).

C4 Grass:
Plants that use C4 fixation tend to prosper in areas where sunlight intensity is strong, temperatures are high, carbon dioxide concentrations are moderate or low, and ground water supply is limited.

CCIS:
Canadian Climate Impacts and Scenarios project (see also CICS)

CFS:
Canadian Forest Service

CGCM2:
Second version of the Coupled Global Climate Model developed by the Canadian Centre for Climate Modelling and Analysis

CICS:
Canadian Institute for Climate Studies

CSIRO Mk2:
The second version of a General Circulation Model developed by the Commonwealth Science and Industrial Research Organization

DGVM:
Dynamic Global Vegetation Models simulate the time-dependent responses of Plant Functional Types to gradual climatic changes

EBM:
Equilibrium Biogeography Model (see also EGVM)

EGVM:
Equilibrium Global Vegetation Models model the fully equilibrated responses of Plant Functional Types to instantaneous climatic changes

ESRI:
Environmental Systems Research Institute, supplier of ArcGIS software used in this study

GCM:
General Circulation Model – See also AOGCM

GDD:
Growing Degree Days

GHG:
Greenhouse Gas

GIS:
Geographic Information System

GISS:
Equilibrium General Circulation Model of the Goddard Institute for Space Studies

HadCM3:
The third version of the Hadley Centre dynamic coupled General Circulation Model

IBIS:
Integrated Biosphere Simulator – See also DGVM

IPCC:
Intergovernmental Panel on Climate Change

IS92:
Predecessor of the SRES emissions scenarios; six emission scenarios with a variety of assumptions generated in 1992 as a supplementary report produced by the IPCC

LAI:
Leaf Area Index

MAPSS:
A landscape to global vegetation distribution model that was developed to simulate the potential biosphere impacts and biosphere-atmosphere feedbacks from climatic change (http://www.fs.fed.us/pnw/corvallis/mdr/mapss/)

MC1:
MAPSS CENTURY v. 1 Corvallis Dynamic Vegetation Model

MCFIRE:
The module within the MC1 DGVM which is responsible for modelling the occurrence of fire disturbance events

MMT:
Mean Monthly Temperature

NPS:
(United States) National Park System

PFT:
Plant Functional Type

SRES:
Special Report on Emissions Scenarios

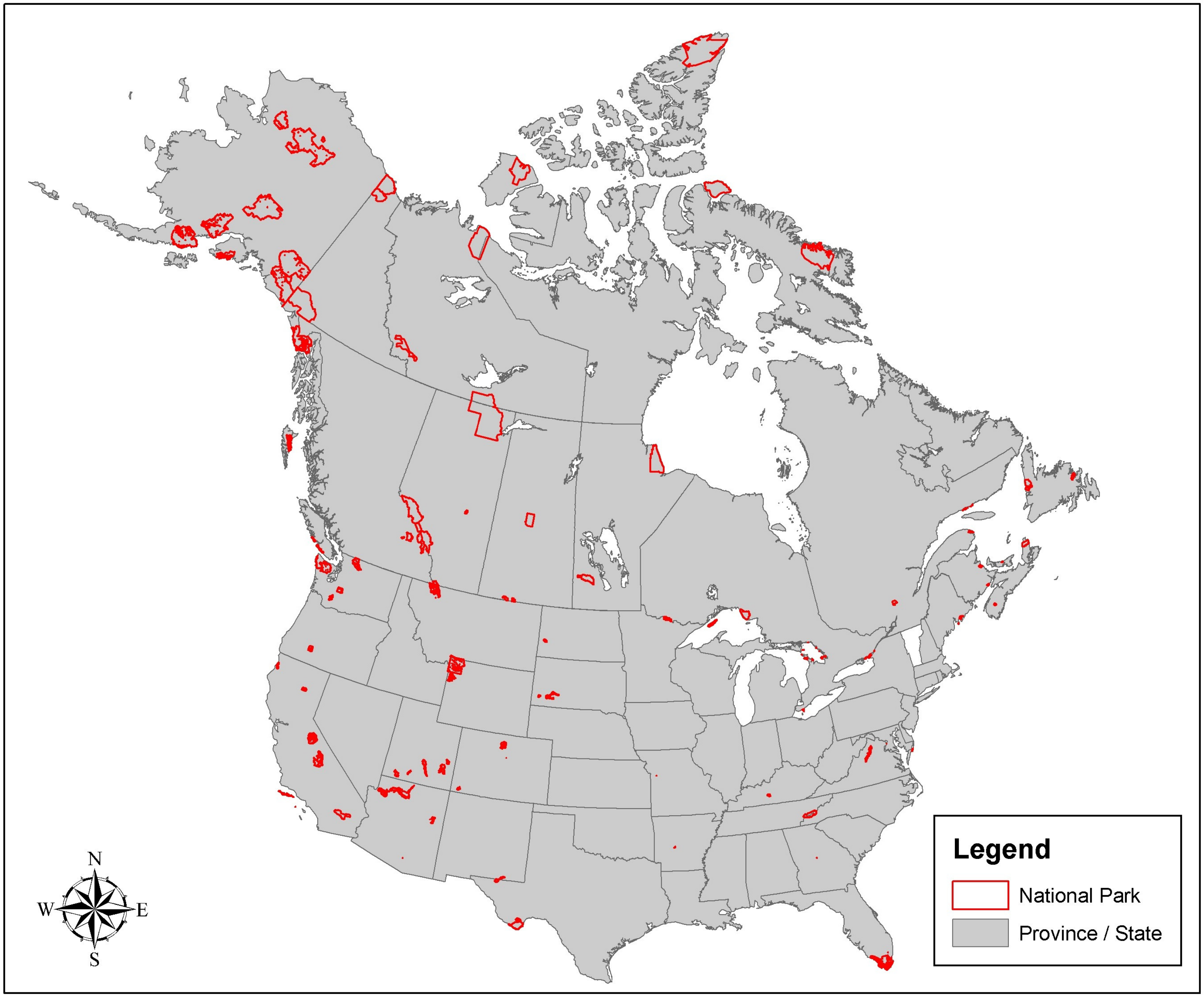
UKMO:
United Kingdom Meteorological Office

VEMAP:
Vegetation/Ecosystem Modeling and Analysis Project

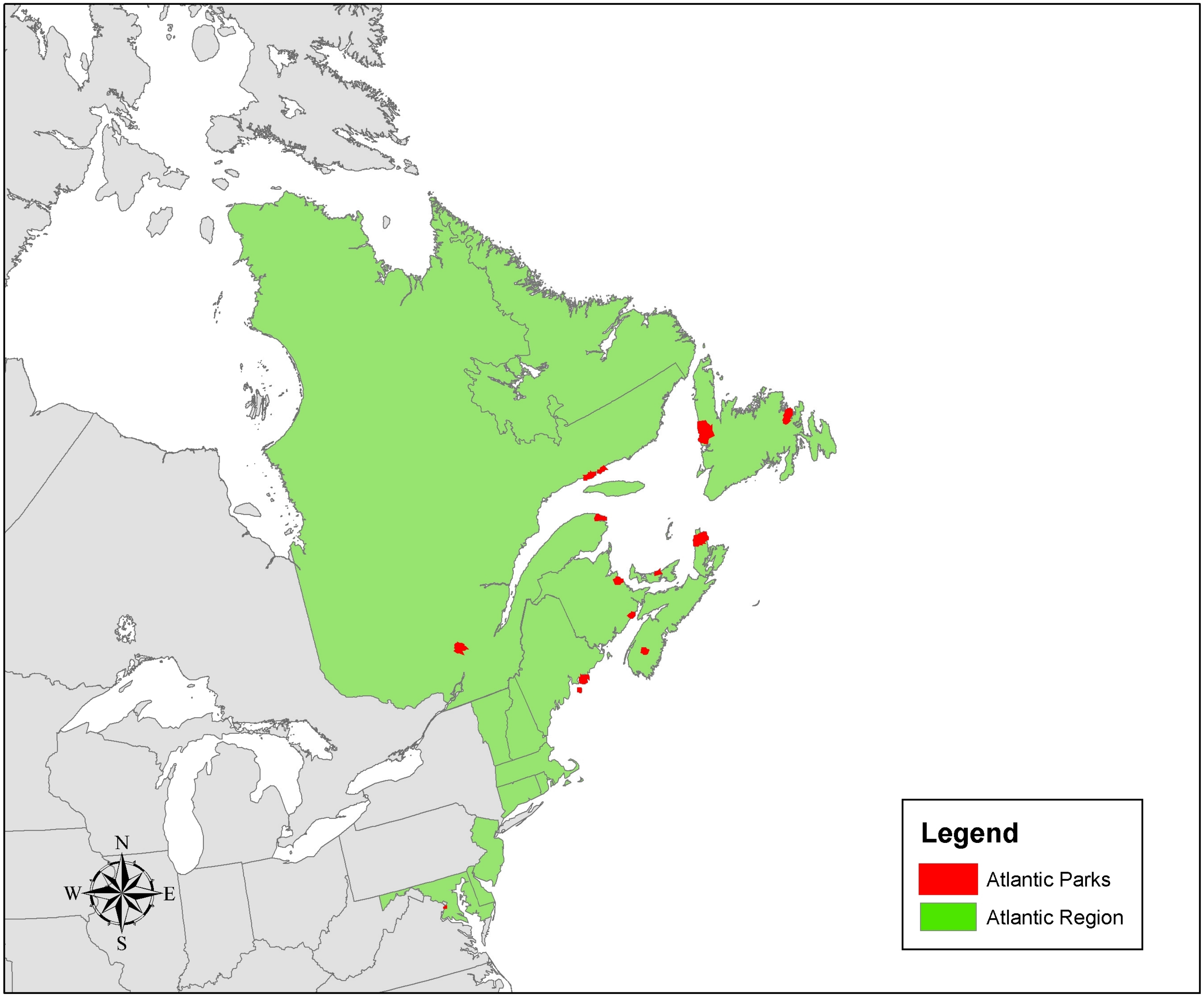
APPENDIX A

NORTH AMERICAN REGIONAL PARK MAPS

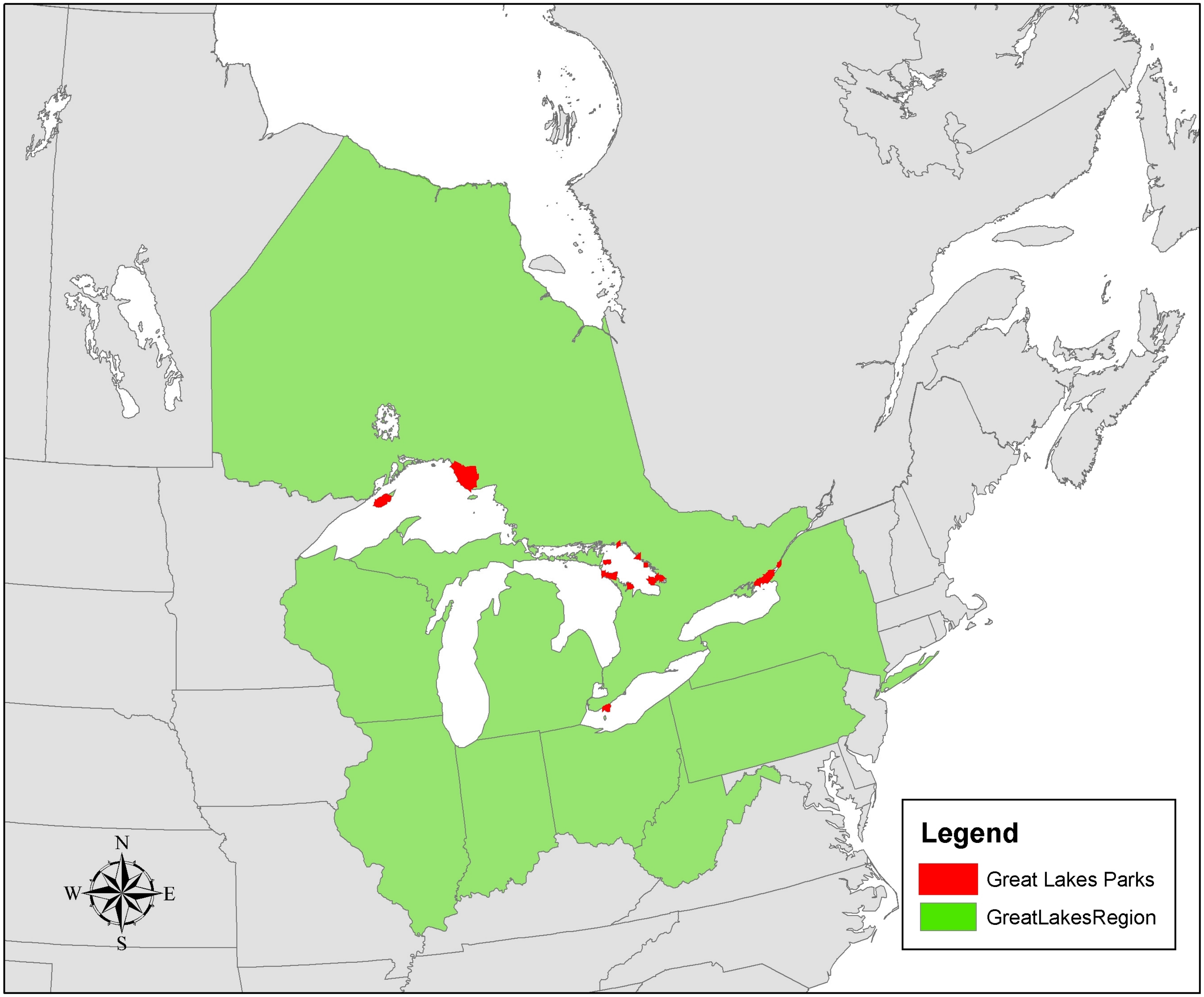
Combined North American National Park System



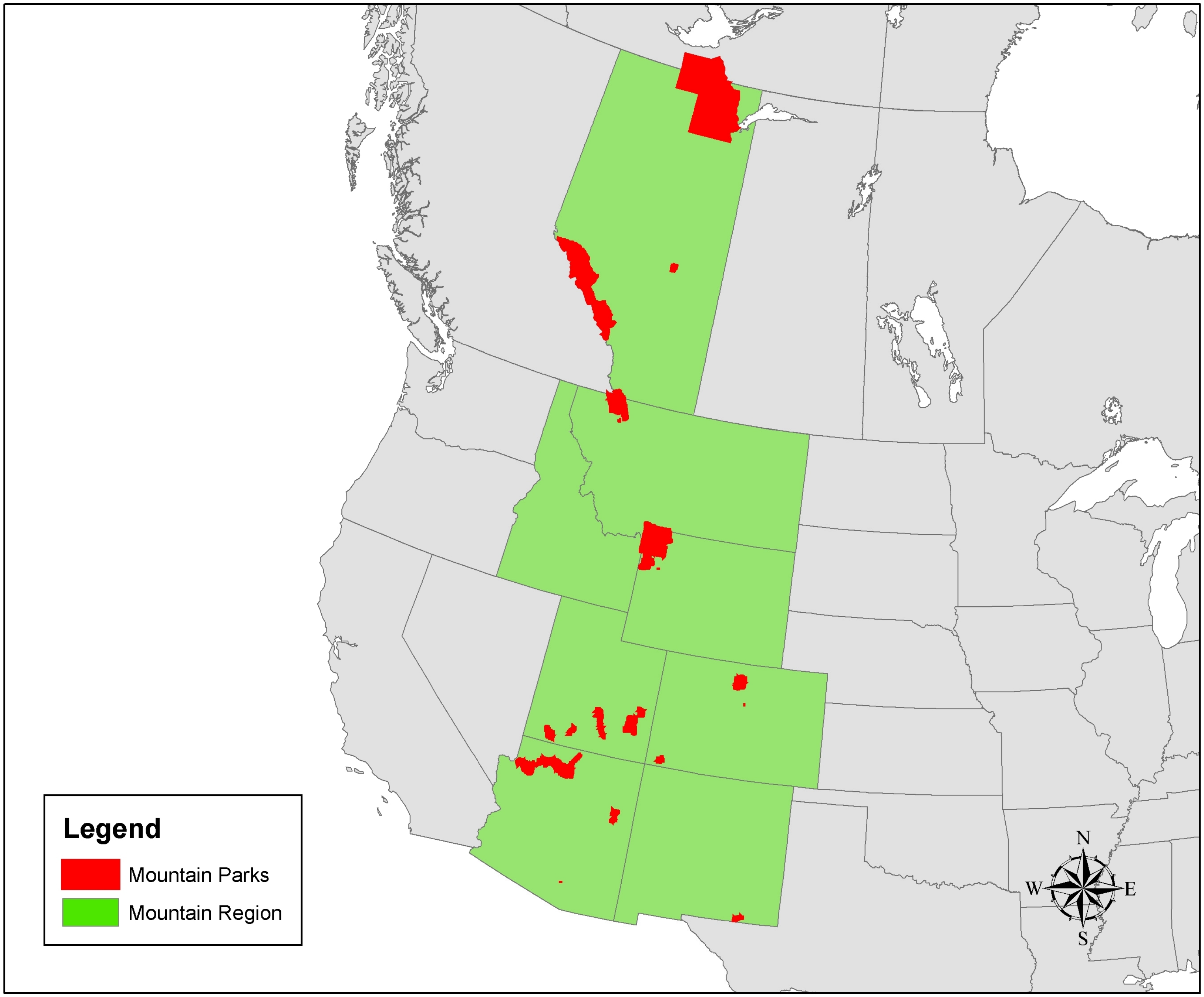
Atlantic Region & National Parks



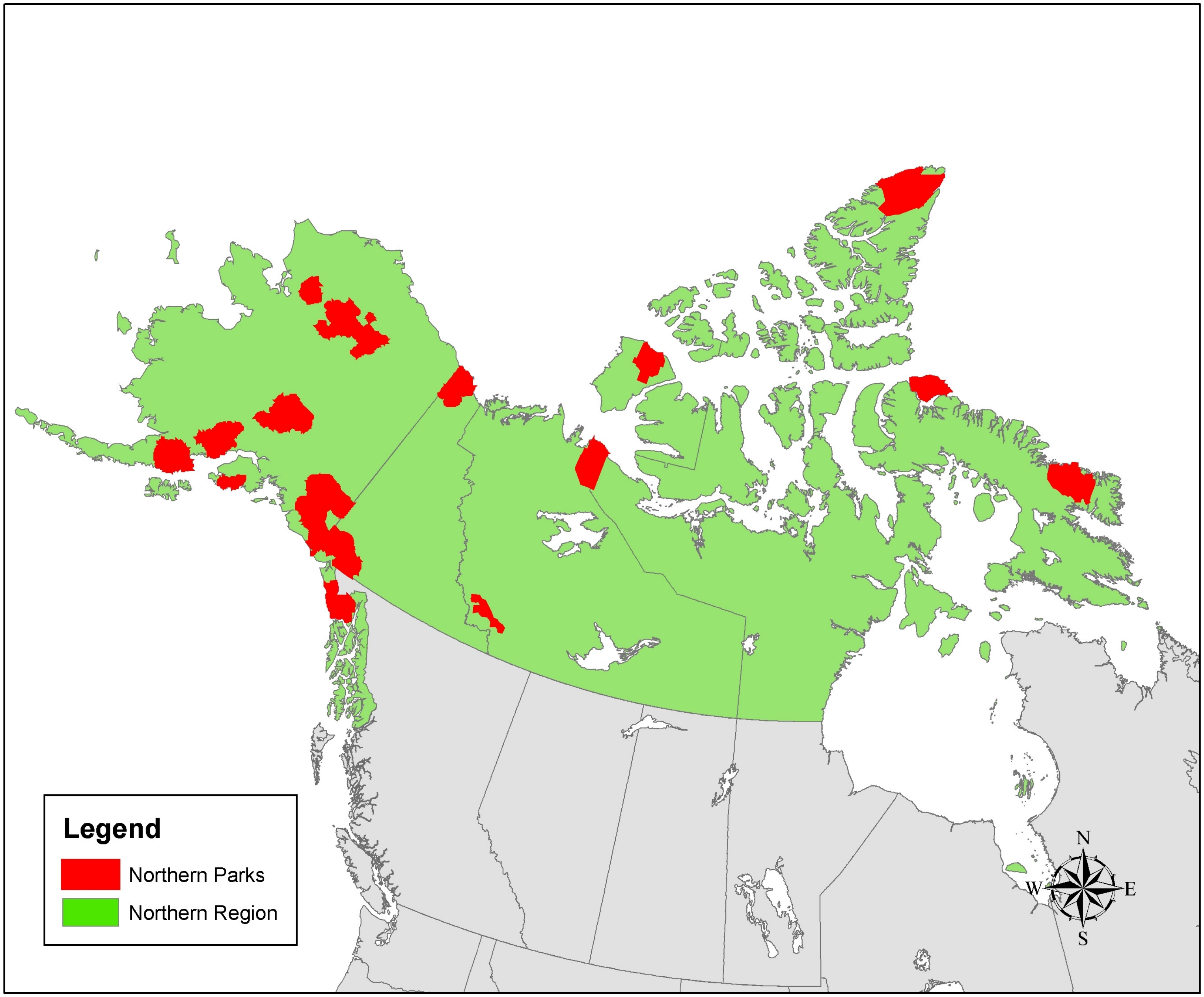
Great Lakes Region & National Parks



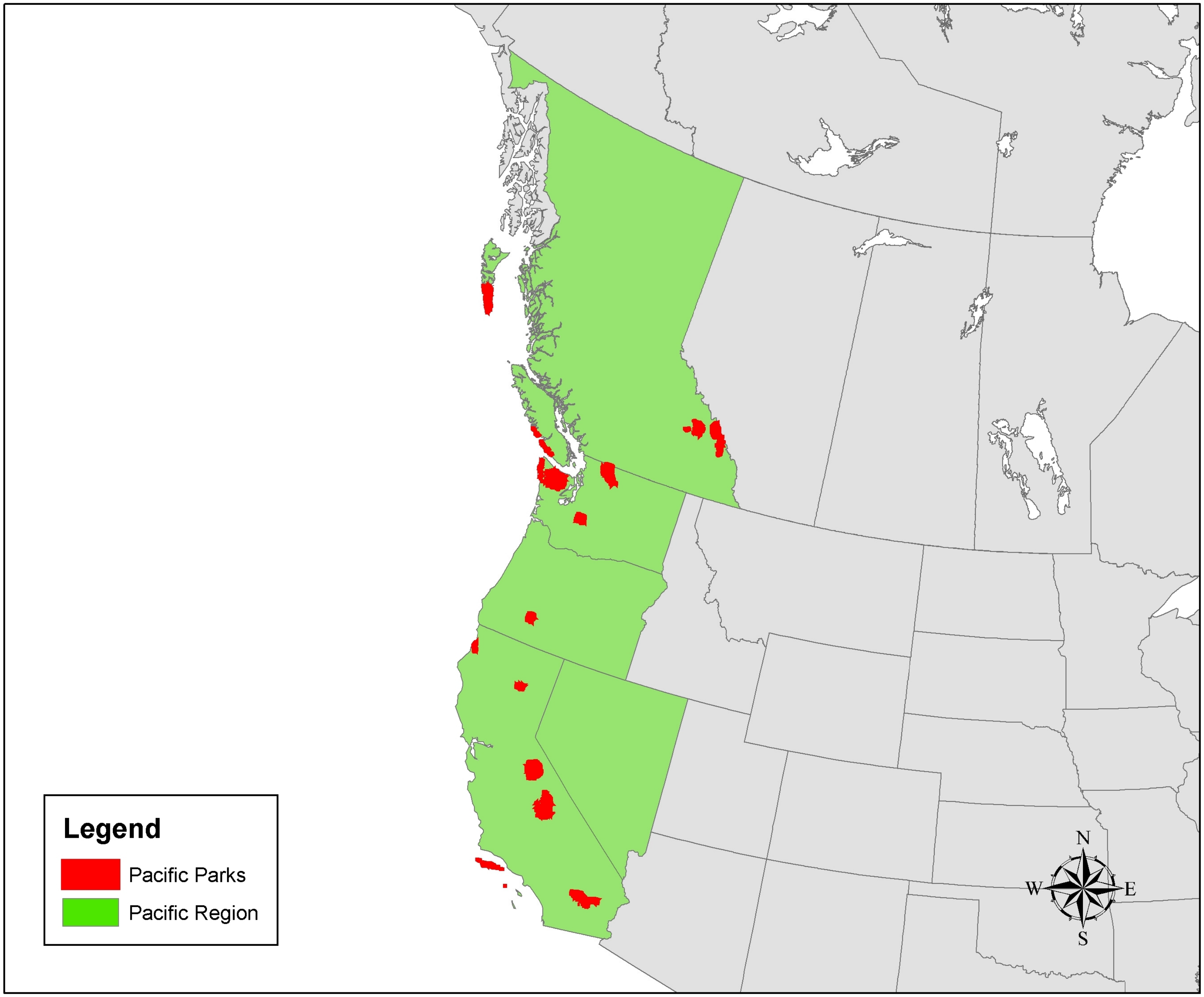
Mountain Region & National Parks



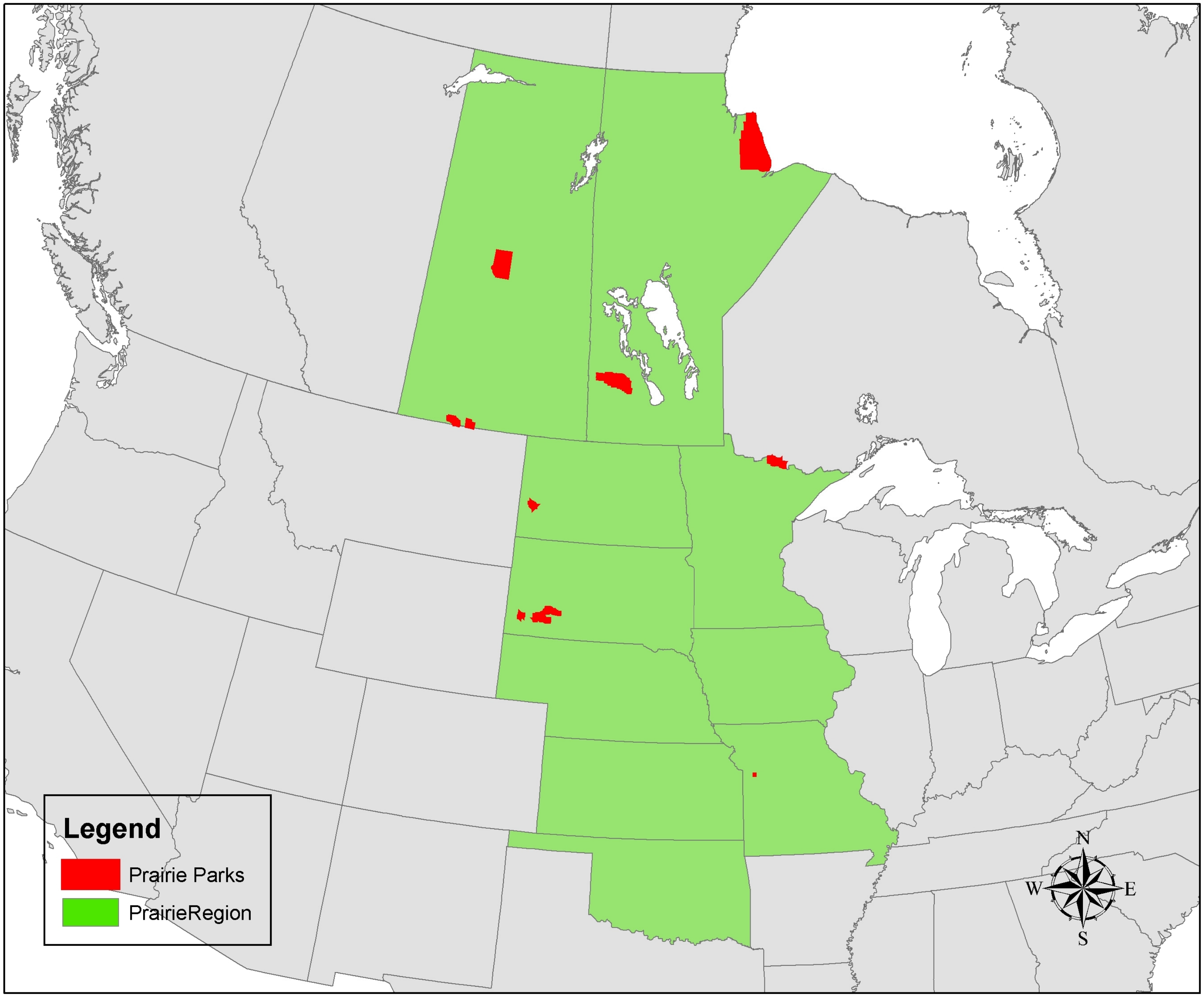
Northern Region & National Parks



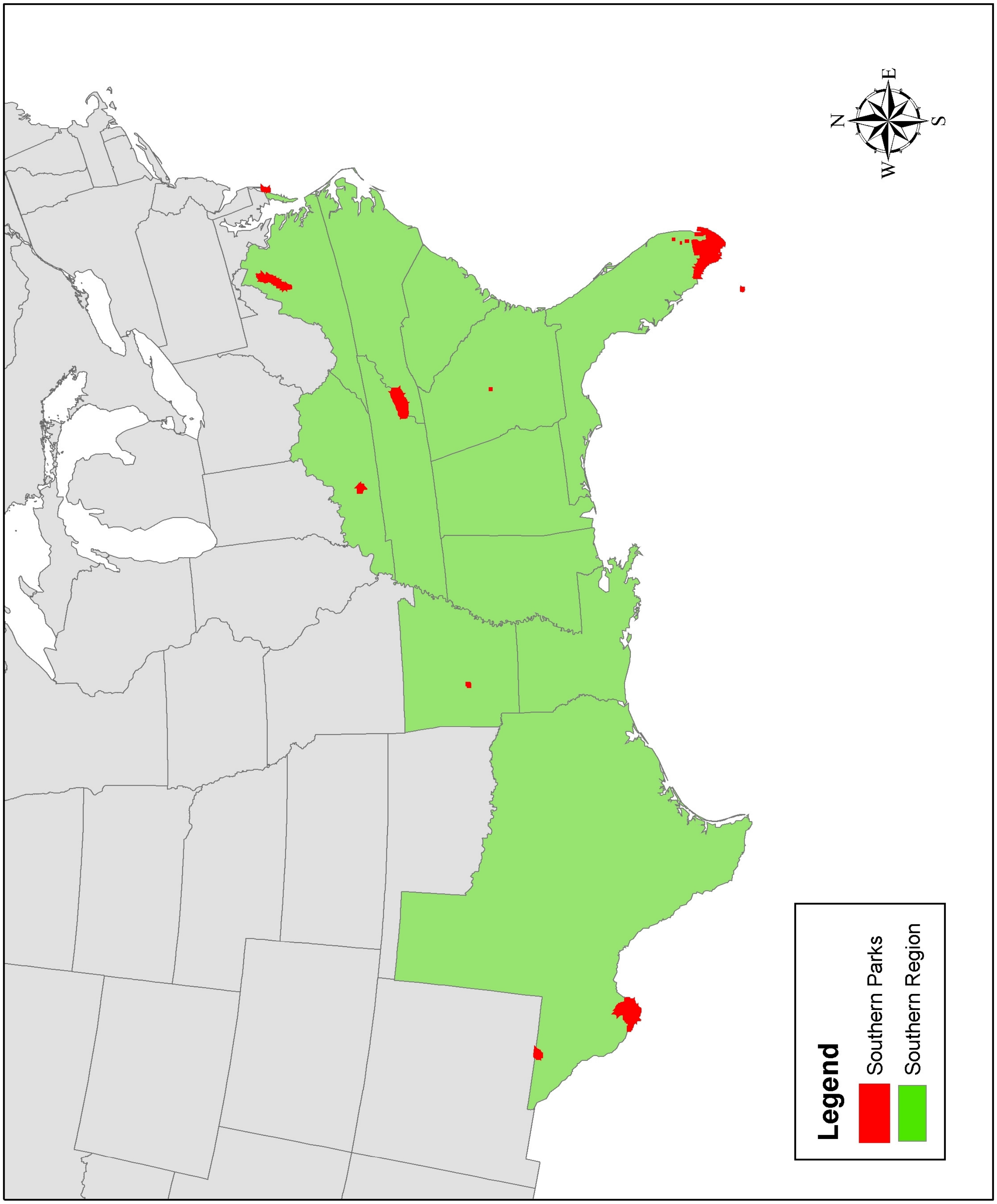
Pacific Region & National Parks



Prairie Region & National Parks



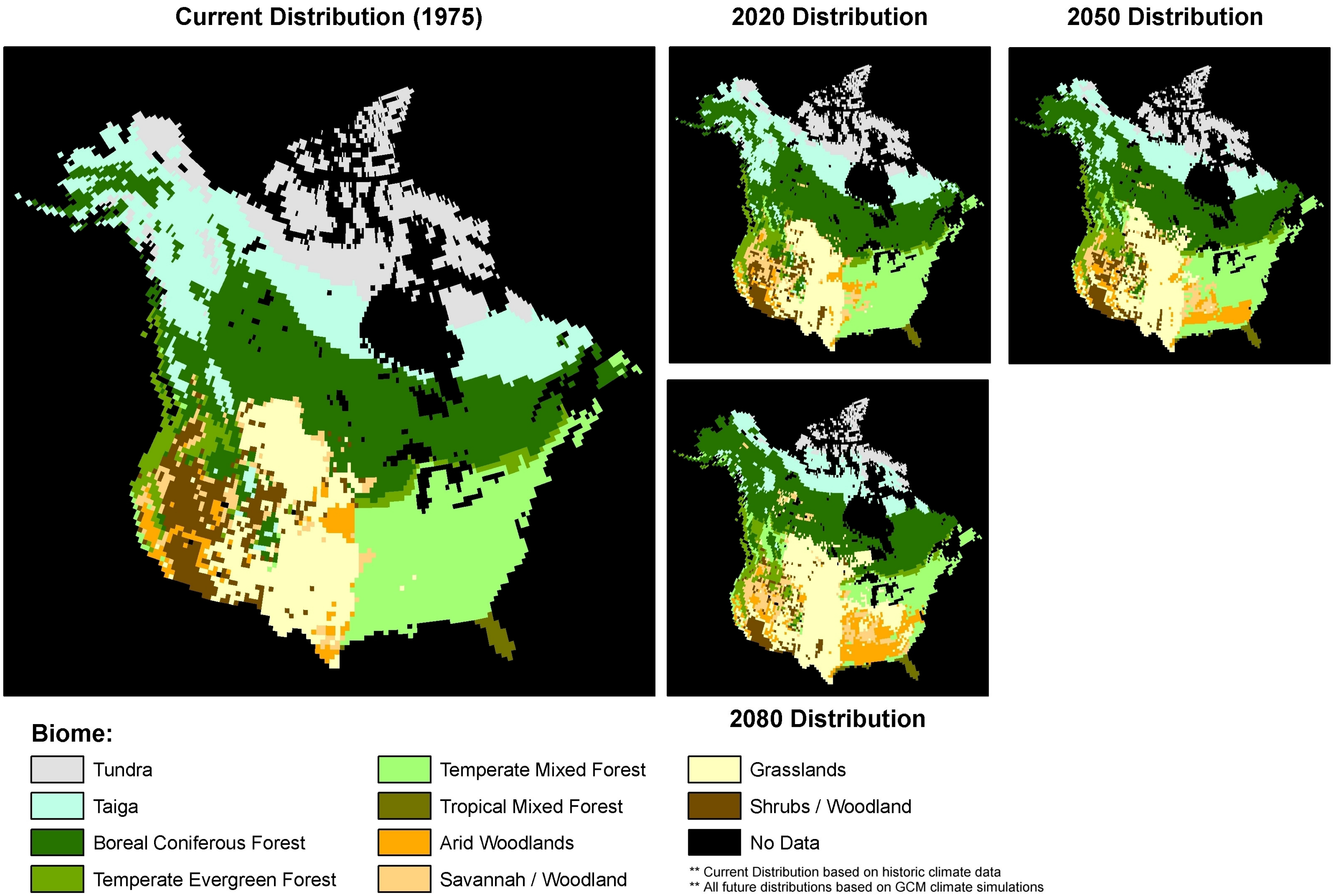
Southern Region & National Parks



APPENDIX B

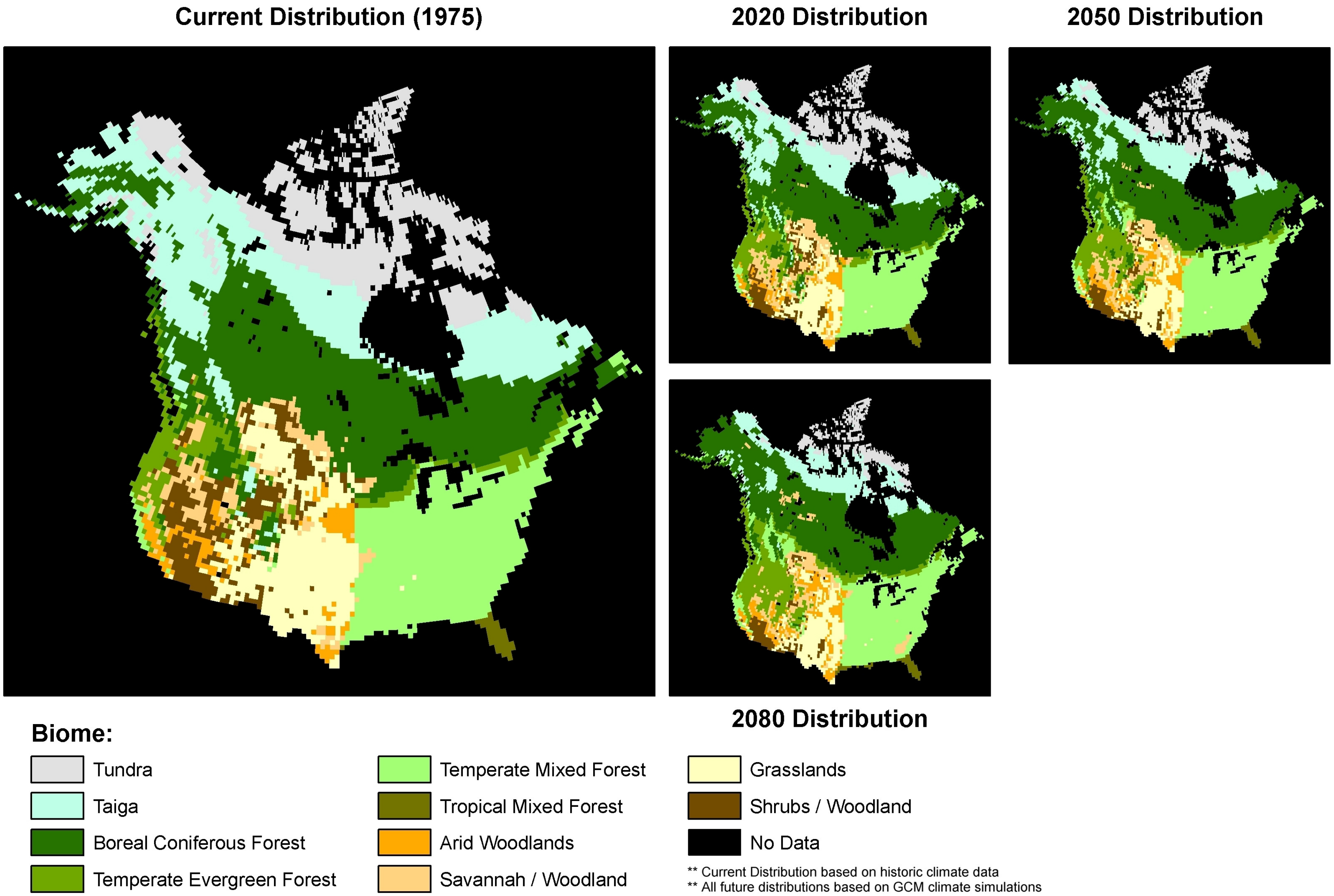
BIOME REPRESENTATION CHANGE
TIME SERIES MAPS

Modelled Biome Extents
CGCM2 A2 Dynamic Fire Scenario



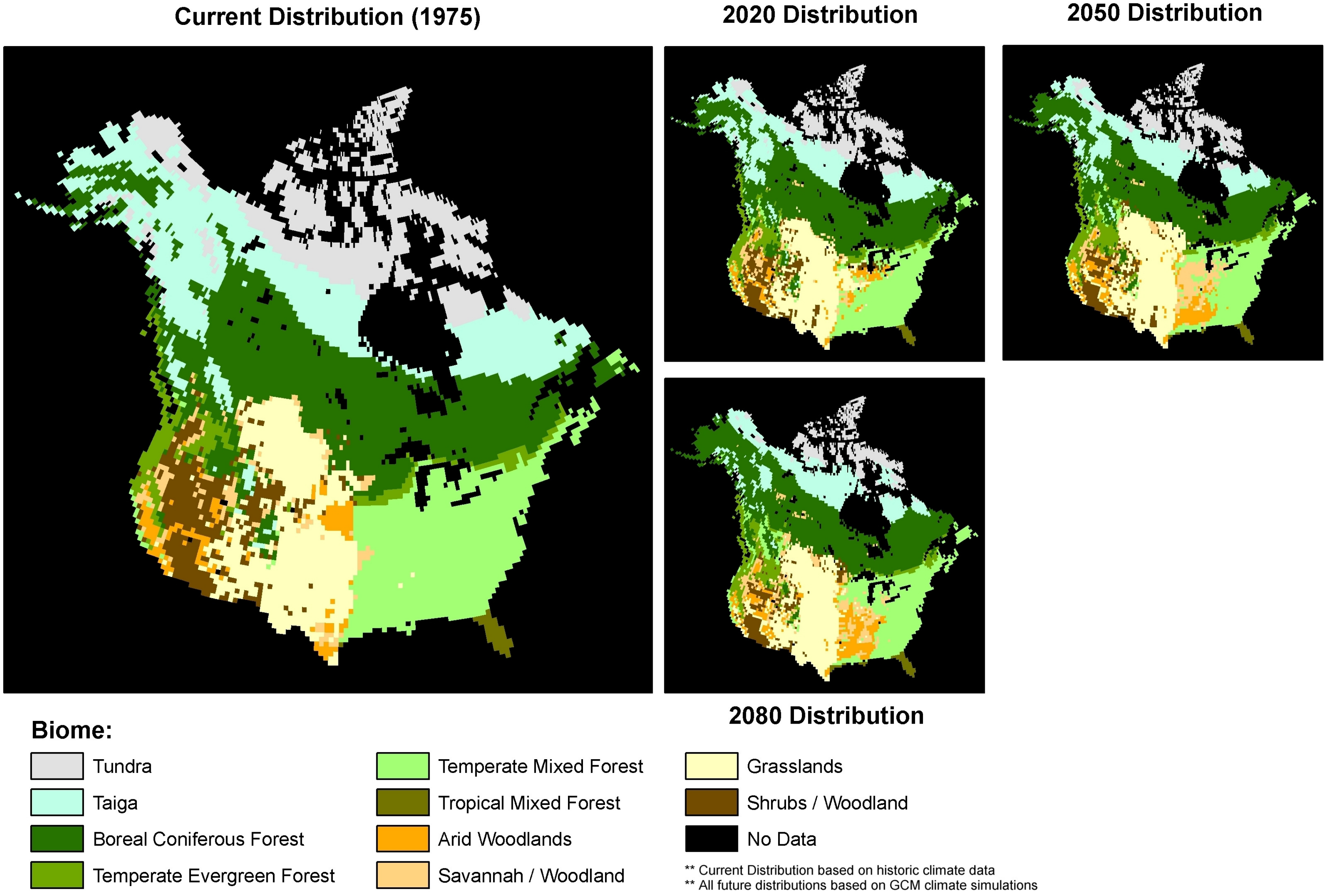
** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
CGCM2 A2 Static Fire Scenario



** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

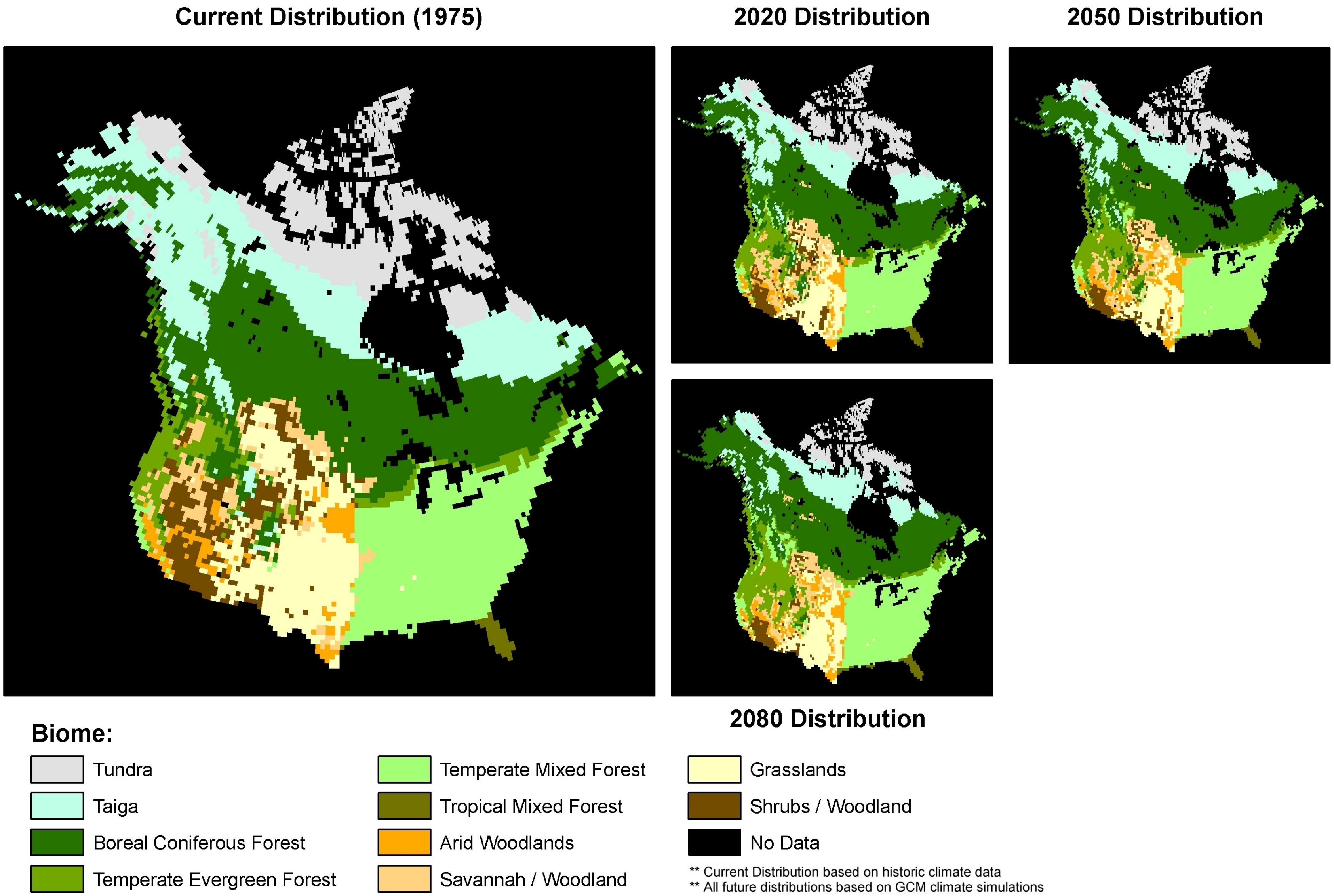
Modelled Biome Extents
CGCM2 B2 Dynamic Fire Scenario



** Current Distribution based on historic climate data

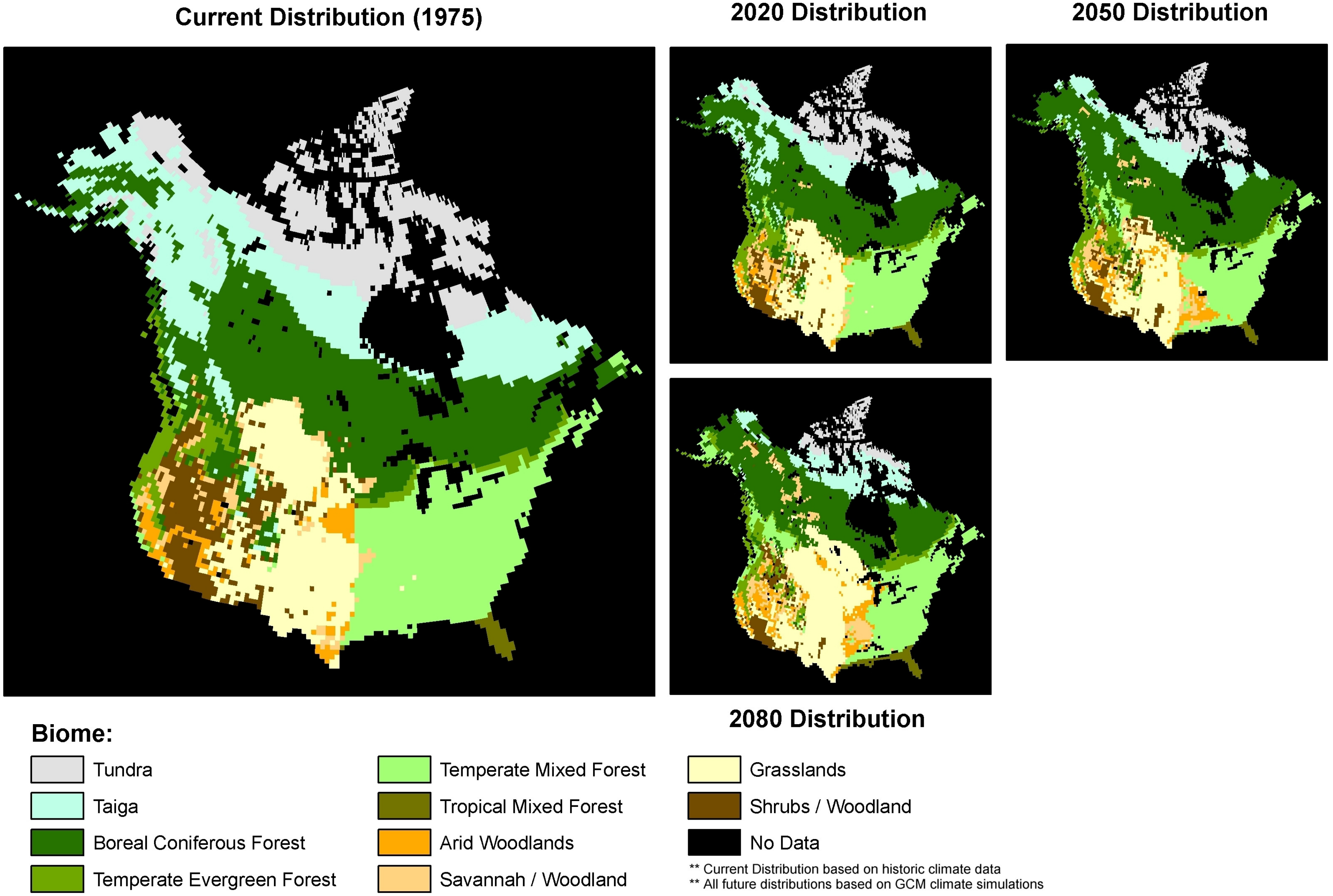
** All future distributions based on GCM climate simulations

Modelled Biome Extents
CGCM2 B2 Static Fire Scenario



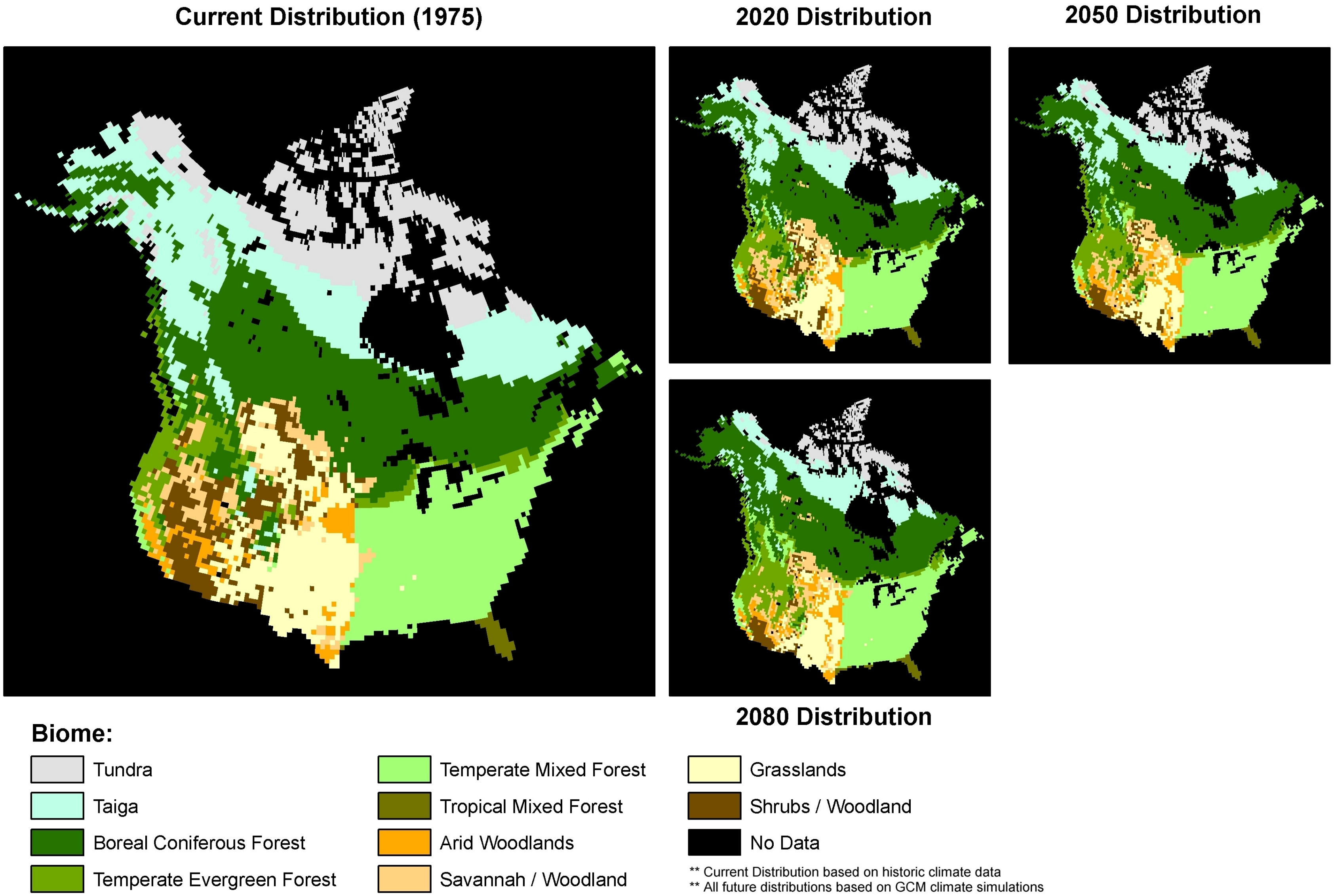
** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
CSIRO Mk2 A2 Dynamic Fire Scenario



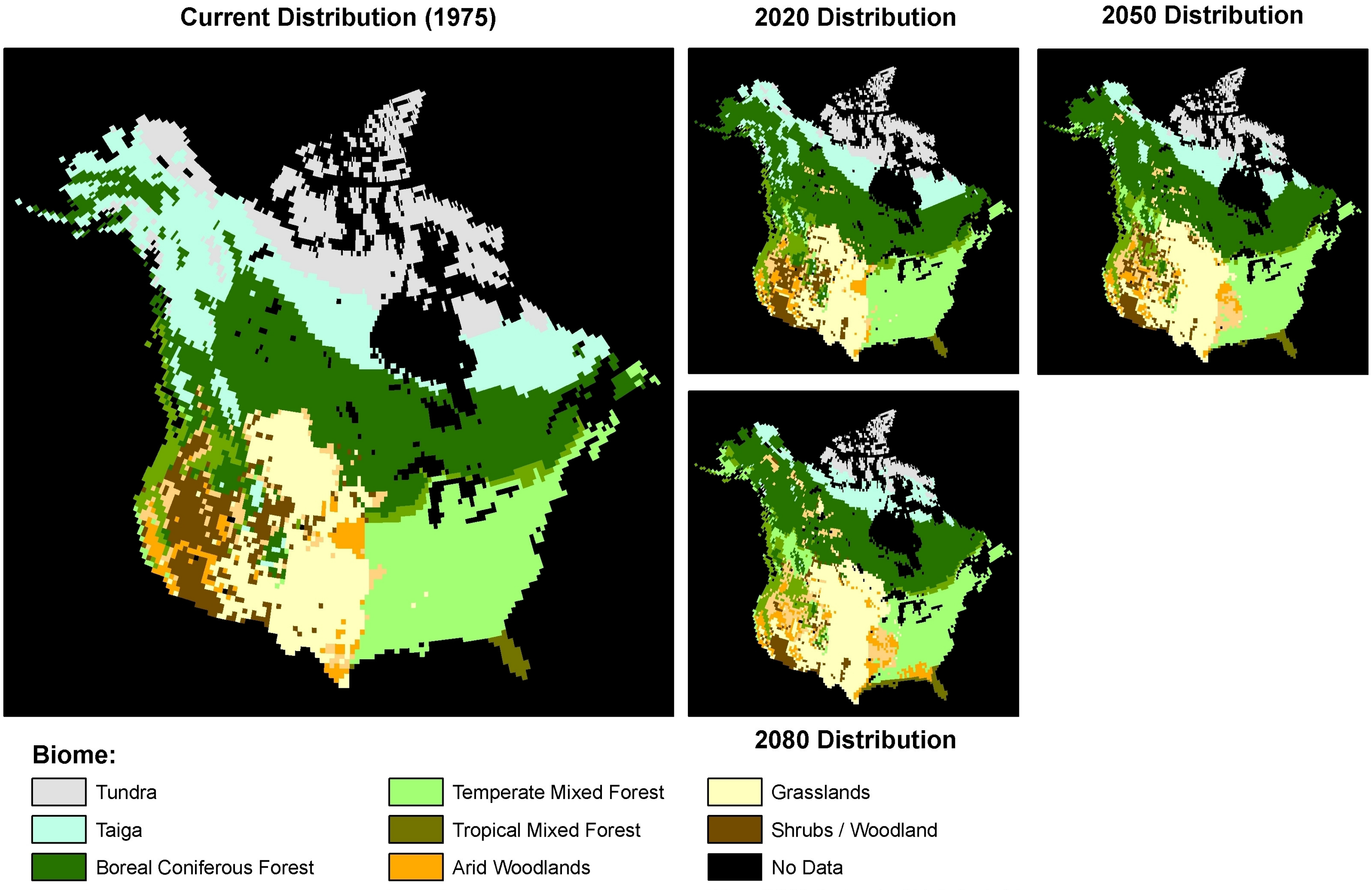
** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
CSIRO Mk2 A2 Static Fire Scenario



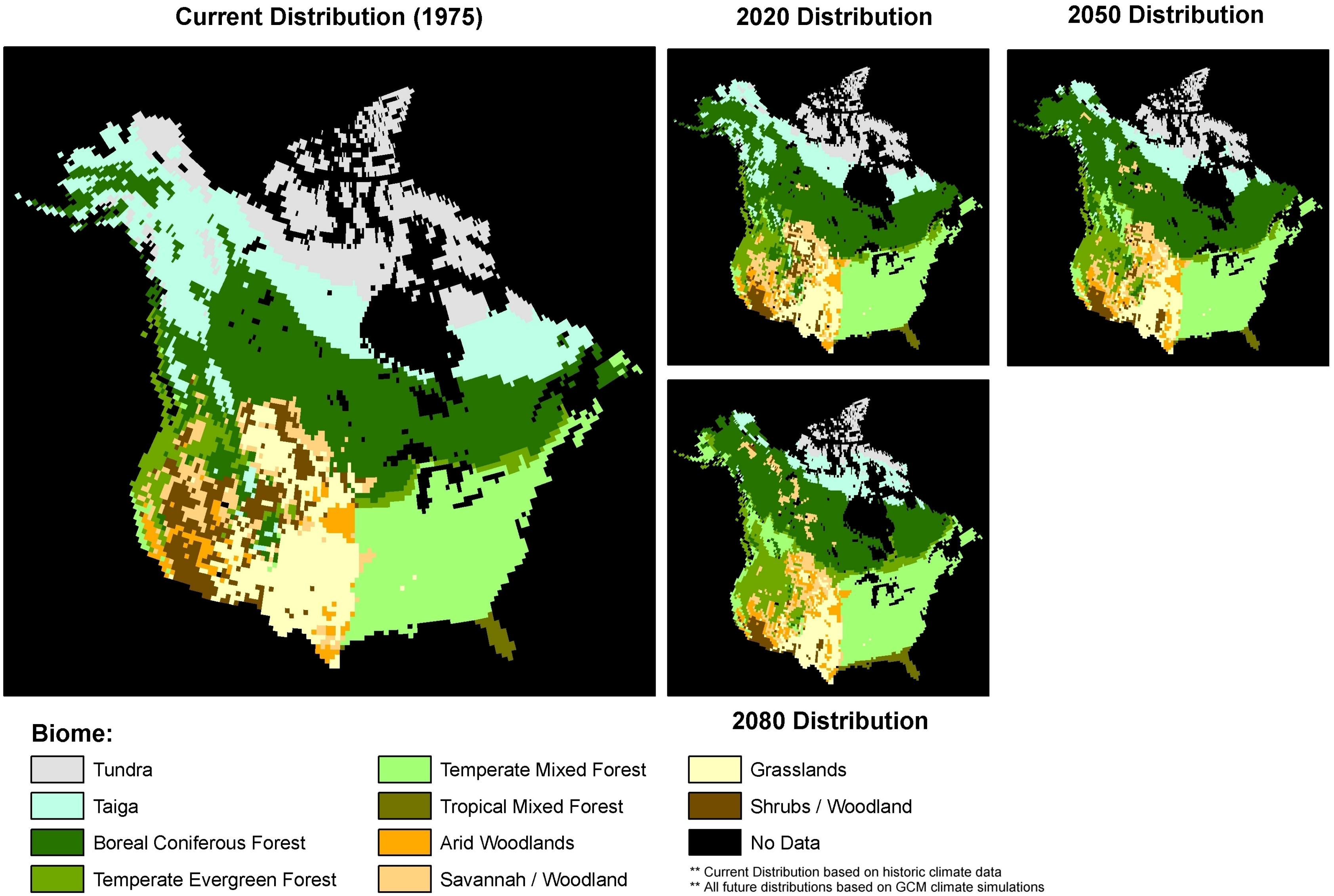
** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
CSIRO Mk2 B2 Dynamic Fire Scenario

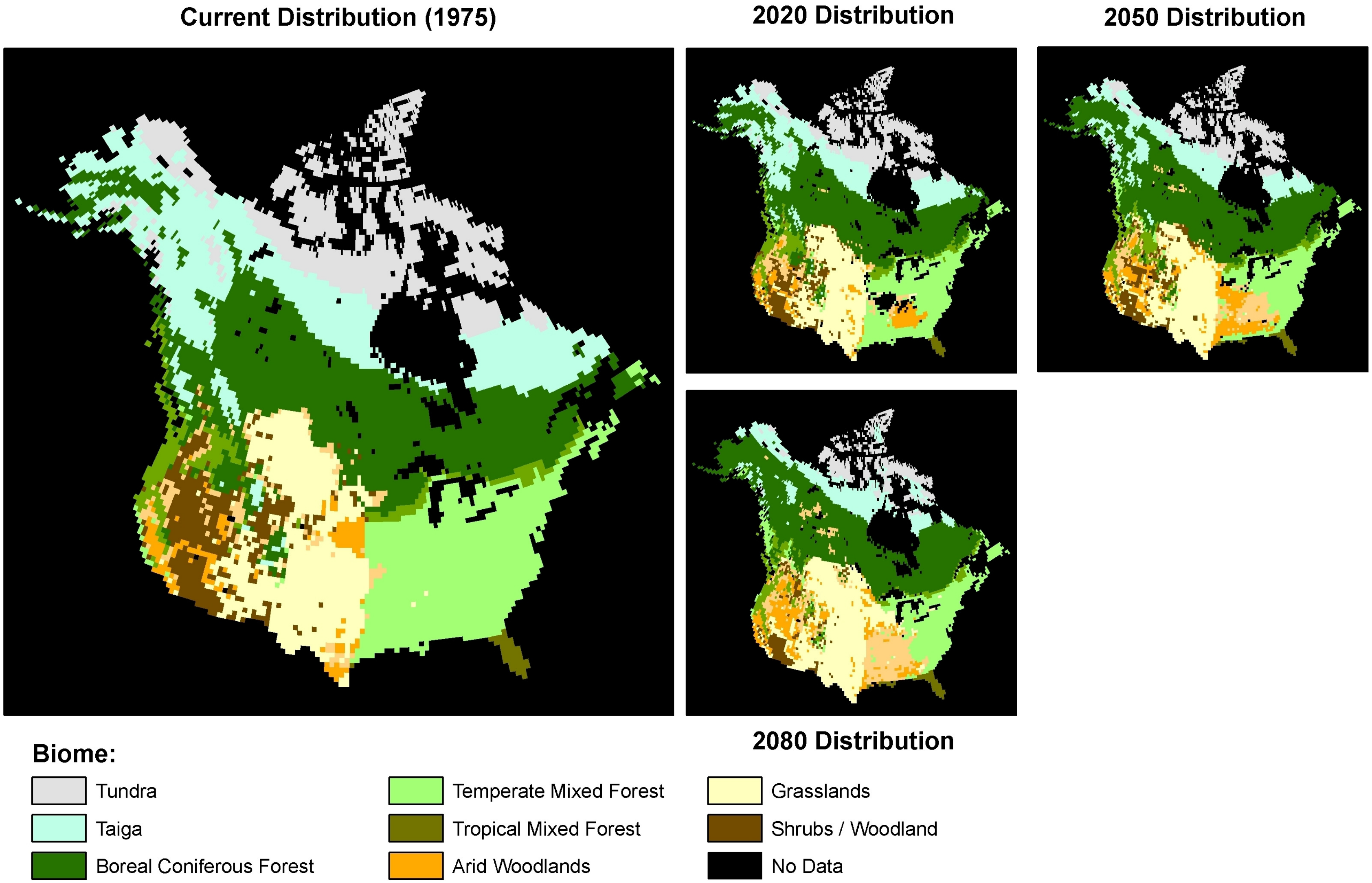


** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
CSIRO Mk2 B2 Static Fire Scenario

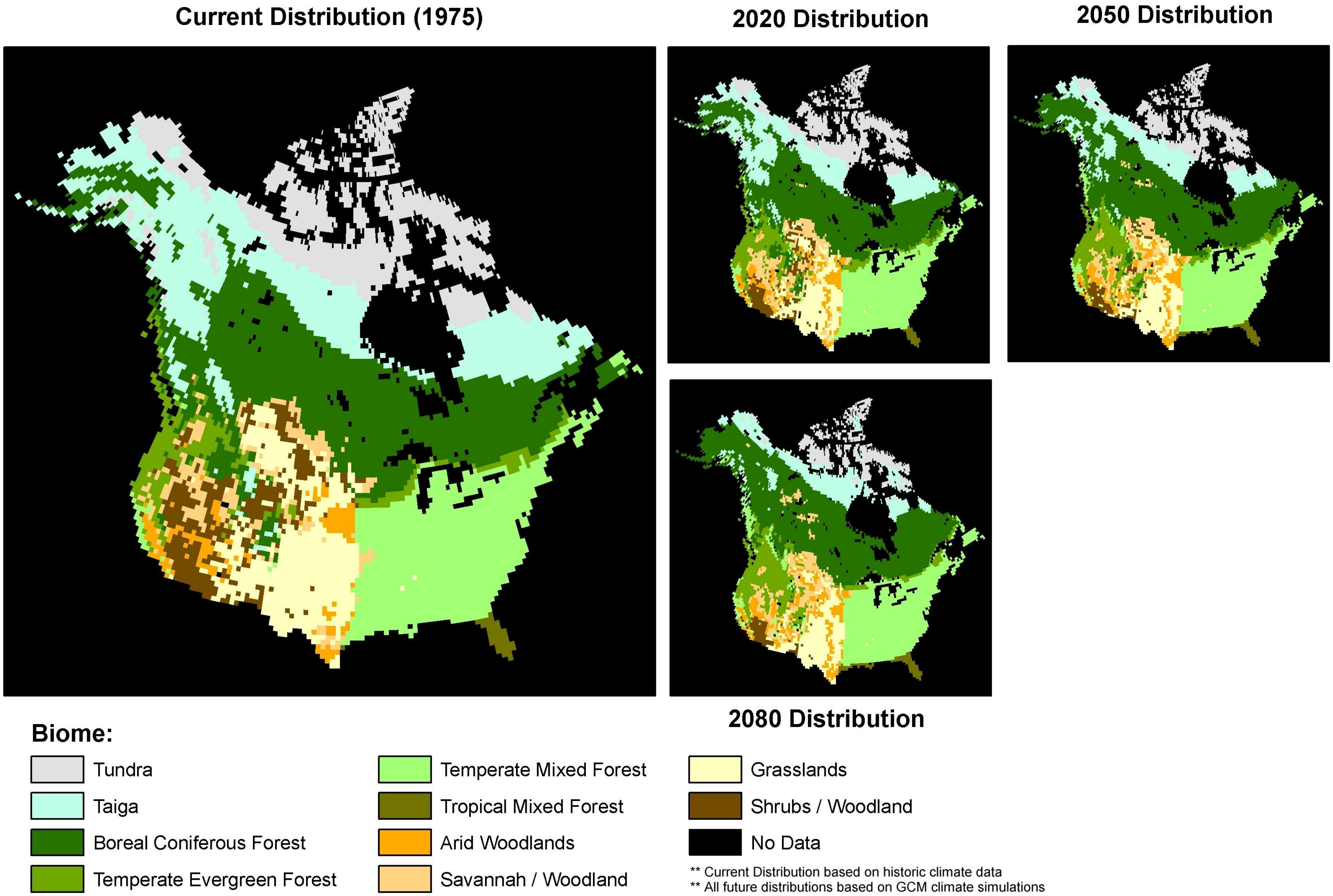


Modelled Biome Extents
Hadley CM3 A2 Dynamic Fire Scenario



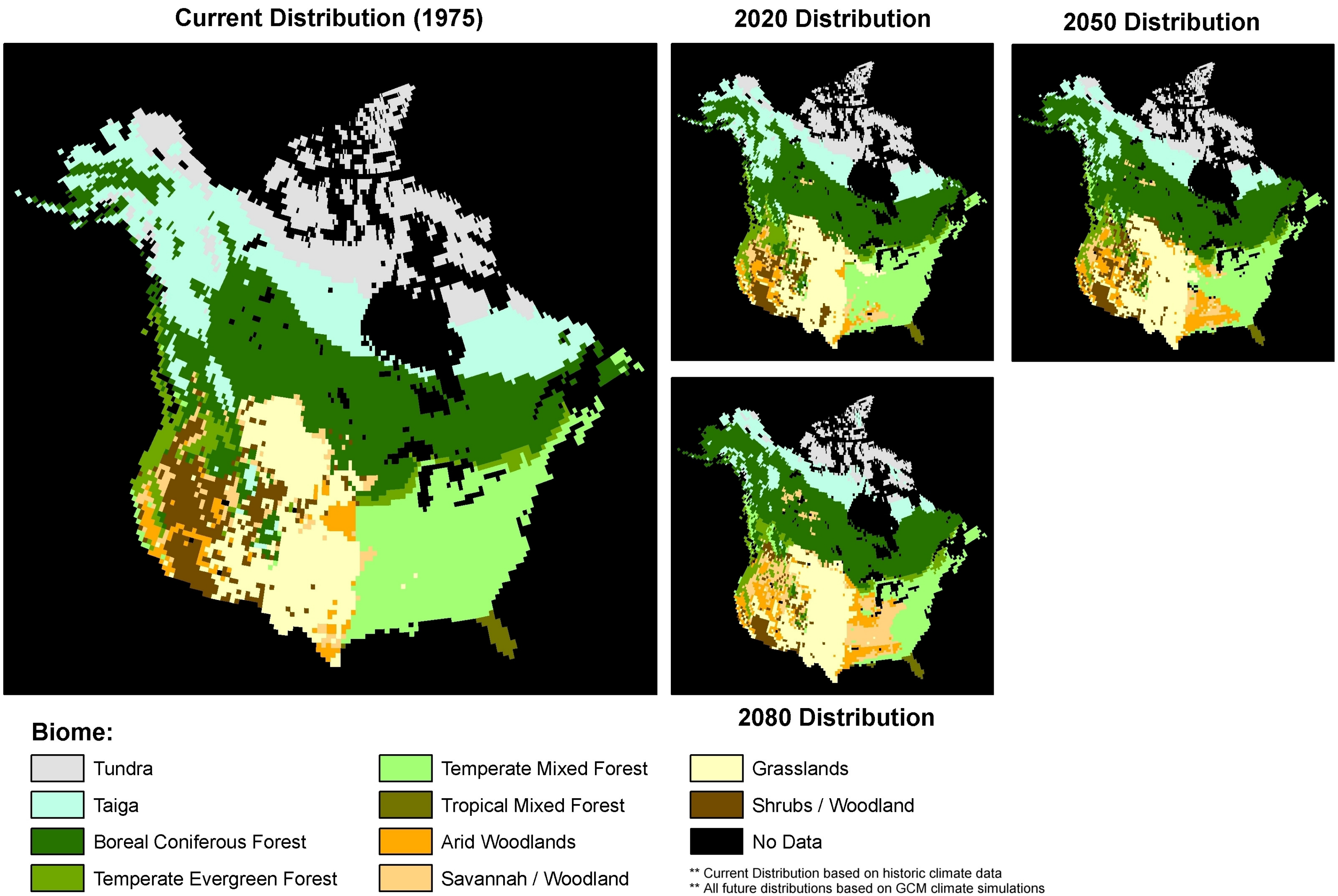
** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
Hadley CM3 A2 Static Fire Scenario



** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
Hadlev CM3 B2 Dvnamic Fire Scenario



Current Distribution (1975)

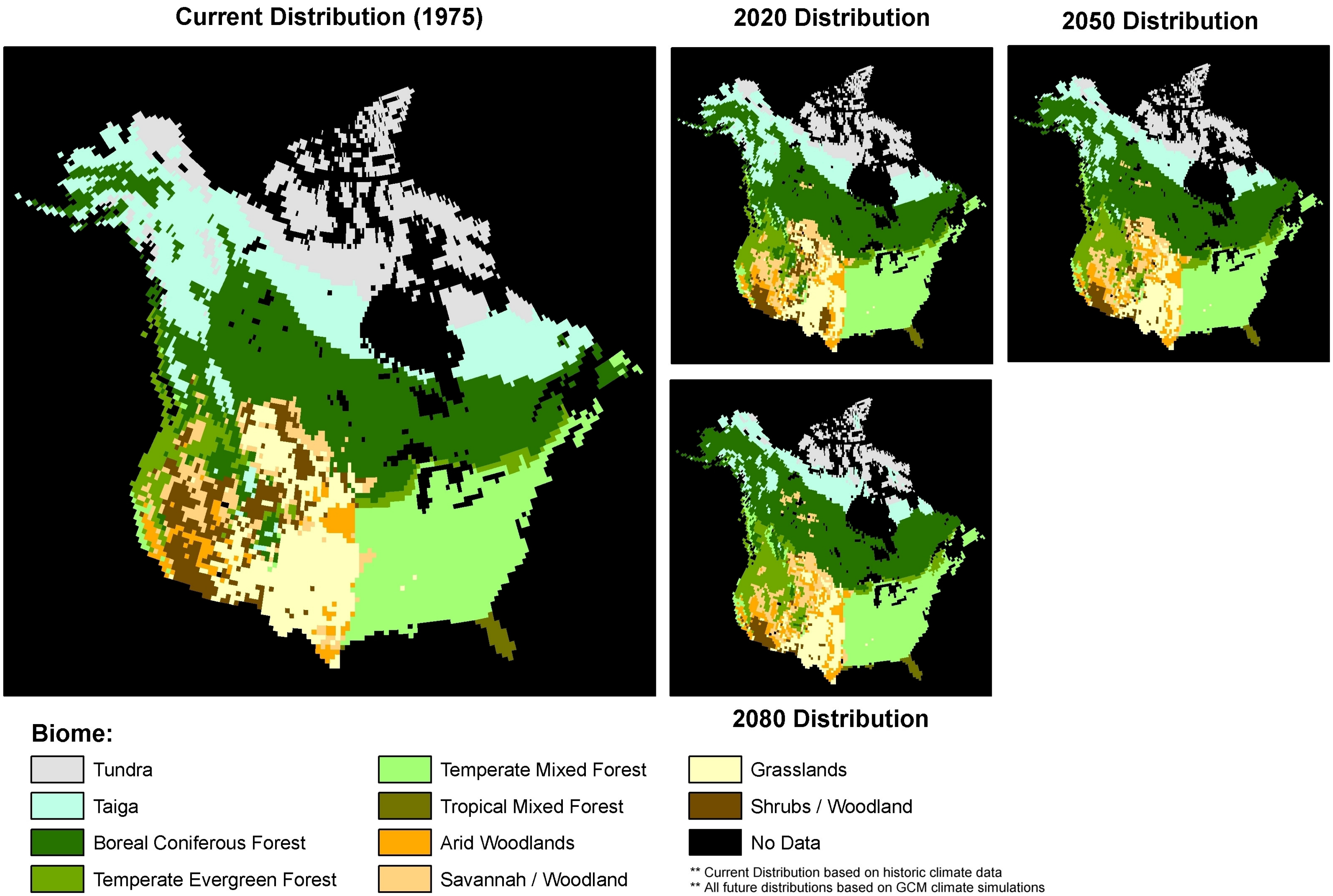
2020 Distribution

2050 Distribution

2080 Distribution

** Current Distribution based on historic climate data
** All future distributions based on GCM climate simulations

Modelled Biome Extents
Hadley CM3 B2 Static Fire Scenario



APPENDIX C

BIOME REPRESENTATION CHANGE
&
SENSITIVITY ANALYSIS TABLES

North American Results
A2 Scenario

	2015 - 2025	Dynamic Fire			Static Fire		
		CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Total #	92						
Total Change		40.0	41.0	38.0	41.0	41.0	43.0
% Change		43.5%	44.6%	41.3%	44.6%	44.6%	46.7%
Rank		2	1	3	2	2	1

	2045 - 2055	Dynamic Fire			Static Fire		
		CGCM2	CSIRO	HadGCM	CGCM2	CSIRO	HadGCM
Total #	92						
Total Change		49.0	49.0	48.0	46.0	48.0	48.0
% Change		53.3%	53.3%	52.2%	50.0%	52.2%	52.2%
Rank		1	1	3	3	1	1

	2075 - 2085	Dynamic Fire			Static Fire		
		CGCM2	CSIRO	HadGCM	CGCM2	CSIRO	HadGCM
Total #	92						
Total Change		59.0	53.0	53.0	55.0	51.0	52.0
% Change		64.1%	57.6%	57.6%	59.8%	55.4%	56.5%
Rank		1	2	2	1	3	2

North American Results
B2 Scenario

	2020	Dynamic Fire			Static Fire		
		CGCM2	CSIRO	HadGCM	CGCM2	CSIRO	HadGCM
Total #	92						
Total Change		37.0	44.0	38.0	41.0	45.0	42.0
% Change		40.2%	47.8%	41.3%	44.6%	48.9%	45.7%
Rank		3	1	2	3	1	2

	2045 - 2055	Dynamic Fire			Static Fire		
		CGCM2	CSIRO	HadGCM	CGCM2	CSIRO	HadGCM
Total #	92						
Total Change		48.0	48.0	42.0	48.0	50.0	46.0
% Change		52.2%	52.2%	45.7%	52.2%	54.3%	50.0%
Rank		1	1	3	2	1	3

	2075 - 2085	Dynamic Fire			Static Fire		
		CGCM2	CSIRO	HadGCM	CGCM2	CSIRO	HadGCM
Total #	92						
Total Change		52.0	52.0	49.0	51.0	56.0	49.0
% Change		56.5%	56.5%	53.3%	55.4%	60.9%	53.3%
Rank		1	1	3	2	1	3

Regional Change Results
A2 Scenario

2015 - 2025		Dynamic Fire			Static Fire	
Region	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Atlantic	1.0	3.0	3.0	1.0	1.0	3.0
Great Lakes	1.0	1.0	1.0	2.0	2.0	2.0
Mountain	14.0	13.0	11.0	15.0	15.0	14.0
Northern	12.0	12.0	12.0	12.0	12.0	12.0
Pacific	10.0	10.0	9.0	7.0	7.0	7.0
Prairie	2.0	2.0	1.0	4.0	4.0	5.0
Southern	0.0	0.0	1.0	0.0	0.0	0.0

2045 - 2055		Dynamic Fire			Static Fire	
Region	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Atlantic	3.0	4.0	3.0	3.0	3.0	3.0
Great Lakes	1.0	1.0	1.0	2.0	2.0	2.0
Mountain	15.0	14.0	13.0	16.0	17.0	16.0
Northern	13.0	13.0	13.0	13.0	13.0	13.0
Pacific	11.0	12.0	12.0	8.0	8.0	9.0
Prairie	4.0	4.0	3.0	4.0	5.0	5.0
Southern	2.0	1.0	3.0	0.0	0.0	0.0

2075 - 2085		Dynamic Fire			Static Fire	
Region	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Atlantic	6.0	5.0	5.0	5.0	4.0	5.0
Great Lakes	3.0	3.0	2.0	4.0	4.0	3.0
Mountain	15.0	14.0	15.0	17.0	17.0	17.0
Northern	13.0	14.0	13.0	13.0	13.0	13.0
Pacific	12.0	11.0	11.0	10.0	9.0	9.0
Prairie	5.0	5.0	4.0	5.0	4.0	5.0
Southern	5.0	1.0	3.0	1.0	0.0	0.0

Regional Change Results
B2 Scenario

2015 - 2025		Dynamic Fire			Static Fire	
Region	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Atlantic	1.0	3.0	2.0	1.0	3.0	2.0
Great Lakes	2.0	1.0	1.0	2.0	2.0	2.0
Mountain	11.0	13.0	12.0	15.0	15.0	14.0
Northern	12.0	13.0	12.0	12.0	12.0	12.0
Pacific	9.0	10.0	10.0	7.0	8.0	8.0
Prairie	2.0	3.0	1.0	4.0	5.0	4.0
Southern	0.0	1.0	0.0	0.0	0.0	0.0

2045 - 2055		Dynamic Fire			Static Fire	
Region	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Atlantic	3.0	5.0	3.0	3.0	4.0	3.0
Great Lakes	2.0	1.0	1.0	2.0	2.0	2.0
Mountain	14.0	14.0	13.0	17.0	17.0	16.0
Northern	13.0	13.0	13.0	13.0	13.0	13.0
Pacific	10.0	11.0	10.0	8.0	9.0	8.0
Prairie	4.0	3.0	1.0	5.0	5.0	4.0
Southern	2.0	1.0	1.0	0.0	0.0	0.0

2075 - 2085		Dynamic Fire			Static Fire	
Region	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Atlantic	4.0	5.0	4.0	4.0	5.0	4.0
Great Lakes	4.0	3.0	2.0	4.0	4.0	2.0
Mountain	14.0	14.0	13.0	17.0	17.0	16.0
Northern	13.0	14.0	13.0	13.0	14.0	13.0
Pacific	11.0	11.0	12.0	9.0	10.0	10.0
Prairie	4.0	4.0	3.0	4.0	6.0	4.0
Southern	2.0	1.0	2.0	0.0	0.0	0.0

Biome Representation Change
A2 Scenario

1975		Dynamic Fire			Static Fire		
Biome	Current	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Arid Woodlands	4.5	4.0	4.0	4.0	5.0	5.0	5.0
Boreal Coniferous Forest	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Grasslands	14.0	16.0	16.0	16.0	12.0	12.0	12.0
Savannah / Woodlands	2.5	3.0	3.0	3.0	2.0	2.0	2.0
Shrubs / Woodlands	10.5	10.0	10.0	10.0	11.0	11.0	11.0
Taiga	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Temperate Evergreen Forest	13.5	13.0	13.0	13.0	14.0	14.0	14.0
Temperate Mixed Forest	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	15.0	15.0	15.0	15.0	15.0	15.0

2015 - 2025		Dynamic Fire			Static Fire		
Biome	Current	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Arid Woodlands	4.5	4.0	4.0	5.0	5.0	5.0	6.0
Boreal Coniferous Forest	33.0	33.0	33.0	32.0	33.0	33.0	32.0
Grasslands	14.0	14.0	15.0	16.0	8.0	8.0	9.0
Savannah / Woodlands	2.5	5.0	5.0	4.0	10.0	10.0	10.0
Shrubs / Woodlands	10.5	9.0	6.0	8.0	9.0	9.0	8.0
Taiga	20.0	19.0	19.0	19.0	19.0	19.0	19.0
Temperate Evergreen Forest	13.5	15.0	16.0	15.0	15.0	14.0	15.0
Temperate Mixed Forest	18.0	21.0	23.0	22.0	22.0	24.0	23.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	14.0	11.0	14.0	14.0	14.0	14.0

Biome Representation Change
A2 Scenario

2045 - 2055		Dynamic Fire			Static Fire		
Biome	**Current**	**CGCM2**	**CSIRO**	**Hadley**	**CGCM2**	**CSIRO**	**Hadley**
Arid Woodlands	4.5	8.0	7.0	8.0	7.0	6.0	6.0
Boreal Coniferous Forest	33.0	30.0	31.0	28.0	30.0	32.0	28.0
Grasslands	14.0	19.0	16.0	17.0	8.0	8.0	9.0
Savannah / Woodlands	2.5	6.0	10.0	11.0	10.0	10.0	12.0
Shrubs / Woodlands	10.5	6.0	6.0	7.0	6.0	5.0	5.0
Taiga	20.0	17.0	15.0	18.0	17.0	17.0	18.0
Temperate Evergreen Forest	13.5	18.0	17.0	15.0	18.0	20.0	21.0
Temperate Mixed Forest	18.0	20.0	29.0	20.0	25.0	25.0	25.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	10.0	7.0	10.0	10.0	12.0	10.0

2075 - 2085		Dynamic Fire			Static Fire		
Biome	**Current**	**CGCM2**	**CSIRO**	**Hadley**	**CGCM2**	**CSIRO**	**Hadley**
Arid Woodlands	4.5	12.0	12.0	9.0	7.0	6.0	9.0
Boreal Coniferous Forest	33.0	19.0	21.0	24.0	22.0	26.0	24.0
Grasslands	14.0	23.0	26.0	22.0	8.0	8.0	9.0
Savannah / Woodlands	2.5	10.0	7.0	11.0	11.0	10.0	12.0
Shrubs / Woodlands	10.5	7.0	7.0	5.0	4.0	5.0	2.0
Taiga	20.0	14.0	9.0	11.0	14.0	14.0	11.0
Temperate Evergreen Forest	13.5	22.0	20.0	20.0	27.0	26.0	22.0
Temperate Mixed Forest	18.0	30.0	37.0	24.0	36.0	27.0	32.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	7.0	5.0	8.0	7.0	9.0	8.0

Biome Representation Change
B2 Scenario

1975 Biome	Current	CGCM2	Dynamic Fire CSIRO	Hadley	CGCM2	Static Fire CSIRO	Hadley
Arid Woodlands	4.5	4.0	4.0	4.0	5.0	5.0	5.0
Boreal Coniferous Forest	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Grasslands	14.0	16.0	16.0	16.0	12.0	12.0	12.0
Savannah / Woodlands	2.5	3.0	3.0	3.0	2.0	2.0	2.0
Shrubs / Woodlands	10.5	10.0	10.0	10.0	11.0	11.0	11.0
Taiga	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Temperate Evergreen Forest	13.5	13.0	13.0	13.0	14.0	14.0	14.0
Temperate Mixed Forest	18.0	18.0	18.0	18.0	18.0	18.0	18.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	15.0	15.0	15.0	15.0	15.0	15.0

2015 - 2025 Biome	Current	CGCM2	Dynamic Fire CSIRO	Hadley	CGCM2	Static Fire CSIRO	Hadley
Arid Woodlands	4.5	5.0	5.0	4.0	5.0	6.0	6.0
Boreal Coniferous Forest	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Grasslands	14.0	15.0	16.0	15.0	8.0	9.0	9.0
Savannah / Woodlands	2.5	3.0	4.0	4.0	10.0	10.0	10.0
Shrubs / Woodlands	10.5	8.0	7.0	6.0	9.0	8.0	8.0
Taiga	20.0	19.0	16.0	18.0	19.0	19.0	18.0
Temperate Evergreen Forest	13.5	14.0	17.0	14.0	14.0	16.0	14.0
Temperate Mixed Forest	18.0	21.0	22.0	23.0	24.0	23.0	23.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	14.0	10.0	14.0	14.0	11.0	14.0

Biome Representation Change
B2 Scenario

2045 - 2055		Dynamic Fire			Static Fire		
Biome	Current	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Arid Woodlands	4.5	8.0	6.0	8.0	6.0	6.0	6.0
Boreal Coniferous Forest	33.0	31.0	27.0	28.0	32.0	31.0	28.0
Grasslands	14.0	18.0	23.0	17.0	8.0	7.0	8.0
Savannah / Woodlands	2.5	5.0	7.0	6.0	10.0	10.0	10.0
Shrubs / Woodlands	10.5	7.0	4.0	6.0	5.0	5.0	6.0
Taiga	20.0	17.0	14.0	18.0	17.0	15.0	18.0
Temperate Evergreen Forest	13.5	18.0	22.0	17.0	20.0	19.0	19.0
Temperate Mixed Forest	18.0	20.0	31.0	20.0	25.0	31.0	22.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	12.0	7.0	12.0	12.0	7.0	12.0

2075 - 2085		Dynamic Fire			Static Fire		
Biome	Current	CGCM2	CSIRO	Hadley	CGCM2	CSIRO	Hadley
Arid Woodlands	4.0	7.0	9.0	10.0	6.0	8.0	8.0
Boreal Coniferous Forest	33.0	25.0	23.0	26.0	26.0	22.0	26.0
Grasslands	16.0	15.0	21.0	16.0	8.0	8.0	7.0
Savannah / Woodlands	3.0	13.0	6.0	11.0	10.0	11.0	10.0
Shrubs / Woodlands	10.0	5.0	4.0	4.0	5.0	3.0	3.0
Taiga	20.0	14.0	14.0	15.0	14.0	9.0	15.0
Temperate Evergreen Forest	13.0	22.0	21.0	21.0	26.0	25.0	23.0
Temperate Mixed Forest	18.0	22.0	39.0	24.0	27.0	44.0	28.0
Tropical Mixed Forest	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Tundra	15.0	9.0	5.0	9.0	9.0	5.0	9.0

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