Alberta's Natural Subregions Under a Changing Climate: Past, Present, and Future

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Executive Summary

The Natural Regions and Subregions classification represents the state-of-the-art in ecological land classification in Alberta. This classification provides a valuable baseline for resource management and conservation planning in the province. It is becoming increasingly apparent, however, that current landscape patterns are destined to change in coming decades as a consequence of global warming. In this report I place the Natural Regions and Subregions into a dynamic framework, describing how they have responded to climate change in the past and how they are expected to change over the next hundred years. Understanding how Natural Regions and Subregions will change over time will improve conservation planning and facilitate adaptation efforts.

The Past

Temperatures in Alberta have been both far colder and far hotter than those we currently experience. The warm climate of the Hypsithermal period (4,000-8,000 years ago) is of particular interest because the ecological patterns of that time can be reconstructed using sediments from lakes and ponds across the province. Most studies suggest that Hypsithermal summer temperatures in Alberta were 1.5-3 °C warmer than at present, which is on the low end of what is expected later this century as a result of global warming. Conditions were also substantially drier at that time, reflecting the combined impact of increased evapotranspiration from higher temperatures and reduced precipitation. Winter temperatures during the Hypsithermal were colder than what is expected for the future, so the Hypsithermal should not be considered a perfect analog for the future climate. Nevertheless, it is the climate during the summer growing season that is most important ecologically.

Reconstructions of Hypsithermal vegetation suggest that Natural Subregions generally shifted one Subregion northward relative to their present distribution. In the Boreal, there is clear evidence of a conversion of Dry Mixedwood to Central Parkland. There is also evidence of a transition of Central Mixedwood to Dry Mixedwood, at lower elevations. Higher elevation sites in the Boreal remained stable during the Hypsithermal.

Pollen records from the Grassland and Parkland are very limited, so it is not known how species composition changed in these Regions during the Hypsithermal. We do know that most lakes were dry, even in the Parkland, which suggests that little more than a dry grassland could have been supported. Evidence of increased aeolian activity implies that active sand dunes were present, and vegetation may have been sparse in some areas.

Compared to the Boreal and Grasslands, the Foothills and Rocky Mountain Regions were relatively stable during the Hypsithermal. There is evidence of upslope movement of tree species, and in some areas there was an increase in the proportion of pine, together with an increase in the rate of fire. The water table decreased, but lakes did not become saline or dry out.

The Present

Mean annual temperature (MAT) is inversely related to latitude and elevation. The spatial pattern is fairly simple, with the mountains and Boreal hill system providing the only significant variations in an otherwise uniform north-south gradient.

Precipitation is highest in the mountains and foothills, where it increases fairly uniformly with elevation. In the rest of province, the highest rates of precipitation are found at mid latitudes and decline as one moves north or south. The northern boundary of Wood Buffalo National Park receives about the same amount of precipitation as Medicine Hat.

The amount of moisture that is available to plants is a function of both temperature and precipitation. Increased temperature causes an increase in the rate of evapotranspiration, which dries out the soil. The Climate Moisture Index (CMI) provides an index of the amount of available moisture on an annual basis. In the southern half of the province CMI increases rapidly with latitude. In the north, CMI is relatively uniform across very large areas, with the notable exception of the hill system. The hills are both cooler and wetter than the surrounding lands and have significantly higher CMI values.

These broad climatic patterns are responsible for most of Alberta's ecological diversity when viewed at the regional scale. Factors other than climate, such as soil type, topography, and disturbance history, become increasingly influential in determining ecosystem type as one moves from the regional scale to the local scale. Subregions represent an intermediate scale — climate is generally the dominant factor in determining Subregion type, but not in all cases.

Bioclimatic envelope models statistically define the unique climate space, or "envelope", of individual ecosystems, based on current eco-climatic associations. Once developed, these models can be used to predict ecosystem type given the future climate as an input. This is the most commonly used approach for predicting changes in the distribution of ecosystems resulting from global warming.

I constructed a suite of bioclimatic envelope models to define the climate space of Alberta`s Subregions, using the mean climate from1961-1990 as the baseline. I limited the development of these models to Subregions for which evidence exists of a strong causal relationship between climate and ecosystem type. These Subregions fall into two main groups: Subregions that are primarily influenced by moisture limitation and Subregions that are primarily influenced by the climatic changes associated with rising elevation. In both groups the Subregions represent points along an ecocline.

The Northern Mixedwood Subregion is another climate-associated ecosystem, but it does not belong to either of the previous two ecoclines. The climate envelope in this case was based on a proxy for the presence of permafrost, the defining feature of this Subregion.

Three Subregions in northeast Alberta — the Kazan Upland, Athabasca Plain, and Peace-Athabasca Delta — experience a boreal climate but are vegetatively quite distinct from the adjacent Central Mixedwood. Unique parent materials are primarily responsible for the distinct vegetation patterns in the Kazan Upland and Athabasca Plain (Precambrian granite and sandstone, respectively). In the case of the Peace-Athabasca Delta it is the extensive delta that is responsible for the unique vegetation patterns. The overriding influence of non-climatic factors on vegetation patterns in these three Subregions means that bioclimatic envelope modeling could not be used for these areas.

Future Climatic Patterns

The climate data for this study were obtained from the ClimateWNA model, which provides downscaled climate data from 24 General Circulation Models (GCMs) used in the Intergovernmental Panel on Climate Change Fourth Assessment. Projections are provided for three 30-year time periods: 2011–40, 2041–70, and 2071–2100 (hereinafter referred to as 2020s, 2050s, and 2080s). Various greenhouse gas emission scenarios are available for each model, and for this study I focused on the high emission A2 scenario and the low emission B1 scenario.

Averaging across all models, the MAT for Alberta is projected to rise by 4.2 °C by the end of the century under the high-emission A2 scenario, and 2.8 °C under the more restrained B1 scenario. None of the models projects an increase of less than 2.0 °C. Accompanying this increase in temperature is an associated 33-56% increase in growing degree-days, which comes largely as a result of an earlier onset of spring.

The average increase in mean annual precipitation (MAP) across all models is 9.4% for the A2 scenario and 7.2% for the B1 scenario. None of the models predicts a decline in MAP. Although overall annual precipitation is projected to increase, most models predict a decline during the summer months. The average decline is 2.4% in July and 6.5% in August for the A2 models and 0.2% in July and 2.3% in August for the B1 models.

Although overall precipitation is projected to increase, most climate models predict that Alberta will become substantially drier in the coming decades. Averaging across all models, CMI decreases from a historical norm of 5.9 cm to -5.1 cm under the A2 scenario and to -0.6 cm under the B1 scenario. The main reason for this decline is that warmer temperatures increase the rate of evapotranspiration from soils and vegetation. In addition, the duration of winter snow cover will be shortened, leading to earlier ground warming and a longer period of evaporative moisture loss. Finally, although total precipitation is projected to increase, precipitation during midsummer, when moisture stress is greatest, is expected to decline.

Future Ecological Patterns

For the detailed analysis of ecological patterns I focused on five GCM-scenario combinations, selected to represent the full range of potential climate outcomes. For readability I labelled these five models on the basis of the defining feature of each: Cool, Median, Hot, Dry, and Wet.

The modeling results suggest that there are two main climate trajectories that need to be considered: dry and wet. The dry trajectory, which is most likely, involves GCMs in which the effects of increased temperature predominate. Increased evapotranspiration from higher temperatures overwhelms any increases in precipitation that may occur, leading to progressive drying of the landscape relative to historic conditions. The Cool and Hot models are representative of minimum and maximum amount of change expected on this trajectory and the Median model represents an intermediate case.

Under the wet climate trajectory, represented by the Wet model, the effects of increased precipitation predominate. Only three GCMs support this outcome, suggesting that it is not likely. Succession under a climate that is both hotter and wetter is difficult to predict because it implies a transition to a climate space that does not currently exist in Alberta. Species from warmer climes would eventually arrive, but major shifts in ecological composition are not likely before the end of the century. This trajectory is not considered in any detail in this report.

The following sections summarize the climatic and successional changes expected in Alberta's major ecosystems under the dry trajectory, which is most likely. Though the rate of change varies among the models, a comparison of the spatial patterns over time indicates that they share a common trajectory. That is, there is a consistent order to the sequence of changes in both the raw climate parameters and the associated climate envelopes. This means that we are not faced with choosing among dozens of potential climatic outcomes arising from different model and scenario combinations. Rather, there is a common pathway of change and the main uncertainty lies in how fast and how far the Subregions will progress along that path.

Most of the information on successional changes is derived from the empirical literature and from information gathered at two expert workshops. The focus is on describing the basic trajectory of ecological change that is expected for each Subregion. Successional pathways are emphasized over specific endpoints because there are too many uncertainties about the timing of changes. An attempt is made to bound the minimum and maximum amount of change expected by the end of the century, using the Cool and Hot models as examples.

Grassland and Parkland

Under the Cool model, representing the least amount of predicted climate change, the Subregion climate envelopes in the Grassland and Parkland shift roughly one Subregion northward by the 2050s. It is reasonable to expect that climatic changes of this extent could be accommodated by changes in the proportions of existing plant communities within each Subregion. That is, communities representing the warm and dry end of the environmental spectrum within a given Subregion will increase, at the expense of communities on the cool and wet end of the spectrum. The mechanism underlying these changes is mainly competition.

Under the Hot model, climatic changes are more extreme than under the Cool model, particular after mid-century. The Parkland will experience the climate of the Dry Mixedgrass by the 2080s. The Dry Mixedgrass in turn will become similar to the driest parts of Wyoming and southern Idaho, where the vegetation is dominated by sagebrush species that are adapted to extreme aridity. This suggests that immigration of species exotic to Alberta will become an important factor under the Hot model. What is unclear is whether the rate of species migration will be able to keep up with the rate of climate change.

Under a warmer climate prairie wetlands will experience reduced runoff and groundwater flows because of regional drying due to increased evapotranspiration. They will also experience increased losses to evaporation, caused by earlier spring melt and higher summer temperatures. As a result, it is expected that the average water level of wetlands will decline and the amount of time that seasonal wetlands are dry will increase. The amount of change will be directly proportional to the amount of warming. It is worth noting that most Grassland and Parkland lakes were dry during the Hypsithermal.

Dry Mixedwood

Under the Cool model the Dry Mixedwood will experience a Parkland climate by mid-century. This will cause an expansion of the small grasslands that already exist along the Peace River lowlands, as well as the appearance of scattered grassy openings elsewhere in the aspen forest.

Under the Hot model, the climate envelope progresses to that of the Dry Mixedgrass in the latter half of the century. Under these conditions aspen would have limited capacity for regeneration. Therefore, widespread transitions to grass are possible after mid-century, at a rate largely determined by the rate of disturbance. Drought, insects, and possibly fire, will be the leading agents of disturbance, opening and expanding gaps in the aspen forest.

Central Mixedwood

Rather than a simple shift northward, as described for the Grassland, the pattern of change in the Central Mixedwood will be strongly influenced by elevation. Lower elevation areas are warmer and will become moisture limited first, beginning with the lowlands along the Peace and Athabasca Rivers. Higher elevation areas will follow. The change from moisture surplus to moisture deficit will affect very large areas once the tipping point is reached because CMI values are relatively uniform across the Boreal.

Under the Cool model, the Dry Mixedwood climate envelope appears in low elevation regions along the Peace and Athabasca Rivers by the 2020s and extends across most of the Subregion by the 2050s. The Parkland climate envelope appears after 2050 in low elevation regions. The loss of most of the white spruce on mesic sites in lower elevation areas seems likely by the end of the century given current rates of fire. At higher elevations the permanent loss of white spruce from mesic sites would be minimal prior to 2050. The timing and distribution of white spruce transitions thereafter would largely depend on the pattern of future fires. It also seems reasonable to expect some expansion of the grasslands that exist along the course of the Peace River.

Under the Hot model, almost the entire Central Mixedwood experiences a Grassland climate envelope by the 2050s. This will preclude white spruce regeneration. However, mature white spruce can withstand dry conditions, as evidenced by hand-planted shelterbelts around farmyards throughout the prairies. Therefore, successional transitions will mainly manifest after the mature trees have been killed by fire or other disturbance. This means that at least half of the original Central Mixedwood forest should still be intact by the end of the century, even if the current rate of fire doubles because of global warming. Additional mortality could occur from severe and prolonged drought if that becomes a significant feature of the climate.

In stands that have been killed by fire the successional patterns are expected to be complex. There is likely to be some influx of pioneer species and those adapted to dry conditions, but also some regeneration back to spruce and aspen. It should be noted that forest losses will continue after 2100 if greenhouse gas emissions are not controlled, leading to the eventual transition of the entire Boreal to grassland.

Peatlands occupy 45% of the Central Mixedwood but only 15% of the Dry Mixedwood. Therefore, a transition to the warmer and drier climate of the Dry Mixedwood, as expected under the Cool model, implies that approximately two-thirds of the peatlands in the Central Mixedwood will dry out and undergo succession to a wooded ecosystem. Given the large extent of the Central Mixedwood (~25% of Alberta), this translates into more than 50,000 km^2 of new terrestrial habitat. It is unclear how quickly the drying will occur — a time lag can be expected because of the ability of peat to absorb and store water during wet periods. As the drying progresses, succession to shrubs and then black spruce forest will follow rapidly. Subsequent transition to a white spruce and aspen mixedwood will occur at a slower pace. Similar transitions can be expected under the Hot model, though succession to forest may become progressively limited once the Subregion is subject to a Grassland climate in the latter half of the century.

Northern Mixedwood and Boreal Subarctic

Successional trajectories in the Northern Mixedwood and Boreal Subarctic will largely be dictated by the dynamics and ecological consequences of permafrost degradation. Permafrost thawing is already underway, but complete melting will take time. Melting is likely to be complete by the end of the century under the Hot model, but some permafrost may remain under the Cool model. The first stage of successional change in areas where melting has occurred will be a transition from open black spruce forest (on frozen ground) to bogs and fens. A gradual drying of the Subregions can be expected as temperatures rise, but this is unlikely to be significant by the end of the century.

Boreal Highlands

Under the Cool model, the Upper and Lower Boreal Highlands both transition to the climate envelope of the Central Mixedwood by the 2020s. This should provide sufficient time for aspen to replace most of the pine at higher elevations by the end of the century, and for the overall character of the Boreal Highlands to become comparable to that of the Central Mixedwood.

Under the Hot model the climate becomes similar to that of the current Dry Mixedwood after 2050 and some of the lower hills eventually experience a Parkland or even Grassland climate. Under this scenario, the Boreal Highlands could transition directly to aspen forest by the end of the century, without white spruce ever becoming prominent. The rate of successional change will be limited by the rate of fire and the rate of aspen dispersal.

Foothills

The Lower Foothills present a challenge because a suitable analog for the predicted hot and wet future climate does not exist in Alberta. Under the Cool model the MAT of the Foothills rises by 2.5 °C by the 2080s. A regional moisture deficit resulting from increased evapotranspiration is unlikely because of the high precipitation inputs. Therefore, the Foothills should remain forested. The main change that can be expected by the 2080s is a general increase in ecological diversity, as species from the Central Mixedwood, Montane, and the Foothills Fescue (to a limited degree) increase in abundance while a legacy of existing Foothills species (especially lodgepole pine) remains intact in favourable sites and in areas that have escaped disturbance. Fire and mountain pine beetle are both important agents of change.

Under the Hot model, the southern part of the Lower Foothills becomes moisture limited as a result of increased evapotranspiration by the 2050s and the entire Subregion is moisture limited by the 2080s. Because successional transitions are limited by the rate of disturbance, it is unlikely that there will be sufficient time for the widespread loss of forest to occur by the end of the century. However, the northward expansion of grasslands from the Foothills Parkland and Foothills Fescue into the southern part of the Foothills is likely under this model.

Rocky Mountains

Vegetative communities in the Rocky Mountains will generally just shift to higher elevations as the climate warms. However, species do not all move at the same rate, and local site conditions, snow pack, and disturbance history can affect pattern of advance, both at treeline and at lower elevations. Therefore, the Alpine, Subalpine, and Upper Foothills will not move upslope as intact units. Instead, the vegetative patterns of the Subregions will blend as the climate warms, increasing ecological diversity (though not permanently).

Other Subregions

The Montane lies at the interface between the prairies and mountains, and is characterized by complex climatic and ecological patterns. With climate warming, the grasslands found at lower elevations and dry sites within the Montane will expand into higher elevations. Under the Cool model at least some parts of the Subregion should remain forested by the 2080s. But under the Hot model it is likely that most of the Subregion will transition to grassland.

In the Peace-Athabasca Delta, climate warming is expected to have two main effects: 1) midwinter thaws in the collecting basins for the Peace and Athabasca Rivers will reduce the volume of peak flows in the spring, and 2) ice will form later and be thinner, lowering the probability of ice jams. These factors are likely to be exacerbated by increasing human withdrawals from the rivers, especially for oil sands extraction. The expected ecological response is a reduction in the extent of wetlands and a progressive conversion of the sedge meadows to shrublands, and eventually to forest.

In the Athabasca Plain, insight into the potential response to climate warming can be gained from the vegetation gradients within the Subregion. The driest sites are open sand, or sand stabilized with grasses. On the windward side of dunes, open jack pine-lichen woodlands develop, with discontinuous lichen mats and widely scattered pine of short stature. On better sites the jack pine stands become continuous and there is more of an understory. As temperatures warm and evapotranspiration increases, a shift to the warm and dry end of this ecological gradient can be expected. This transition could be gradual, but severe and prolonged drought might hasten the process, should it occur.

Successional changes in the Shield as a result of warming will be limited, mainly because the majority of the Region is comprised of bedrock outcroppings that are unvegetated. The pine forests on the coarse sandy soils between the outcroppings will follow the same successional patterns as described for the Athabasca Plain. The overall effect will be the gradual expansion of the unvegetated bedrock outcroppings.

1. Introduction

Over the past several decades much effort has been devoted to ecological land classification in Alberta. The culmination of these efforts is the 2005 map of Natural Regions and Subregions (Fig. 1.1), and the report that accompanies it (Natural Regions Committee, 2006). There are six Natural Regions, defined on the basis of broad biophysical patterns. The Natural Regions are subdivided into 21 Natural Subregions, characterized by vegetation, climate, elevation, soil, and other physiographic differences within a given Natural Region (Table 1.1).

The Natural Region classification provides a valuable baseline for resource management and conservation planning in the province. It is becoming increasingly apparent, however, that current landscape patterns are destined to change in coming decades as a consequence of global warming. The current landscape represents a single page in the continually evolving story of Alberta's biophysical landscape. In this report I place the Natural Regions and Subregions into a dynamic framework, describing how they have responded to climate change in the past and how they are expected to change over the next hundred years.

Climate is one of the main determinants of ecosystem patterns at the regional scale, so a warming climate will cause the current boundaries of Natural Regions and Subregions to shift (Walther et al., 2002; Schneider et al., 2009). Rising temperatures over the past century have already resulted in a variety of ecological changes. Spring flowering has advanced by two weeks, the treeline is moving upslope, permafrost is melting, and aspen is growing at elevations that were previously unsuitable (Roush, 2004; Camill, 2005; Landhäusser et al., 2010; Beaubien and Hamann, 2011).

Understanding how Natural Regions and Subregions are likely to change in the future will improve conservation planning and facilitate adaptation efforts. This has particular relevance for policies and plans that are currently based on fixed benchmarks, such as

Table 1.1. Natural Regions and Subregions of Alberta

Natural Region	Natural Subregion
Rocky Mountain	Alpine
	Subalpine
	Montane
Foothills	Upper Foothills
	Lower Foothills
Grassland	Dry Mixedgrass
	Mixedgrass
	Northern Fescue
	Foothills Fescue
Parkland	Foothills Parkland
	Central Parkland
	Peace River Parkland
Boreal Forest	Dry Mixedwood
	Central Mixedwood
	Lower Boreal Highlands
	Upper Boreal Highlands
	Athabasca Plain
	Peace-Athabasca Delta
	Northern Mixedwood
	Boreal Subarctic
Canadian Shield	Kazan Upland

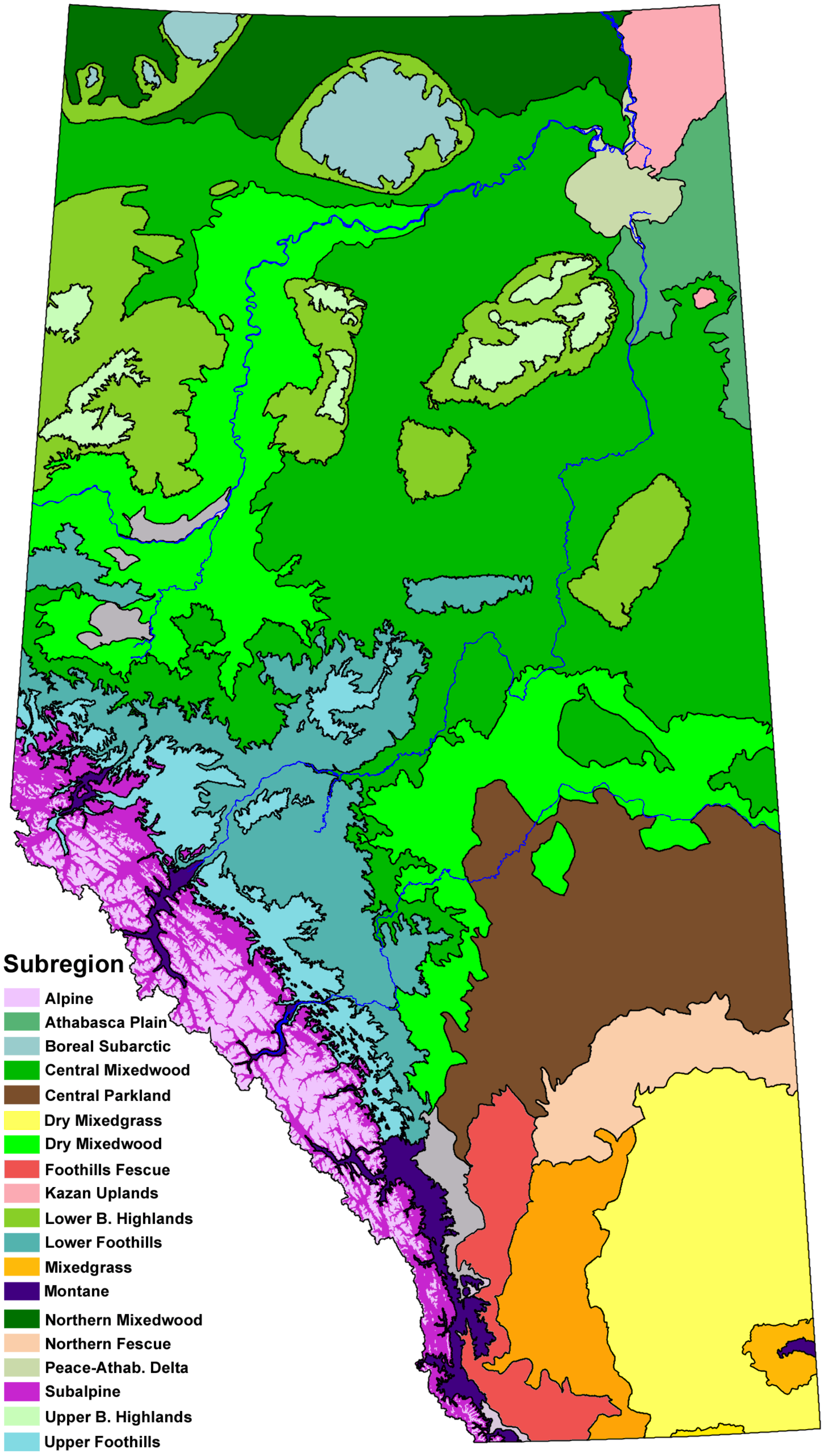

Fig. 1.1. The Natural Subregions of Alberta.

the preindustrial forest or the current range of species of special interest. There is also direct relevance to planning initiatives that are linked to the current extent and distribution of Natural Regions and Subregions, such as the selection of new protected areas and the implementation of conservation offsets.

This paper is divided into three main sections: the past, the present, and the future. In the first section I provide a synthesis of what is known about ecological patterns in Alberta during Hypsithermal period (~6,000 years ago), when temperatures were approximately 2 °C warmer than at present. Ecological reconstructions from this period provide valuable insight into how Alberta's ecosystems have responded to climatic warming in the past. In the second section I describe the current relationships between climate and ecosystem patterns in Alberta and I use these relationships to construct a suite of bioclimatic envelope models. In the final section I summarize and map the climate projections from a group of General Circulation Models (GCMs) and describe how the spatial distribution of bioclimatic envelopes is anticipated to change. I also describe the successional changes expected to occur within individual Subregions as their climates change. The three sections of the report are interrelated but can be read independently.

The scope of this report is limited to the province of Alberta over next 100 years. Natural Subregions represent the spatial scale for the bioclimatic envelope modeling and the descriptions of successional trajectories. The focus is on natural ecosystem processes, using vegetation as a proxy for the complete biotic assemblage of each Subregion. Human land uses, though they have significantly modified natural landscapes in some areas, represent a layer of complexity that is not addressed in this report.

I have adopted a number of conventions in the text to enhance readability. When referring to specific Natural Regions and Natural Subregions I use the core name only (e.g., the Mixedgrass Natural Subregion is referred to as the Mixedgrass). Plants are referred to by their common names; the scientific names are provided in Appendix 1. Acronyms are limited mainly to the core set of climate parameters (Table 1.2). Finally, climate models that are featured in the results have been assigned meaningful labels.

Table 1.2. List of acronyms.

Acronym	Item
CMI	Climate Moisture Index
GCM	General Circulation Model
MAP	Mean Annual Precipitation
GDD	Growing Degree-Days
MAT	Mean Annual Temperature
MCMT	Mean Temperature of Coldest Month
MWMT	Mean Temperature of Warmest Month
SEAS	Seasonality

2. The Past

At the scale of a human lifetime, climate is perceived to be relatively stable. But across longer time spans the dominant theme is change. Temperatures in Alberta have been both far colder and far hotter than those we currently experience.

Of particular interest, within the context of this report, are the climatic changes that have occurred during the Holocene – the period since the end of the last glaciation 10,000 years ago. Ecological responses to climate changes during the Holocene can be reconstructed using sediments from lakes and ponds across the province. These sediments provide a chronological record of pollen, fossils, and hydrological conditions, which together provide a window into regional ecology over time. Much less can be determined about the ecology of earlier periods because the ecological slate was effectively wiped clean by the last glaciation.

2.1 Holocene Climate

Glaciations occur in cycles, largely determined by cyclical changes in earth's orbit (Pielou, 1991). The climatic effect of these cycles is to vary the amount of contrast between summer and winter temperatures. Total annual solar inputs averaged across the globe are not affected by the orbital cycles.

Glaciations are initiated when the contrast between summer and winter temperatures reaches a critical minimum, and summer melting fails to remove the winter snow at high latitudes of the northern hemisphere (Pielou, 1991; Imbrie et al., 1992). Glacial periods end when the orbital cycles align to produce maximum variability between summer and winter, resulting in rapid summer thawing of the ice.

Whereas solar insolation at a given latitude can be accurately determined using orbital models, surface temperature must be inferred from paleontological proxies. In Alberta, the available proxies include vegetation type, invertebrate fauna, and location of the treeline. Based on such proxies it is generally accepted that the period of maximum warmth, known as the Hypsithermal, occurred between 4,000 and 8,000 years ago in Alberta, though some regional variability exists (Vance et al., 1995; Lemmen et al., 1997; Viau et al., 2006; Sundqvist et al., 2010). Maximal warmth did not occur when summer insolation was greatest, approximately 9,000 years ago, because ice sheets still covered much of Canada at that time, reflecting sunlight back into space and absorbing heat as they melted.

Most studies suggest that summer temperatures during the Hypsithermal were 1.5-3 °C warmer than current temperatures (Vance et al., 1995; Vettoretti et al., 1998; Strong and Hills, 2003; Kaislahti Tillman et al., 2010). Conditions were also substantially drier at this time, reflecting the combined impact of increased evapotranspiration from higher temperatures and reduced precipitation (MacDonald and Reid, 1989; Vance et al., 1995; Lemmen et al., 1997). It is not possible to determine which factor was most important (evapotranspiration or precipitation), because their effects on ecological indicators in the paleontological record are similar.

A gradual cooling in summer temperatures has occurred since the Hypsithermal, reflecting the inexorable progression of the orbital cycle towards the next glaciation. An unappreciated benefit of the current rise in CO_2 levels is that it is now virtually certain that the next orbital minimum will not trigger another glaciation (Tzedakis et al., 2012).

2.2 Ecosystem Patterns During the Hypsithermal

Initial ecosystems after the retreat of the ice sheets were dominated by sparse tundra-like vegetation. This was followed by a shrub phase and then a rapid influx of tree species typical of the boreal forest, especially white spruce (Ritchie and MacDonald, 1986). By 9,000 years ago, even the most northern parts of the province were forested (Ritchie and MacDonald, 1986). Southern Alberta was ice-free earlier than other parts of the province and the transition from forest to grasslands had already occurred by the early Holocene (Churcher, 1975).

The ecological patterns of the mid-Holocene — the Hypsithermal — are of particular interest in the context of this report because the warm and dry climate of this period is comparable to the future climate predicted by many of the less-extreme global climate models (see Section 4). Ecological descriptions for individual regions, based primarily on the pollen record (Table 2.1), are provided below. While useful insights can be gained from the study of the Hypsithermal, it is important to bear in mind that it is not a perfect analog for future climates. Seasonality was greater during the Hypsithermal than at present and precipitation was likely lower.

Modern ecological patterns were established in most areas soon after the Hypsithermal ended, approximately 4,000 years ago. Although smaller climatic fluctuations, such as the Medieval Warm Period and the Little Ice Age, occurred in the late Holocene, the ecological effects are not discernable in the paleontological records of most study sites.

Grasslands/Parkland

Unfortunately, pollen records for the Grassland and Parkland are very limited, so it is not known how the vegetation in these Regions responded to the warm and dry conditions of the Hypsithermal. A reduction in ground cover can be inferred from evidence of increased aeolian activity during this period (Bryan et al., 1987; Vance et al., 1995).

The vast majority of water bodies in the Palliser Triangle region dried up during the Hypsithermal and many lakes in the Parkland were dry as well (Vance et al., 1983; Vance et al., 1995; Lemmen et al., 1997). A high-resolution record of hydrological changes in Chappice Lake, near Medicine Hat, indicates that an inverse relationship between temperature and lake levels was also evident in the late Holocene (Vance et al., 1993). Water levels were low during the (warm) Medieval Warm Period (950-1250 CE), and water levels were high during the (cold) Little Ice Age (1400-1850 CE). It is not clear if this relationship has any predictive value, but if it does, it means that very low water levels could again be a prominent feature of the Grassland once temperatures rise in the future.

Dry Mixedwood

Pollen records from the Hypsithermal are available for five lakes situated in the southern component of the Dry Mixedwood (Fig. 2.1). The most notable feature of these lakes

Table 2.1. Paleoecology study sites in Alberta with data for the Hypsithermal period.

Study Site	Subregion	Citation
Buffalo Lake	Dry Mixedwood	Schweger and Hickman, 1989
Chalmers Bog	Montane	Mott and Jackson, 1982
Chappice Lake	Dry Mixedgrass	Vance et al.,1992; Vance et al., 1993
Eaglenest Lake	Upper Boreal Highlands	Vance, 1986
Elk Island Pond	Dry Mixedwood	Forbes and Hickman, 1981; Vance et al., 1983
Fairfax Lake	Upper Foothills	Schweger and Hickman,1989; Hickman and Schweger, 1993
Goldeye Lake	Upper Foothills	Schweger and Hickman,1989; Hickman and Schweger, 1993
Hastings Lake	Dry Mixedwood	Forbes and Hickman,1981; Vance et al., 1983
Lofty Lake	Central Mixedwood/ Dry Mixedwood	Lichti-Federovich, 1970; MacDonald, 1986; MacDonald and Reid, 1989; Schweger and Hickman, 1989
Lone Fox	Upper Boreal Highlands	MacDonald, 1987b
Maligne Valley	Subalpine	Kearney et al., 1987
Mariana Lake	Lower Boreal Highlands	Hutton et al., 1994; Hickman and Schweger, 1996
Moore Lake	Central Mixedwood/ Dry Mixedwood	Schweger and Hickman, 1989; Hickman and Schweger, 1993; Hickman and Schweger, 1996
Smallboy Lake	Dry Mixedwood	Vance et al., 1983
Spring Lake	Lower Foothills	White and Mathewes, 1986; Hickman and White, 1989
Toboggan Lake	Montane	MacDonald, 1989
Wabamun	Dry Mixedwood	Holloway et al., 1981; Hickman et al., 1984; Schweger and Hickman, 1989
Wilcox Pass	Subalpine	Beaudoin and King, 1990
Wild Spear Lake	Boreal Subarctic	MacDonald, 1987a
Yamnuska Bog	Montane	MacDonald, 1982
Yesterday Lake	Upper Boreal Highlands	MacDonald, 1987b

is that most were dry during the Hypsithermal (Vance et al., 1983). Pollen reconstructions suggest that the regional vegetation during the Hypsithermal was an open aspen parkland, with local variations in the amount of grass present (Vance et al., 1983; Hickman et al., 1984). These sites are currently characterized by closed boreal mixedwood forest, with aspen generally dominating.

Central Mixedwood and Boreal Highlands

Two of the Central Mixewood sites — Lofty Lake (near Lac la Biche) and Moore Lake

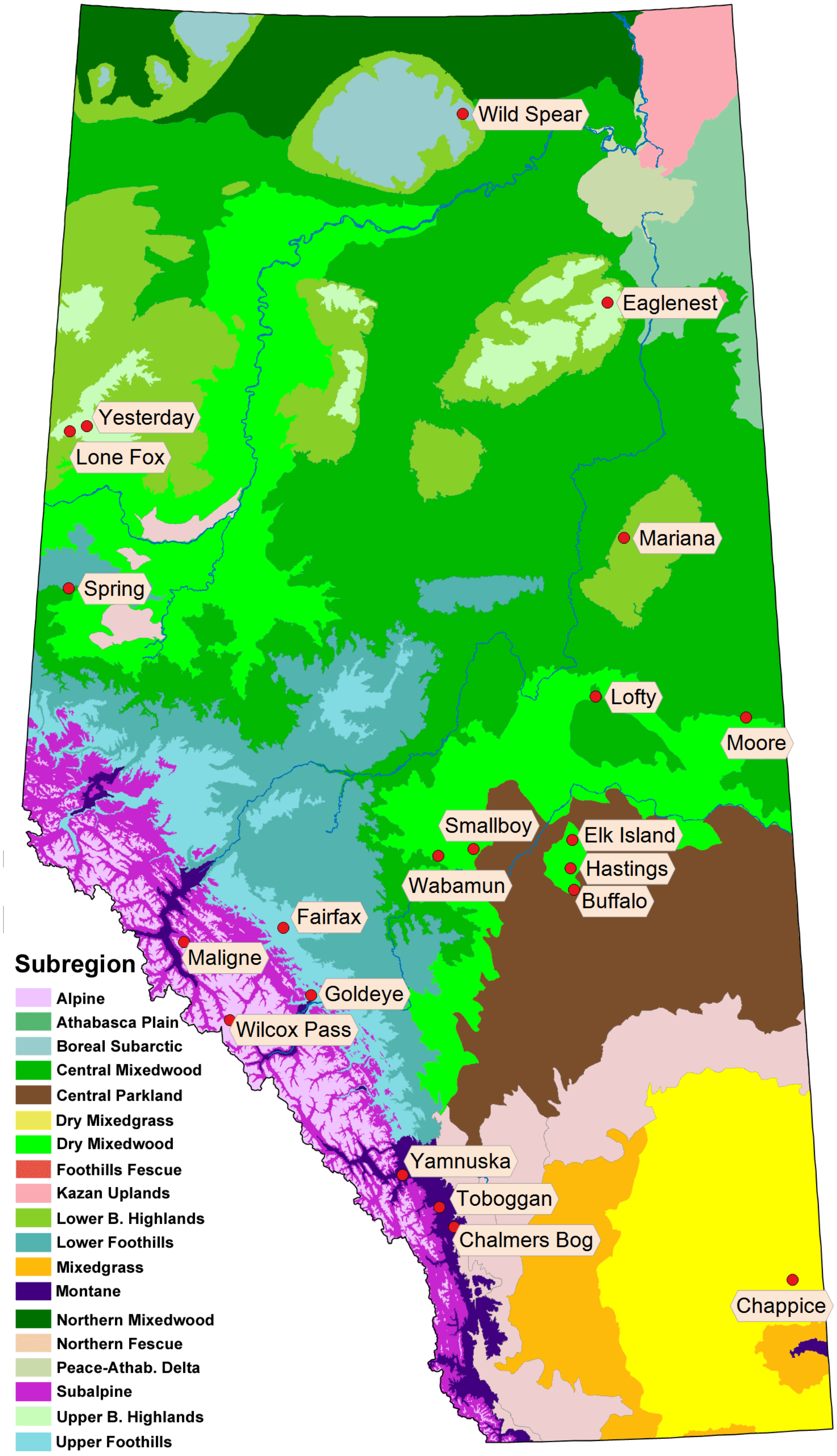

Fig. 2.1. Paleoecology study sites in Alberta with data for the Hypsithermal, overlaid on the Natural Subregions of Alberta.

(near Cold Lake) — lie near the boundary with the Dry Mixedwood (Fig. 2.1). During the Hypsithermal, the water level of Moore Lake may have dropped by 15 m and Lofty Lake largely dried up (Schweger and Hickman, 1989; Hickman and Schweger, 1993). The closed forests of both sites were replaced by a combination of open aspen, grassland, and localized jack pine (Lichti-Federovich, 1970; Hickman and Schweger, 1993; Hickman and Schweger, 1996).

The Mariana Lake site, in the Lower Boreal Highlands approximately 130 km north of the Lofty Lake site, transitioned to an aspen-dominated forest (Hutton et al., 1994; Hickman and Schweger, 1996). Sphagnum was absent from the Mariana Lake site for most of the Hypsithermal, indicating that conditions necessary for the maintenance of peatlands were no longer present. These findings suggest that a Dry Mixedwood ecosystem was present. The continued presence of spruce in the area suggests that the change to parkland vegetation observed in Lofty Lake and Moore Lake did not occur here.

The pollen record from three high elevation northern sites — Eaglenest Lake, Lone Fox, and Wild Spear Lake (Fig. 2.1) — were all stable during the Hypsithermal (Vance, 1986; MacDonald, 1987a; MacDonald, 1987b) .

Foothills and Rocky Mountains

The main change in Foothills sites during the Hypsithermal was an increase in pine at the expense of spruce at higher elevations, and an increase in the rate of fire (MacDonald, 1982; White and Mathewes, 1986). In the Montane, there was a decline in pine and spruce, and an increase in open ground indicators (Mott and Jackson Jr, 1982; MacDonald, 1989). In the Rocky Mountains, there was an upslope migration of white spruce and an upward shift in the treeline of up to 200 m (Luckman, 1986; Kearney and Luckman, 1987; Beaudoin and King, 1990).

The water table in the Foothills declined, but in contrast to the plains, lakes did not become saline or dry out during the Hypsithermal (Hickman and Schweger, 1993; Beierle and Smith, 1998). Many of the Rocky Mountain glaciers, particularly in southern Alberta, melted completely during the Hypsithermal (Beierle and Smith, 1998; Leonard and Reasoner, 1999). These glaciers re-established after the Hypsithermal, reaching their maximum extent during the Little Ice Age (1400-1850 CE).

Conclusions

Summer temperatures during the Hypsithermal cannot be precisely quantified, but most studies suggest they were between 1.5-3 °C warmer than today. This amount of warming is on the low end of what is expected later this century as a result of global warming (see Section 4). Summers during the Hypsithermal were also drier than today, which is what most climate models predict will happen in the future. The winter climate of the Hypsithermal was colder than what is predicted for the future, so the Hypsithermal should not be considered a perfect analog for the future climate. Nevertheless, it is the climate during the summer growing season that is most important ecologically (Lemmen et al., 1997).

The reconstructions of Hypsithermal vegetation suggest that Natural Subregions shifted approximately one Subregion northward relative to their present distribution. In the Boreal, the Lofty Lake and Moore Lake sites provide clear evidence of a conversion of Dry Mixedwood to Central Parkland. The increase in aspen and virtual disappearance of peatlands from the Mariana Lake site, in the Lower Boreal Highlands, implies that much of the Central Mixedwood may have transitioned to Dry Mixedwood. Higher elevation sites in the Boreal were relatively stable during the Hypsithermal.

Pollen records from the Grasslands and Parkland are very limited, so it is not known how species composition changed in these Regions. The fact that most lakes were dry, even in the Parkland, suggests that little more than a dry grassland could have been supported. Evidence of increased aeolian activity implies that active sand dunes were present, and vegetation may have been sparse in some areas.

Compared to the Boreal and Grasslands, the Upper Foothills and Rocky Mountains were relatively stable during the Hypsithermal. There is evidence of upslope movement of tree species, and at higher elevations there was an increase in the proportion of pine, together with an increase in the rate of fire. The water table decreased, but lakes did not become saline or dry out. No information is available from the main body of the Lower Foothills, so it is not known how the vegetation of this large Subregion responded to the warmer Hypsithermal climate.

I have attempted to reconstruct the broad ecological patterns of the Hypsithermal by reassigning the ecosystem type of current Subregion polygons on the basis of the Hypsithermal pollen data (Fig. 2.2). The assumptions underlying this reconstruction are that the available pollen study sites are representative of the Subregion they are located in and that the Subregion polygons reflect enduring landscape features. This reconstruction should be considered a coarse approximation because the number of study sites is low, particularly at low elevations.

Strong and Hills (2003, 2005) are less conservative in their interpretation of the paleontological data and suggest that parkland ecosystem covered much of the Boreal lowlands during the Hypsithermal (Fig. 2.3). In an alternative reconstruction by Dyke (2005), the Parkland shifts north by ~150 km but the rest of northern Alberta remains as boreal forest. The reason for this discrepancy is that Dyke simply averages the findings from the northern study sites and applies this result across all of northern Alberta. This is not reasonable because the available study sites in northern Alberta are all from high elevation sites and provide no indication of what was happening in the lowlands below. Until additional data from the Boreal lowlands are collected, uncertainty regarding the state of the Boreal in Hypsithermal will remain. But a reconstruction that accounts for the ecological effects of elevation on ecological patterns will be much closer to the mark than one that does not (see Section 3).

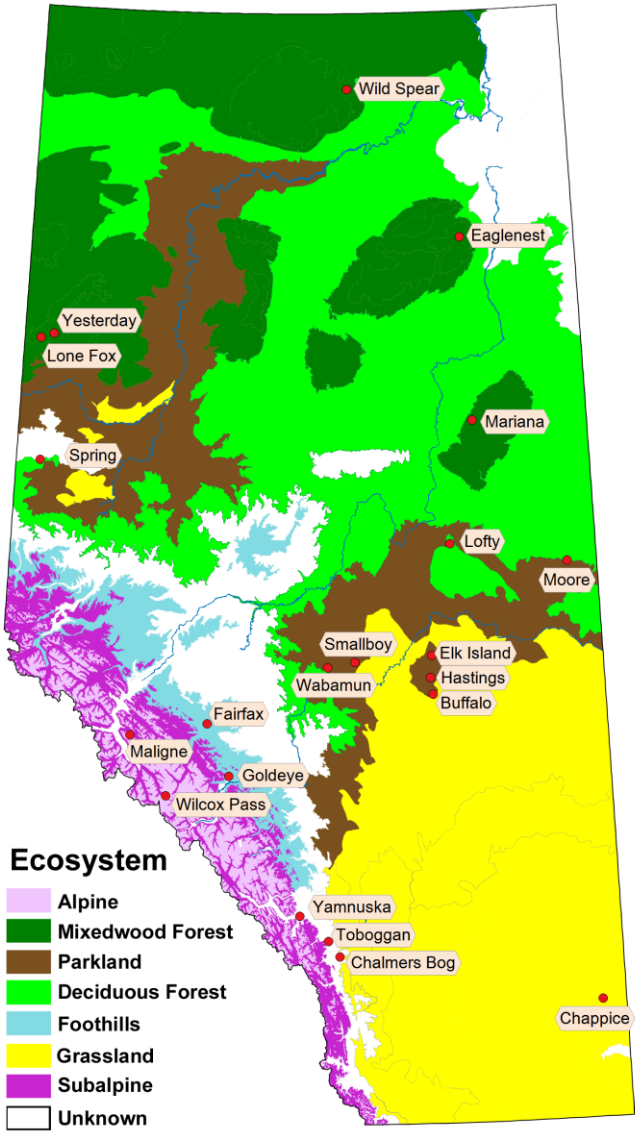

Fig. 2.2. A reconstruction of major ecosystem types of the Hypsithermal period.

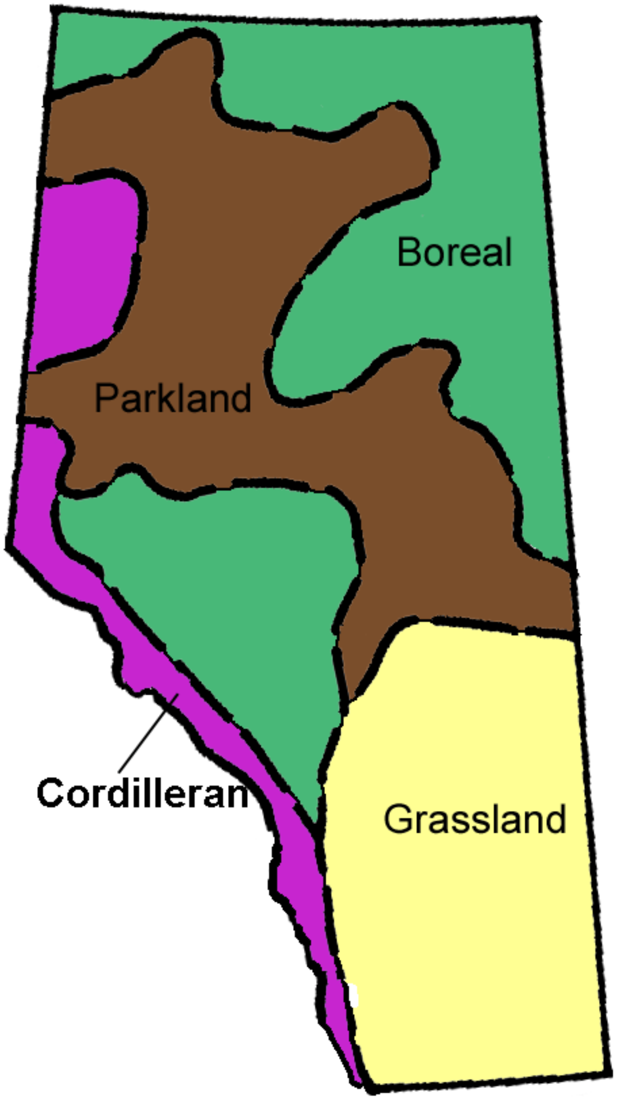

Fig. 2.3. Ecosystem reconstruction for the Hypsithermal period, derived from Strong and Hills, 2005.

3. The Present

3.1 Current Ecosystem Patterns

Ecosystem classification involves categorizing complex ecological systems, that often transition seamlessly from one to the next, into discrete ecologically meaningful spatial units. Most often, the ecological inventory data available for this task are quite limited in terms of the species included, resolution, and spatial coverage, precluding a strictly quantitative approach to classification. For Alberta's Natural Region classification the determination of what constitutes an ecologically meaningful unit was made using an expert-based approach that built on decades of land classification efforts at the provincial and national scales (Natural Regions Committee, 2006). It represents the state-of-the-art in ecological land classification in the province and has stood the test of time in terms of its validity and effectiveness in characterizing regional ecological patterns and processes.

In my analysis of eco-climatic patterns I used Natural Subregion polygons to define the ecosystems of interest. The boundaries between adjacent Subregions are typically defined with reference to just one or two biophysical attributes, such as soil type and elevation, which serve as indicators for the entire unit. The models I developed (Section 3.3) replace the static indicators used in the initial Subregion classification with dynamic climate-based indicators that can be projected into the future. Table 3.1 provides a summary of the key ecological features of each Subregion and the attributes used for their differentiation. I refer the reader to the Natural Regions and Subregions report for detailed information on the biophysical attributes of each Subregion (Natural Regions Committee, 2006).

3.2 Current Climatic Patterns

Although Alberta's climate has never been truly static, by convention the period from 1961-1990 is used to represent the historical "norm". The idea is to average out year-to-year variations to obtain a reasonable representation of the climate that Alberta's vegetative communities have adapted to. In this section I review the spatial patterns evident in the 1961-1990 dataset. The data were obtained from the ClimateWNA model (see Appendix 2 for methodology). The same dataset was used to construct the bioclimatic envelope models described in the following section. A summary of climate values for the historical reference period, by Subregion, is provided in Table 3.2.

Mean annual temperature (MAT) is inversely related to latitude and elevation. The spatial pattern is fairly simple, with the mountains and Boreal hill system providing the only significant variations in an otherwise uniform north-south gradient (Fig. 3.1).

The spatial pattern of mean annual precipitation (MAP) is more complex. Precipitation is highest in the mountains and foothills, where it increases fairly uniformly with elevation (Fig. 3.2). In the rest of Alberta, the highest rates of annual precipitation are found at mid latitudes and decline as one moves north or south. The northern boundary of Wood Buffalo National Park receives about the same amount of precipitation as Medicine Hat.

Table 3.1. Summary of the dominant vegetation of Alberta's Natural Subregions[1].

Subregion	Vegetation
Lower Foothills	The Lower Foothills have the most diverse forests in Alberta. Aspen, balsam poplar, white birch, lodgepole pine, black spruce, white spruce, and tamarack grow as pure stands or as mixtures on a variety of slopes and aspects. Pure deciduous stands are more common at lower elevations. The transition from Central Mixedwood to Lower Foothills is defined by the appearance of lodgepole pine stands.
Upper Foothills	Typically, even-aged fire-origin lodgepole pine stands, often with an understory of black spruce. White spruce stands occur along river valleys and on lower slopes; white spruce-Engelmann spruce hybrids occur at higher elevations. The transition to Upper Foothills is marked by the transition from mixedwood-dominated forests to conifer-dominated forests.
Subalpine	Open stands of Engelmann spruce and subalpine fir are dominant at higher elevations, with stunted individuals and krummholz islands near treeline; closed lodgepole pine forests are prevalent at lower elevations. The transition to Subalpine is marked by the shift from white spruce to Engelmann spruce.
Alpine	Plant growth is limited to low growing shrubs and herbs in protected areas. The growing season is too short for tree growth. The transition to Alpine is defined by the tree line.
Montane	Complex patterns are present. Lodgepole pine, Douglas fir and aspen stands occur on easterly and northerly aspects and grasslands on southerly and westerly aspect at lower elevations. Closed mixedwood and coniferous forests dominated by lodgepole pine occur at higher elevations.
Dry Mixedgrass	Semiarid prairie with low-growing grasses, and shrubs and herbs that are adapted to summer droughts. Associated with brown Chernozemic soils.
Mixedgrass	Community types are similar to those found in the Dry Mixedgrass. However, the higher productivity and occurrence of species associated with cooler and moister conditions differentiate this Subregion from the Dry Mixedgrass. Associated with dark brown Chernozemic soils.
Northern Fescue	Community types are similar to those found in the Dry Mixedgrass. The dominance of plains rough fescue differentiates this Subregion from the other grassland Subregions. Associated with dark brown Chernozemic soils.
Central Parkland	Transitional between grasslands and forest. Native vegetation is usually an aspen–grassland mosaic. Fescue prairies dotted with aspen groves occur in the driest areas to the south and east. In central areas, with increased moisture, aspen forest and plains rough fescue grasslands are found in roughly equal proportion. Higher precipitation to the north and west promotes closed aspen forests within which small grassland patches may occur. Associated with black Chernozemic soils.

[1] Extracted from the Natural Regions and Subregions of Alberta report (Natural Regions Committee, 2006) .

Table 3.1 (continued).

Subregion	Vegetation
Dry Mixedwood	Characterized by aspen forests with scattered white spruce. Treed or shrubby fens occupy about 15% of the Subregion.
Central Mixedwood	A mosaic of aspen, mixedwood and white spruce forests on uplands, with extensive areas of mainly black spruce fens in low-lying areas and jack pine stands on sandy soils to the east. Wet, poorly drained fens and bogs overlie almost half the area.
Lower Boreal Highlands	Vegetation is similar to the Central Mixedwood, but more diverse including balsam poplar and white birch forests in seepage areas. Lodgepole pine–jack pine hybrids are common in pure and mixed stands with black spruce and deciduous species.
Upper Boreal Highlands	Predominantly coniferous forests (lodgepole pine–jack pine hybrids, with white and black spruce) with locally extensive wetlands in low-lying portions of the plateaus.
Athabasca Plain	Jack pine forests with lichen understories and low shrublands with sedge fens in low areas and some unvegetated areas (active dunes). Associated with dry sandy soils.
Peace-Athabasca Delta	Many large and small lakes, extensive sedge meadows, and willow-dominated shrublands underlain by wet mineral soils. The Subregion is defined by the extent of the delta.
Northern Mixedwood	Wetlands with organic soils are the dominant landscape feature, and permafrost occurs over significant areas. Black spruce is common both on uplands and in wetlands; deciduous and mixedwood stands are uncommon. The Subregion is defined by the extent of discontinuous permafrost, using a temperature proxy.
Boreal Subarctic	Stunted open black spruce stands with shrub, moss and lichen understories and peatland complexes occur over most of the area. Permafrost is extensive. Well drained upland areas occupy minor areas of the Subregion, and a variety of upland forests may occur.
Kazan Upland	Sixty percent of the landscape is exposed bedrock. Open jack pine, aspen and birch stands occur where the soil is sufficiently deep. Acidic bogs and poor fens occur adjacent to the many small lakes. The Subregion is defined by the extent of Precambrian bedrock, the westernmost edge of the Canadian Shield.

Table 3.2. Summary of climatic data for the 1961-1990 reference period, by Subregion.[1]

Subregion	MAT	MWMT	MCMT	GDD5	SEAS	MAP	CMI
Alpine	-2.3	8.8	-12.9	397	21.7	1,233	103.1
Athabasca Plains	-1.6	16.3	-23.5	1,253	39.8	402	2.8
Central Mixedwood	-0.1	15.9	-19.9	1,250	35.7	458	4.1
Central Parkland	2.3	16.5	-14.5	1,399	30.9	447	-4.1
Dry Mixedgrass	4.1	18.6	-12.3	1,711	31.0	330	-28.7
Dry Mixedwood	1.1	16.0	-17.0	1,311	33.0	459	0.4
Foothills Fescue	3.9	16.3	-9.7	1,387	26.0	470	-8.2
Foothills Parkland	3.0	14.8	-10.0	1,157	24.8	529	3.5
Kazan Upland	-2.9	15.9	-25.2	1,149	41.1	367	3.2
Lower B. Highlands	-1.3	15.0	-21.3	1,107	36.3	447	6.5
Lower Foothills	2.0	14.7	-12.4	1,152	27.1	592	17.0
Mixedgrass	4.4	17.5	-10.1	1,562	27.6	393	-20.3
Montane	2.1	13.8	-10.5	1,008	24.4	625	18.7
Northern Fescue	2.9	17.2	-13.6	1,494	30.8	386	-14.9
N. Mixedwood	-2.8	15.6	-24.5	1,125	40.1	375	2.3
Peace-Athab.Delta	-1.6	16.5	-23.8	1,282	40.3	382	-0.1
Peace Parkland	1.3	15.7	-16.1	1,289	31.8	450	-0.3
Subalpine	-0.1	11.4	-11.6	677	22.9	916	61.7
Subarctic	-4.1	13.7	-24.8	846	38.5	430	13.4
Upper B. Highlands	-1.8	14.2	-21.2	993	35.4	477	12.7
Upper Foothills	1.6	13.4	-10.8	965	24.1	660	28.3
Province	**0.6**	**15.5**	**-17.0**	**1,229**	**32.6**	**490**	**5.9**

[1] MAT = Mean Annual Temperature; MWMT = Mean Warmest Month Temperature; MCMT = Mean Coldest Month Temperature; GDD5 = Growing Degree-Days above 5 C; SEAS = Seasonality; MAP = Mean Annual Precipitation; CMI = Climate Moisture Index. See text for explanations of each parameter.

The amount of moisture that is available to plants is a function of both temperature and precipitation. Increased temperature causes an increase in the rate of evapotranspiration, which dries out the soil. The Climate Moisture Index (CMI) provides an index of the amount of available moisture on an annual basis. It is calculated by subtracting potential evapotranspiration from precipitation using monthly climate data (Hogg, 1997).

In the southern half of the province CMI increases rapidly with latitude because the effects of precipitation and temperature are additive (i.e., precipitation increases and temperature decreases as one moves north; Fig. 3.3). In the northern half of the province the precipitation cline reverses and so temperature and precipitation have opposing effects on CMI. As a result, CMI values in the north are relatively uniform across very

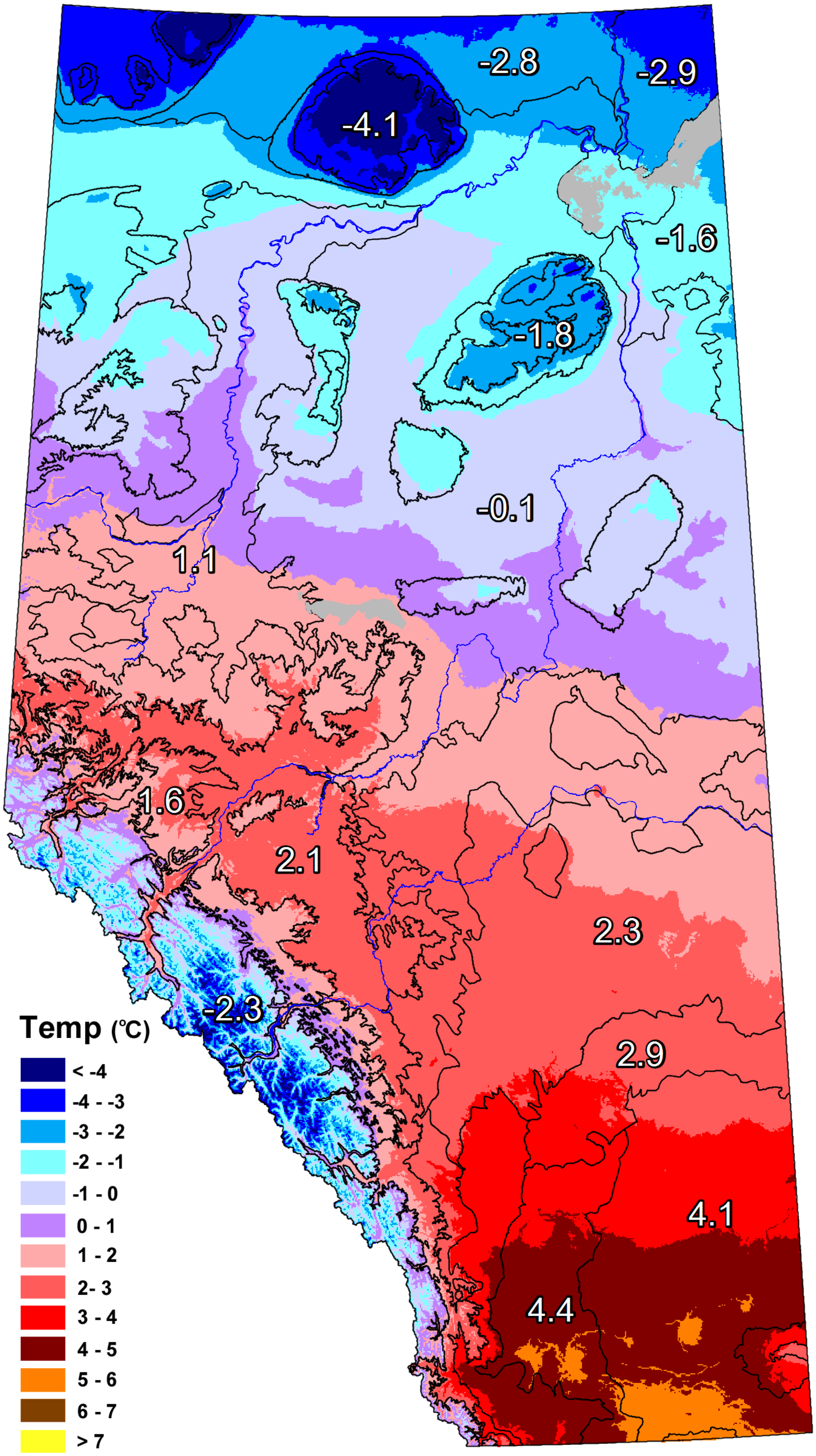

Fig. 3.1. MAT for the 1961-1990 reference period. Natural Subregions are outlined in black and the average MAT for the larger Subregions is shown on the map.

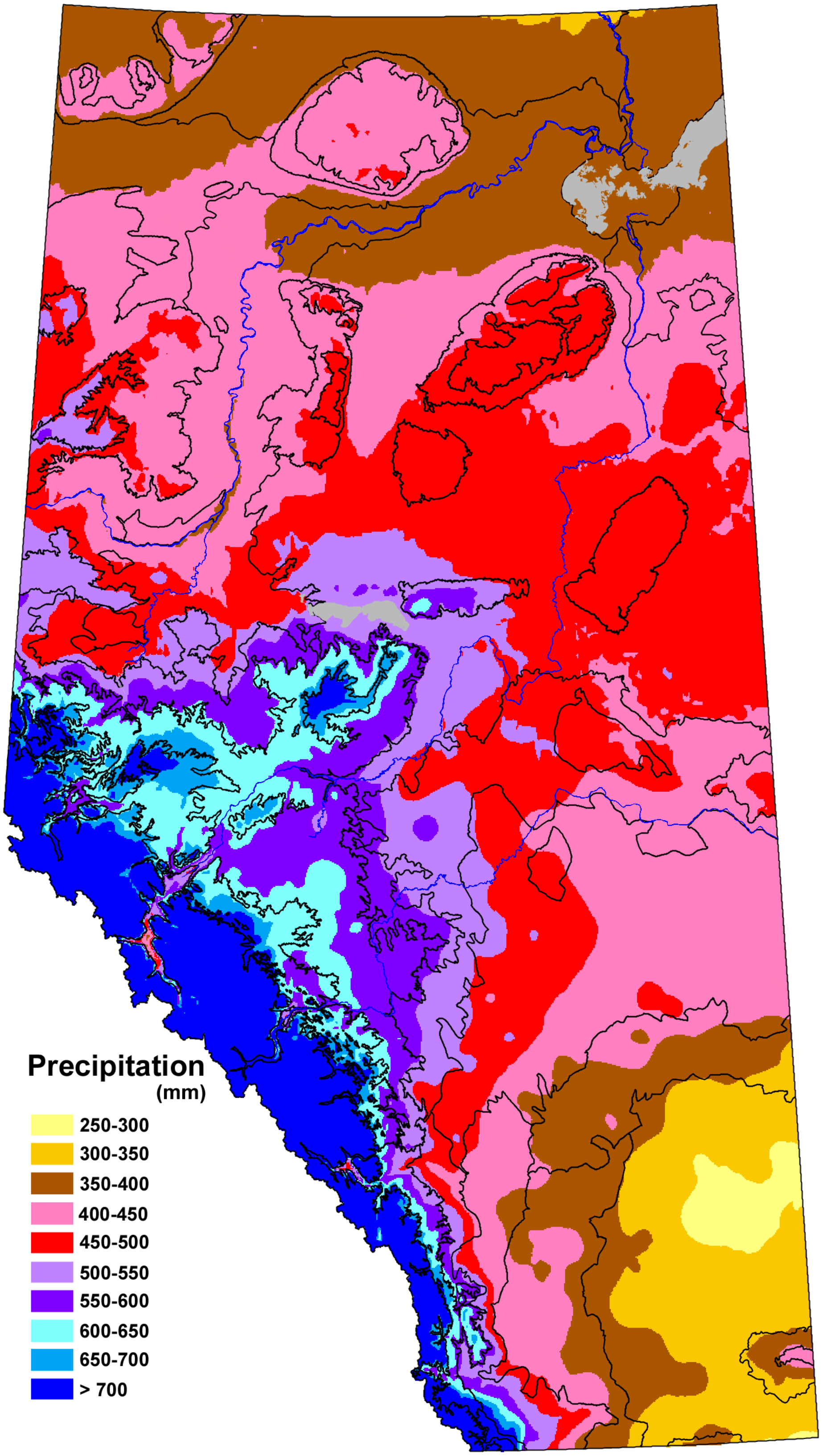

Fig. 3.2. MAP for the 1961-1990 reference period. Natural Subregions are outlined in black.

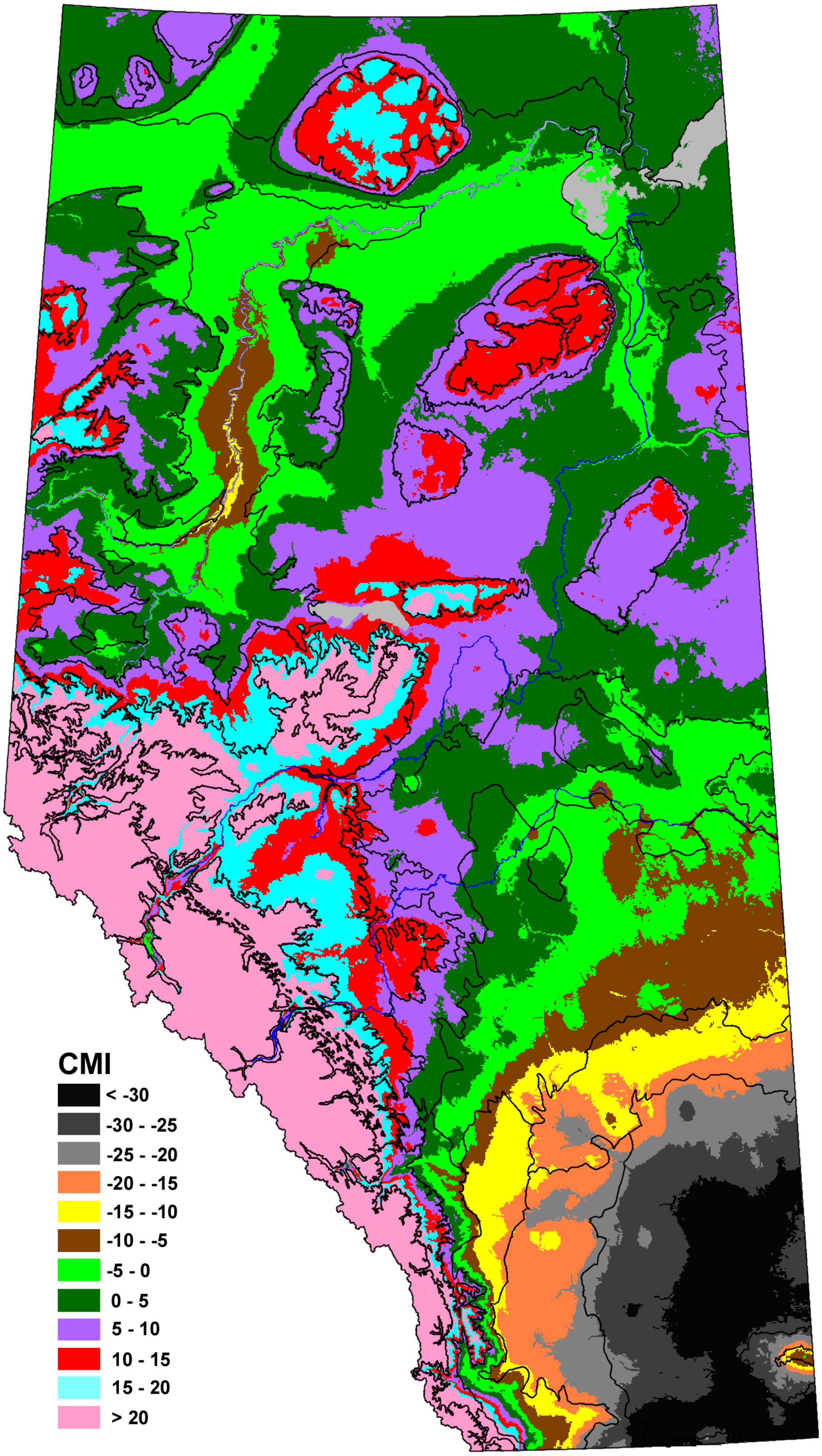

Fig. 3.3. CMI for the 1961-1990 reference period. Natural Subregions are outlined in black.

large areas, with the notable exception of the Boreal hill system. The hills are both cooler and wetter than the surrounding lands and have significantly higher CMI values.

The uniformity of CMI values in the north has important implications with respect to the impacts of climate change. It means is that small changes in CMI will affect very large areas of land, once the moisture limitation tipping point is reached.

Seasonality (SEAS) and growing degree-days (GDD) and are two additional variables that influence vegetation patterns. SEAS is the difference between the mean warmest monthly temperature and the mean coldest monthly temperature (Fig. 3.4). Large seasonal differences in temperature are associated with continental climates. GDD provides the number of degree-days that support plant growth, using a break point of 5°C (Fig. 3.5). Methodology for the derivation of these variables is provided in Wang et al. 2012.

3.3 Bioclimatic Envelope Models

Bioclimatic envelope models statistically define the unique climate space, or "envelope", of individual ecosystems, based on current eco-climatic associations. (Pearson and Dawson, 2003; Hamann and Wang, 2006). Once developed, these models can be used to predict ecosystem type given the future climate as an input. This is the most commonly used approach for predicting changes in the distribution of ecosystems resulting from global warming.

An important consideration in the use of bioclimatic envelope models is that their reliability is scale dependent. Factors other than climate, such as soil type, topography, and disturbance history, become increasingly influential in determining ecosystem type as one moves from the regional scale to the local scale. Subregions represent an intermediate scale — climate is generally the dominant factor in determining Subregion type, but not in all cases.

For this study I restricted the development of bioclimatic envelope models to Subregions for which evidence exists of a strong causal relationship between climate and ecosystem type. These Subregions fall into two main groups: Subregions that are primarily influenced by moisture limitation, and Subregions that are primarily influenced by the climatic changes associated with rising elevation. In both groups the Subregions represent points along an ecocline. I incorporated these ecoclines into the bioclimatic envelope models for each group, increasing the power of the statistical associations and constraining the predictions of future ecosystem changes to pathways that make sense ecologically (i.e., Subregions can move up or down an ecocline, but jumps between ecoclines are not permitted).

3.3.1 Grassland to Boreal Model

At the most fundamental level, Alberta's ecosystems can be divided into those that are forested and those that are not. The main factor responsible for this differentiation is available moisture, which can be measured in terms of CMI (Hogg, 1994; Hogg and Hurdle, 1995). Closed forests are generally found where moisture is not a limiting factor, corresponding to CMI values greater than zero (i.e., where annual precipitation exceeds potential evapotranspiration). An overlay of the Subregion boundaries on the map of CMI values (Fig. 3.3) confirms this relationship to be generally true, though the

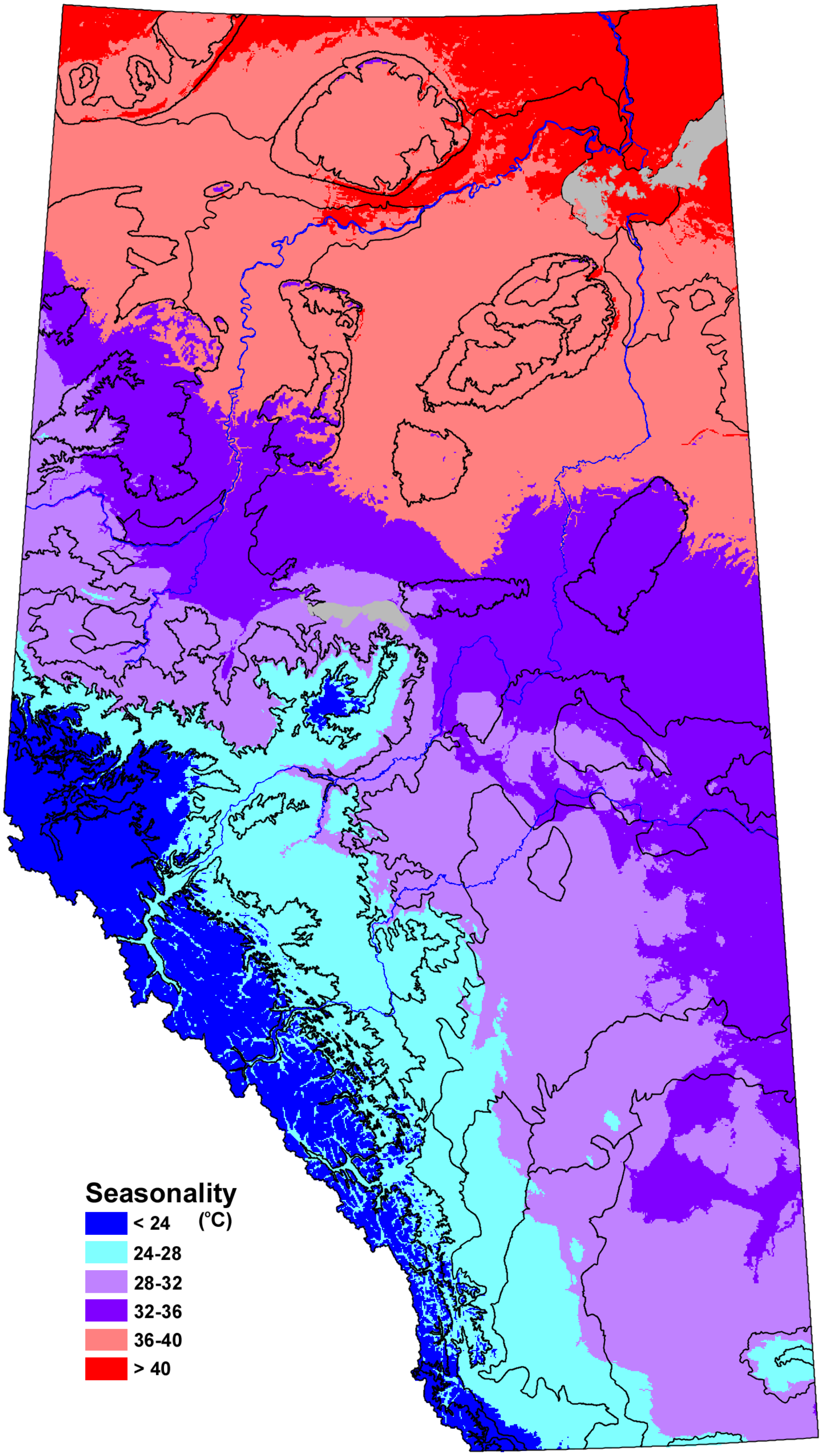

Fig. 3.4. Seasonality for the 1961-1990 reference period. Natural Subregions are outlined in black.

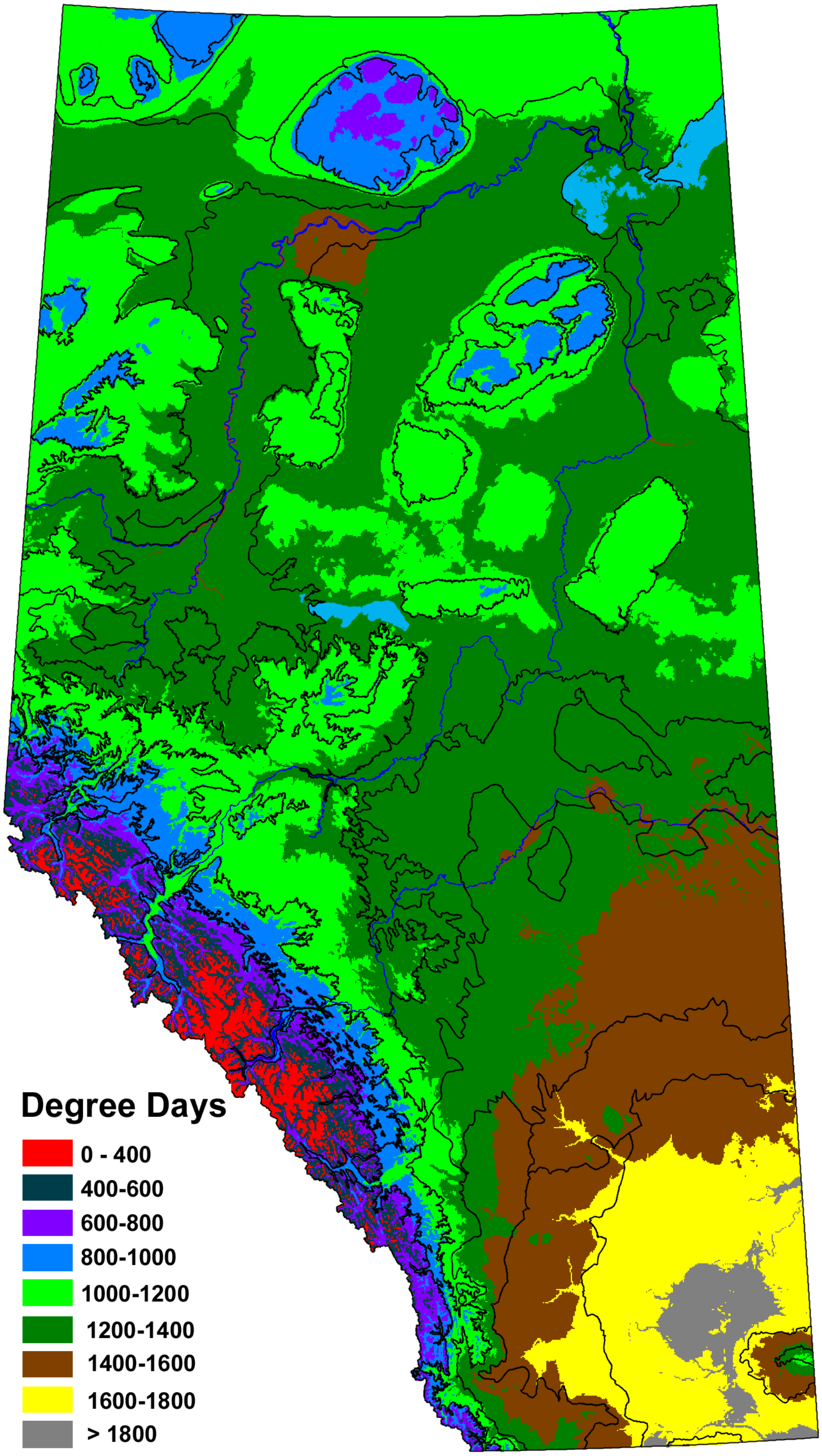

Fig. 3.5. Growing degree-days greater than 5 °C for the 1961-1990 reference period. Natural Subregions are outlined in black.

actual amount of forest in the northern Dry Mixedwood is greater than what is expected on the basis of CMI.

In those parts of the province where moisture is limiting there is a direct relationship between CMI and the type of ecosystem present (Fig. 3.6). Areas with the lowest CMI values, in the far southeast of the province, are associated with dry shortgrass prairie. CMI values increase as one moves northward, accompanied by a gradual increase in the height of vegetation, the addition of isolated stands of aspen, and eventually closed aspen forests once CMI values approach zero (Natural Regions Committee, 2006).

These observations form the basis of the bioclimatic envelope model developed for differentiating Subregions within the Grassland, Parkland, and Boreal Regions (Table 3.3). Because the Subregions involved represent an ecological gradient (dry to wet), an ordinal regression approach was used to construct the model. To improve the fit of the model, additional climatic variables besides CMI were incorporated, including MAT, MAP, SEAS, and GDD. Detailed methodology is provided in Appendix 2.

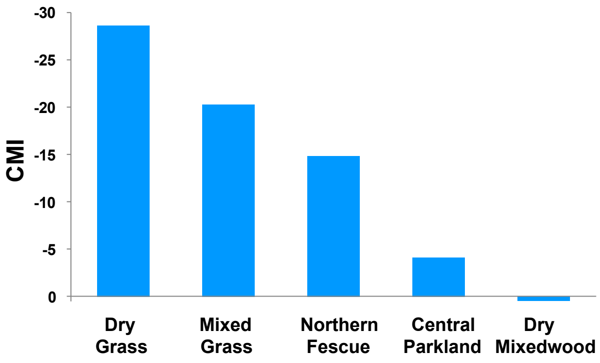

Fig. 3.6. Mean CMI for the 1961-1990 reference period, for selected Subregions.

When provided with historical climate data the model can reliably predict the type of Subregion expected (Fig. 3.7). Misclassification errors are limited to the boundaries between Subregions. This confirms that the association between climate and ecosystem type is strong; however, additional considerations need to be taken into account when the model is used with climate data from future periods (see Section 4.2).

3.3.2 Mountains and Hills Model

The second major climatic gradient affecting ecological patterns in Alberta is related to elevation (Fig. 3.8). The most influential parameter is GDD, which falls by approximately 72 degree-days for every 100 m gain in elevation, after accounting for latitude (Fig. 3.5). Precipitation is also influenced by elevation, though the effect is most pronounced in the Foothills and Rocky Mountains, where MAP increases by approximately 50 mm for every 100 m of elevation gained.

The influence of elevation on regional ecological patterns is most apparent in its effects on the competitive interaction between aspen and lodgepole pine (both pure stands and jack pine x lodgepole pine hybrids). Aspen and lodgepole pine are both shade-intolerant pioneer species that grow best on mesic upland sites. Aspen is the superior

Table 3.3. Ecosystem types included in the Grassland to Boreal Model.

Modeled Ecosystem	Natural Subregion
Dry grass	Dry Mixedgrass
Mixed grass	Mixedgrass and Northern Fescue
Parkland	Central Parkland
Deciduous	Dry Mixedwood
Mixedwood	Central Mixedwood

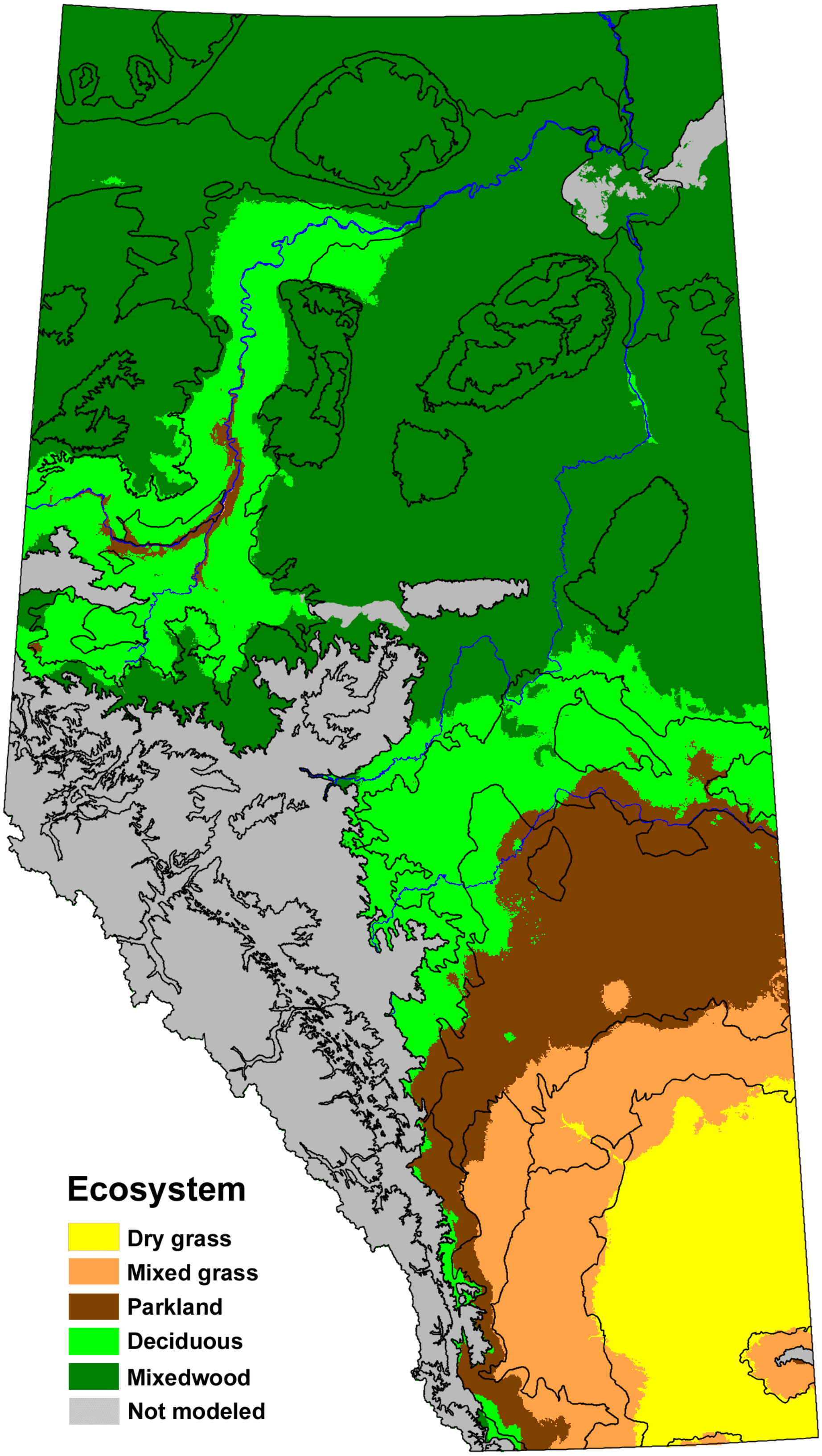

Fig. 3.7. Predicted ecosystems for the Grassland to Boreal Bioclimatic Envelope Model, using climate data from the 1961-1990 reference period as input.

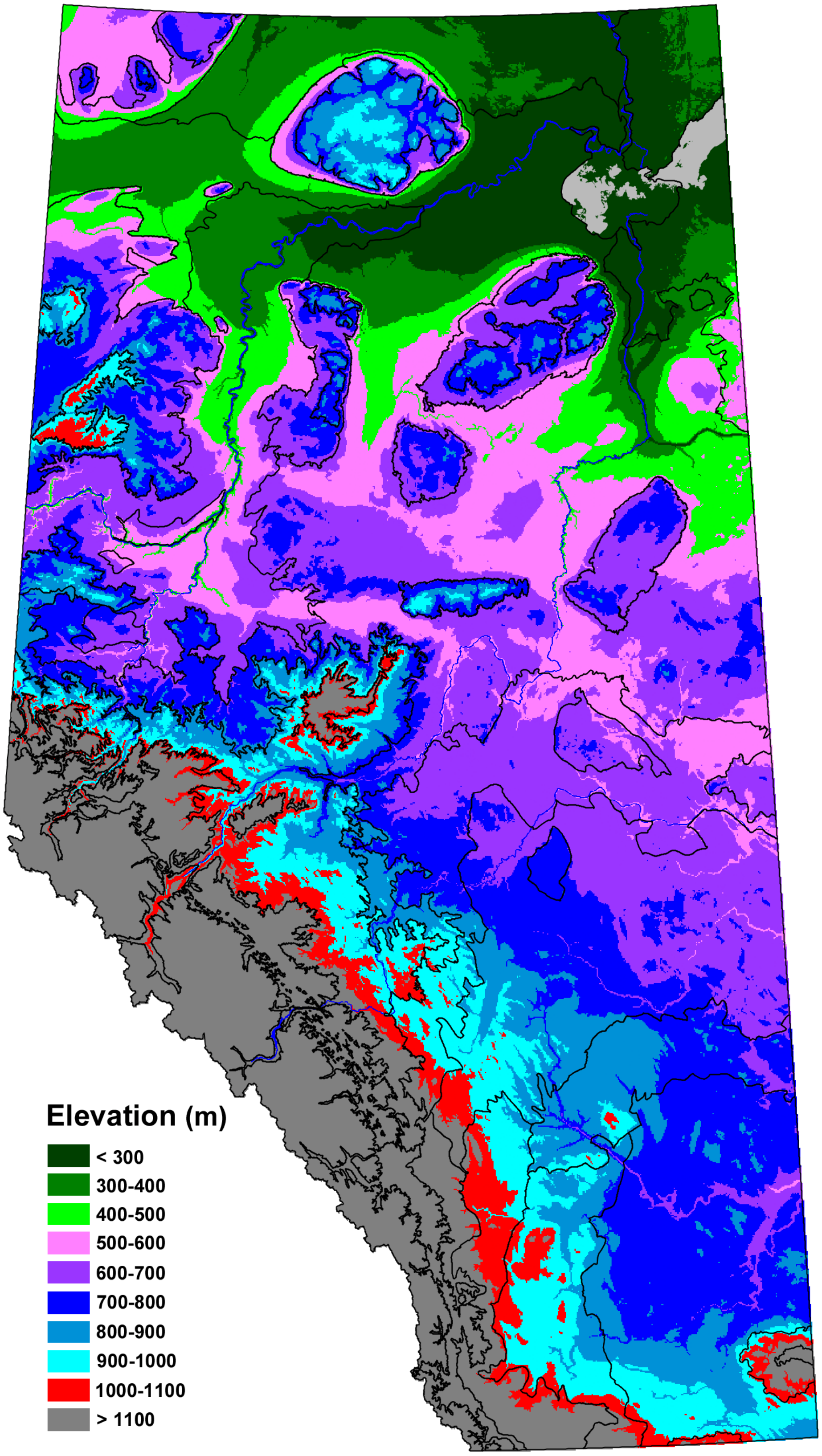

Fig. 3.8. Elevation. Natural Subregions are outlined in black.

competitor at low elevations, limiting the pine to higher elevations where the growing season is short and the competitive balance is reversed (Farmer et al., 1988; Kenkel, 1994; Rweyongeza et al., 2007). Low temperatures affect aspen by slowing root and leaf growth and through damage to leaves from spring frosts (Lieffers et al., 2001).

The relative proportion of lodgepole pine and aspen serves as the primary differentiating feature of several Subregions in the Boreal and Foothills (Table 3.1). Lodgepole pine is generally absent on the Boreal plain but increases in abundance with elevation, at the expense of aspen. Aspen is generally absent in the Upper Boreal Highlands and the Upper Foothills (Natural Regions Committee, 2006).

At the highest elevations lodgepole pine is itself replaced by species that are better able to survive under extreme conditions. These species transitions again serve as important indicators of ecosystem type (Table 3.1). In the Rocky Mountains, the appearance of Engelmann spruce and subalpine fir marks the transition from Upper Foothills to the Subalpine (Natural Regions Committee, 2006). In the Boreal, the elevated plateaus of the Boreal Subarctic are characterized by permafrost-affected peatlands overlain with stunted stands of black spruce (Natural Regions Committee, 2006).

These observations form the basis of the second set of bioclimatic envelope models developed for this study. Separate models were developed for the Boreal hill system and for the Foothills/Rocky Mountains because the Boreal hills experience greater seasonality and less precipitation than the Foothills and Rocky Mountains. For the Boreal hills, an ordinal regression approach was again used because the Subregions involved — Central Mixedwood, Lower Boreal Highlands, Upper Boreal Highlands, and Boreal Subarctic — represent an ecological gradient (Appendix 2). The variables in the model included MAT, MAP, GDD, CMI and SEAS. The ability of the model to predict Subregion type on the basis of historical climate is again quite good, confirming a strong association between climate and ecosystem type for these Subregions (Fig. 3. 9).

Although elevation is also the primary determinant of ecological type in the Foothills, the eco-climatic relationships are more complex here than in other Regions. In the north, the Lower Foothills transition to Central Mixedwood following the same gradient as described for the Boreal hills. But in the south, the Lower Foothills transition to Montane and Foothills Fescue. This presents a challenge for bioclimatic envelope modeling, precluding the use of a single gradient model. Instead, I employed a machine-learning approach (Random Forests) that links ecosystem type to climate variables using nonlinear decision tree classification (Table 3.4; Appendix 2). The model fit using historical climate data is excellent (Fig. 3.10). However, the ability of this model to reliably predict bioclimatic envelopes under future climates is uncertain in the Lower Foothills, because a future hot and wet Lower Foothills climate has no close analogue among existing Subregions (see Section 4.2).

3.3.3 Northern Mixedwood Model

The Northern Mixedwood is another climate -associated ecosystem, but it does not belong to either of the previous two ecoclines. Much of the Subregion vegetated by open, stunted black spruce stands growing on permafrost. The presence of widespread discontinuous

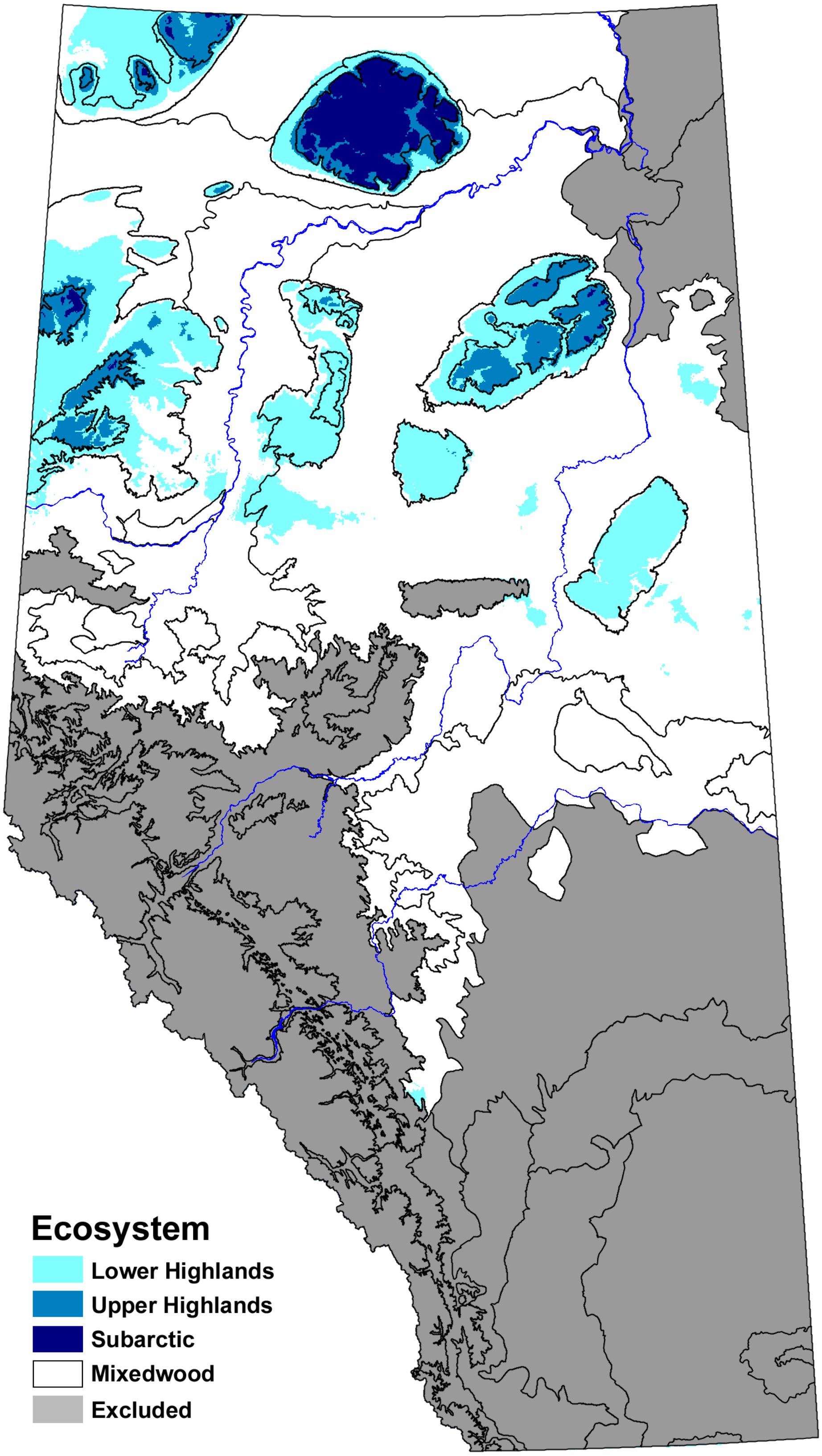

Fig. 3.9. Predicted ecosystems for the Boreal Highlands Bioclimatic Envelope Model, using climate data from the 1961-1990 reference period as input.

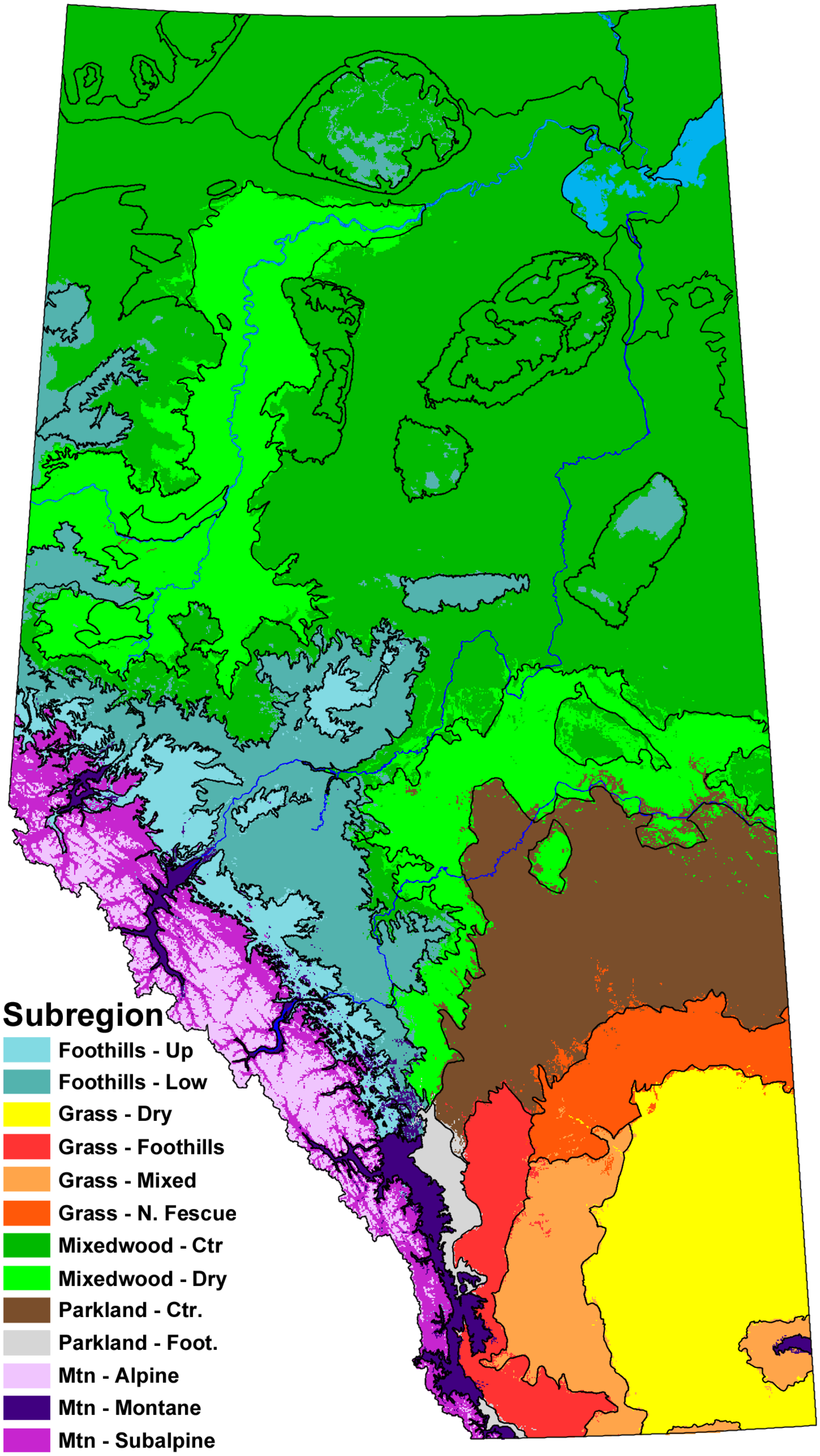

Fig. 3.10. Predicted ecosystems the Foothills Bioclimatic Envelope Model, using climate data from the 1961-1990 reference period as input.

Table 3.4. Ecosystem types included in the Foothills Bioclimatic Envelope Model.

Natural Subregion
Alpine
Central Mixedwood
Central Parkland
Dry Mixedgrass
Dry Mixedwood
Foothills Fescue
Foothills Parkland
Lower Foothills
Mixedgrass
Montane
Northern Fescue
Subalpine
Upper Foothills

permafrost differentiates this Subregion from the Central Mixedwood to the south. The presence of permafrost is an important factor because vegetative growth patterns on permafrost are unique.

Detailed maps of the extent of permafrost are unavailable for most of northern Alberta, but MAT provides a reasonable proxy. The boundary of the Northern Mixedwood and its associated Organic Cryosolic soils is approximated by the -2 °C isocline (Fig. 3.1). This isocline serves as a simple bioclimatic envelope for the Northern Mixedwood.

3.3.4 Other Subregions

Three Subregions in northeast Alberta — the Kazan Upland, Athabasca Plain, and Peace-Athabasca Delta — experience a boreal climate but are vegetatively quite distinct from the adjacent Central Mixedwood. Unique parent materials are primarily responsible for the distinct vegetation patterns in the Kazan Upland and Athabasca Plain (Precambrian granite and sandstone, respectively). In the case of the Peace-Athabasca Delta it is the extensive delta that is responsible for the unique vegetation patterns. The overriding influence of non-climatic factors on vegetation patterns in these three Subregions means that climatic envelope modeling is of little value here. Instead, the impacts of climate change must be based on what is known about ecological gradients and patterns within the Subregions themselves and about the physiological tolerances of the plant species present.

The Peace River Parkland was not included in the bioclimatic envelope modeling because it was considered to be too small for effective model development. This Subregion is captured at a coarser scale in the Grassland to Boreal Model.

4. The Future

4.1 Future Climatic Patterns

Several research centres around the globe have developed GCMs that provide projections of the earth's future climate under various greenhouse gas emission scenarios (Appendix 2). The Intergovernmental Panel on Climate Change has helped coordinate these efforts, establishing standard data formats, emission scenarios, and reference periods (IPCC, 2000). Climate change projections from GCMs are typically provided at coarse spatial resolutions of 200 km or more and monthly time steps. Finer scale projections are derived through the application of various downscaling techniques.

The downscaled climate data used in this study were obtained from the ClimateWNA model (Wang et al., 2012). The ClimateWNA model uses interpolated weather station data for downscaling. In addition to providing high resolution historical climate data, downscaled projections are available for 24 GCMs used in the Intergovernmental Panel on Climate Change Fourth Assessment (Meehl et al., 2007). Projections are provided for three 30-year time periods: 2011–40, 2041–70, and 2071–2100 (hereinafter referred to as 2020s, 2050s, and 2080s).

Three emission scenarios are available in ClimateWNA for most models: A2, A1B, and B1 (IPCC, 2000). In the A2 scenario, greenhouse gas emissions rise continuously, reaching the highest levels of all scenarios by the end of the century. In the A1B scenario, emissions initially rise faster than in the A2 scenario, but peak around mid-century and then decline. The B1 scenario follows the same pattern as the A1B scenario, but the mid-century peak is lower, and the subsequent decline in emissions is faster. Additional detail on the emission scenarios is provided in Appendix 2.

For detailed analysis it was not practical to work with all model and scenario combinations. Therefore, I focused the analysis on five models, selected to represent the full range of potential climate outcomes (Fig. 4.1). For readability I labelled these five model-scenario combinations on the basis of the defining feature of each: Cool (HADCM3-B1), Median (ECHAM5-A2), Hot (HADGEM-A2), Dry (GFDL-CM2.1-A2), and Wet (CGCM3-A2). The Cool label is meant to distinguish the Cool model from the other hotter models. But this model is not actually cool, it predicts a temperature rise of almost 3 °C. To improve readability I did not include output maps for all models in the main text. The omitted maps can be found in Appendix 3.

4.1.1 Temperature

Recent temperature trends provide a useful context for the projections of future climate change. Alberta and Saskatchewan have experienced the largest increase in temperature of all Canadian provinces over the last 100 years (data for the Territories not available; Zhang et al., 2000). Alberta`s MAT has increased by approximately 1.4 °C in this period (Fig. 4.2). Much of this increase has occurred since 1970, following a cooling trend in the 1950s and 1960s (Fig. 4.2). Warming in winter and spring contributed the most to the positive trend in annual temperature and daily minimum temperatures have increased more than daily maximum temperatures

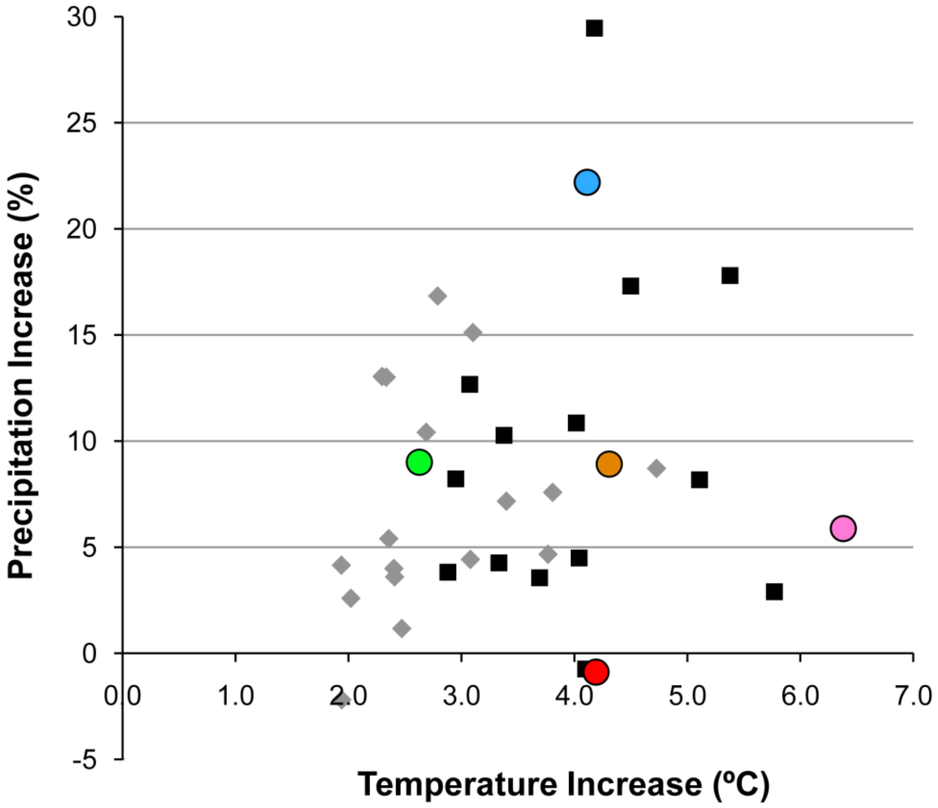

Fig. 4.1. MAT vs. MAP for the 2080s for the GCMs available in ClimateWNA. Blue = Wet model; Green = Cool model; Orange = Median model; Pink = Hot model; Red = Dry model; black squares = other A2 models; grey diamonds = other B1 models.

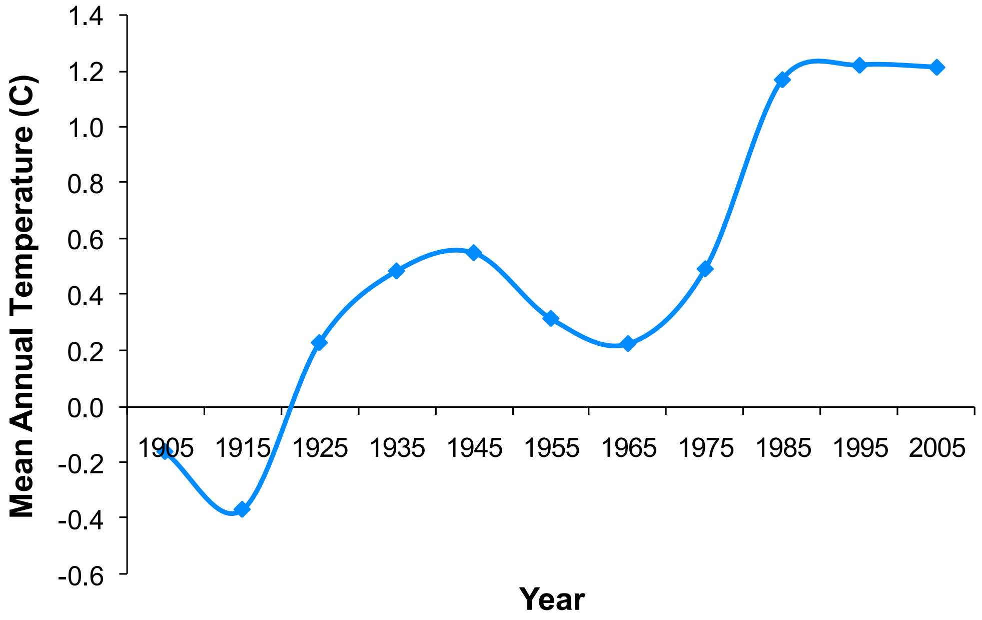

Fig. 4.2. Alberta MAT from 1905 to 2005, by decade

(Zhang et al., 2000; Beaubien and Hamann, 2011).

Averaging across all models, the MAT for Alberta is projected to rise by 4.2 degrees by the end of the century under the high-emission A2 scenario, and 2.8 degrees under the more restrained B1 scenario. None of the models projects an increase of less than 2.0 degrees. This suggests that substantial warming of Alberta is inevitable, even with dedicated global efforts to rein in greenhouse gas emissions. This is not to say that efforts to limit emissions are futile. The ecological impacts of warming are much greater under the A2 scenario. For example, the question of whether or not the Boreal remains forested will depend in large part on whether the A2 or B1 emission scenario is ultimately realized (see Section 4.3.4). It is also worth noting that the B1 scenario implies a stabilizing trend, whereas the A2 scenario will lead to substantial additional warming in the next century.

It is expected that there will be more warming of the coldest months than of the hottest months, leading to a small decrease in seasonality. (Table 4.1). But the main theme is the large overall increase in both summer *and* winter temperature, and the associated 33-56% increase in GDD, which comes largely as a result of an earlier onset of spring (Table 4.1).

The temporal trajectory of temperature increase follows that of the emissions trajectories described earlier (Fig. 4.3). The A2 and A1B scenarios are fairly similar, except that the rate of change increases after 2050 in the A2 scenario, whereas it begins to moderate in the A1B scenario. The B1 scenario is similar to the other scenarios until the 2050s, but exhibits a slower rate of increase thereafter. GCM type also contributes to the divergence of projections over time (Fig. 4.4).

Though the amount of temperature increase varies among GCMs, the spatial pattern of distribution is quite stable (Fig. 4.5). This is because GCM projections are produced at a very coarse scale — the fine-scale spatial pattern in temperature distribution evident in the output maps is primarily a function of

Table 4.1. Change in temperature parameters between the 1961-1990 reference period and the 2080s, averaged across all GCMs.

	Scenario	
Parameter	**A2**	**B1**
MAT (°C)	4.2	2.8
MWMT (°C)	4.3	2.5
MCMT (°C)	5.1	3.9
GDD (%)	55.6	33.2
SEAS (°C)	-0.8	-1.3

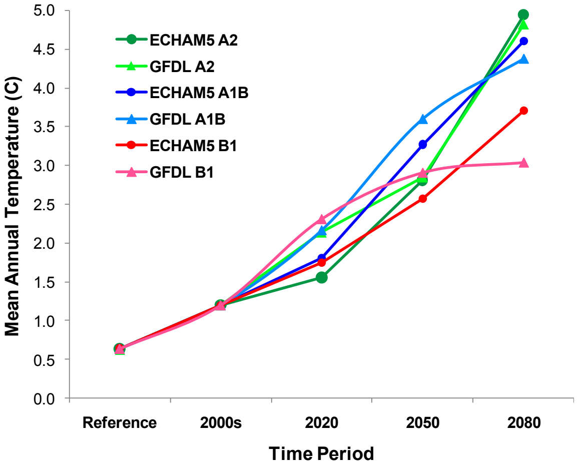

Fig. 4.3. Alberta MAT trajectories for two representative GCMs and three scenarios.

local topography. Similar consistency in spatial patterns is evident in the projections of GDD (Fig. 4.6).

4.1.2 Precipitation

In contrast to MAT, no long-term trend in MAP is evident at the provincial scale over the past 100 years (Fig. 4.7). Most models predict that MAP will increase in the future (Fig. 4.8). The average provincial increase across all models is 9.4% for the A2 scenario and 7.2% for the B1 scenario. None of the models predicts a decline in MAP.

The basic spatial pattern of the distribution of MAP remains relatively unchanged in the future (Fig. 4.9). Again, what mainly changes among models is the amount of precipitation falling, not its pattern of distribution.

Although overall annual precipitation is projected to increase, most models predict a decline during the summer months, or at least

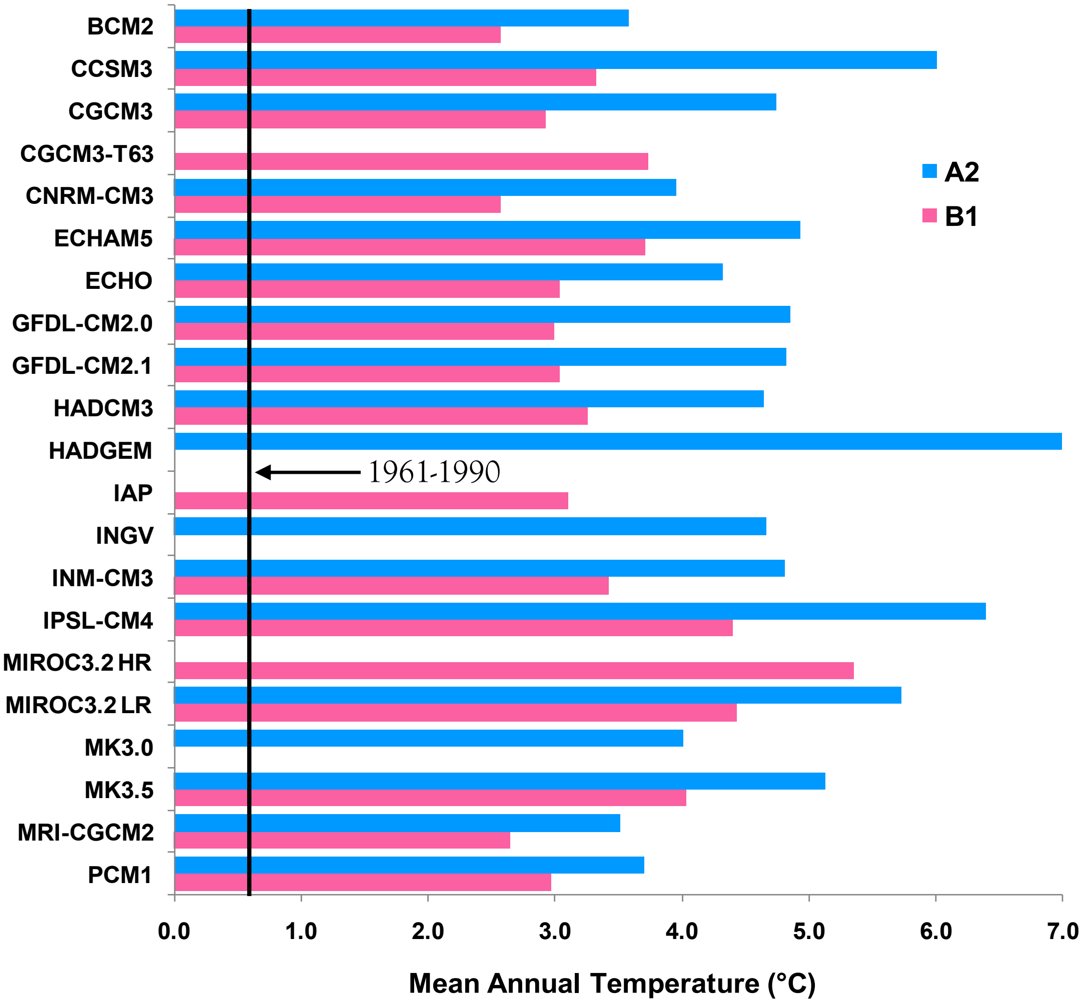

Fig. 4.4. Alberta MAT in the 2080s, by GCM, for the A2 and B1 scenarios. The black vertical line indicates the MAT for the 1961-1990 reference period.

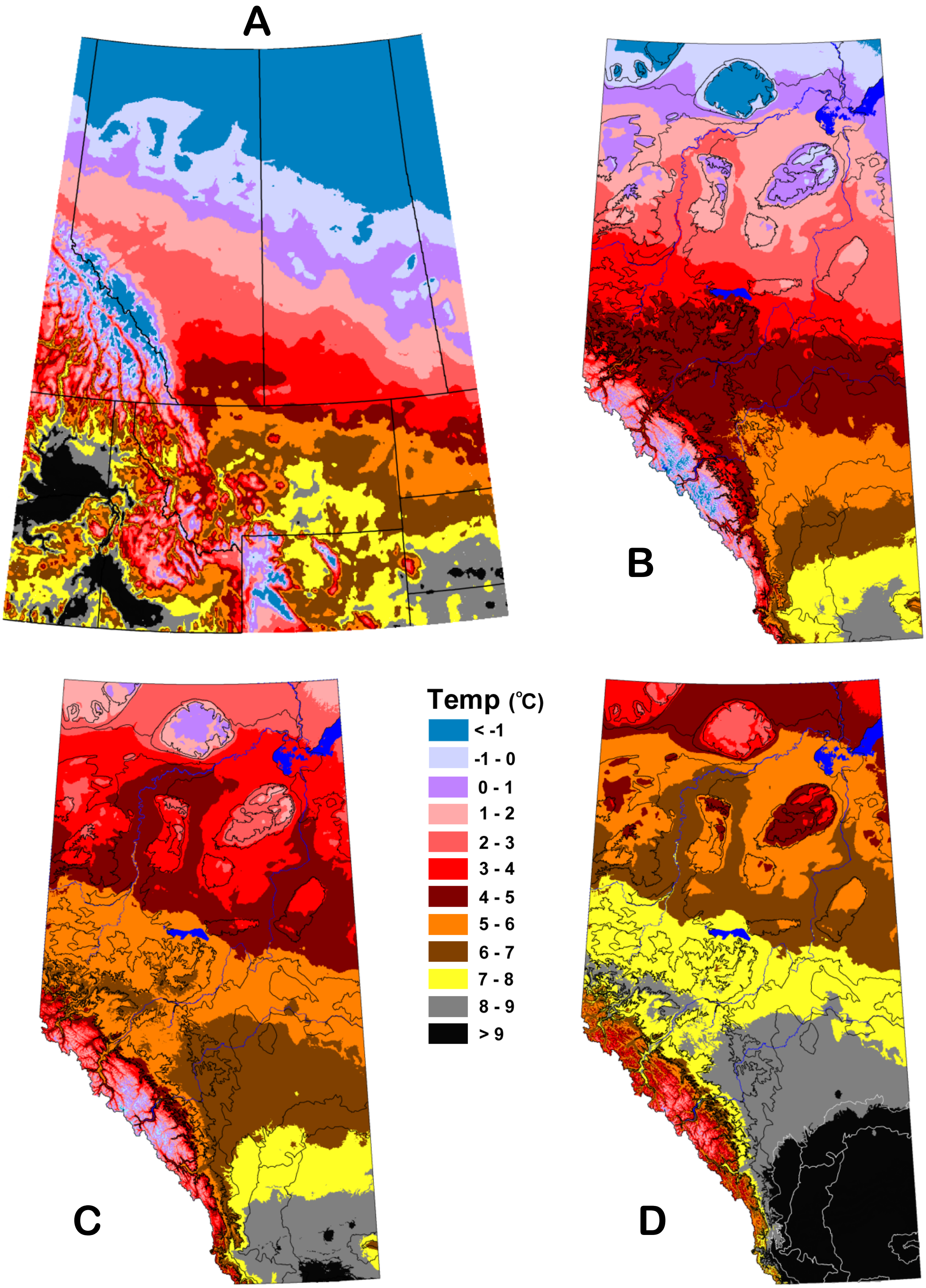

Fig. 4.5. MAT in 1961-1990 (Panel A) and in the 2080s: Panel B = Cool model; Panel C = Median model; Panel D = Hot model.

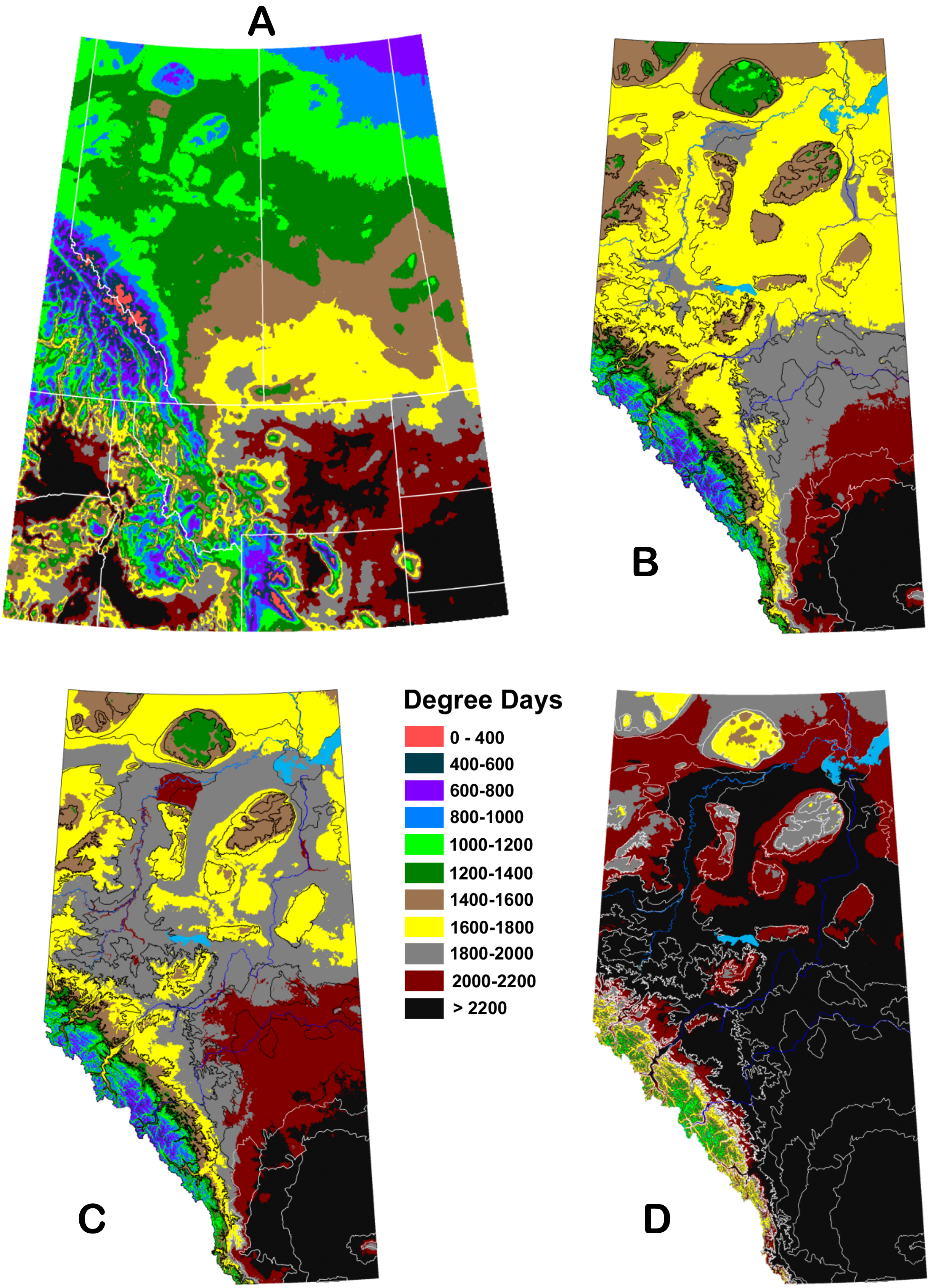

Fig. 4.6. Mean growing degree-days in 1961-1990 (Panel A) and in the 2080s: Panel B = Cool model; Panel C = Median model; Panel D = Hot model.

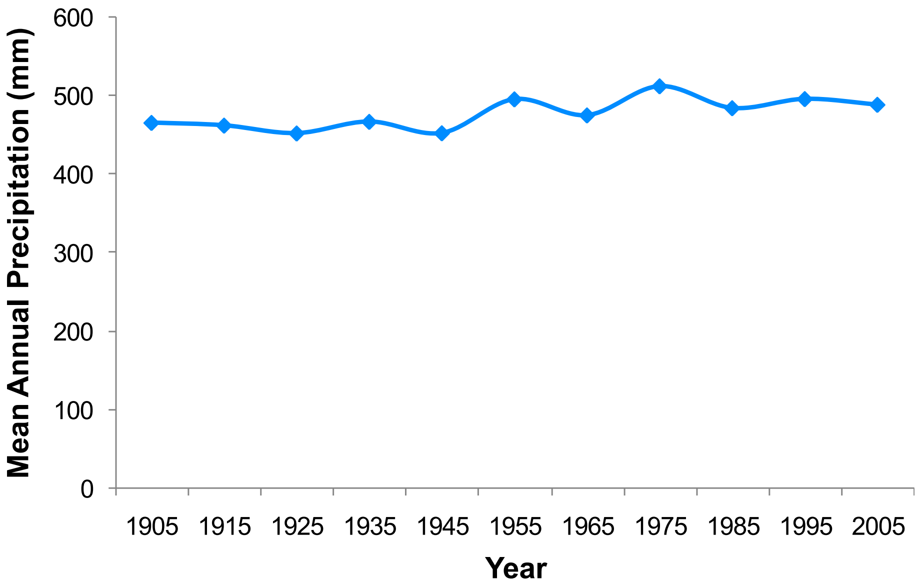

Fig. 4.7. Alberta MAP from 1905 to 2005, by decade.

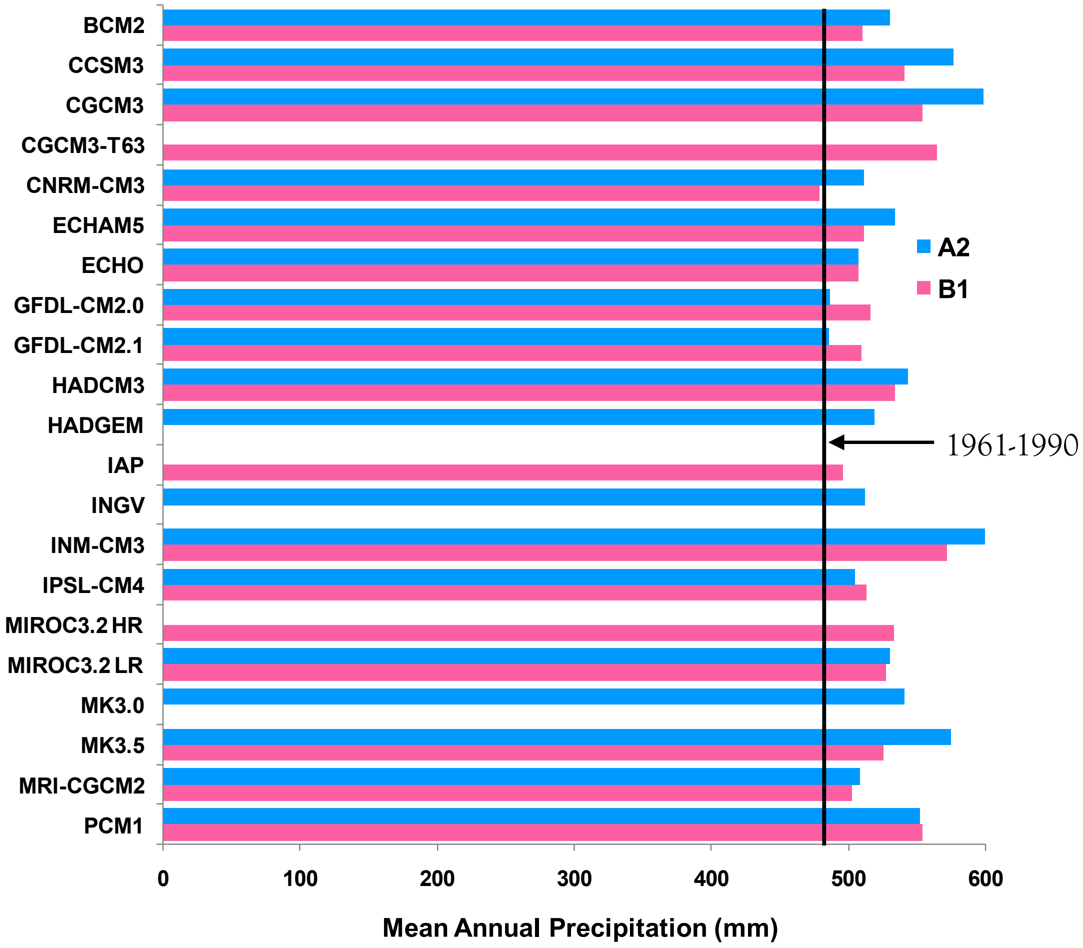

Fig. 4.8. Alberta MAP in the 2080s, by GCM, for the A2 and B1 scenarios. The vertical line indicates the MAP for the 1961-1990 reference period.

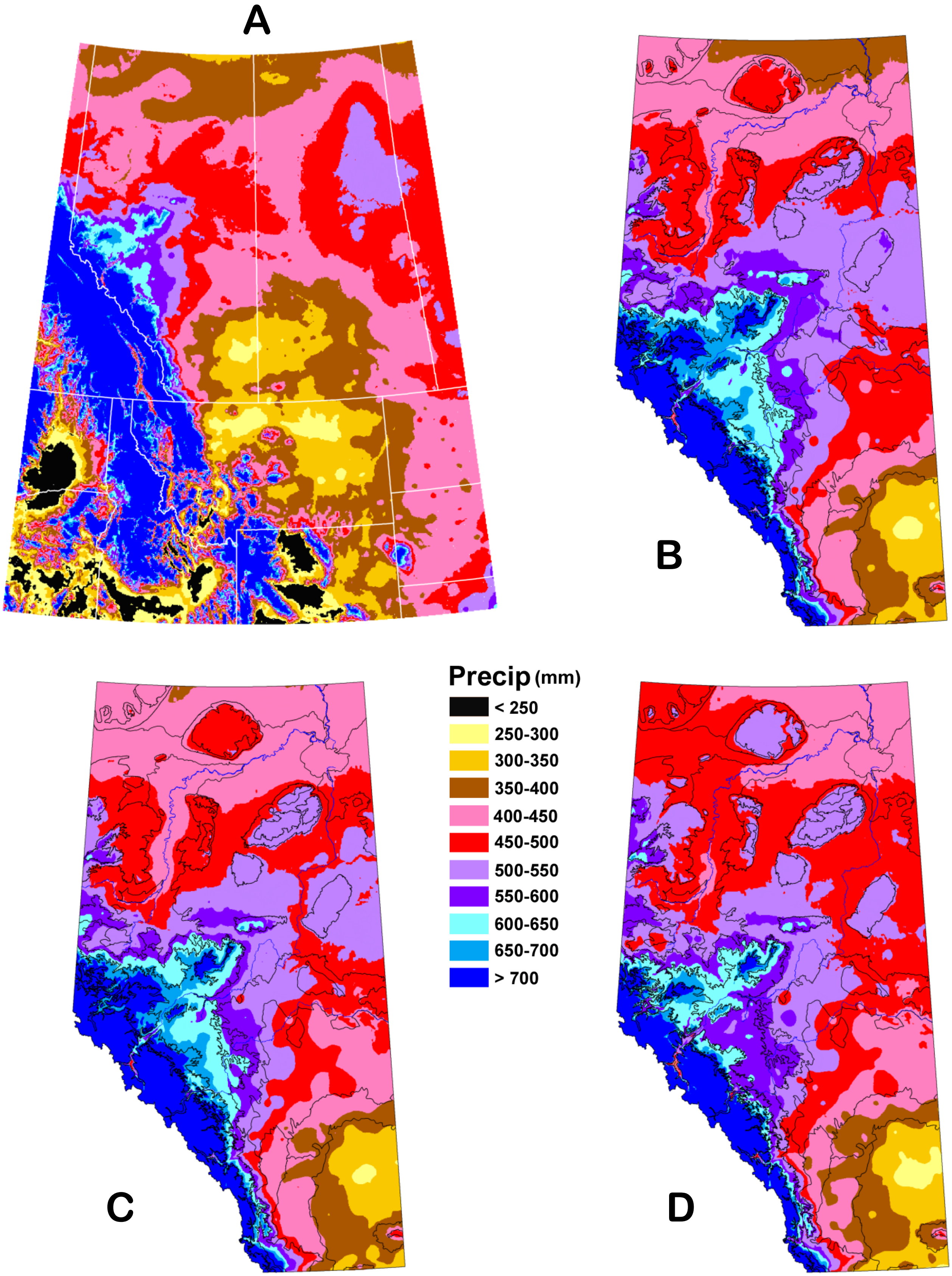

Fig. 4.9. MAP in 1961-1990 (Panel A) and in the 2080s: Panel B = Cool model; Panel C = Median model; Panel D = Hot model.

no increase (Fig. 4.10). The average decline is 2.4% in July and 6.5% in August for the A2 models and 0.2% in July and 2.3% in August for the B1 models.

4.1.3 Available Moisture

Although overall precipitation is projected to increase, most climate models predict that Alberta will become substantially drier in coming decades. Averaging across all models, provincial mean CMI decreases from 5.9 cm for the historical norm to -5.1 cm under the A2 scenario and to -0.6 cm under the B1 scenario. The main reason for this decline is that warmer temperatures increase the rate of evapotranspiration from vegetation and soils. In addition, although total precipitation is projected to increase, precipitation during midsummer, when moisture stress is greatest, is expected to decline (Fig. 4.10). Finally, the duration of winter snow cover will be shortened, leading to earlier ground warming and a longer period of evaporative moisture loss (though this is not included in CMI as calculated).

The spatial distribution of future CMI is of particular interest because the zero isocline provides a coarse indication of the division between forested and unforested ecosystems (Fig. 4.11). An examination of CMI values for the Central Mixedwood indicates that the possibility of it remaining in a fully forested state over the long term is remote, though not all parts will be affected equally (Fig. 4.12). Only three GCMs maintain a positive CMI in the Central Mixedwood by the 2080s, and one of these appears to be an outlier (the low-ranked Russian model). In general, the declines in CMI are more extreme for the A2 runs than for the B1 runs (Fig. 4.12).

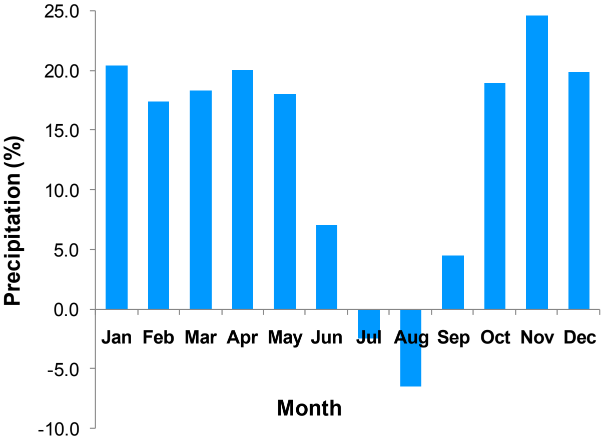

Fig. 4.10 Mean monthly precipitation averaged across all GCMs running the A2 scenario.

There is general agreement among the models that the Grassland and Parkland, which already experience a moisture deficit, will face additional drying in the future. At a minimum we can expect a northward shift of CMI values from northern Montana into Alberta's Grassland, and Grassland CMI values into the Parkland (Fig. 4.11). In the most extreme case, represented by the Hot model, Alberta's grasslands would experience the CMI values from the driest parts of Wyoming.

4.1.4 Extreme Events — Drought

The long-term climatic trends discussed in the previous sections are subject to considerable year to year variability. The occurrence of drought is of particular interest, given its ecological effects and because a long-term record, dating back several hundred years, is available in the form of tree-ring growth (St. George et al., 2009).

What we know from the tree-ring record for Alberta is that severe prolonged droughts, such as that of the 1930s, have occurred roughly two or three times each century (see Fig. 8 in St. George et al., 2009). Some periodicities in the tree-ring record, linked to the

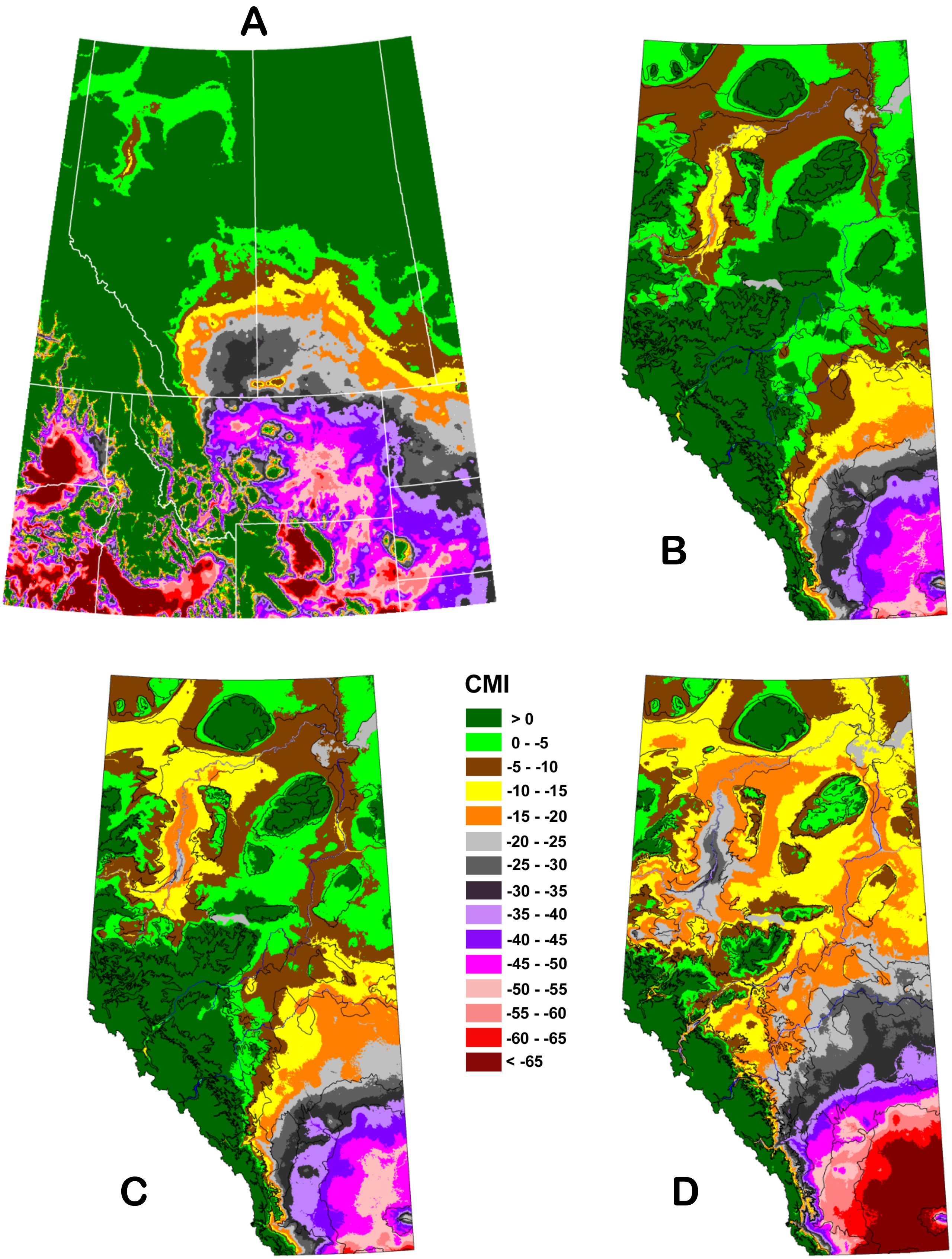

Fig. 4.11. Mean CMI in 1961-1990 (Panel A) and in the 2080s: Panel B = Cool model; Panel C = Median model; Panel D = Hot model.

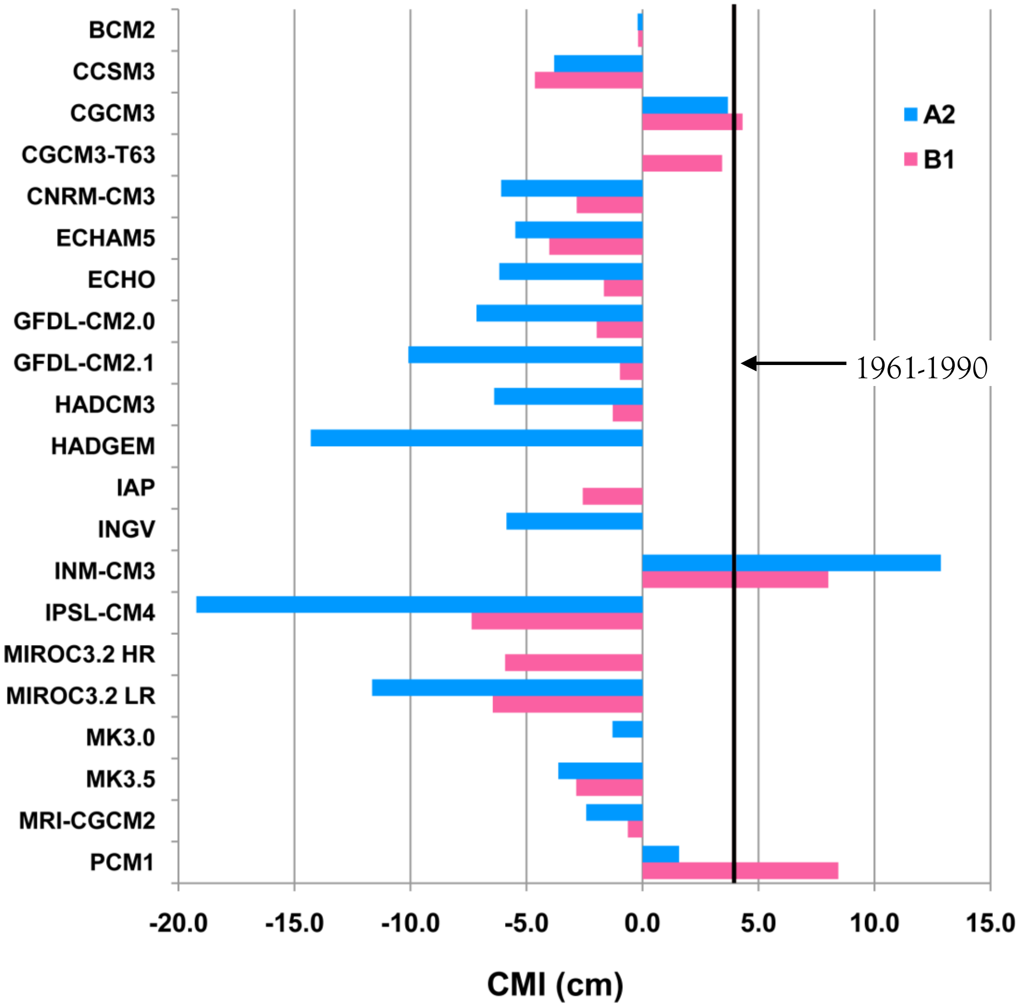

Fig. 4.12. CMI for the Central Mixedwood in the 2080s, by GCM, for the A2 and B1 scenarios. The black vertical line indicates the moisture index for the 1961-1990 reference period.

Pacific Decadal Oscillation, have been discerned statistically (Sauchyn et al., 2011; Lapp et al., 2013). However, this applies mainly to the Rocky Mountains and Foothills where Pacific moisture is the dominant influence. On the plains, moisture patterns reflect a complex interplay between inputs from the Pacific Ocean and from the Gulf of Mexico, resulting in great temporal variability (Liu et al., 2004; Rannie, 2006; St. George et al., 2009).

Droughts also exhibit complex spatial patterns, as illustrated by the drought of the early 2000s (Fig. 4.13). Annual time slices from 1999-2005 indicate that the drought was a prolonged event, tracking across the prairie provinces in an amoebic fashion over several years until normal conditions finally returned (Hanesiak et al., 2011). In the peak year of 2001, the large declines in precipitation in southeast Alberta were offset by stable or increased precipitation in the northwest, such that the mean provincial MAP declined by less than 5%. This general lack of regional coherence, reflective of complex climatic processes, is typical of prairie droughts (Rannie, 2006; St. George et al., 2009).

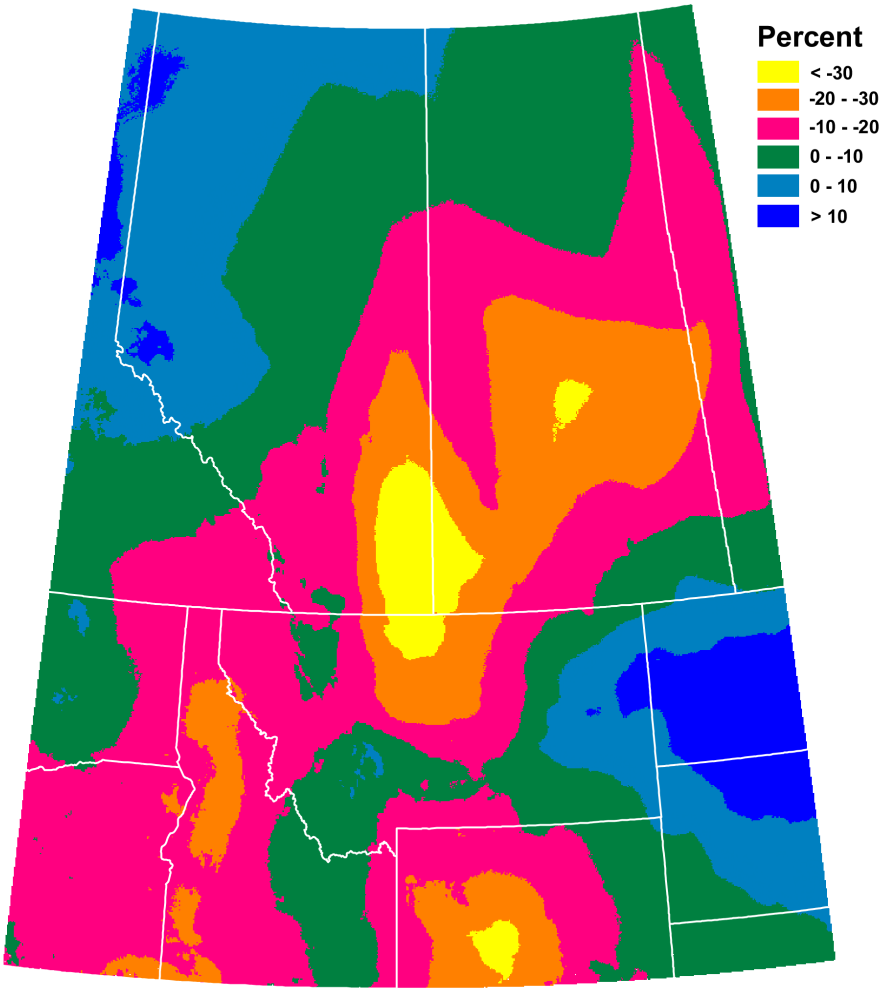

Fig. 4.13. Percentage difference in MAP in 2001 relative to the 1961-1990 reference period.

The complexity and lack of spatial coherence in regional climatic processes means that the onset, duration, and severity of drought are effectively unpredictable. Because of this, the occurrence of drought cannot be effectively integrated into projections of future climate change. The best we can do is to assume that historical patterns will continue. However, the trend towards generally drier conditions across much of Alberta implies that severe dry spells will become more frequent in the future and affect more of the province, simply because the baseline has shifted (Fig. 4.11). In addition, several studies predict that climatic variability will increase under global warming, implying that extreme wet and dry years could become more common on the prairies (Kharin and Zwiers, 2000; Kharin et al., 2007; Mladjic et al., 2011).

4.2 Future Bioclimatic Envelopes

4.2.1 Grassland to Boreal Model

The Grassland to Boreal Model was applied to Subregions that are expected to respond to moisture limitation in a consistent and predictable way (Table 3.2). It was assumed that the included Subregions represent an ecological gradient, and that climatically induced transitions will occur along this gradient (see Section 3.3.1).

Under the Cool and Wet models climate envelopes shift one to two Subregions northward by the 2080s (Figs. 4.14 and 4.15). Under the Hot model almost the entire province, save for high elevation areas, experiences the Dry Mixedgrass climate envelope (note that the model was limited to Alberta ecosystems, so transitions to US climate envelopes could not occur). The results for the Dry and Median models are intermediate.

A comparison of the temporal progression of the models indicates that, though the rate of change varies among models, they share a common spatial trajectory. That is, there is a consistent order to the spatial sequence of change in the climate envelopes. This reflects the spatial concordance in temperature and precipitation patterns among the GCMs noted earlier (Section 3.2).

The basic pattern of change is well illustrated by the envelope for the Grassland under the Hot model (Fig. 4.16). The first stage involves a northward shift into the Central Parkland, followed by a progressive movement into the Dry Mixedwood. The Grassland envelope then begins to occupy the Central Mixedwood, beginning in the lowlands along the Peace River, followed by other low elevation areas. In the final stage the envelope extends northward and into higher elevation areas until it occupies all of the Boreal but the Boreal Subarctic. The same basic pattern of change is evident in the Parkland and Deciduous Forest envelopes (Figs. 4.17 and 4.18). The other GCMs follow the same spatial trajectory, but do not progress as quickly or as far.

The consistent sequence of envelope changes among the GCMs means we are not faced with choosing among dozens of potential outcomes arising from different model and scenario combinations. Rather, there is a common pathway of change and the main uncertainty lies in how fast and how far the Subregions will progress along that path. This will depend in large part on the future trajectory of greenhouse gas emissions.

4.2.2 Boreal Highlands Model

The Boreal Highlands Model was applied to Subregions that represent an elevation gradient within the Boreal Region: Central Mixedwood → Lower Boreal Highlands → Upper Boreal Highlands → Boreal Subarctic. Because temperature is the main climatic parameter that changes along this gradient, all GCMs predict a rapid transition in the existing climatic envelopes. In the Cool model, the current climatic profile of the Central Mixedwood will be experienced in the Lower Boreal and Upper Boreal Highlands by 2020 and the Boreal Subarctic by 2050 (Fig. 4.19). The other models predict an even faster climatic transition.

4.2.3 Foothills Model

The Foothills is the most difficult Region to model because it includes two distinct transitional interfaces: the Boreal to the north, and the Montane, Parkland, and Foothills Fescue to the south (Fig. 1.1). Because of this complexity a decision tree classification was used to develop the envelope model, and no assumptions were made concerning ecological gradients (see Section 3.3.2).

A number of general trends for the Foothills are evident in the results from the five GCMs studied. In the first stage (2050s for most models) there is incursion of the Central Mixedwood climate envelope into the south-

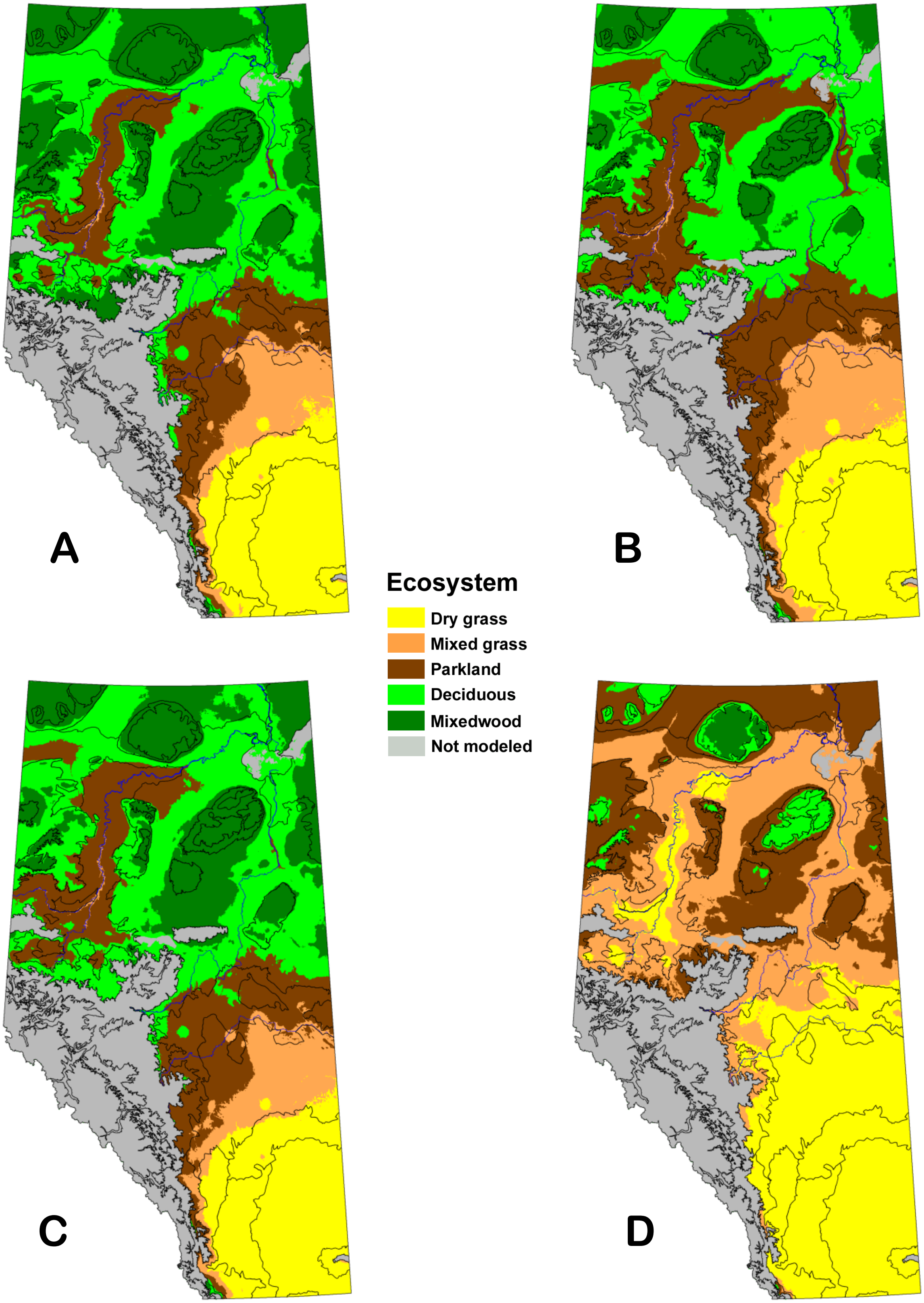

Fig. 4.14. Grassland to Boreal Bioclimatic Envelope Model for the **2050s**: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model. See Fig. 3.7 for historical reference.

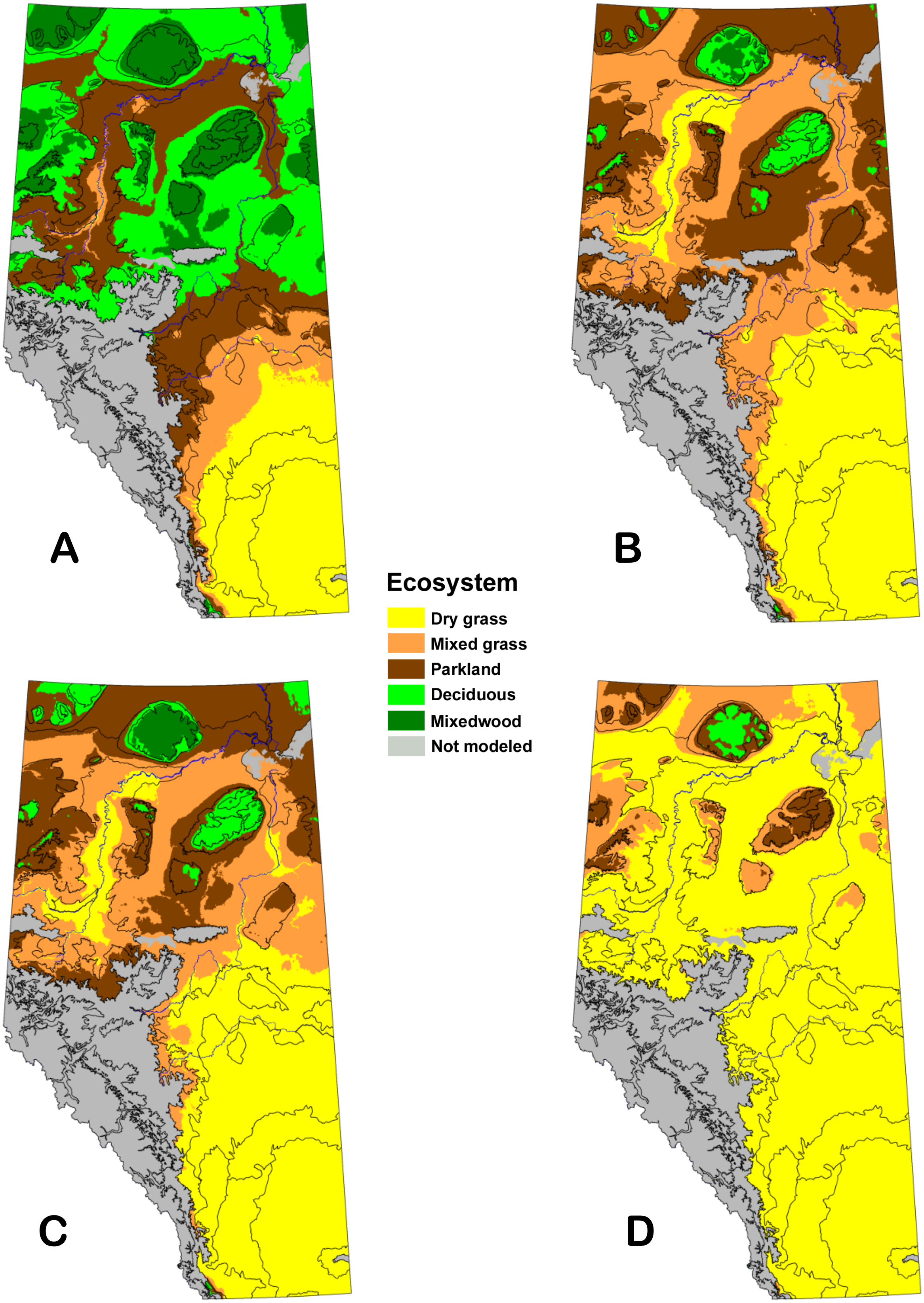

Fig. 4.15. Grassland to Boreal Bioclimatic Envelope Model for the **2080s**: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model. See Fig. 3.7 for historical reference.

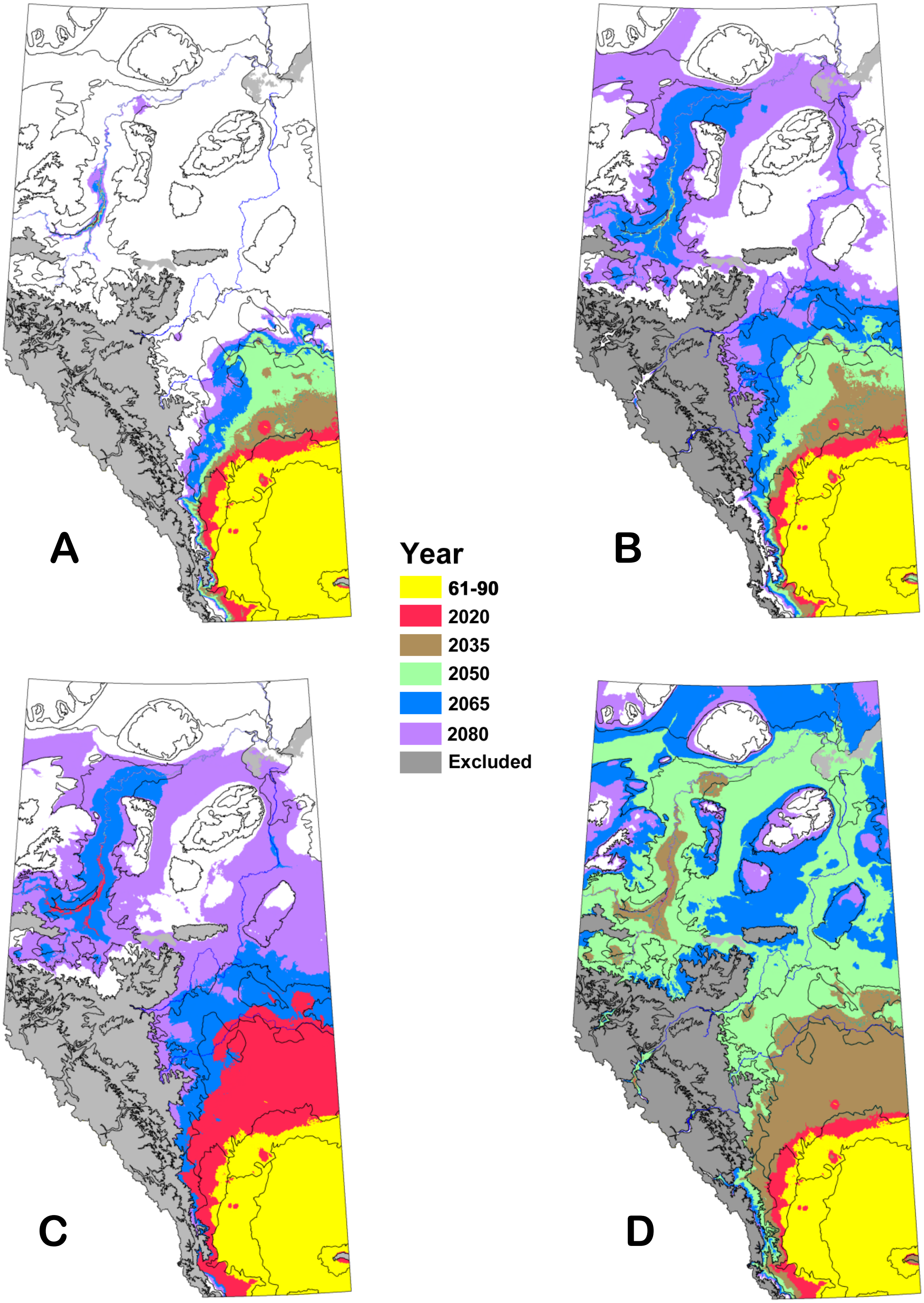

Fig. 4.16. Temporal change in the combined Dry Grassland and Mixedgrass climate envelopes: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model.

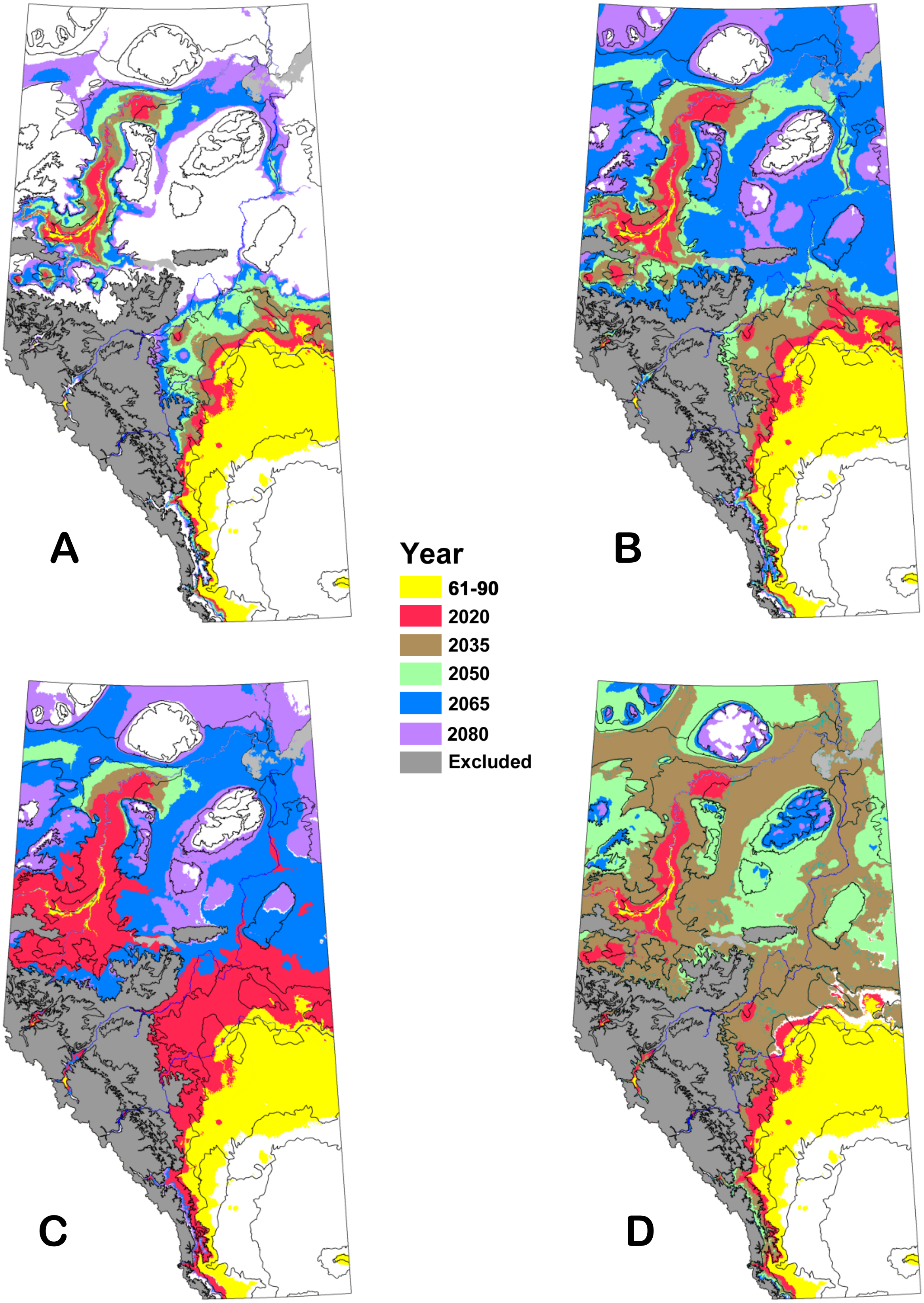

Fig. 4.17. Temporal change in the Parkland climate envelope: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model.

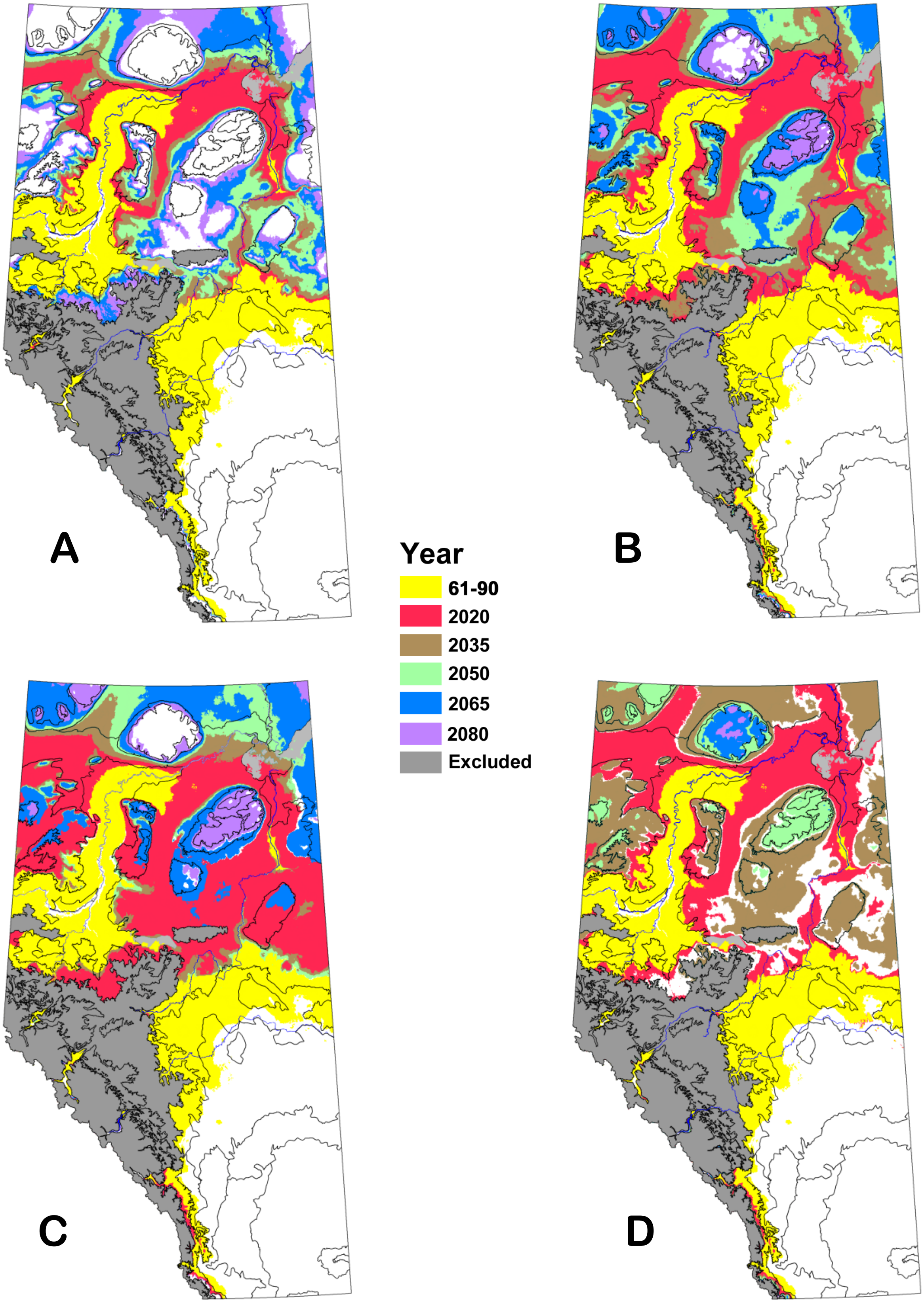

Fig. 4.18. Temporal change in the Deciduous Forest climate envelope: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model.

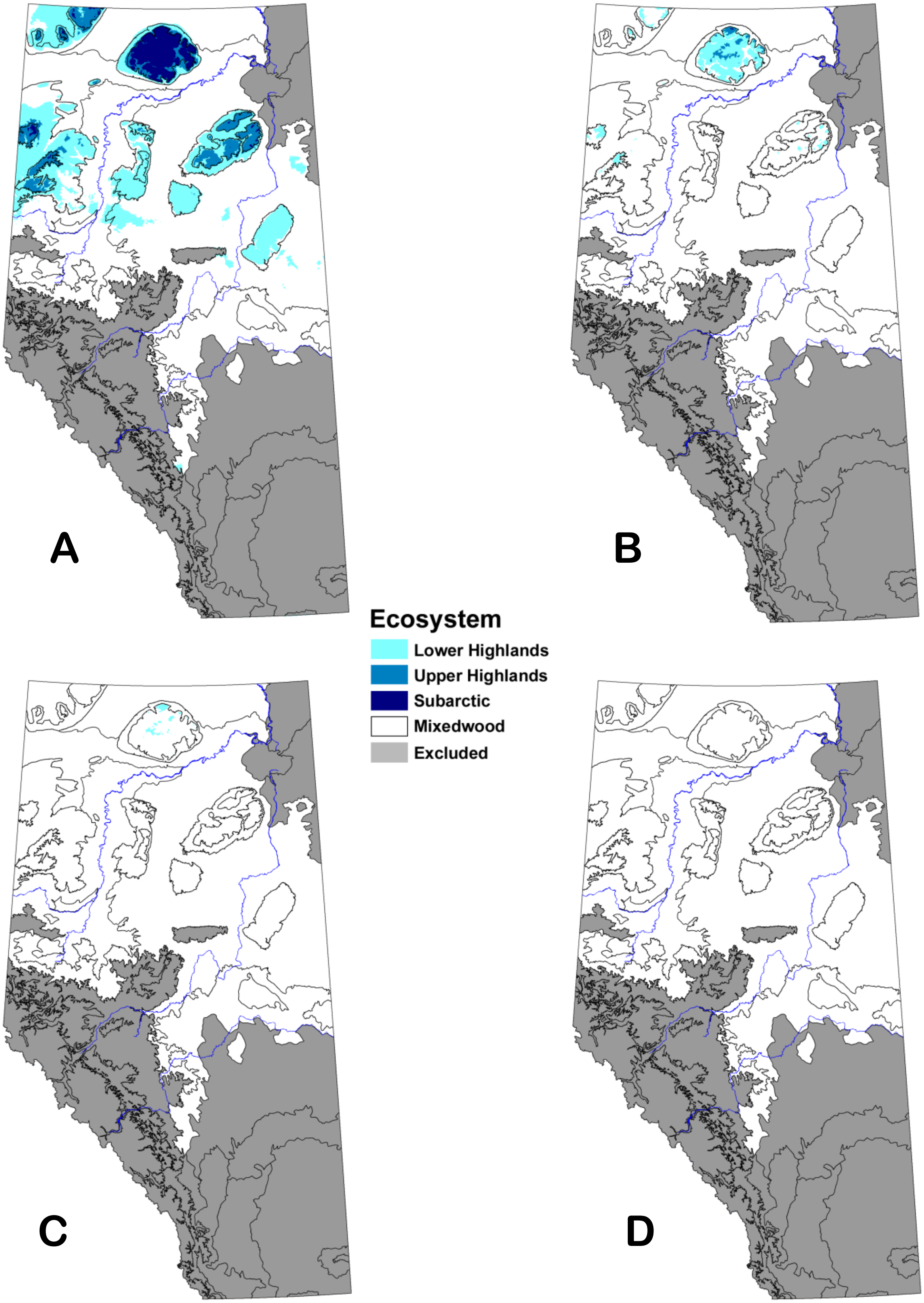

Fig. 4.19. Boreal Highlands Bioclimatic Envelope Model for 1961-1990 (Panel A) and for the Cool model: Panel B= 2020s; Panel C = 2050s; Panel D = 2080s.

ern half of the Lower Foothills, though the northern boundary remains stable (Fig. 4.20). At the same time, the climate envelope of Upper Foothills is largely replaced by a combination of Lower Foothills and Montane climates. Transitions in the Alpine and Subalpine are largely vertical, so not much is evident in the envelope maps except some replacement by Upper Foothills in northern areas. The other notable change at this stage is that at low elevations the Lower Foothills become surrounded on all sides by Parkland and Foothills Fescue climate envelopes, save for a small buffer of Central Mixedwood.

The Hot, Median, and Dry models predict that, by the 2080s, the climate envelope of the Upper and Lower Foothills will most closely resemble the current Foothills Fescue climate (Fig. 4.21). Under these models a Montane climate will be present at the current boundary between the Upper Foothills and Subalpine and most of the Alpine will transition to a Subalpine climate. These findings are questionable because the warm and wet climate of the Foothills in the 2080s has no analog among existing Subregions. The model is forced to identify the Subregion that provides the closest overall match (Fescue) — there is no option for "none of the above". This being the case, the climate envelope results should be used cautiously and in combination with the raw climate parameters when assessing ecosystem responses for this Subregion (see Section 4.3.8).

4.2.4 Permafrost Model

The Permafrost Model, applicable specifically to the Northern Mixedwood, uses the -2 °C isocline of MAT as a proxy for the widespread occurrence of discontinuous permafrost during the 1961-1990 reference period (Section 3.3.3). Climate warming that has occurred since the reference period has shifted this isocline to the NWT border, which implies that the current climate of the Northern Mixedwood can no longer be meaningfully distinguished from the reference climate of the Central Mixedwood (Fig. 4.22). The reason for this rapid transition is that most of Alberta's 1.4 °C rise in MAT over the past century has occurred since 1980. This suggests that widespread thawing of the permafrost in the Northern Mixedwood is already underway and will accelerate as temperatures continue to rise in the future (Vitt et al., 2000; Jorgenson et al., 2001).

4.3 Successional Trajectories

This section explores the successional changes that are likely to occur within Subregions as their climatic envelopes change. Most of the information is derived from the empirical literature, including studies of ecological responses to warming that has already occurred over the past century (especially at high latitudes), responses to prolonged droughts, and basic studies of competition and succession. Also included are insights into successional trajectories from two expert workshops involving the working group that developed the Natural Regions and Subregions report.

The climate modeling results suggest that there are two main climate trajectories that need to be considered: dry and wet. The dry trajectory, which is most likely, involves GCMs in which the effects of increased temperature predominate. Increased evapotranspiration from higher temperatures overwhelms any increases in precipitation that may occur, leading to progressive drying of the landscape relative to historic conditions. The Cool and Hot models are representative of minimum and maximum amount of

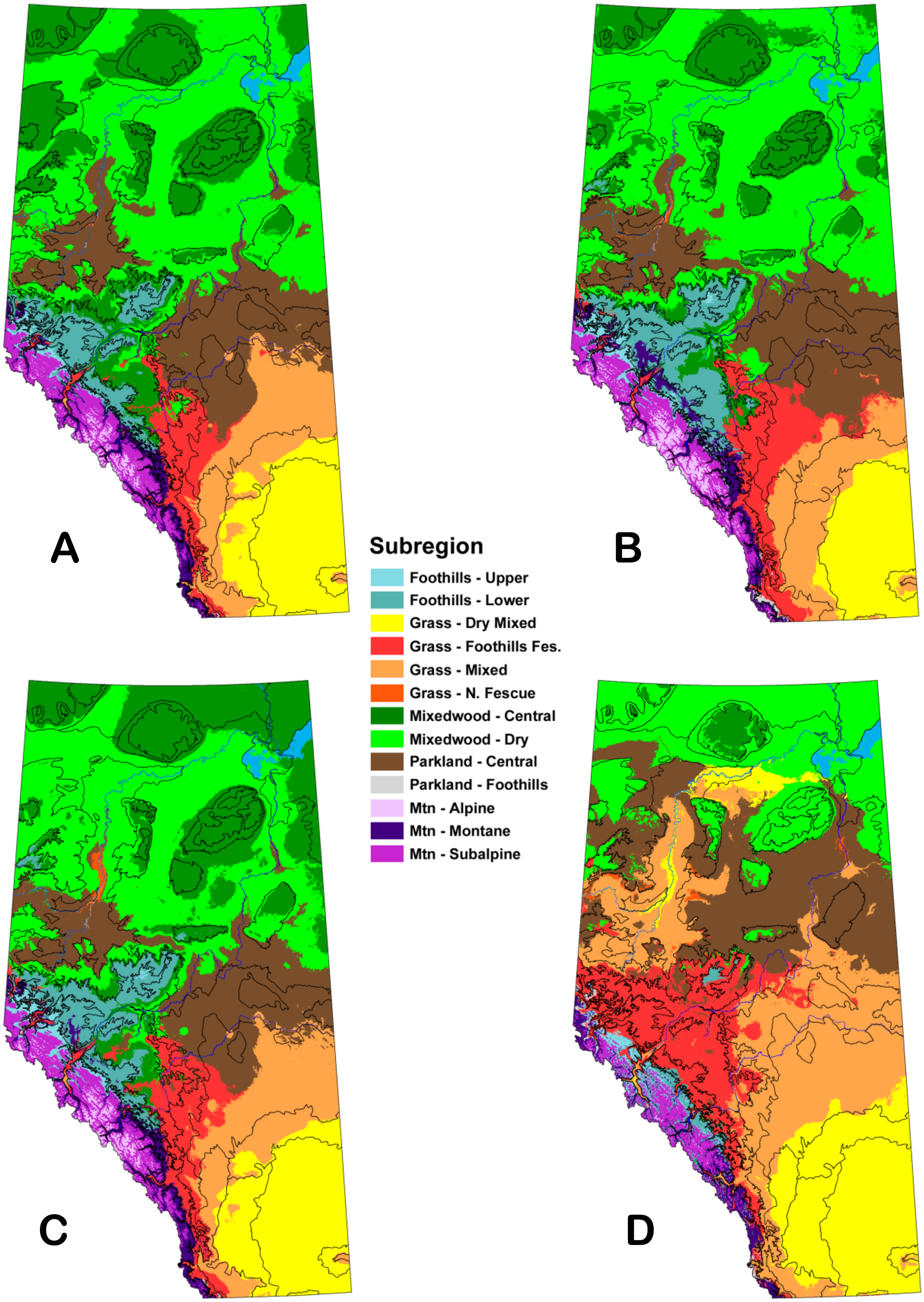

Fig. 4.20 Foothills Bioclimatic Envelope Model for the **2050s**: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model. See Fig. 3.10 for historical reference.

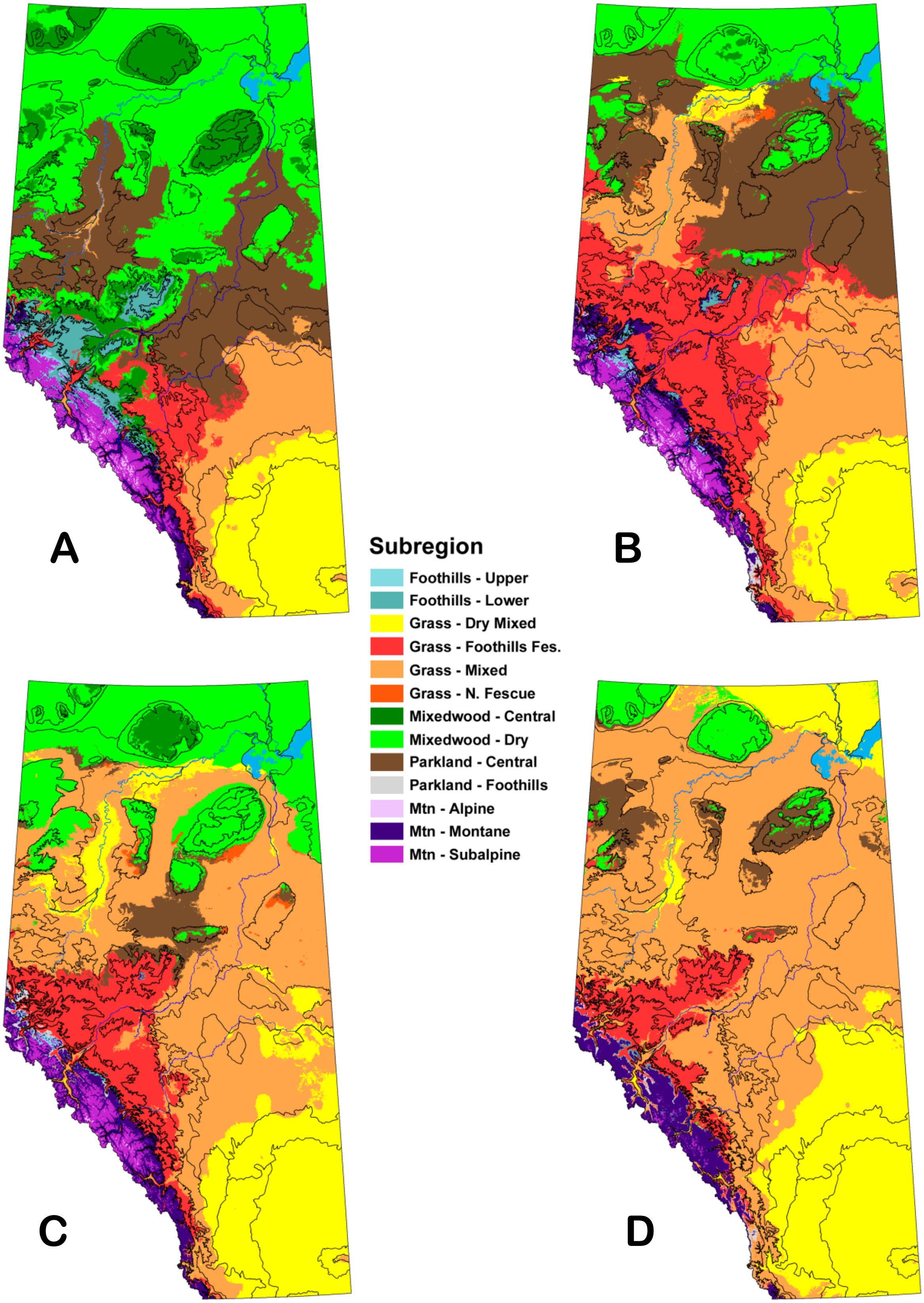

Fig. 4.21. Foothills Bioclimatic Envelope Model for the **2080s**: Panel A= Cool model; Panel B = Median model; Panel C = Dry model; Panel D = Hot model. See Fig. 3.10 for historical reference.

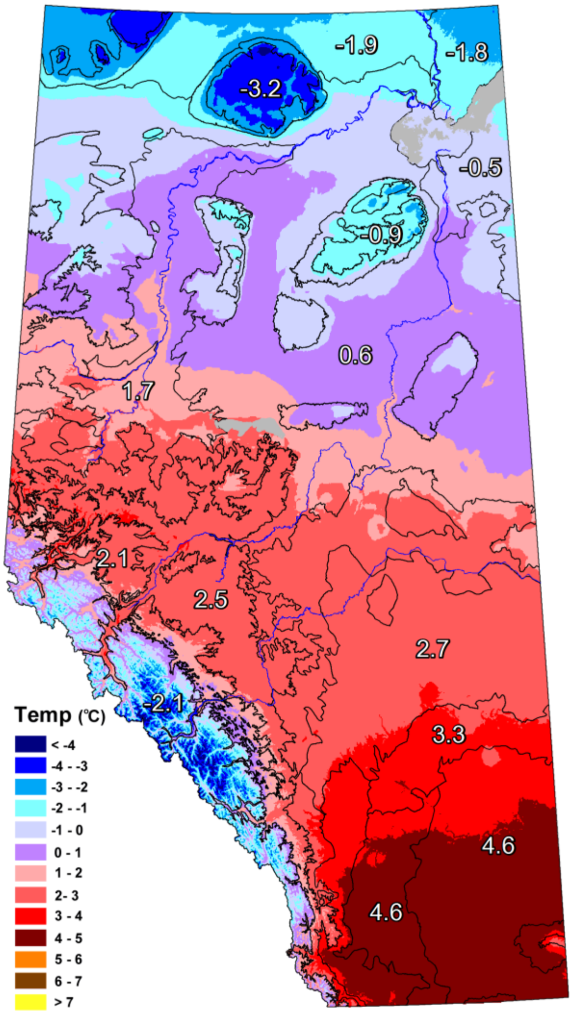

Fig. 4.22. Alberta MAT for 2000-2009.

change expected on this trajectory and the Median model represents an intermediate case.

Under the wet climate trajectory, represented by the Wet model, the effects of increased precipitation predominate. Only three GCMs, including the low-ranked Russian model, support this outcome, suggesting that it is less likely. But it cannot be entirely discounted. Succession under a hotter and wetter climate is difficult to predict, because it implies a transition to a climate space that does not exist in Alberta. The bioclimatic envelope changes predicted under the Wet model (which are fairly similar to those of the Cool model; Appendix 3) are all suspect because of this.

Under the wet climate trajectory, species from warmer climes would eventually arrive, but major shifts in ecological composition are not likely before the end of the century. The distance to comparable hot and wet climate spaces (e.g., Minnesota) is too great, and competition from established vegetation would delay successful immigration. In the interim, a degree of local reorganization of plant communities is likely to occur, in response to changes in the mean climate as well as to increased climatic variability. No further consideration of the wet trajectory is provided in this report.

The remainder of this section is devoted to the dry climate trajectory, which is most likely to occur. The focus is on describing the ecological changes expected for each Subregion. It is assumed that these changes, reflecting basic ecological responses to climatic warming, should be relatively consistent among GCMs, at least as a first approximation. This assumption is reasonable because the spatio-temporal patterns of climate change are quite stable among GCMs (see Sections 4.1 and 4.2). The variability lies mainly in the rate of change – the "when", not the "what". Given the uncertainty around timing, I emphasize trends over specific endpoints. But I do attempt to bound the minimum and maximum amount of change expected by the end of the century, using the Cool and Hot models as examples.

4.3.1 Grassland

Within Alberta, the Grassland and Parkland present the least complexity with respect to predicting the successional changes likely to occur in response to climatic warming. This is because the constituent Subregions do not represent distinct entities, but waypoints along a relatively uniform ecological gradient responding to a relatively uniform climatic gradient (Fig. 3.6). Transitions between Subregions are gradual and plant communities common to one Subregion are generally also found in adjacent Subregions, albeit in more limited distribution (Natural Regions Committee, 2006). Furthermore, with the exception of the Cypress Hills, there are few topographical features on the plains to complicate the climatic or ecological patterns.

The results for the Cool model provide an indication of the least amount of change that is likely to occur (Figs. 4.11, 4.14-4.16). Under this model, the Subregion climate envelopes in the Grassland shift roughly one Subregion northward by the 2050s For example, the Northern Fescue would experience the current climate of the Dry Mixedgrass, and so on.

It is reasonable to expect that climatic changes of this rate and magnitude could be accommodated by changes in the proportions of existing plant communities within each Subregion.[1] That is, communities representing the warm and dry end of the environmental spectrum within a given Subregion will increase, at the expense of communities on the cool and wet end of the spectrum. Detailed descriptions of grassland plant communities and their climatic associations are provided in the ecosite gradient diagrams in the Natural Regions report (Natural Regions Committee, 2006) and in the Alberta government's grassland plant community guides (Adams et al., 2004; Adams et al., 2005; Kupsch et al., 2012). At the regional scale, a progressive change in relative proportion of plant community types will manifest as a gradual northward shift in Subregion boundaries.

The mechanism underlying these changes is mainly competition. The species mix at a given site is a reflection of the competitive advantages and disadvantages of individual species with respect to the local microclimate (e.g., related to slope and aspect), edaphic conditions and disturbances such as grazing and fire (Gleason, 1939; Austin and Smith, 1989). This competitive balance is constantly refined and adjusted in response to changing conditions. Grassland systems do have a certain degree of ecological inertia, arising from the advantage that established plants have over incoming seed and from the adaptive capacity that most prairie plants have for handling common types of short-term disturbances. But this inherent stability has limits.

The ecological changes resulting from the drought of the 1930s, reviewed by Coupland (1958), provide a useful example. The basal cover of the ungrazed grassland ecosystem in southeast Alberta declined by approximately 50% over the course of the drought, similar to declines recorded in other parts of the Great Plains. Even the most xeric species decreased in numbers and more mesic ones survived only in the most favoured locales. The decrease in cover was most rapid in the first two years of the drought. Thereafter, drought-resistant species began to occupy the vacated sites of mesic species, resulting in

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[1] *The term plant community is used in this report to refer to the assemblage of plants typically found on sites that share the same environmental conditions, including climate, soils, slope, and aspect.*

some increase in overall cover. Once the rains returned in the 1940s, the original character of the grasslands was restored fairly rapidly through successional processes (Thorpe, 2011). This example illustrates that grassland systems have substantial ecological plasticity. The climatic changes predicted by the Cool model fall well within the range of what has historically been accommodated through local competitive reorganization.

In the case of the Dry Mixedgrass, a northward shift of one Subregion implies a transition to ecosystems found in the northern United States (Fig. 4.23). Although I did not include United States ecosystems in the envelope modeling, an examination of the raw climate inputs provides a good indication of what can be expected (Figs. 4.5, 4.9, 4.11). The climate space of interest is found in central and eastern Montana, where the dominant ecosystem is a Grama-Needlegrass-Wheatgrass grassland. Precipitation here is nearly identical to southeast Alberta, implying that increasing temperature is the main cause of existing ecological differences.

Vegetation transitions into the United States are gradual, again involving changes in the relative proportions of plant community types (Barker and Whitman, 1988; Vandall et al., 2006). The dominant grass species in the Grama-Needlegrass-Wheatgrass grassland are closely matched to those in Alberta's Dry Mixedgrass Subregion (Table 4.2). The main differences exist in the relative proportions of the dominant species, and the representation of secondary species. There are a few secondary species, such as Buffalograss, which gains importance in the southern part of the Grama-Needlegrass-Wheatgrass, that are not found in Alberta (Barker and Whitman, 1988; Vandall et al., 2006).

The Hot model, on the other end of the climate spectrum, provides an indication of the maximum amount of change that may occur in the Grassland by the end of the century. Because all GCM projections are fairly similar until 2050, the successional changes described for the Cool model should apply to the Hot model until mid-century. Climatic changes in the latter half of the century are more extreme under the Hot model, and ecological transitions are more difficult to predict. The trend of local rebalancing of community types, favouring communities associated with hotter and drier sites, will continue. But the immigration of exotic species, better adapted to dry conditions, will become increasingly important. What is unclear is whether the rate of species migration can match the rate of climate change, especially under the hottest and driest scenarios.

Under the Hot model, the CMI values of the Dry Mixedgrass Subregion become similar to the driest parts of Wyoming and southern Idaho. The ecosystems in these areas are largely Sagebrush Steppe (Fig. 4.23). While several grass species remain common to those in Alberta's Dry Mixedgrass (Table 4.2), there is increasing dominance by sagebrush species not found in Alberta, that are adapted to extreme aridity (Vandall et al., 2006). It is unlikely that all the foreign species of the Sagebrush Steppe will migrate northward at the same rate. Therefore, some mixing of current ecosystem associations can be expected to occur (Malcolm et al., 2002; Midgley et al., 2006).

Inactive sand dune areas are present in several parts of the Grassland and Parkland Regions (Fig. 4.24). Although these sites are currently stabilized by vegetation, they were active dunes during the Hypsithermal period

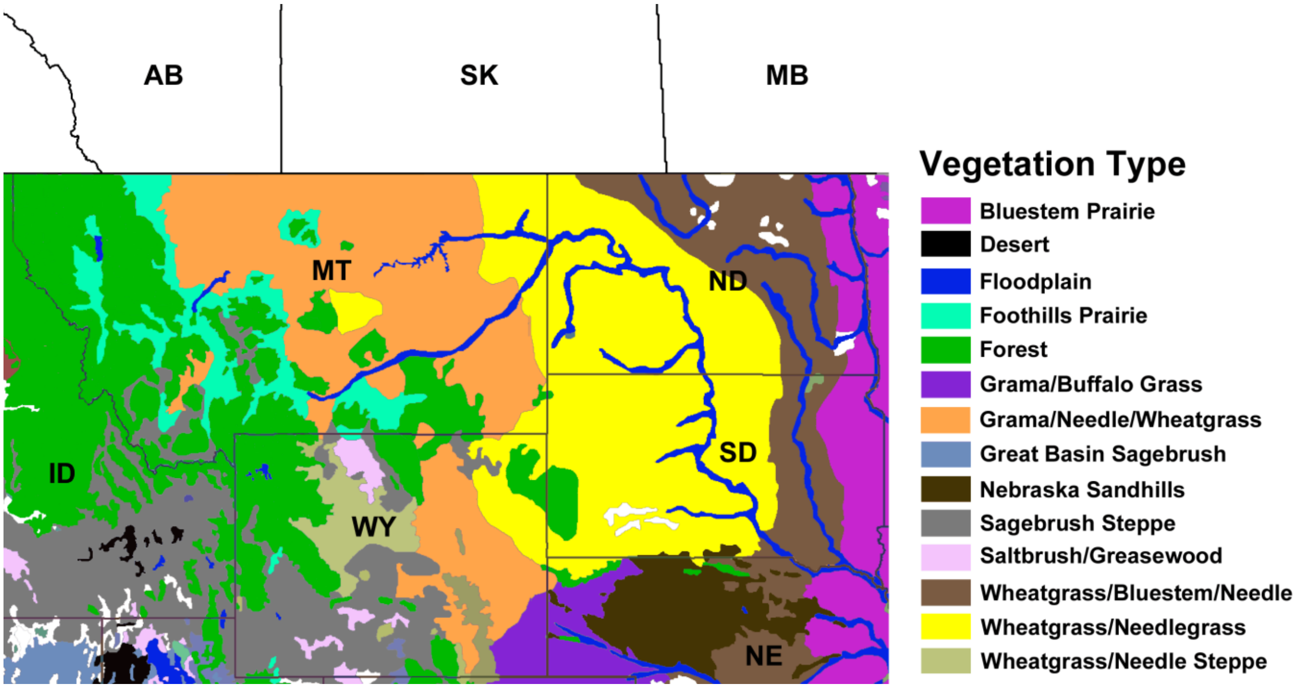

Fig. 4.23. Vegetation zones for northern US states, based on Kuchler (1964).

Table 4.2. Common grass species of three vegetation zones. Derived from Appendix 4 of Vandall et al., 2006. D = Dominant; S = Secondary; A = Absent.

Grass Species	Dry Mixedgrass (AB)	Grama-Needlegrass-Wheatgrass (US)	Sagebrush Steppe (US)
Blue grama	D	D	S
Bluebunch wheatgrass	A	A	D
Buffalograss	A	S	A
Green needlegrass	S	S	A
June grass	S	S	S
Needle-and-thread	D	D	D
Northern wheatgrass	D	D	A
Plains bluegrass	A	A	D
Plains reedgrass	S	A	A
Sandberg's bluegrass	S	S	S
Sedges	S	S	A
Western porcupine grass	S	A	A
Western wheatgrass	D	D	D

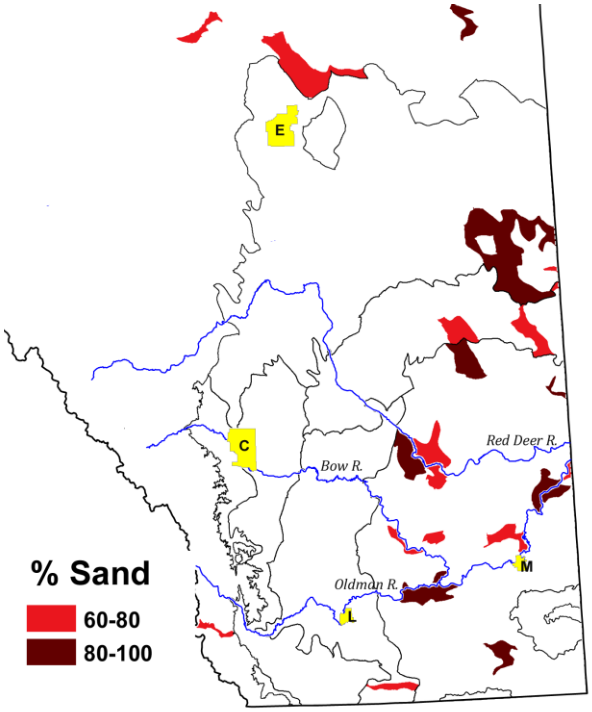

Fig. 4.24. Percent sand in the soil, from the Soil Landscapes of Canada, version 3.2 (2011). Major cities shown in yellow.

(Wolfe et al., 2006). Some sites in Saskatchewan were active as recently as the 1700s (Wolfe et al., 2001). If the projections of the Hot model or some of the other hot and dry models are realized, these sites can be expected to become active again.

Under the current climate, the large majority of the wetlands in the prairie pothole region are seasonal, holding water in the spring but drying out during the summer (Johnson et al., 2010). Others are semi-permanent, holding water in some years but dry in others. Permanent lakes are also present, but not common. Under a warmer climate wetlands will experience reduced runoff and groundwater flows because of regional drying due to increased evapotranspiration (Larson, 1995). They will also experience increased losses to evaporation, caused by earlier spring melt and higher summer temperatures. As a result, it is expected that the average water level of wetlands will decline and the amount of time that seasonal wetlands remain dry will increase (Johnson et al., 2010). There is little time lag associated with this process. However, the inherent variability in annual precipitation is likely to obscure long-term temperature-related trends for several decades. I did not attempt to quantify the potential change in water levels or hydroperiod, but the amount of change will be directly proportional to the increase in temperature. It is worth noting that lakes in the Grassland and Parkland, except those fed by deep groundwater sources, were largely dry during the Hypsithermal (see Section 2).

4.3.2 Parkland

For the Parkland, the minimum expected change, as reflected by the Cool model, is a transition to the climate of the Northern Fescue by the 2050s (Fig. 4.14). The maximum expected change, as projected by the Hot model, is a shift to the climate of the Dry Mixedgrass in the second half of the century (Figs. 4.11, 4.14).

The Parkland is part of the Grassland ecological gradient and will respond to climate change in much the same way as described for the grasslands. Long-distance species migration should not be a major issue, even under the Hot model, because many of the drought-tolerant species found in the Dry Mixedgrass (e.g., June grass, needle-and-thread, and blue grama) are already present in the Parkland (Natural Regions Committee, 2006). In any event, only small remnants of native prairie remain in the Parkland, so a discussion of ecosystem transitions is somewhat academic in this case (Weerstra, 2003). It is worth noting that the current high level of cultivation within the Parkland is unlikely to be sustainable if a transition to a Dry Mixedgrass climate does occur. The implication is that cultivated lands may transition to rangelands with at least some component of native grasses.

Aspen, because of its complex dynamics and importance to the Parkland ecosystem, merits special mention. The abundance of aspen steadily declines from the northern boundary of the Central Parkland towards the Dry Mixedgrass, indicating that moisture availability is an important limiting factor (Hogg, 1994; Hogg and Hurdle, 1995). However, over the past century aspen has been steadily encroaching on grasslands — the opposite of what is expected in the face of rising temperatures and stable precipitation (Fent and Richard, 1999). The implication is that aspen is better able to compete with grasslands than is reflected in its historical distribution. Fire suppression and the loss of bison, among other factors, have been proposed as explanations, but there is no consensus on which factor is (or was) most important (Campbell et al., 1994; Hogg, 1994; Coppedge and Shaw, 1997). Given that widespread recurrent prairie fires and disturbance from bison are no longer significant concerns, the main issue for the future is the relationship between aspen and drought (with insects, disease, and agriculture as secondary factors).

Some insights can be gained from the 2001/2002 drought, which affected a large area of parkland in central Alberta and Saskatchewan. A survey of the affected parkland ecosystem after the drought showed that 35% of the above-ground biomass was dead (Michaelian et al., 2011). Follow-up measurements indicated that annual mortality remained high (4-6%) for at least five years after the drought. Although aspen is clonal and has the capacity for regrowth if the root system remains viable, there are limits to its regenerative abilities. Prolonged or repeated drought can kill the clone, either directly or by increasing its susceptibility to attack by insects or disease (Frey et al., 2004; Hogg et al., 2008).

What can be concluded from these findings is that under the Cool model, aspen is likely to stop expanding and possibly undergo a minor contraction. If the increase in mean temperature is more substantial, then the associated drying would reduce the competitive and regenerative ability of aspen. Mortality caused by drought and insect attack would increasingly result in a transition to grass (Hogg et al., 2002; Hogg et al., 2005). Under the Hot model the expectation is that all aspen will be lost from the Parkland by the end of the century, except for sheltered moist locations such as river valleys.

4.3.3 Dry Mixedwood

The main feature of successional change expected in the Dry Mixedwood is a progressive conversion of deciduous forest to grassland through an intervening parkland stage. The amount of change will depend on how much drying occurs. All of the stages in this transition are already present in the Grande Prairie area (though most of the area is now cultivated). One can envisage how grasslands similar to those in the Grande Prairie region will begin to extend northward along the Peace River as temperatures rise. In fact, small grasslands are already present along the Peace River lowlands all the way into Wood Buffalo National Park (Moss, 1952; Schwarz and Wein, 1997).

Strong and Hills (2003) suggest that the Peace River grasslands were continuous with those in the south during the Hypsithermal period. Indeed, over half of the current species in the Grande Prairie area are the same as those in the Northern Fescue (Moss, 1952). One can conclude that a lack of suitable grass species will not be a limiting factor for the transition of the northern Dry Mixedwood to a grassland system. Its similarity to southern grasslands will increase over time as the Northern Fescue community moves north, reducing migration distances. Also, progressive drying will reduce competition from northern species adapted to moist conditions. Competition from exotic species, such as smooth brome, Kentucky bluegrass, timothy, and Canada thistle will be (and is now) an important factor in the successional trajectories of grasslands, especially in roaded areas (Sumners and Archibold, 2007; Thorpe, 2011).

The mechanisms and dynamics of successional change will be similar to those described for the Parkland, with aspen again playing a central role. Drought and insects will be the leading agents of disturbance, opening and expanding gaps in the aspen forest (Hogg et al., 2002; Hogg et al., 2008). The mortality caused by the drought of 2001-2002 provides a good example of this process (Michaelian et al., 2011). Fire may also become an important source of disturbance. Losses to fire in the Dry Mixedwood are currently low, likely because of human settlement. But this could change if fire suppression efforts become less effective under a hot and dry climate. Given aspen's strong regenerative capacity, permanent changes will only occur once moisture levels have consistently declined to a point that they limit regeneration of aspen and tip the competitive balance in favour of grasslands.

The Cool model predicts a progressive transition to a Parkland climate over the next few decades. By the end of the century it would be reasonable to expect an expansion of scattered grassy openings in the aspen forest, particularly in the southern component of the Dry Mixedwood and along the Peace River.

Under the Hot model there is a further progression to a Dry Mixedgrass climate in the latter half of the century. Widespread change is unlikely prior to the 2050s because aspen should still have the capacity to regenerate effectively in response to drought and fires during this period. But successful regeneration would decline after mid-century, so widespread transitions become increasingly likely, beginning with south and west-facing slopes. The rate of disturbance will be a key determinant of the rate of transition after 2050.

4.3.4 Central Mixedwood

Rather than a simple northward transition, as described for the Grassland, the pattern of change in the Central Mixedwood will be strongly influenced by elevation (Figs. 4.15-4.18). Lower elevation areas are warmer and are predicted to become moisture limited first, beginning with the lowlands along the Peace and Athabasca Rivers. Higher elevation areas will follow. The change from moisture surplus to moisture deficit will affect very large areas almost simultaneously once the tipping point is reached because CMI values across the Boreal are relatively uniform (Fig. 3.3). This spatial pattern is the same for both the Cool and Hot models, though transitions are faster and more extreme under the Hot model.

Within the Central Mixedwood, vegetation patterns are strongly influenced by site moisture conditions and this needs to be considered when predicting successional pathways. Mesic sites are characterized by an aspen-white spruce mixedwood, hydric sites are characterized by peatlands surrounded by black spruce, and xeric sites on sandy soils are typically dominated by jack pine (La Roi, 1992; Natural Regions Committee, 2006).

Sit moisture conditions in the Central Mixedwood are not a function of climatic patterns, but of local topography and soil type. The Subregion is relatively flat, so excess water does not run off effectively and instead tends to pool in low lying areas. Because of the cool temperatures characteristic of this Subregion, decomposition in the wetlands is very slow, leading to the accumulation of peat. Each of the above-noted plant communities will respond to climate change differently, so each is discussed in turn.

Mesic Sites

In mesic areas, successional change will initially involve a gain in aspen at the expense of white spruce, leading to a forest composition characteristic of the Dry Mixedwood. White spruce declines because of poor seed germination and seedling growth under dry conditions and because it cannot mature fast enough to produce cones when the rate of disturbance is high (Hogg and Schwarz, 1997). Aspen can still reproduce effectively under these conditions, in part because it is clonal and can reproduce asexually through suckering (Lieffers et al., 2001). The differential regeneration ability of these two species is clearly apparent in the Parkland, where aspen is widespread but white spruce is restricted to sheltered moist areas such as the north-facing banks of river valleys (Natural Regions Committee, 2006).

Although white spruce seedlings are very sensitive to moisture stress, mature trees can remain viable under quite dry conditions, as evidenced by hand-planted shelterbelts around farmyards throughout the prairies (Hogg and Schwarz, 1997; Chhin and Wang, 2008). The fact that mature white spruce can withstand dry conditions means that successional transitions will usually only manifest after the mature trees have been killed by fire or other disturbance.

With additional warming, the next stage of successional change in mesic areas involves the appearance and enlargement of grassy openings in the forest. The mechanisms are the same as those described for the Dry Mixedwood.

Under the Cool model the Dry Mixedwood climate envelope appears in the low elevation regions along the Peace and Athabasca Rivers by the 2020s and extends across most of the Subregion by the 2050s (Fig. 4.18). The Parkland climate envelope appears after 2050 in low elevation regions (Fig. 4.17). The loss of most of the white spruce from low elevation areas by the end of the century seems likely under the Cool model and current rates of fire. Aspen is already the most prominent species in these areas. It also seems reasonable to expect some expansion of the grasslands that exist along the Peace River valley. At higher elevations in the Central Mixedwood the permanent loss of white spruce would be minimal prior to 2050 and the timing and distribution of transitions thereafter would depend on the pattern of future fires.

Under the Hot model, almost the entire Central Mixedwood experiences a Grassland climate envelope by the 2050s (Fig. 4.16). Because the transition to a moisture limited system happens so quickly the main factor in determining the rate of succession will be fire. Provincial fire records show that, on average, 0.32 % of the Central Mixedwood has burned per year since 1980.[1] Under global warming the rate of fire in western Canada may double by 2050 and increase by over three times its historical rate by the end of the century (Balshi et al., 2009).

If the average rate of burning were to immediately double to 0.6% per year, at least half of the original Central Mixedwood forest would still be intact at the end of the century, assuming a random distribution of fire occurrence. The remaining mature trees should be able to withstand the Grassland climate associated with the Hot model (Hogg and Schwarz, 1997). However, additional mortality could occur from severe and prolonged drought if that becomes a significant feature of the climate. Losses can also be expected from ongoing forest clearing by the petroleum industry and from harvesting by the forest industry if efforts at regeneration prove unsuccessful in the dry climate of the Hot model.

As an aside, under the A2 scenario greenhouse gas emissions do not stabilize by 2100, as they do under the B1 scenario. This means that climate warming and associated forest transitions will continue after 2100, resulting in the eventual conversion of most of Alberta's boreal forest to grassland.

It is difficult to predict what the successional trajectory will be under the Hot model in stands that have been killed by fire. A complex transitional mosaic is most likely. The regeneration of aspen and white spruce would be severely compromised under a Grassland climate, but it is unlikely that regeneration would fail uniformly across the entire Subregion. On sites where regeneration has failed, pioneer species and those best adapted to drier conditions will be favoured. However, transition to a typical grassland will be constrained by the limited number of dry-adapted grass species available in forested areas, and possibly by soil type as well. Invasion by exotic grass species may be of particular concern given the extensive road network (a source of exotic species) in the Boreal and the relative absence of native grass species (Sumners and Archibold, 2007; Thorpe, 2011). Finally, the response of the forest industry has not been considered here, but it is likely to influence successional trajectories in some manner (e.g., by planting of exotic dry-adapted tree species).

Hydric sites

In both the Cool and Hot models (and most of the others), the total amount of surplus water in the Central Mixedwood is expected to decline as a result of increased evapotranspiration. The decline is proportional to the rise in temperature, offset by any increase in precipitation. Because temperatures increase over time, the rate of drying increases over time as well.

A decline of surplus water translates into a decline in the amount of water stored in wetlands (Fig. 4.25). All parts of the Central Mixedwood will be affected because the increase in temperature will be experienced everywhere. If temperatures become high enough, as expected under many models, potential evapotranspiration will exceed precipitation (i.e., CMI < 0; Fig. 4.12). In this

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[1] *Historical wildfire database available at: http://www.srd.alberta.ca/Wildfire/WildfireStatus/HistoricalWildfireInformation/SpatialWildfireData.aspx*

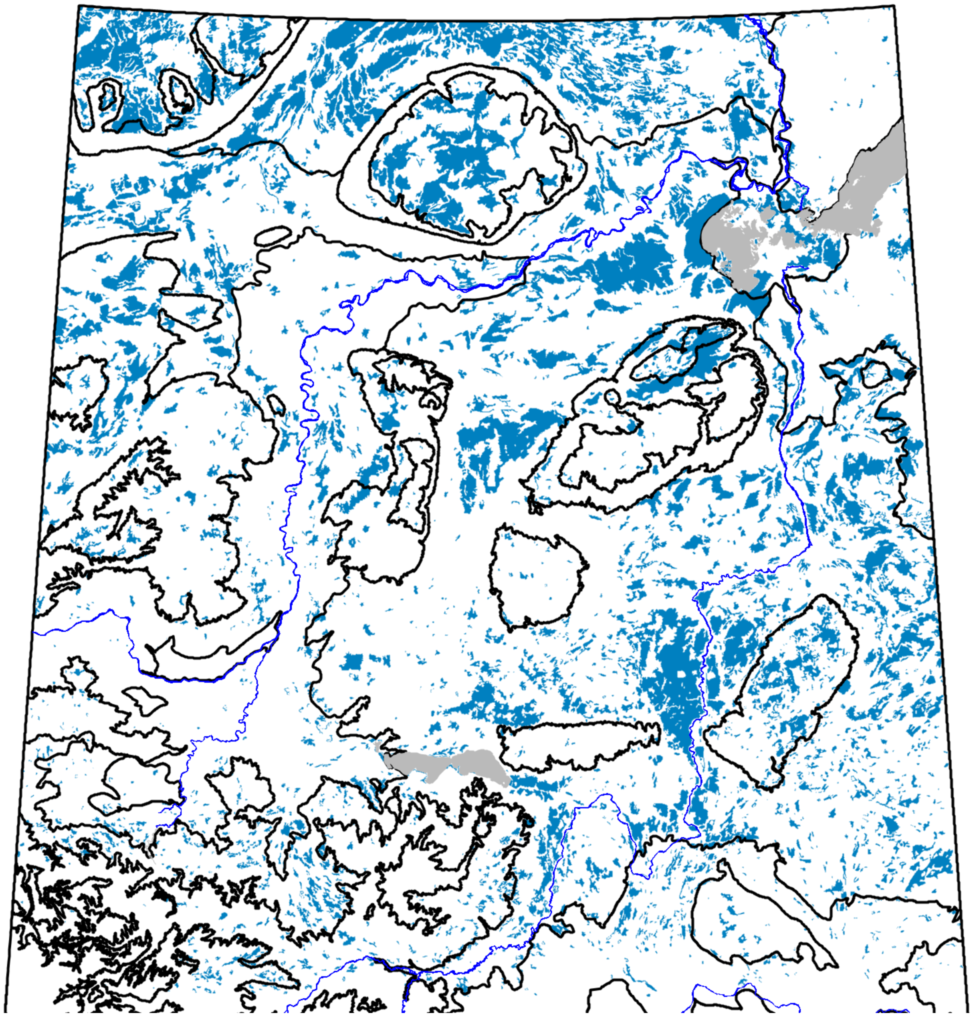

Fig. 4.25. Landscape polygons containing greater than 75% peatland. From the Alberta Peatland Inventory, produced by Dale Vitt in 1996.

case the only remaining water bodies will (eventually) be those fed by ground water or deep enough to sustain summer evaporative losses and outflows until they are replenished by spring run-off. In other words, the Boreal wetland system will transition to a system characteristic of the Parkland or Grassland.

As regional water levels decline, individual wetlands will shrink and the drying peripheral zones will be invaded by herbaceous and woody vegetation (Dang and Lieffers, 1989). This process has already been documented in Alaska in response to the regional drying that has occurred in the Kenai Peninsula since the 1950s (Klein et al., 2005; Berg et al., 2009). The reported rate of change was 12-14% per decade for converting herbaceous area to shrubland and 8% per decade for converting nonforest to forest. This indicates that successional change can occur quite rapidly once drying has occurred. Fire is not a rate-limiting factor in this process. Within the wetlands themselves, the rate of peat accumulation will slow as temperatures rise and hasten the rate of decomposition

(Hogg, 1994). In areas where CMI is less than approximately 6 cm, most bogs and fens will transition to marshes (Gignac et al., 2000).

Farther out from the wetlands, the black spruce stands on sites that are intermediate between wetlands and mesic uplands will progressively be displaced by upland tree species, after fire. The black spruce in turn will expand in the direction of the drying wetlands (Dang and Lieffers, 1989; Macdonald and Yin, 1999).

Given that the Central Mixedwood covers more than 25% of Alberta, and approximately 45% of this Subregion is occupied by bogs and fens, the potential consequences of wetland drying are enormous. If the extent of these wetlands were to decline to the 15% currently found in the Dry Mixedwood it would translate into more than 50,000 km^2 of new mesic habitat. A further decline to the extent of wetlands in the Central Parkland (10%) would translate into an additional 9,000 km^2 of mesic area.

Peatland transitions should be well underway by the end of the century, given that even the Cool model predicts Dry Mixedwood conditions by the 2050s (Fig. 4.18). It is only because of low temperatures that this Region is currently as wet as it is — the precipitation inputs are similar to those of the Parkland and Grassland. In the absence of surplus water, the low relief and poor drainage of the Boreal plains will not maintain wet conditions anymore than they do on the prairies. That said, the ability of peat to absorb and store water during wet periods will likely slow the transition. Future contributions of ground water represent another uncertainty.

Under the Cool model, the drying and successional transitions should generally keep pace with the changing climate, though the transition of black spruce forests to upland forests will be limited by the rate of fire and the availability of seed. Under other models, warmer temperatures will speed the drying and the initial stages of succession, but successional changes involving forest species will continue to lag. Under the extreme case of the Hot model, conditions flip, after 2050, from being too wet to being too dry for forest ecosystems. But, given the large amount of water stored in the system, a transition of hydric sites to grassland by the end of the century seems unlikely. It is unclear what the intermediate stages might be.

Xeric sites

Jack pine is the dominant tree species on dry sandy soils in the Central Mixedwood, Dry Mixedwood and Central Parkland, though it is not common in the latter (Natural Regions Committee, 2006). Jack pine actually grows best on mesic sites, but is outcompeted by aspen on these sites (Farmer et al., 1988; Kenkel, 1994). The competitive balance with aspen is reversed on xeric sites because of several physiological adaptations jack pine has for survival on nutrient poor dry sandy soils (Bliss and Mayo, 1980). Given these competitive relationships, there is no expectation that aspen will become dominant on xeric sites as a result of rising temperatures, as it will on mesic sites. Instead, these sites will remain essentially unchanged, even under a Parkland climate. An increase in the rate of fire should not have much effect, other than producing a younger age structure, because jack pine already experiences a high rate of disturbance and is adapted to it.

Mountain pine beetle has been observed in lodgepole pine x jack pine hybrids and may eventually infest jack pine stands (Rice et al., 2007; Rice and Langor, 2009). But the mortality associated with mountain pine beetle is not likely to have a major ecological effect in the Central Mixedwood. This is because, unlike the Foothills, there is no expectation that aspen will expand into the sites where jack pine has been killed, for the reasons outlined above. Jack pine stands may, on average, become younger because of more frequent disturbance, but there should be no successional transition. Regenerating beetle-killed stands could be more open than fire-origin stands, given the lack of fire to open cones and prepare a seedbed. Additional information on the effects of mountain pine beetle is provided in Section 4.3.8.

Under the Cool model the Central Mixedwood never progresses beyond a Parkland climate, so no substantive changes are expected on xeric sites. The Hot model projects a grassland climate for the Central Mixedwood by the 2050s. Jack pine is not found in the Grassland, so it is expected that jack pine stands will eventually disappear under the Hot model, presumably transitioning to grass and shrub communities once climatic conditions become too extreme.

4.3.5 Northern Mixedwood

Successional trajectories in the Northern Mixedwood will largely be dictated by the dynamics and ecological consequences of permafrost degradation. Discontinuous permafrost is widespread in the peatlands that cover most of the Subregion (Fig. 4.25). Organic accumulations in Sphagnum-dominated peatlands serve to insulate the subsurface and preserve below-freezing temperatures during the summer (Halsey et al., 1995). In this way permafrost can exist under climatic conditions that do not support permafrost in other soils.

The formation of ice in peatlands causes an expansion in volume which raises the surface a metre or more above the regional water table (Camill, 2005). Drier conditions on the elevated plateaus promote the growth of black spruce forests with understories of Labrador tea and various mosses and lichens (Camill, 1999). Subsequent thawing of the plateau, due to rising temperatures, causes subsidence and the formation of wet collapse scars dominated by a treeless cover of Sphagnum mosses, *Carex* species and aquatic forbs (Camill, 2005). These collapse scars expand laterally over time as the surrounding permafrost plateaus thaw, causing black spruce to lean toward the thawing edge and eventually to subside and drown as the thawing margin passes. In effect, the thawing of permafrost results in the conversion of a forested ecosystem to an aquatic one (Jorgenson et al., 2001; Camill, 2005).

Once developed, permafrost may persist in disequilibrium with warmer climates and exist in areas where it cannot presently redevelop (Vitt et al., 2000). Mapping of past and present permafrost distribution in the peatlands of the western boreal indicates that permafrost degradation began after the Little Ice Age ended (~1850), but only 9% has degraded since that time (Vitt et al., 2000; Jorgenson et al., 2001). Camill (2005) reported that the rate of permafrost thawing has accelerated since 1950 and suggests that permafrost will disappear across the discontinuous permafrost zone by 2100 if the MAT continues to increase at its current rate.

Given that the discontinuous permafrost isocline has already shifted to the NWT border (Section 4.2.4), it can be concluded that permafrost thawing in the Northern Mixedwood is underway. But complete melting will take time. Thawing is likely to be complete by the end of the century under the Hot model, but some permafrost patches may remain under the Cool model. The first stage of successional change in areas where thawing has occurred will be a transition from open black spruce forest to bogs and fens (Camill, 1999). But this is not a stable state. The rise in temperature responsible for the melting of the permafrost also increases the rate of evapotranspiration. Given that precipitation inputs in the Northern Mixedwood are no greater than those in the Mixedgrass, a gradual drying of the Subregion can be expected as temperatures rise. This will result in a transition back to a terrestrial system, through the successional processes described for hydric sites in the Central Mixedwood.

What remains unclear is how long these transitions will take. Given that 1) the current MAT in the Northern Mixedwood is still well below zero, 2) the thawing process is subject to inherent lags, and 3) there is a tremendous amount of water stored in the system, it does not seem likely that the Subregion as a whole will progress much beyond the wetland stage by the end of the century, though the existing upland forests are likely to expand somewhat. That said, rapid drying in the latter part of the century must be considered a possibility under the Hot model. The resulting vegetative changes are difficult to predict in this case.

4.3.6 Boreal Highlands

The Upper and Lower Boreal Highlands are floristically similar to the Central Mixedwood, but the relative proportion of species changes with elevation. In particular, at higher elevations, lodgepole pine or lodgepole pine x jack pine hybrid communities with low species diversity replace more diverse mixedwood stands containing aspen (Natural Regions Committee, 2006). Black spruce fens and bogs, similar to those in the Central Mixedwood, are present in low lying areas on the plateaus.

Once temperatures are similar to those of the Central Mixedwood the competitive balance between lodgepole pine and aspen will be reversed, favouring aspen (see Section 3.3.2). Although this change in competitive abilities is likely already underway, successional transitions will occur at a slower pace. Being shade intolerant, the advance of aspen will be limited by the rate that openings are created by fire or possibly as a result of mountain pine beetle. Fire has the added effect of exposing mineral soil, which greatly enhances the ability of aspen to regenerate from seed (Turner et al., 2003; Romme et al., 2005). Local differences in seed source availability, initially favouring pine, will also delay the transition.

The increase in temperature in the Boreal Highlands will increase the rate of evapotranspiration, resulting in less surplus water and a contraction of the wetlands (as described for the Central Mixedwood).

Under the Cool model, the Upper and Lower Boreal Highlands both transition to the climate envelope of the Central Mixedwood by the 2020s (Fig. 4.19). This should provide sufficient time for aspen to replace most of the pine at higher elevations by the end of the century, and for the overall character of the Boreal Highlands to become comparable to that of the Central Mixedwood. Subsequent succession of aspen to white spruce may be limited, however, if the rate of fire increases in the future.

Under the Hot model the climate of the Boreal Highlands becomes similar to that of the current Dry Mixedwood by the 2050s, and some of the lower hills eventually transition to a Parkland and even a Grassland climate (Fig. 4.18). Under this scenario, the Subregions are likely to transition directly to aspen forest by the end of the century, without white spruce ever becoming prominent. The rate of successional change will again be limited by the rate of fire and the rate of aspen dispersal.

4.3.7 Boreal Subarctic

The Boreal Subarctic, restricted to the highest of the Boreal hills, is characterized by open stunted stands of black spruce underlain by organic deposits with extensive permafrost. Successional changes in response to rising temperature are expected to be similar to those described for the Northern Mixedwood. The Boreal Subarctic is 1.3 °C colder than the Northern Mixedwood, however, so it will likely take longer for the permafrost to melt. Nevertheless, widespread conversion of the currently forested system to a largely aquatic system is likely by end of the century under both the Cool and Hot models. Because of the colder starting point it is unlikely that a significant amount of drying will occur in the Boreal Subarctic, even under the Hot model, though some expansion of the existing upland forests can be expected.

4.3.8 Foothills and Rocky Mountains

Ecological relationships in the Rocky Mountain and Foothills Regions largely reflect the influence of a climatic gradient that is linked to elevation. As temperatures rise, it is expected that plant communities typical of low elevations will intergrade with and over time replace plant communities found at higher elevations.

Foothills

The Lower Foothills present a challenge because a suitable analog for the future climate does not exist among existing Subregions. The closest overall match for most GCMs, given the high temperatures of the 2080s, is the climate envelope of the Foothills Fescue (Fig. 4.21). However, CMI values in the Lower Foothills remain positive in the 2080s (suggesting a forested ecosystem) for all but the Hot model (Fig. 4.11). In this case, the raw climate parameters likely provide a more a more reliable guide for determining succession patterns than the bioclimatic envelope model does.

Despite the complexities of the Foothills climate, three successional trends seem highly likely. The first is a change in the competitive balance between aspen and lodgepole pine, similar to that described for the Boreal Highlands (also see Section 3.3.2). The relative proportion of these two species is the main indicator for the boundary between the Upper and Lower Foothills and between the Lower Foothills and Central Mixedwood (Natural Regions Committee, 2006). As the proportion of aspen increases at the expense of lodgepole pine the boundaries between these Subregions will shift upslope and may become somewhat blurred as they do so.

The expansion of aspen within the Foothills is already underway. Landhäusser et al. (2010) report the establishment and growth of aspen at elevations in the Upper Foothills that were previously unsuitable. The main limiting factor for successional change is the need for fire or other disturbance to remove the existing trees and to expose mineral soil for optimum seedling establishment. Seed source is also a factor, but aspen has a windblown seed that can establish up to 15 km from the source tree (Turner et al., 2003; Landhäusser et al., 2010). Nevertheless, the advantage of having a local seed source will provide a competitive advantage to lodgepole pine for a considerable time.

The second successional trend, which is also already underway, is a change in forest structure resulting from infestation by the mountain pine beetle (Schneider et al., 2010). Winters have been too cold for pine beetle survival until recently, so the large even-aged tracts of lodgepole pine characteristic of the Foothills largely originated from fire and logging. The future trajectory of the pine beetle in Alberta (epidemic vs. endemic) is uncertain; however, the beetle population is now established east of the Rocky Mountains and its continued presence here is all but certain given the predicted rise in temperatures (Safranyik et al., 2010).

If beetle-infested stands are clearcut and replanted, the status quo can be maintained. But many infested stands will be left to regenerate naturally, either because of logistical and capacity limitations or because they are protected, inoperable or uneconomic. The regeneration of these stands is highly variable, depending in large part on the species composition of the understory (Collins et al., 2011). Regeneration back to pure lodgepole pine is possible, but transition to a mixed-species stand is more likely (Collins et al., 2011; Diskin et al., 2011; Kayes and Tinker, 2012). Beetle-killed stands do not necessary favour aspen because mineral soil is not exposed. But to a limited extent, ideal conditions for aspen seedlings may be created as killed snags fall, exposing soil around root balls and creating pits that trap moisture (Pelz and Smith, 2013). It can be concluded that the overall net effect of the introduction of pine beetle will be an increase in regional ecological diversity, as formerly pure, even-aged lodgepole pine stands transition to more complex communities.

The third successional trend that could occur, though not immediately, is the northward movement of species that are currently found in the Montane, such as Douglas fir. Grassland openings, which occur on southerly and westerly aspects of the Montane, are also likely to appear in some parts of the Lower Foothills if temperatures and drying increase sufficiently.

By the 2080s, the MAT of the Foothills rises by 2.5 °C under the Cool model and 3.9 °C under the Median model. A regional moisture deficit resulting from increased evapotranspiration is unlikely in either case because of the high precipitation inputs in the Foothills (Fig. 4.11). Consequently, the Foothills should remain forested under both the Cool and Median models. The main change that can be expected by the 2080s is a general increase in ecological diversity, as species from the Central Mixedwood, Montane, and the Foothills Fescue (to a limited degree) increase in abundance while a legacy of existing Foothills species (especially lodgepole pine) remains intact in favourable sites and in areas that have escaped disturbance.

The rate of transition will, in part, be determined by the rate of fire which, as previously mentioned, is likely to increase under a warmer climate. The loss of pine from mountain pine beetle infestation will also likely influence the rate of ecosystem transition. Finally, forest harvesting must also be considered, though the net effect on successional pathways is difficult to predict. One the one hand, the active planting of lodgepole pine will delay successional change. But on the other hand, clearcutting increases the availability of site conditions ideal for the establishment of aspen seed (Landhäusser et al., 2010).

Under the Hot model, the southern part of the Lower Foothills becomes moisture limited as a result of increased evapotranspiration by the 2050s and the entire Subregion is moisture limited by the 2080s (Fig. 4.11). Because successional transitions will be limited by the rate of disturbance it is unlikely that there will be sufficient time for the widespread loss of forest to occur by the end of the century. But the northward expansion of grasslands and shrub communities from the Foothills Parkland and Foothills Fescue into the southern part of the Lower Foothills is likely under this model. The Upper Foothills should remain forested, though species from the Lower Foothills and Montane will become increasingly prevalent.

Alpine and Subalpine

Successional trajectories in the Alpine and Subalpine are less complex than those in the Foothills. Vegetative communities will generally just shift upslope as the climate warms (Luckman and Kavanagh, 2000; Roush, 2004). This being the case, the Upper Foothills climate envelope provides a reliable analog. However, species do not all move at the same rate, and local site conditions, snow pack, and disturbance history can affect pattern of successional change, both at treeline and at lower elevations (Roush, 2004; Mamet and Kershaw, 2012). Therefore, the vegetative communities of the Alpine and Subalpine will not move upslope as intact units. Instead, ecosystems that include elements of both old and new communities will arise as the climate warms, increasing ecological diversity (at least temporarily).

The rate of upslope migration of the treeline has been and will continue to be highly variable. In some sites in the Rocky Mountain national parks, the treeline has risen by more than 150 m over the past century, whereas other sites have remained almost unchanged (Luckman and Kavanagh, 2000; Roush, 2004). It is worth noting that a vertical rise of 150 m over a century implies a spatial change that is very small relative to the anticipated changes in other Subregions.

Over time, the extent of Alpine vegetation is expected to decrease as it is replaced from below by Subalpine vegetation. In part, this is because the upslope movement of Alpine vegetation will eventually be limited by a lack of suitable sites (e.g., slopes become too steep, lack of soil, etc.). In addition, the upward movement of the Alpine is likely to be slower than the upward movement of the Subalpine, because of the lower temperatures and poorly developed soils above treeline. The rate of growth and regeneration will actually be quite slow in both Subregions, because of the cold climate, so the amount of successional change that occurs by the end of the century may be limited.

Successional processes at lower elevations in the Subalpine are expected to be similar to those described for the Foothills, with disturbance again serving as a rate limiting factor.

Montane

The Montane lies at the interface between the prairies and mountains and is characterized by complex climatic and ecological patterns. With climate warming, the grasslands and open woodlands found at lower elevations and dry sites within the Montane are expected to expand into higher elevations. Under the Cool model at least some parts of the Subregion should remain forested by the 2080s. Under the Hot model it is likely that much of the Subregion will transition to grassland. Movement of Montane species upslope into the Subalpine and northward into the Foothills can be expected.

4.3.9 Other Subregions

In the remaining Subregions factors other than climate have a dominant role in determining ecological patterns. This means that bioclimatic envelopes from neighbouring Subregions provide little insight into potential ecological responses to climate change. However, some guidance is available from the eco-climatic associations that exist within the Subregions themselves. For the Peace-Athabasca Delta, a substantial body of research into the effects of climate change is available.

Peace-Athabasca Delta

Although precipitation is low in the Peace-Athabasca Delta (similar to the Mixedgrass), water is the defining feature of this Subregion, as a result of inputs from the Peace and Athabasca Rivers. The delta and its northward extension into Wood Buffalo National Park are very flat and subject to extensive periodic flooding. Though the flooding events are intermittent, they occur often enough to prevent the establishment of mature forest. Thus, the terrestrial vegetation is characterized by extensive sedge meadows with willow shrublands and balsam poplar on elevated levees (Natural Regions Committee, 2006).

Studies of the long-term hydrodynamics of the delta indicate that water flows are highly variable over time, and that several multi-decade intervals without a major flood have occurred during the past 300 years (Meko, 2006; Wolfe et al., 2006). It has also been shown that ice-jamming is the main mechanism capable of recharging the elevated perched basins across the broader delta. In the absence of ice blockage, flood levels do not rise high enough to affect all areas. During periods without major flooding, willows expand into areas that begin to dry out, altering the vegetative composition of the landscape (Timoney and Argus, 2006). Subsequent flooding kills the willows, resetting the landscape to its initial state. Thus, periodic flooding, related to ice jams, constitutes a disturbance regime that maintains the system in a state of permanent disequilibrium.

Climate warming is expected to have two main influences on the delta: 1) midwinter thaws in the collecting basins for the Peace and Athabasca rivers will reduce the volume of peak flows in spring, and 2) ice will form later and be thinner, lowering the probability of ice jams (Timoney et al., 1997; Beltaos et al., 2006). These factors are likely to be exacerbated by increasing human withdrawals from the rivers, especially for oil sands extraction (Schindler and Donahue, 2006). The expected ecological response is a reduction in the extent of wetlands and a progressive conversion of the sedge meadows to shrublands, and eventually to forest (Timoney and Argus, 2006; Wolfe et al., 2012). This process will not occur quickly, however, because sporadic flood events are still likely to occur for some time, albeit less frequently. Whenever they do occur, the floods will kill the woody vegetation and reset the ecological clock.

Athabasca Plain

The boundary of the Athabasca Plain follows the contours of a large area of Precambrian sandstone overlain by coarse textured gravels and sands. Dune fields are present in some areas, and while most are stabilized by vegetation, areas of open sand up to several square kilometres in size do exist (Natural Regions Committee, 2006). The dominant vegetation in this Subregion is a jack pine-lichen woodland of variable density (Carroll and Bliss, 1982). The structure of these forests is remarkably simple. Canopies are generally even-aged, uniform in height, and comprised of a monoculture of jack pine. Groundcover is predominately a continuous mat of lichens. Wetlands are present in low-lying areas, particularly in the eastern part of the Subregion.

Given the sandy soils and low moisture inputs — similar to the MixedGrass — it is remarkable that forest exists here at all. But jack pine has many adaptations for surviving in this habitat (Bliss and Mayo, 1980). In particular, the canopy is effective in capturing precipitation from light rains and the trees have a shallow wide root system for quickly capturing water that penetrates into the ground. The lichen mat also plays a key role, reducing evaporative losses to the atmosphere and capturing precipitation. In summary, the pine-lichen association is well adapted to dry sites, but unlike prairie grassland communities, pine cannot go dormant during dry intervals.

An indication of how this Subregion will respond to climate warming can be gained from the vegetation gradients within it (Carroll and Bliss, 1982; Natural Regions Committee, 2006). The driest sites are open sand, or sand stabilized with grasses such as sand heather and June grass. On the windward side of dunes, open jack pine-lichen woodlands develop, with discontinuous, desiccated lichen mats and widely scattered pine of short stature. On better sites the jack pine stands becomes denser and taller, with herbs and low shrubs as well as lichen in the understory. In the few moist pockets that occur, pure or mixed stands of aspen and white birch with a more diverse understory are found. As temperatures warm and evapotranspiration increases, a shift to the warm and dry end of this ecological gradient can be expected. This transition could be gradual, but severe and prolonged drought might hasten the process, should it occur.

The Athabasca Plain already experiences a high rate of fire and is adapted to it. It is in fact the only Subregion that has been completely burned since 1950. Jack pine can produce cones in a little as ten years, so even if the rate of fire increases in the future, it is unlikely to cause widespread regeneration failure. In any case, the only successional pathway that is viable in this Subregion, given the sandy soils, is pine regenerating back to pine. It can be concluded that the interplay between climate change, fire, and succession will not be as significant here as it is in many other Subregions.

The potential effects of mountain pine beetle would be similar to those described in the section on xeric sites within the Central Mixedwood (Section 4.3.4).

Canadian Shield

The Canadian Shield is characterized by extensive outcrops of Precambrian bedrock, representing the westernmost edge of the Canadian Shield. The bedrock outcroppings are composed of granite and account for approximately 60% of the total area (Natural Regions Committee, 2006). These outcrops have remained unvegetated since the last glaciation through a combination of 1) granite's high resistance to weathering, 2) low precipitation, and 3) a high rate of fire. Coarse gravelly and sandy soils occur between the bedrock outcrops and support communities dominated by jack pine. Greater species diversity is found on moister sites, mainly in bands adjacent to the wetlands and lakes that exist in low-lying areas.

As the climate warms the rate of evapotranspiration will increase, causing water levels within wetland areas to decline. The adjacent mesic communities are expected to contract towards the remaining water. The pine forests will likely follow the same pattern described for the Athabasca Plains — once available moisture levels become too low the stands will begin to regenerate less effectively and open up . The overall effect is an expansion of bedrock-dominated landscapes and a more discontinuous distribution of vascular plant communities.

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Appendix 1. Plant Names

Common Name	Scientific Name
Aspen	*Populus tremuloides*
Black spruce	*Picea mariana*
Bluebunch wheatgrass	*Agropyron spicatum*
Blue grama	*Bouteloua gracilis*
Buffalograss	*Buchloe dactyloides*
Canada thistle	*Cirsium arvense*
Engelman spruce	*Picea engelmannii*
Green needlegrass	*Stipa viridula*
Jack pine	*Pinus banksiana*
June grass	*Koeleria macrantha*
Kentucky bluegrass	*Poa pratensis*
Labrador tea	*Ledum groenlandicum*
Lodgepole pine	*Pinus contorta*
Needle-and-thread	*Stipa comata*
Northern wheatgrass	*Agropyron dasystachyum*
Plains bluegrass	*Poa arida*
Plains reedgrass	*Calamagrostis montanensis*
Sandberg's bluegrass	*Poa secunda*
Sand heather	*Hudsonia tomentosa*
Sedges	*Carex spp.*
Smooth brome grass	*Bromus inermis*
Subalpine fir	*Abies bifolia*
Timothy	*Phleum Pratense*
Western porcupine grass	*Stipa curtiseta*
Western wheatgrass	*Agropyron smithii*
White birch	*Betula papyrifera*
White spruce	*Picea glauca*

Appendix 2. Methodology

The bioclimatic envelope modeling involved a two-step process. First, I constructed a statistical model that quantified the relationship between Subregion type, as a categorical variable, and a suite of climate variables for the 1961-1990 reference period. I then used this model to predict Subregion type using projected climate from future periods. I assessed model fit on the basis of the overall rate of misclassification and the spatial distribution of the misclassified cells. Three different envelope models were constructed for three different subsets of Subregions (see below). All statistical modeling was performed in the R statistical package.[1]

Subregion polygons came from the 2005 version of the Natural Regions and Subregions of Alberta map, downloaded from the Alberta Tourisms Parks and Recreation web site.[2] Historical climate data for the province were obtained from the ClimateWNA model, using a cell size of 1 km^2 (Wang et al., 2012). ClimateWNA provides downscaled climate data for the 1961-1990 reference period, derived from weather station data interpolated using the PRISM and ANUSPLIN models.

ClimateWNA also provides downscaled climate projections for the suite of GCMs in the Coupled Model Intercomparison Project of the Intergovernmental Panel on Climate Change Fourth Assessment (Meehl et al., 2007; Table A2.1). The spatial resolution of the GCMs is coarse, typically 1.5-5 degrees. Downscaling with ClimateWNA makes it possible to compare the future climate and historical reference climate at the same high resolution (1 km^2 in my case). For most GCMs, projections are available for the A2, A1B, and B1 emissions scenarios (see Box 1). For the bioclimatic envelope modeling I focused on five GCM-scenario combinations, selected to represent the full range of potential climate outcomes: HADCM3-B1 (Cool), ECHAM5-A2 (Median), HADGEM-A2 (Hot), GFDL-CM2.1-A2 (Dry), and CGCM3-A2 (Wet). The older vintage and low-ranked GISS model was

Box 1. Emission Scenarios

The A1 scenario 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. The A2 scenario describes a very heterogeneous world with continuously increasing global population. The underlying theme is self-reliance, instead of collaboration. The B1 scenario describes a convergent world with a global population that peaks in midcentury 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.

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[1] Available at: http://www.r-project.org/

[2] Available at: http://www.albertaparks.ca/albertaparksca/library/downloadable-data-sets.aspx

Table A2.1. Overview of the GCMs used in the study.

Model	**Country**	**Originating Group**
BCM2	Norway	Bjerknes Centre for Climate Research
CCSM3	USA	National Center for Atmospheric Research
CGCM3	Canada	Canadian Centre for Climate Modelling & Analysis
CGCM3-T63	Canada	Canadian Centre for Climate Modelling & Analysis
CNRM-CM3	France	Centre National de Recherches Météorologiques
ECHAM5	Germany	Max Planck Institute for Meteorology
ECHO	Germany / Korea	Meteorological Institute of the University of Bonn
GFDL-CM2.0	USA	NOAA / Geophysical Fluid Dynamics Laboratory
GFDL-CM2.1	USA	NOAA / Geophysical Fluid Dynamics Laboratory
HADCM3	UK	Hadley Centre for Climate Prediction and Research
HADGEM	UK	Hadley Centre for Climate Prediction and Research
IAP	China	LASG / Institute of Atmospheric Physics
INGV	Italy	Instituto Nazionale di Geofisica e Vulcanologia
INM-CM3	Russia	Institute for Numerical Mathematics
IPSL-CM4	France	Institut Pierre Simon Laplace
MIROC3.2 HR	Japan	Center for Climate System Research
MIROC3.2 LR	Japan	Center for Climate System Research
MK3.0	Australia	CSIRO Atmospheric Research
MK3.5	Australia	CSIRO Atmospheric Research
MRI-CGCM2	Japan	Meteorological Research Institute
PCM1	USA	National Center for Atmospheric Research

not included in any of the analyses or data summaries.

I calculated the CMI for each cell in the climate grid using the Penman-Monteith equation, as described by Hogg (1997). The required data for this calculation included monthly temperature and precipitation, from ClimateWNA, as well as a digital elevation model. The other climate variables used in the bioclimatic envelope model came directly from ClimateWNA. To minimize computing time, I used a random sample of 10,000 1 km^2 cells from each Subregion for constructing the statistical models. For Subregions less than 10,000 km^2, all available cells were used.

I used two different approaches for developing the statistical models. For the Grassland to Boreal Model and the Boreal Highlands Model I used an ordinal regression approach (Bender and Benner, 2000; Guisan and Harrell, 2000). Ordinal regression models are specialized cases of the general linear model. They are applicable in cases where the dependent variable is categorical but can be ordered or ranked, though the real distance between categories is unknown. The Subregions in the Grassland to Boreal Model comprise an ordered set of ecosystems arrayed along a gradient of CMI values (Table A2.2). The Subregions in the Boreal Highlands represent an ordered set of ecosystems arrayed along an elevation gradient (Table

Table A2.2. Ordering of dependent variables in the Grassland to Boreal Model.

Subregion	Order
Dry Mixedgrass	1
N. Fescue	2
Mixedgrass	2
Central Parkland	3
Dry Mixedwood	4
Central Mixedwood	5

Table A2.3. Ordering of dependent variables in the Boreal Highlands Model.

Subregion	Order
Central Mixedwood	1
Dry Mixedwood	1
Northern Mixedwood	1
Lower B. Highlands	2
Upper B. Highlands	3
Boreal Subarctic	4

A2.3). The ordinal regression models were constructed in R using the *RMS* package. A summary for each model is provided in Tables A2.4 and A2.5.

The ordinal regression approach was not appropriate for the Foothills Model because the Subregions involved are subject to multiple climatic gradients. Instead, I used *Random Forests*, as implemented in R, which makes no assumptions about the structure of the dependent variable or its relationship with the independent variables. *Random Forests* uses a computer learning approach to construct a classification tree that minimizes the overall rate of misclassification (Breiman, 2001). A summary for this model is provided in Table A2.6 and Fig. A2.1.

Table A2.4. Output summary for the Grassland to Boreal Model.

n = 60,000
Model: lrm(formula = NSR ~ (CMI + MAT + TD)^2 + MAP + GDD5, data = nsr.samp)
Model likelihood ratio test: p <0.0001
$r^2 = 0.95$

Variable	Coefficient	S.E.	p
y>=2	-25.7036	0.8314	<0.0001
y>=3	-34.2469	0.8406	<0.0001
y>=4	-40.1881	0.8455	<0.0001
y>=5	-46.339	0.8587	<0.0001
CMI	-0.9031	0.0371	<0.0001
MAT	2.9495	0.2047	<0.0001
TD	1.9715	0.0462	<0.0001
MAP	0.0412	0.0014	<0.0001
GDD5	-0.0325	0.0009	<0.0001
CMI * MAT	-0.0502	0.0022	<0.0001
CMI * TD	0.042	0.001	<0.0001
MAT * TD	-0.0252	0.0034	<0.0001

Table A2.5. Output summary for the Boreal Highlands Model.

n = 60,000
Model: lrm(formula = NSR ~ (CMI + MAT + TD)^2 + MAP + GDD5, data = nsr.samp)
Model likelihood ratio test: p <0.0001
$r^2 = 0.89$

Variable	Coefficient	S.E.	p
y>=2	45.587	0.8374	<0.0001
y>=3	41.8629	0.8296	<0.0001
y>=4	37.7087	0.8271	<0.0001
CMI	-1.1759	0.0482	<0.0001
MAT	-9.3214	0.2236	<0.0001
TD	-0.858	0.035	<0.0001
MAP	0.0388	0.0011	<0.0001
GDD5	-0.0273	0.0009	<0.0001
CMI * MAT	-0.078	0.0033	<0.0001
CMI * TD	0.021	0.0014	<0.0001
MAT * TD	0.2083	0.0042	<0.0001

Table A2.6. Output summary for the Foothills Model.

Model: randomForest(formula = NSR ~ CMI + MAT + MAP + MWMT + MCMT + TD + GDD5 + slope + Eref + AHM + SHM + NFFD + MSP + PAS + EMT + bFFP + FFP + eFFP, data = nsr.samp, mtry = 3, ntree = 500, proximity = FALSE, importance = TRUE)

OOB estimate of error rate: 5.17%

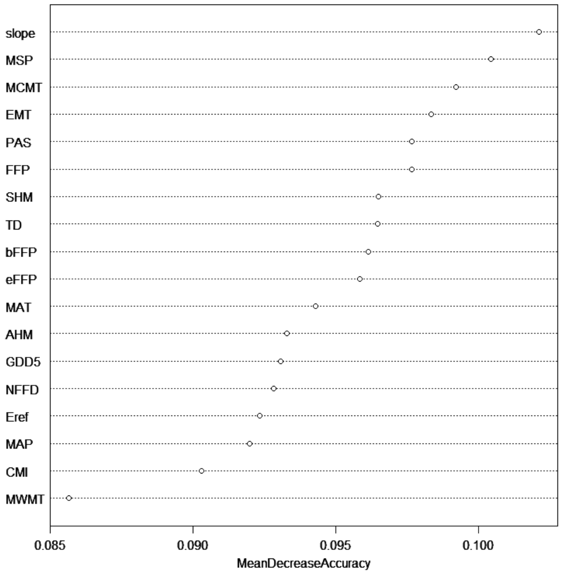
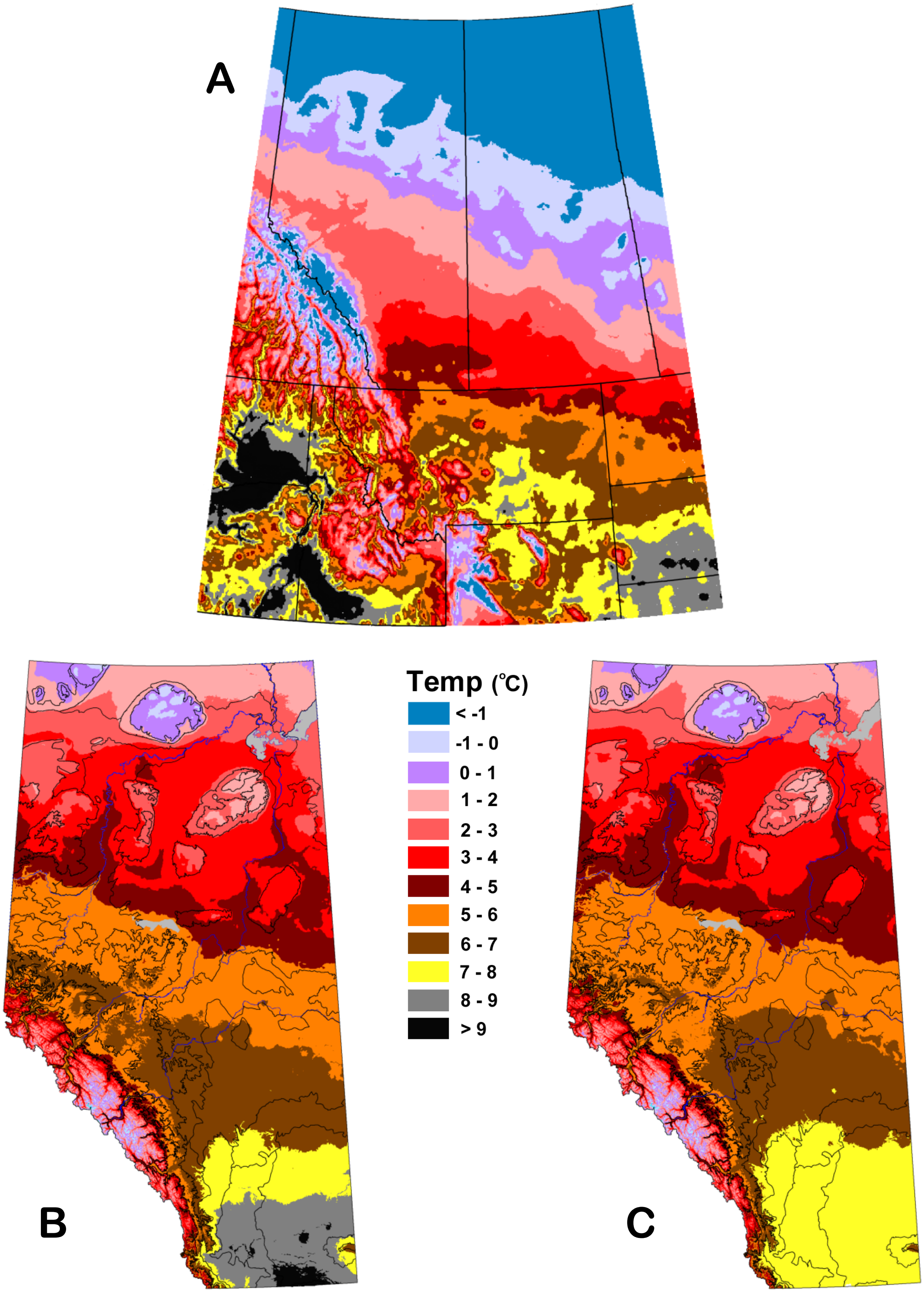
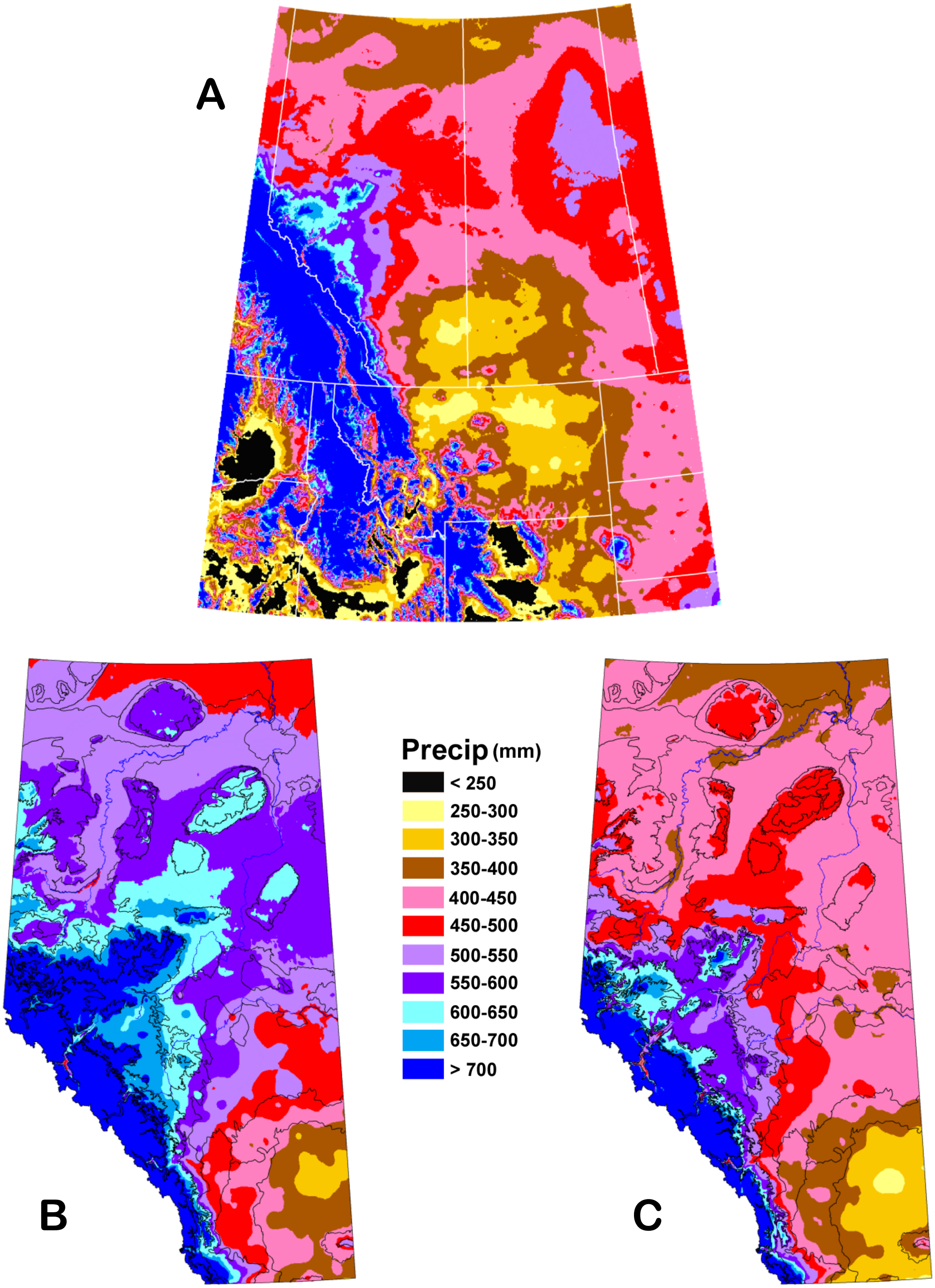


Fig A2.1 Variable importance plot for the Foothills Model.

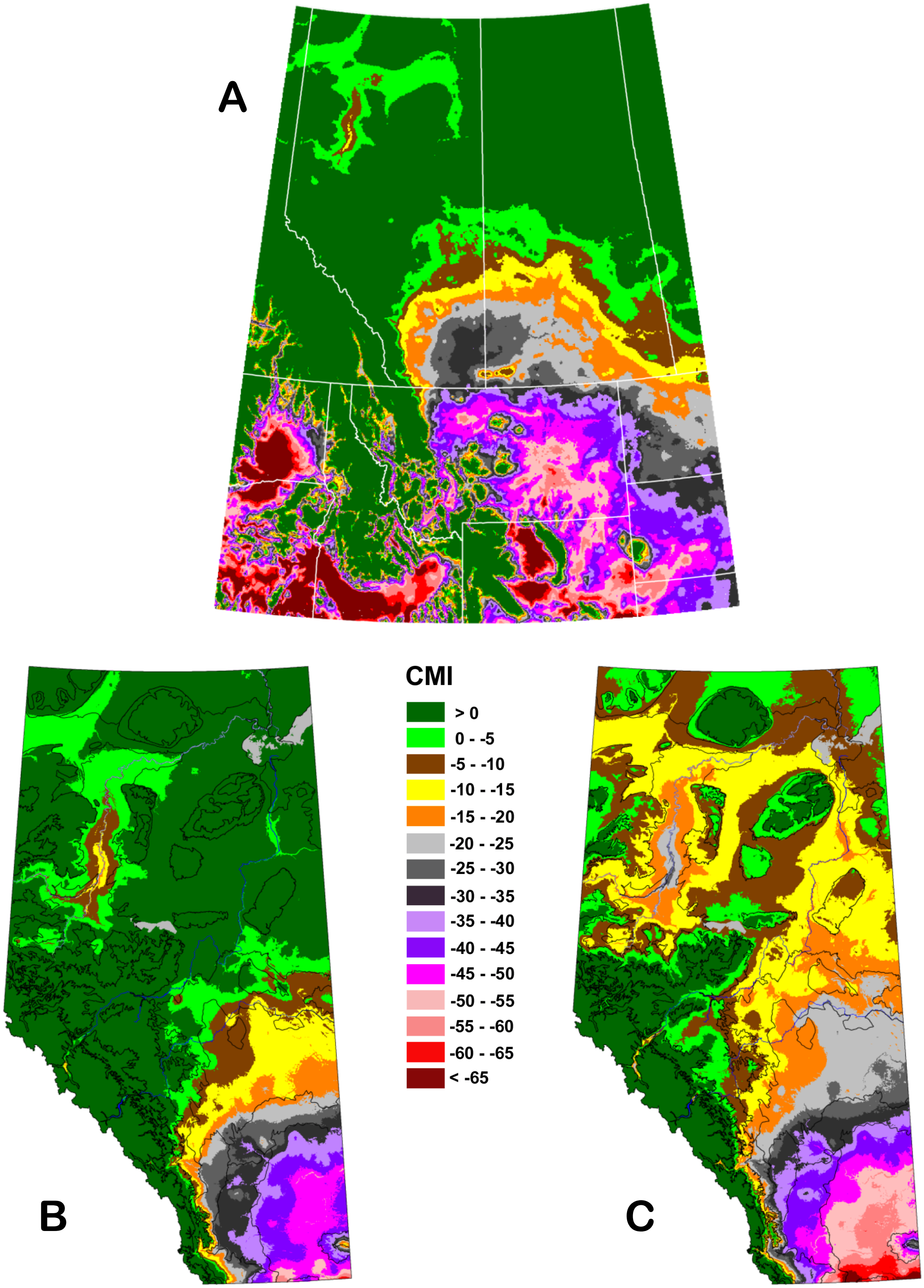
Appendix 3. Supplemental Maps



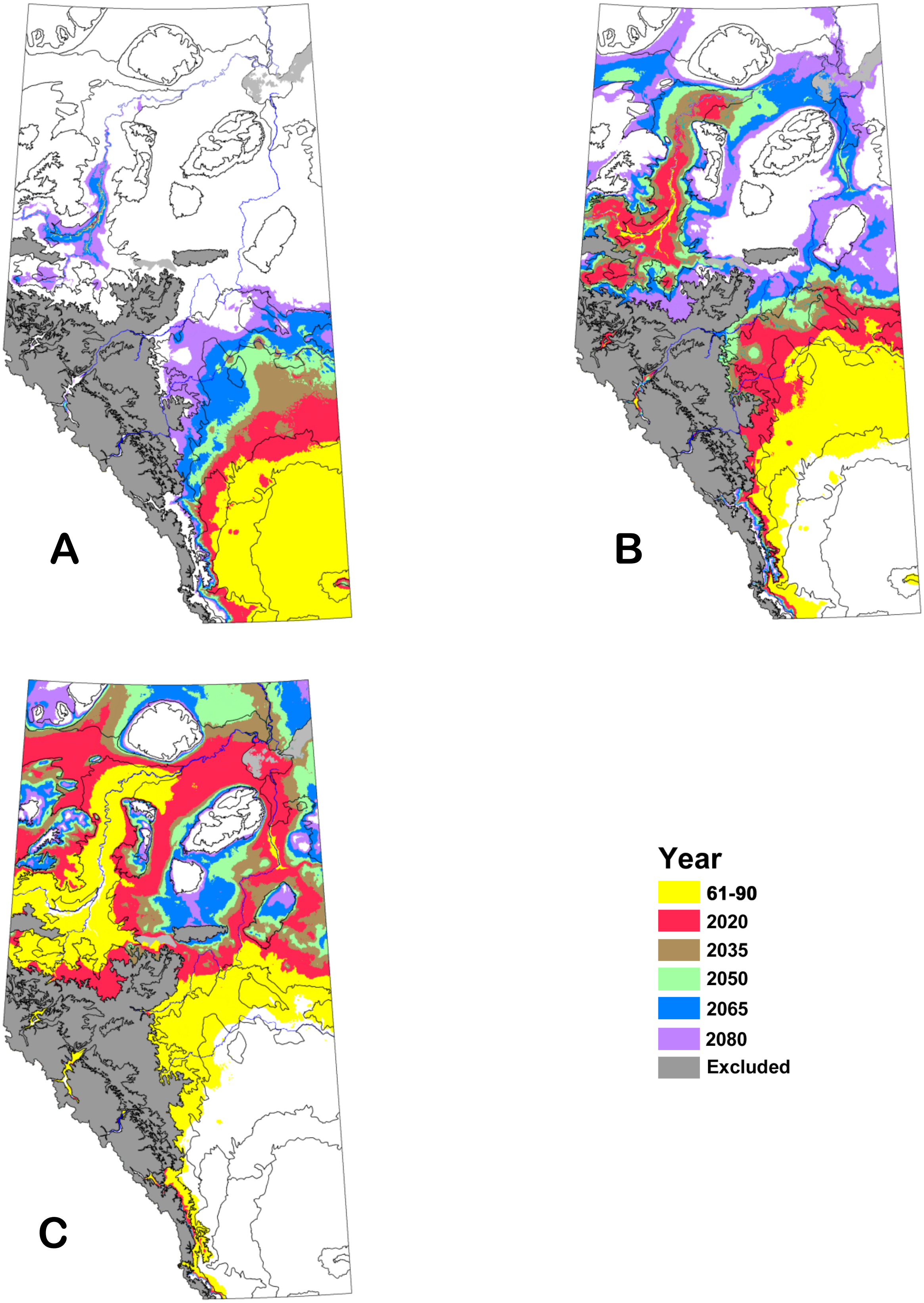
MAT in 1961-1990 (Panel A) and in the 2080s: Panel B = Wet model; Panel C = Dry model.



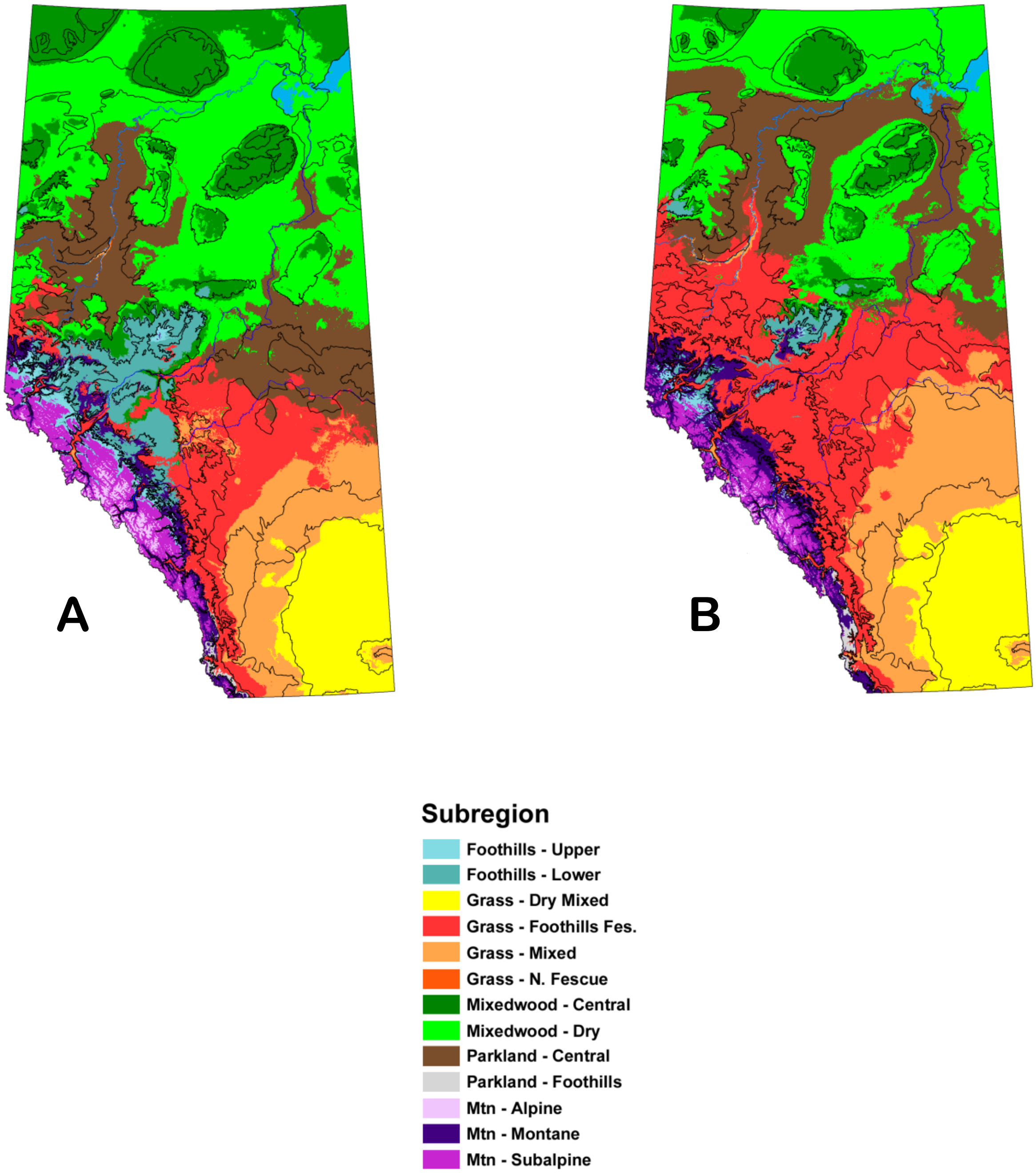
MAP in 1961-1990 (Panel A) and in the 2080s: Panel B = Wet model; Panel C = Dry model.



Mean CMI in 1961-1990 (Panel A) and in the 2080s: Panel B = Wet model; Panel C = Dry model.



Temporal change in the climate envelopes for the Wet model: Panel A= Grassland; Panel B = Parkland; Panel C = Deciduous Forest.



Foothills Bioclimatic Envelope Model for the Wet model: Panel A=2050s; Panel B = 2080s.