

Sharing Canada's Last Frontier

Creating a Conservation Network to Ensure Continued
Wildlife Connectivity in the Mackenzie River Basin

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As authors of this Group Project report, we archive this report on the Bren School's website such that the results of our research are available for all to read. Our signatures on the document signify our joint responsibility to fulfill the archiving standards set by the Bren School of Environmental Science & Management.

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The Bren School of Environmental Science & Management produces professionals with unrivaled training in environmental science and management who will devote their unique skills to the diagnosis, assessment, mitigation, prevention, and remedy of the environmental problems of today and the future. A guiding principal of the School is that the analysis of environmental problems requires quantitative training in more than one discipline and an awareness of the physical, biological, social, political, and economic consequences that arise from scientific or technological decisions.

The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a year-long activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Partner Organization



The Yellowstone to Yukon Conservation Initiative (Y2Y) is a joint Canada-U.S. not-for-profit organization, whose primary goal is to protect and connect habitat from Yellowstone National Park in the U.S. to Yukon in Canada. Y2Y takes pride in being the only organization dedicated to securing the long-term ecological health of this entire region. Their approach to conservation is both scientific and collaborative, focusing on local issues that may affect the region and working with over 300 partners—including scientists, conservation groups, landowners, businesses, government agencies and First Nations communities. Y2Y believes that without a unified vision for the landscape, local conservation efforts may be too isolated and therefore less effective in maintaining the ecological integrity of the area. Y2Y wants to ensure that conservation efforts in the area maintain large-scale objectives, and will thus become continentally significant — paraphrased from Y2Y website “About US” webpage, <https://y2y.net/about-us> (“About Us,” n.d.).

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Acronyms and Abbreviations

ABMI—Alberta Biodiversity Monitoring Institute

AER—Alberta Energy Regulator

AIC—Akaike information criterion

AOGCM—Atmosphere-Ocean Global Circulation Model

AUC—Area under the curve

BLM—Boundary length modifier

GDP—Gross domestic product

GPS—Global Positioning System

IPCC—Intergovernmental Panel on Climate Change

IUCN—International Union for the Conservation of Nature

MRB—Mackenzie River Basin

NEB—National Energy Board

NFI—National Forest Inventory

NGX—Natural Gas Exchange

NWT—Northwest Territories

PIM—Precious and industrial metals

PU—Planning unit

RCP—Relative concentration pathway

SDM—Species distribution model

SPF—Species penalty factor

Y2Y—Yellowstone to Yukon Conservation Initiative

Abstract

Canada's Mackenzie River Basin (MRB) covers over one-fifth of Canada's landmass and is considered one of the most intact and resource-rich natural areas remaining in North America. Three natural resources in the MRB—timber, hydrocarbons, and minerals—present a valuable economic opportunity for resource extraction industries in Canada. Therefore, any conservation plan developed to maintain this region's ecological integrity must also account for these economic interests. To facilitate conservation planning and identify high priority biodiversity conservation areas in the MRB, caribou (*Rangifer tarandus*) were used as umbrella species due to their large home ranges and sensitivity to human disturbance. Using the species distribution modelling software, MaxEnt, we mapped relative rate of occurrence for three caribou types—boreal woodland caribou, mountain woodland caribou, and barren-ground caribou—based on historical and future bioclimatic variables projected to 2050. Resource value was assessed for timber, hydrocarbons, and minerals based on their location, volume, and current market prices. We then used the conservation planning software, MARXAN, to design reserves which achieved caribou conservation targets (17%, 50% and 80% of caribou range) while minimizing the total cost of the reserve system. Reserves built under a historical climate and two future emission scenarios were highly similar. Therefore, we conclude that caribou habitat is unlikely to shift dramatically by mid-century. Furthermore, we find that it is more cost effective to conserve 50% or greater of caribou range, as there is a disproportionate increase in ecological value relative to cost at this conservation target. Larger reserves (50% of caribou range or more) substantially increase protection of the eight ecozones in the MRB, and more consistently represent the land cover types and river systems in the region. However, these reserves may inadequately account for biodiversity and watershed health in the southern portions of the MRB. This is not surprising given that the majority of human activity and high value resources lie within Alberta—the southernmost province in our study region.

Executive Summary

Canada's Mackenzie River Basin (MRB) is considered one of the most intact and resource-rich natural areas remaining in North America. At 1.8 million km², the MRB covers over one-fifth of Canada's landmass. This region provides valuable ecological services and resources for a wide variety of species, including humans. Three natural resources in the MRB—timber, hydrocarbons, and minerals—present a valuable economic opportunity for resource extraction industries in Canada. However, harvesting of these resources can cause habitat degradation, fragmentation, and loss. Any conservation plan that aims to preserve the MRB's ecological integrity must balancing the economic and ecological interests of the region.

When faced with conservation planning on such a large scale, the use of an appropriate umbrella species can simplify the difficulty involved in attempting to conserve for and manage every aspect of the landscape. Due to their large home ranges and sensitivity to human disturbance, caribou (*Rangifer tarandus*) were selected as an appropriate umbrella species to facilitate the identification of high priority conservation areas in the MRB. The species distribution modelling software, MaxEnt, was used to map relative rate of occurrence for three caribou types—boreal woodland caribou, mountain woodland caribou, and barren-ground caribou—using historical and future bioclimatic variables projected out to mid-century (2050). Resource value was assessed for timber, hydrocarbons, and minerals based on their location, volume, and current market prices. With these two features of the landscape modeled, the conservation planning tool, MARXAN, was used to design a reserve network which achieves caribou conservation targets (17%, 50% and 80% of caribou range) while minimizing the cost of the reserve system.

The umbrella species concept assumes that a single species can adequately represent the regional biodiversity that exists within its range. To qualitatively determine whether our simulated reserves adequately represent biodiversity and other ecosystem services, we examined each reserve's representation of ecozones, land cover types, major river sub-basins, and major rivers. Economic impacts and reserve feasibility were assessed by examining reserve effect on each territory and province and the three natural resource extraction industries we valued.

The few differences observed between reserves designed under a historical climate and two future emissions scenarios suggest that caribou habitat is unlikely to shift dramatically by mid-century (2050). Furthermore, our findings suggest that it is more cost effective to conserve 50% or greater of caribou range than 17%, as there is a disproportionate increase in ecological value relative to cost at this conservation target. Larger reserves (50% or more of caribou range) substantially increase protection of the eight ecozones and more consistently represent the land cover types and river systems with high ecosystem services. However, these reserves may inadequately account for biodiversity and watershed health in the southern portions of the MRB. This is not surprising given that the majority of human activity and high value resources lie within Alberta—the southernmost province in our study region. However, due to this high value, certain land cover types (eg. deciduous forests),

ecozones (eg. boreal plains), and river sub-basins (eg. the Peace and Athabasca rivers) are consistently under-represented in each reserve created. These consistent shortfalls highlight potential inadequacies of MARXAN and of the umbrella species concept in determining reserves networks.

In an attempt to determine how reserve costs may differ with greater biodiversity representation, we examined the effect of two different conservation target setting methods on reserve design. These two methods allowed more equal representation of caribou range as well as ecozones or major river sub-basins, respectively. We found that when ecozones or river sub-basins were used in conjunction with caribou range to set conservation targets, the southern portions of the MRB were better represented. However, this resulted in reserves that were significantly costlier, even at low conservation targets.

While our results indicate that caribou are generally a good umbrella species for conservation at this large scale, lack of inclusion of the southern region of the MRB highlights pieces of the system that may be underrepresented by such a coarse-scale conservation plan. Efforts to rectify the shortcomings of these reserves are found to substantially increase the cost, which would likely disproportionately impact Alberta. Our results can be used to support and influence the management of the MRB to promote the ecological integrity of the region while balancing the interests of three major natural resource extraction industries.



The Mackenzie River Basin



Chapter 1. The Mackenzie River Basin

Overview

Study Area

The Mackenzie River Basin (MRB) is the largest river basin in northern Canada and covers an area of approximately 1.8 million km². This equates to roughly one-fifth of the total land area of Canada (Government of Canada, n.d.). Its watershed encompasses parts of five Canadian provinces and territories, including Alberta, Saskatchewan, British Columbia, the Northwest Territories (NWT), and Yukon. Based upon the needs of our client the Yellowstone to Yukon Conservation Initiative (Y2Y), a nonprofit conservation organization, our analyses focus on the portions of the basin that lie within the provincial boundaries of Alberta, NWT, and the Yukon (**Figure 1.1**).

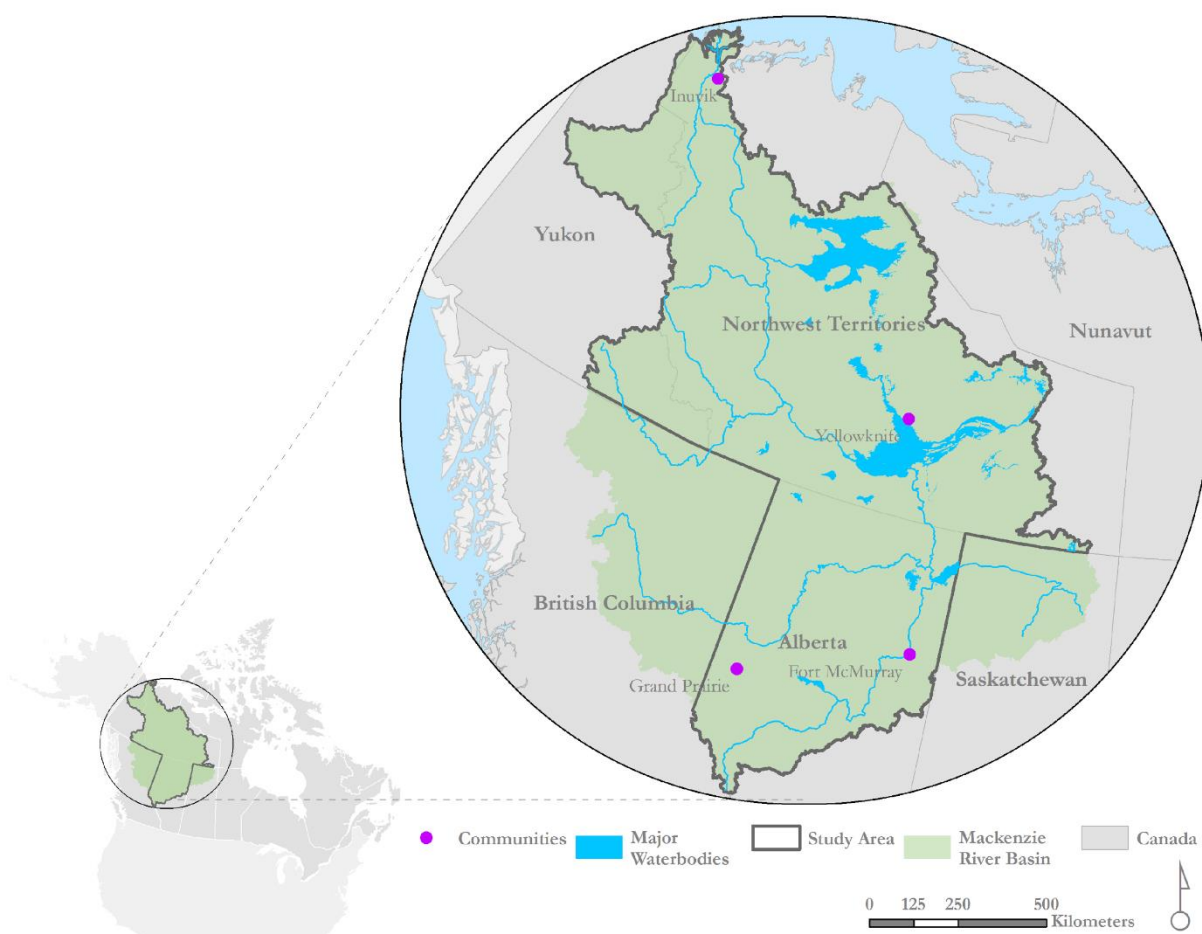


Figure 1.1. Map of the Mackenzie River Basin in Canada. Study Area is outlined in dark grey.

Natural Landscape

At 4,241 km in length, the Mackenzie River system is the largest north-flowing river system in North America, and is second in total size only to the Mississippi-Missouri River system (“Mackenzie River in Canada,” 2016). This river system is composed of six major sub-basins, each containing its own major river or lake (“Mackenzie River Basin Board,” n.d.). These sub-basins include the Athabasca, the Peace, the Liard, the Peel, the Great Slave, and the Mackenzie-Great Bear basins. The Mackenzie River system ultimately flows into the Beaufort Sea and supplies roughly 11% of the freshwater entering the Arctic Ocean (*The Mackenzie River Basin*, 2013).

The MRB is widely considered to be one of the most intact large-scale ecosystems remaining in North America (*The Mackenzie River Basin*, 2013). The MRB encompasses a wide variety of climatic and geographical conditions, in large part due to its size. At a coarse scale, this variability can be characterized by ecozones, which are large landscapes having roughly similar features, climate, and organisms throughout (Bernhardt, n.d.). The National Ecological Framework for Canada has identified 15 broad-scale terrestrial ecozones throughout Canada. Of these 15, there are nine ecozones present in the MRB (**Appendix 1**).

Land cover classification also provides insight into the types of ecosystems that make up the MRB. Most notably, it is estimated that roughly 63% (1,137,000 km²) of the MRB is covered in boreal forest, with around 93% of this being virgin. Boreal forests cover nearly 2.7 million km² of Canada, meaning that around 40% of the country’s boreal forests lie within the MRB (Natural Resources Canada, 2016). In addition, valuable wetland ecosystems make up another 18% (324,900 km²) of the MRB, and an estimated three-quarters of the region is underlain by permafrost—partially or completely frozen ground (*The Mackenzie River Basin*, 2013).

The ecosystems found throughout the MRB provide habitat for an array of sensitive wildlife including fish, migratory birds, and relict populations of large mammals. It is estimated that there are roughly 53 species of fish in the MRB (*The Mackenzie River Basin*, 2013), including lake whitefish, a highly valuable food source to First Nations people in the area (*The Mackenzie River Basin*, 2013). Over 215 migratory bird species have been identified in the Mackenzie Delta portion of the MRB, including many endangered species such as the whooping crane and peregrine falcon (*The Mackenzie River Basin*, 2013). Each year, millions of these migratory birds are estimated to pass through the MRB, using the Mackenzie Delta and the Peace-Athabasca Delta as valuable breeding and resting habitat (“IBA Site Listing,” n.d.). Furthermore, large iconic mammals including caribou, moose, grizzly bear, and wolves can be found throughout the region.

Human Landscape

Although the basin is geographically large, the human population is relatively small. In 2013, only about 400,000 people lived within the MRB, making up just over 1% of Canada’s population (*The Mackenzie River Basin*, 2013). This population tends to be centered in the southern portions of the MRB, with over 90% of these people living in the Peace and Athabasca river drainage areas, primarily

in Alberta (*The Mackenzie River Basin*, 2013). The northern parts of the MRB are sparsely populated, and most residents belong to several First Nation communities, including the Dehcho, Sahtu and Tlicho nations.

People within the MRB rely on its rich natural resources either for subsistence or as a source of economic livelihood. Harvesting non-renewable natural resources—such as minerals, hydrocarbons, and timber—is the most valuable economic activity that occurs within the MRB. In 2015, Canada's natural resource sector accounted for 17% of nominal gross domestic product (GDP) and accounted for roughly 1.77 million jobs in Canada ("Key Facts", 2016). In general, valuable natural resource areas include timber products in the Peace River headwaters, natural gas and oil in Western Alberta, bitumen production in Eastern Alberta, and precious metals and diamonds throughout the NWT and Yukon.

The timber industry, which relies on Canada's nearly 400 million hectares of forest, contributed CA\$21.3 billion, or 1.4% of nominal GDP to the national economy in 2015 and employs roughly 40,000 Canadians annually (Natural Resources Canada, 2016).

All of the provinces and territories in the MRB have oil and natural gas reserves. In 2015, the oil and natural gas industry accounted for 7.3% of nominal GDP for Canada ("Key Facts", 2016). Canada has the third largest oil reserves in the world, totaling 171 billion barrels. The Alberta oil sands produce 77% of the national supply and have a total reserve of 165 billion barrels (Canadian Association of Petroleum Producers, 2016). Currently, Alberta produces roughly 2.3 million barrels of oil per day, with the majority of this production taking place within the MRB. While the sustained future of this extraction depends on future oil prices and infrastructure development, conservative economic models predict that peak production will continue to increase to 5.7 million barrels per day by 2036 (National Energy Board, 2016). Additionally, demand for natural gas is expected to double by 2035 due to technological advances (Canadian Association of Petroleum Producers, 2016).

Canada is also politically attractive for mineral investment due to its stable economy and generous tax regimes for developers. In 2015, the mineral and metals mining industry employed 373,000 people, and generated US\$32 Trillion, or roughly 3.4% of GDP (Natural Resources Canada, 2016). Although mining operations are limited within the MRB, significant reserves of gold, diamonds and tungsten are scattered across Saskatchewan, the NWT, Yukon, Alberta, and British Columbia.

Global Importance

The continued ecological health and function of the MRB is important for the people of Canada and for global climate systems. Most notably, the MRB plays a major role in the global carbon cycle, as its vast amounts of forests, wetlands, and peatlands are estimated to store enormous amounts of carbon. Although no specific estimates of carbon storage for the MRB have been released, recent research suggests boreal forests themselves account for half of all forest carbon storage in the world (Schindler & Lee, 2010). The boreal forest of Canada alone is one of the largest remaining carbon stores on the planet (Hebblewhite, 2017). Additionally, the forests and peatlands of the boreal forest

often overlay significant permafrost deposits that trap significant amounts of carbon dioxide and methane. Globally, the permafrost region contains twice as much carbon as there is currently in the atmosphere (Tamocai et al., 2009; Zimov, Schur & Chapin, 2006). Boreal freshwater lakes also store a significant amount of terrestrial carbon (Dillon & Molot, 1996). When carbon reserves from forests, peatlands, permafrost, and lakes are all taken into account, studies suggest that global boreal forests can store up to four times more carbon than tropical forests (*The Mackenzie River Basin*, 2013).

Threats to the Mackenzie River Basin

While the majority of the MRB remains relatively untouched, we have chosen to focus this project on the two primary threats to the region—large-scale natural resource extraction and climate change. While we recognize that other threats to the ecological health and connectivity of the MRB do exist (for example, hydropower and agricultural expansion), these exist outside of the scope of this analysis and will not be included.

Natural Resource Extraction

Natural resource extraction and energy development are some of the leading threats to biodiversity and ecosystem services worldwide (Boyce, 2012; Butt et al., 2013; Allred et al., 2015). Within the MRB, timber harvest can cause forest conversion and alter age class, structure, and landscape configuration of the boreal forest (Venier et al., 2014). Commercial timber harvest, even when following guidelines for sustainable harvest, can change landscape configuration by selectively harvesting higher value trees, compacting and degrading soil quality and function (Voldseth, Palik, & Eliof, 2011), and lowering coarse woody debris volume (Brassard & Chen, 2008). These structural changes in the boreal forest affect bird, fungal, amphibian, and mammal diversity (Venier et al., 2014).

Another poignant example of the negative effects of resource extraction within the MRB comes from the continued development of the Athabasca oil sands. The oil sands area of Alberta lies under nearly 140,000 km² of boreal forest (Pembina Institute, 2016). It is estimated that current plans for the oil sands expansion could destroy roughly 30,000 hectares of peatland, release millions of tons of stored carbon, and drastically reduce carbon sequestration potential (Rooney, Bayley & Schindler, 2012). Bitumen extraction within the oil sands region can negatively impact water quality in the MRB through the accumulation, and potential leaking, of mature fine tailings. Mature fine tailings are contaminated fluid by-products of oil sands operations that are stored in vast holding lakes across Alberta. These most often contain cyanide, phenols, arsenic, cadmium, chromium, copper, lead, zinc, bitumen, and/or naphthenic acids (“Syncrude to Pay,” 2010). The Natural Resource Defense Council estimates tailing lakes could kill between 8,000 and 100,000 migrating birds annually (Wells, Casey-Lefkowitz, Chavarria, & Dyer, 2008). Additionally, studies indicate 13 priority pollutants under the United States Clean Water Act have been released via air and water to the Athabasca River and its watershed (Kelly et al., 2010). Finally, full life cycle analysis of the oil sands (production to combustion) estimates that emissions from this resource could be eight to 37% greater than emissions from conventionally harvested oil in the rest of Canada and the United States (*Setting the Record Straight*, 2010), and 23% higher than oil harvested and refined in Europe (Grant, Huot, Lemphers, Dyer & Dow, 2013).

While the primary effect of resource extraction is immediate species displacement, another important effect is how these activities can fragment habitat. For example, edge effects influence air temperature, humidity, soil temperature, and light intensity which directly impact species composition, ecosystem structure, and essential ecosystem processes (Murcia, 1995). For example, when old growth boreal forest is harvested for timber and the creation of energy infrastructure, habitat fragmentation increases. This benefits certain species such as moose (*Alces alces*) and white tailed deer (*Odocoileus virginianus*), but negatively affects species that require large, contiguous areas including grizzly bear and caribou.

Climate Change

Global climate models project a 1-4°C global surface air temperature increase in the 21st century (IPCC, 2013). Even greater increases are expected in Arctic regions, with average temperature increases around 5-7°C (Kattsov et al., 2005). Air temperatures in the MRB have warmed by over 1.7°C over the past century (Cohen, 1997), more than twice the global average temperature increase over the same period (IPCC, 2013). Such drastic warming throughout the MRB is likely to have dramatic effects on the ecosystem processes of the region and the well-being of those that live there.

The most dramatic impact of an increase in air temperatures is on the long-term stability of the permafrost. Up to 75% of the MRB lies within permafrost zones (“Mackenzie River Basin Board.” n.d.). With an increased melting rate of permafrost, a great deal of infrastructure in the MRB, particularly in the NWT, is threatened (Nelson, Anisimov & Shiklomanov, 2001; Government of NWT, 2008). The melting permafrost will release great quantities of carbon dioxide and methane, which will in turn increase the rate of warming in the region (Cohen, 1992).

In recent decades, it has been shown that Canada has generally become wetter, with an increase in annual precipitation of about 16% between 1950 and 2010 (Mekis & Vincent, 2011; Price et al. 2013). More specifically, at most weather stations throughout Canada, total precipitation has increased through spring and fall, and generally declined in winter (Mekis et al., 2011). Furthermore, climate projections out to 2100 indicate that the dominant form of precipitation in the Arctic region will transition from snow to rain. A change in Arctic precipitation may have severe wide-ranging consequences to hydrology and therefore ecosystem dynamics (Bintanja & Andry, 2017).

Climate change is projected to increase the frequency and severity of fires in the boreal forests (Stocks et al., 1998; Duffy, Walsh, Graham, Mann, & Rupp, 2005; Soja et al. 2007). This will result in skewing the age distribution towards younger forest stands, subsequently resulting in a decrease in the carbon storage of northern forests (Kurz & Apps, 1995) and decreased availability of old growth forests habitat (Esseen, Renhorn, & Pettersson 1996; Schneider et al. 2012). Furthermore, since wildfires maintain the age structure, species composition, and floristic diversity of the boreal forest (Heinselman, 1981), any alteration to the natural fire regime has the potential to drastically alter these attributes (Johnstone & Chapin, 2006; Mansuy, Gauthier, Robitaille, & Bergeron, 2012). For the MRB,

this could translate into species range reduction, habitat degradation, increased competition from species migrating further northward, and the arrival of new diseases and parasites (Cohen, 1992; Lemmen, Warren, Lacroix & Bush, 2008).

Current Conservation Planning and Practices in Canada and the MRB

The importance of land protection, according to the International Union for the Conservation of Nature's (IUCN) strictest definition (categories I and II), has been highlighted in the last two centuries by the increased rate of development throughout North America. However, conservation planning practice has generally focused on protecting unique or highly biodiverse regions (Margules & Pressey, 2000; Locke, 2013). In recent decades, systematic conservation planning has gained popularity as a method by which to achieve more representative conservation of general biodiversity and land features, while accounting for the feasibility of larger land reserve implementation and maintenance (Margules & Pressey, 2000).

In an effort to account for the importance of land protection, Canada has a number of national goals which aim to protect Canada's natural heritage for the benefit of future generations. In 2014, Canada launched its National Conservation Plan, which provides a framework for the advancement of conservation efforts across the country. The plan will invest \$252 million over five years to advance land conservation, restoration, and environmental stewardship (Environment and Climate Change Canada, 2014). The National Conservation Plan also complements Canada's proposed 2020 Biodiversity Goals and Targets for Canada which aims to protect at least 17% of terrestrial and inland waters by 2020. As of 2015, 10.6% (1.05 million km²) of Canada's terrestrial area and 0.9% (51 thousand km²) of its marine territory are recognized as protected. Within the MRB, roughly 9.5% of its terrestrial area is protected to some extent (IUCN, 2016).

Problem Statement

While the Mackenzie River Basin remains relatively untouched from many types of human disturbance, the future of the MRB lies in management strategies which understand its vulnerability and balance both ecological and economic needs. The five provincial and territorial jurisdictions which manage the MRB have the opportunity to conserve the health and function of the ecosystems that exist there, while continuing to develop its valuable economic resources. Furthermore, these partnerships can increase the resilience of ecosystems and human communities under projected future climate change. Faced with these two competing land uses—conservation of natural resources to maintain ecological integrity and natural resource extraction for the benefit of continued economic development—how can managers ensure that the MRB will continue to provide both in a sustainable way?

Our Solution

When developing a conservation strategy for a large area such as the MRB, selecting conservation priorities can be challenging. Recent advances in conservation science have illuminated the importance of ecological connectivity in maintaining ecosystem health, rendering the traditional conservation strategy of protecting isolated wilderness areas within developed landscapes unsatisfactory (Locke, 2014). One reason this strategy is considered unsatisfactory is that the movement and dispersal abilities of animals are severely limited, leading to greater inbreeding and loss of genetic diversity within isolated fragments (Frankham, Briscoe, & Ballou, 2002). Maintaining or increasing ecological connectivity is also a frequently proposed strategy to help reduce the negative effects of climate change on biological diversity (Heller & Zavaleta, 2009).

One way to develop a conservation strategy which maintains ecological connectivity is through single-species conservation of migratory or wide-ranging species. However, the success of such a strategy lies in the ability of the chosen species to protect all other co-occurring species. The umbrella species concept suggests that conserving certain wide-ranging species can provide a “protective umbrella” for other species and maintain co-occurring species (Roberge & Angelstam 2004). Species which make good candidates as umbrella species are thought to have certain characteristics, including large-body size, large home ranges, high trophic level, high metabolic requirements, patchy distributions, and dependence upon successional, rare, or unpredictable habitats and resources (McNab, 1963; Wilcox, 1984).

Caribou as an Umbrella Species

Caribou have many characteristics that make them well-suited to act as umbrella species in the MRB. These characteristics include large annual home ranges, sensitivity to human disturbance, and dependence upon old-growth boreal forest habitat (Bichet, Dupuch, Hebert, Le Borgne & Fortin, 2016). Caribou annual home ranges exceed the home ranges of most other boreal species (Swihart, Slade & Bergstrom, 1988). The annual home range of certain caribou populations typically reach 1,000 km² (Faille et al., 2010) and some can reach 4,000 km² (Brown, Mallory & Rettie, 2011). Other herbivores of similar body mass generally have home ranges closer to ~45–200 km² (Swihart et al., 1988). By having such large home ranges, caribou can maintain low population densities and thereby decrease predation risks, increase winter foraging success, and easily migrate between winter and summer ranges (Brown et al., 2011; Fryxel, Greever & Sinclair, 1988). Therefore, using boreal caribou as an umbrella species could conserve habitat over disproportionately large areas. Caribou are also highly sensitive to habitat change. General guidelines for caribou habitat management require a level of landscape disturbance not exceeding 35%, and management practices that are more effective at preserving boreal caribou populations have proven suitable for maintaining the broader animal communities in the boreal forest (Bichet et al., 2016).

Finally, the species represents a valuable cultural icon to the people of Canada, particularly to the First Nation communities who rely heavily on caribou as a traditional food item (NWT DNR, 2011)

Therefore, caribou's charismatic and cultural status can be used as a tool to acquire financial support and raise conservation awareness (Sergio, Newton, Marchesi & Pedrini, 2006). The conjunction of their status as an iconic species of Canada, their ecological reliance on large tracts of untouched wilderness, and their sensitivity to change make caribou particularly suited as a focal species of conservation in the MRB.

Caribou in the Mackenzie River Basin

Caribou once existed throughout most of Canada and even into parts of the northern lower forty-eight states of the United States (**Figure 1.2**). However, their numbers have been reduced throughout much of their historical range along the southern edge of the boreal forest due to a combination of human land use change, industrial and agricultural development, and overhunting (IUCN Red List). In Canada, it is estimated that caribou have declined in abundance over three generations by an average of 52% to an estimated 1.3 million individuals in 2015 (IUCN Red List).



Figure 1.2. Current caribou distribution throughout North America (brown), and historical southern extent (red line).

Caribou in the MRB have been classified into two subspecies—woodland caribou (*Rangifer tarandus caribou*) and barren-grounds caribou (*Rangifer tarandus groenlandicus*)—according to morphology and reproductive segregation (Environment Canada, 2012). While the two subspecies can interbreed, they remain isolated due to habitat preferences during the fall mating season (COSEWIC, 2011). Despite their differences, all caribou rely on similar resources. All caribou feed on arboreal and terrestrial lichen, particularly in the winter when other forage sources are limited (Dunford, McLoughlin, Dalerum & Boutin, 2006; Environment Canada, 2012; COSEWIC, 2014). Therefore, caribou seek out areas with lower snow accumulation in the winter to allow them to more easily access terrestrial lichen sources.

Barren-grounds caribou are migratory and highly gregarious, while woodland caribou are sedentary and solitary (COSEWIC, 2011). The barren-grounds herds migrate from their wintering ground in the boreal forest to their secluded spring calving grounds in the tundra (Courtois & Ouellette, 2007). Overall, the barren-grounds herds are less susceptible to predation pressures than the southern woodland populations due to their herding behavior and reduced wolf numbers in the tundra (Courtois et al., 2007; Muller-Wille, 1978). Despite this, their numbers have plummeted in recent years, likely as a result of unsustainable hunting pressure (NWT DNR, 2011). In 2013, it was estimated that there were around 729,000 individuals; however, overall decline was between 45-50% from peak numbers in the mid-1990s. Decline was between 70-98% for six of these subpopulations (IUCN Red List, n.d.).

Woodland caribou, which inhabit the boreal forests across all of Canada, are further divided into two ecotypes—boreal and mountain—within the MRB (**Figure 1.3**). This delineation is based solely on habitat and ecological preference differences within subspecies, which have evolved due to population isolation. Herds of both ecotypes spend the majority of their time in old-growth boreal forest dominated by jack pine, black spruce or lodgepole pine as well as fens, peat bogs and muskegs (Edmonds, 1991; Stuart-Smith et al., 1997; Rettie & Messier, 2000; Courtois, 2003; Brown, Rettie, Brooks & Mallory, 2007; Boreal Caribou ATK Reports, 2010-2011; Environment Canada, 2012). All woodland caribou ecotypes are considered solitary because they avoid predation by segregating themselves across landscapes and maintaining low densities (Bergerud & Elliot 1998; Weclaw & Hudson 2004; Environment Canada, 2012). The primary difference between the boreal and mountain ecotypes is in seasonal movements. Boreal caribou are considered sedentary; although they travel great distances in the pursuit of ideal forage and calving grounds, they do not migrate seasonally (Weclaw & Hudson, 2004; Environment Canada, 2012). By contrast, mountain caribou undergo seasonal migrations from foothill habitats in the winter to alpine habitats in the spring and summer to protect their calves from predation (Dawe, 2011; COSEWIC, 2014).

Caribou are highly sensitive to many types of disturbance. Their reproductive rate is lower than other ungulate species, making them unable to quickly react to increased environmental pressures (McLoughlin, Dzus, Wynes & Boutin, 2003; Weclaw & Hudson, 2004). Furthermore, expanding human development in the Canadian North, and in the boreal forests in particular, has increased the

number of habitat patches that are no longer suitable to caribou (Weclaw & Hudson, 2004; Sorensen et al., 2008; Schneider, Hauer, Dawe, Adamowicz & Boutin, 2012). GPS-collared woodland boreal caribou have been tracked and observed avoiding recently (6-20 year old) clear-cut areas during calving and rutting periods (Dyer, O'Neill, Wasel & Boutin, 2001; Hins, Ouellet, Dussault, & St-Laurent, 2009). Furthermore, expanding linear features, roads, and clear-cut areas from resource extraction increase caribou exposure to wolves—a major predator—(Bergerud, 1974; McLoughlin et al., 2003), and this interaction has been shown to be the leading cause of caribou mortality within herds exposed to high concentrations of human development (Seip, 1992; Schneider et al. 2012).

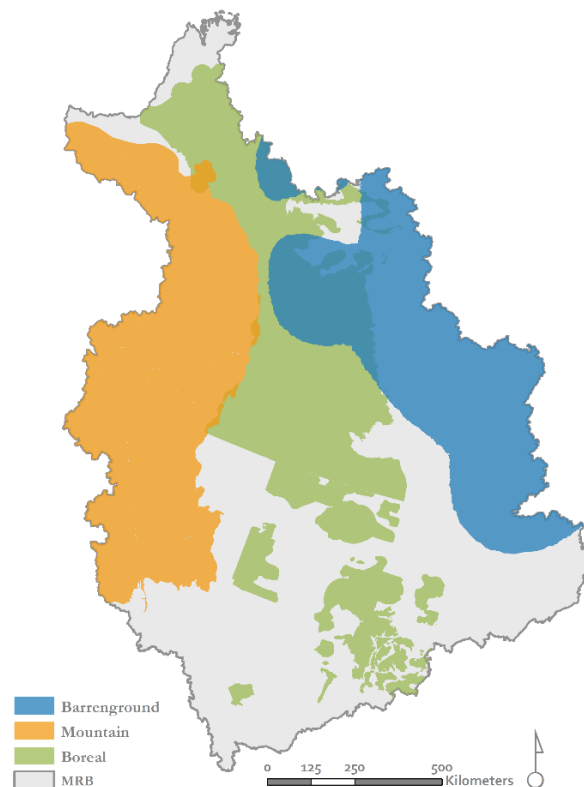


Figure 1.3. Caribou types within the Mackenzie River Basin (MRB), as delineated by the Canadian Government.

Global climate change is also predicted to be an additional stressor to caribou populations, as a changing climate is likely to affect caribou phenology and habitat. Habitat loss may occur through shifts in temperature and precipitation, associated species range shifts, as well as alterations to the fire regime. Fire maintains the natural heterogeneity of the boreal forest, including lichen biomass, a primary food source for caribou (Weber & Flannigan, 1997). Associated threats to caribou phenology include changes in seasonal availability of food resources, increasing insect harassment, and increasing incidence of extreme weather events (Eastland & White, 1992; Miller & Gunn, 2003; Sharma, Couturier & Cote, 2009; Festa-bianchet, Ray, Boutin, Cote & Gunn, 2011).

Project Goal and Specific Objectives

The primary goal of this project is to create a series of reserve designs within the MRB, which balance the ecological needs of caribou with the economic needs of natural resource extraction. To account for the complex needs of effective conservation, this project uses caribou as an umbrella species to represent overall health and connectivity of the natural ecosystems within the MRB.

This goal will be met through the following three project objectives:

1. Model historical caribou habitat and under projected future emission scenarios.
2. Calculate resource extraction value for three resource extraction industries—timber, hydrocarbons, and minerals.
3. Create optimized natural reserve designs which meet a variety of caribou conservation goals, while minimizing the loss of potential resource extraction value.

Project Significance

The results of this analysis will allow Y2Y to identify areas within the MRB for which to focus future conservation efforts. Therefore, the project deliverables will have a significant impact on the future management of the MRB by providing materials and analysis for Y2Y to:

1. Plan a reserve network in the MRB.
2. Influence stakeholder opinion regarding management options in the MRB.

A photograph of a caribou (deer) with large, velvet-covered antlers, standing in a lush green forest. The antlers are prominent and spread wide, framing the text. The caribou is looking directly at the camera, and its body is partially obscured by the dense foliage in the foreground.

II

Modeling Caribou Habitat

Chapter 2. Modeling Caribou Habitat

Overview

The use of an umbrella species in setting conservation targets is only possible when relatively accurate range maps of the species exist. While the ranges of each type of caribou that occur within the MRB have been created by the provincial and territorial governments, they do not account for the potential of caribou range changes because of future climate change. To understand where caribou are likely to occur now and into the future, this analysis uses caribou presence points and bioclimatic variables to map each ecotype's relative rate of occurrence under historical and future emission scenarios.

Niche-based species distribution modelling (SDM) can provide researchers and managers with an understanding of a species' habitat selection preferences (Phillips, Anderson & Schapire, 2006). The selection of appropriate methods to model species distributions is largely dependent upon the type and quality of data used as inputs into the model—for example, whether species occurrence data are in the form of presence-only or presence-absence. In many cases, the use of presence-absence data is ideal for species distribution modelling; however, these data are often unavailable. In general, the ability to identify true absences is made difficult by the possibility that a species was present at a site, but not observed (MacKenzie et al., 2002; Gu & Swihart, 2004). All caribou occurrence data within our study area are presence-only, and are based on direct and indirect observations and GPS locations (provided by the Government of NWT ENR).

The species distribution modelling software, MaxEnt, was chosen to model caribou relative rate of occurrence due to its ability to outperform other modelling tools using presence-only data (Hernandez, Graham, Master & Albert, 2006; Phillips et al., 2006; Merow, Smith & Silander, 2013). MaxEnt can also be used to model potential range shifts in response to climate change, which some other SDM methods (including resource selection functions) cannot do. Furthermore, MaxEnt's popularity as a modelling software and relative ease of use allow the results to be more easily understood and reproduced in future analyses.

MaxEnt begins by using a species presence locations as well as a set of environmental predictors across a gridded study region. The program then extracts background location samples (ie. values for each environmental predictor at a given location) and compares these to presence locations. From this, a relative rate of occurrence is calculated based on the relative probability that a cell is contained in a collection of presence samples.

MaxEnt was used to model caribou relative rate of occurrence for both historical (1981-2010 means) and projected future (2041-2070 means) emission scenarios. There are four general scenarios of future emissions, known as Representative Concentration Pathways (RCP), that describe potential changes to future radiative forcing based on global greenhouse gas concentrations (**Figure 2.1**). These scenarios are known as RCP2.6 (also referred to as RCP3-PD), RCP4.5, RCP6, and RCP8.5 and were

adopted in the fifth assessment report (AR5) by the Intergovernmental Panel on Climate Change (IPCC).

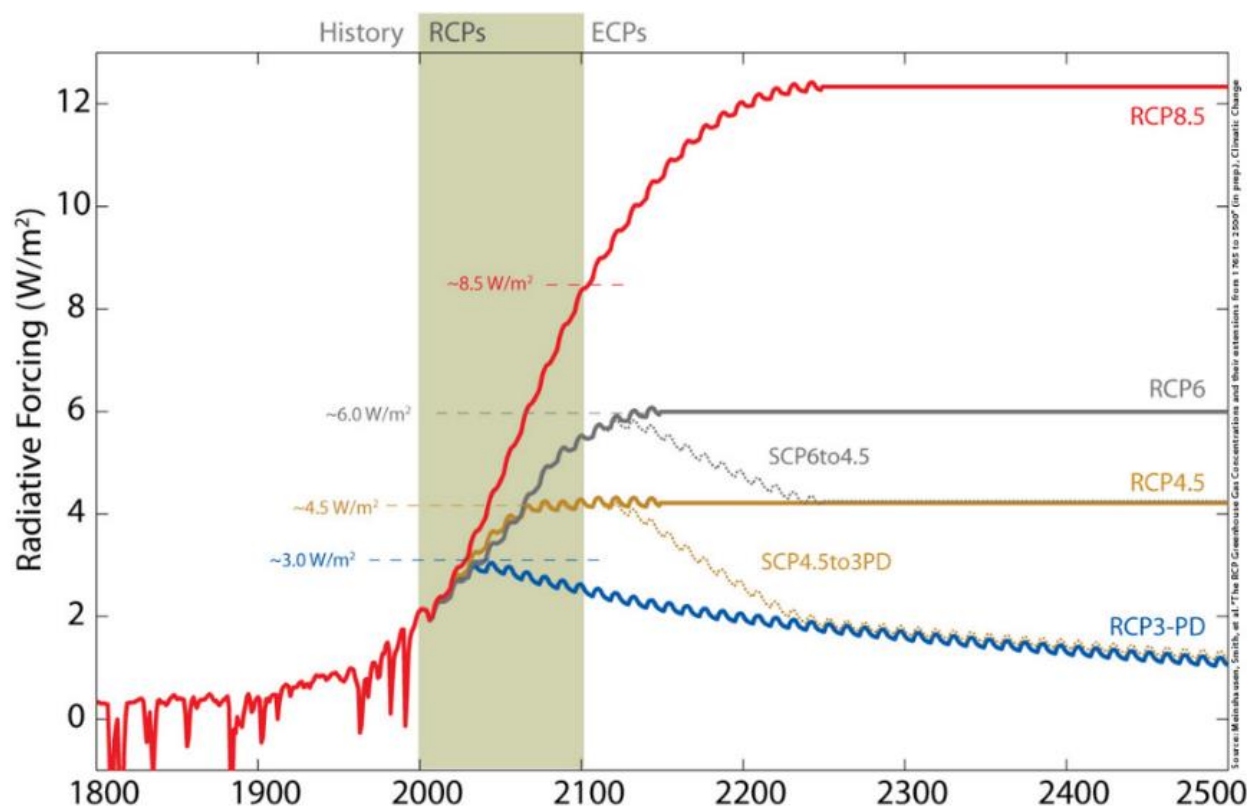


Figure 2.1. RCP scenarios describing potential change to future radiative forcing based on projected greenhouse gas emissions. Source: Meinshausen, et al. 2011.

To account for the uncertainty surrounding future climate change, two mid-century RCPs were used—RCP4.5 and RCP8.5. RCP4.5 describes an intermediate concentration trajectory, while RCP8.5 describes a business-as-usual scenario with a high concentration trajectory. Based on these projections, the increase in global mean surface temperature by the end of the 21st century (2081-2100) relative to 1986-2005 is likely to be 1.4°C to 3.1°C under RCP4.5 and 2.6°C to 4.8°C under RCP8.5. These two emissions scenarios were chosen because they account for the most realistic range of probable warming scenarios in northern Canada. Because the northern portions of Canada have already experienced 1.7°C of warming over the past century, the RCP4.5 scenario is the most realistic lower bound scenario for this analysis.

Methods

Data

All data used in this section of the analysis fit into two broad categories: species presence and bioclimatic variables. All spatial data were projected into Canada Albers Equal Area Conical projection.

Species Presence

Species presence data within our study area were gathered from multiple sources, including the Alberta Biodiversity Monitoring Institute (ABMI), the Government of Alberta, and the Government of the NWT (**Appendix 2**). The ABMI monitors biodiversity in Alberta by sampling 1,656 evenly distributed permanent terrestrial and wetland survey sites. Survey site coordinates are within approximately 5.5 km of the precise geographic coordinates. Woodland boreal caribou presence data were taken from the ABMI “Incidental Vertebrate Observations” and “Winter Snowtracking” data sets. The Government of the NWT further provided woodland boreal caribou individual home ranges (which were transformed into presence locations based on the centroid of each range), northern mountain woodland caribou GPS collar data, and barren-ground caribou GPS collar data.

Bioclimatic Variables

Bioclimatic variables were taken from the AdaptWest Project, “Historical and Projected Climate Data for North America (CMIP5 scenarios)” at 1 km resolution. The data are based on the Parameter Regression of Independent Slopes Model (PRISM; Daly et al., 2008) interpolation method for historical climate, and the Coupled Model Intercomparison Project Phase 5 (CMIP5) database corresponding to the 5th IPCC Assessment Report for future projections. This dataset contains 27 biologically relevant variables, including seasonal and annual temperature and precipitation means, extremes, growing and chilling degree days, snowfall, potential evapotranspiration, and several drought indices. Eight individual Atmospheric-Ocean General Circulation Models (AOGCM) were used for modeling future climate scenarios, which were chosen to represent all major clusters of similar AOGCMs (**Appendix 3**; Knutti et al., 2013). All variables were clipped to the study region using ArcGIS suite version 10.4.

Analyses

Due to the high degree of intercorrelation associated with many of the 27 potential bioclimatic variables, a subset of 12 variables was chosen a priori based upon their ecological relevance to caribou (**Appendix 4**).

Pearson’s correlation coefficients were then calculated on a random sample of 10,000 pixels of the 12 variables to help choose sets of variables with low intercorrelation ($p < \pm 0.7$) for model selection. These values were then used to choose a set of five models which were run in MaxEnt using boreal caribou presence points and tested for relative model fit (**Table 2.1**). One method to evaluate model performance uses the MaxEnt output for the value of the area under the receiver operating

characteristic curve (AUC). While the AUC value is often reported in literature as an estimate of model fit, it generally favors models having a higher number of input variables. For initial model selection, the Akaike Information Criterion (AIC) is preferable because it provides greater penalty for increasing number of variables. AIC values were calculated using the environmental niche modeling software ENMTools. Model 1 was chosen as it had the lowest relative AIC score (**Table 2.1**). The variables chosen within this model are: the Julian date on which the frost-free period begins, mean annual temperature, precipitation as snow, and summer precipitation.

The bioclimatic variables in Model 1 (**Table 2.1**) were used to model all three caribou ecotypes in individual MaxEnt ‘runs’. The following settings were set for each MaxEnt run of all three caribou ecotypes. The maximum number of background points was set at 10,000. We selected 90% of presence data for training and the remaining 10% for test points. A total of 10 replicate runs was set for model building, with replicated run types being set to subsample. Random seeding was also selected. All other values were kept as defaults.

Table 2.1. Models used for MaxEnt analysis with related AIC scores.

Model	Bioclimatic Variable	AIC score
1	The Julian date on which the frost-free period begins	1909.73
	Mean annual temperature (°C)	
	Precipitation as snow (mm)	
	Summer precipitation (mm)	
2	Mean annual precipitation (mm)	1946.04
	Mean annual temperature (°C)	
	Mean temperature of the warmest month (°C)	
3	Mean annual precipitation (mm)	2005.58
	Mean temperature of the coldest month (°C)	
	Mean temperature of the warmest month (°C)	
4	Degree-days above 5°C	1993.41
	Mean annual precipitation (mm)	
	Mean temperature of the coldest month (°C)	

Results and Discussion

Historical Caribou Range Models

The historical caribou range occurrence model predicted caribou occurrence with a high degree of confidence for both boreal (AUC = 0.89) and mountain woodland (AUC = 0.87) caribou ecotypes. The barren-ground caribou model had a low model fit (AUC = 0.57) suggesting a great deal of uncertainty in barren-grounds range maps. The model outputs created using the historical climate model were compared to caribou range maps created for each ecotype by the Canadian government (Environment Canada, 2012). MaxEnt-derived caribou ranges were found to be similar to the government ranges for all three caribou, despite the low AUC value produced by the barren-ground caribou (Figure 2.2). However, there are some notable differences in our MaxEnt model when compared with government ranges—particularly for the boreal woodland and mountain woodland caribou models. For both types of caribou, this is likely due to data limitations. For boreal woodland caribou, government ranges are bounded by arbitrary jurisdictional boundaries in the southern portions of their range, and presence points were unavailable for the far northern portions. For mountain woodland caribou, differences arise from the fact that presence points were not provided for the southern portions of their range. This is inconsequential, as these areas are not within our study area.

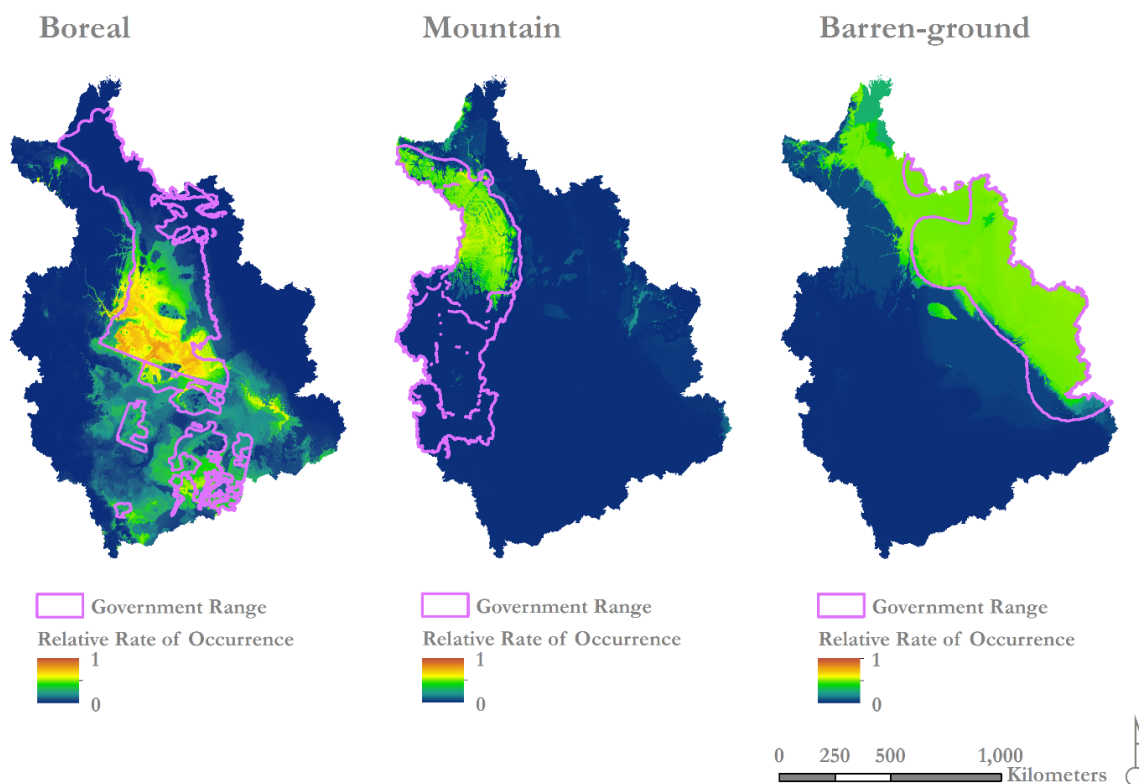


Figure 2.2. Historical MaxEnt model outputs and government-created range maps for boreal woodland, mountain woodland, and barren-ground caribou. Warmer colors represent areas of higher relative rate of caribou occurrence, while cooler colors represent lower relative rate of occurrence. Pink outlines shows government-created range maps for comparison purposes.

Barren-ground caribou habitat preferences and responses to environmental stochasticity are still poorly understood (NWT ENR, 2011). Therefore, uncertainty in our model's ability to predict barren-ground caribou occurrence was not unexpected. Because the chosen bioclimatic variables predict woodland caribou occurrence well, and because woodland and barren-ground caribou ranges overlap in significant portions of the MRB, we made the assumption that these variables were the most representative predictors of barren-ground caribou habitat—despite having a low AUC value. We were confident making this assumption because our historical climate-derived MaxEnt model outputs were similar to the government ranges. The government ranges in the NWT are defined and managed according to calving grounds as it is often difficult to tell where barren-ground caribou will be at other times of the year. Given that our model was similar to the government range for barren-ground caribou, we are confident our model includes important calving grounds (Fisher, Roy, & Hiltz, 2009).

Projected Caribou Ranges Under Future Climate Change

For comparison between historical and projected future emission scenarios, we used the same set of variables identified as having highest model fit to model both future emission scenarios—RCP4.5 and RCP8.5. We found that the models for boreal and mountain woodland caribou predicted relative rate of occurrence with a high degree of confidence (AUC > 0.85, **Table 2.2**). Again, these variables produced low model fit for barren-ground caribou (AUC < 0.57, **Table 2.2**). However, we assumed that the four bioclimatic variables were the most representative of barren ground occurrence given the modeling uncertainty for barren-ground caribou.

Table 2.2. Area Under the Curve (AUC) values for boreal woodland, mountain woodland, and barren-ground caribou, under RCP4.5 and RCP8.5 emission scenarios, for eight Atmosphere-Ocean General Circulation Models (AOGCM).

	Boreal woodland		Mountain woodland		Barren-ground	
Model	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
CCSM4	0.88	0.87	0.87	0.87	0.57	0.57
CNRM-CM5	0.88	0.90	0.87	0.87	0.57	0.56
CanESM2	0.89	0.88	0.87	0.87	0.57	0.56
GFDL-CM3	0.89	0.89	0.87	0.86	0.56	0.56
HadGEM2-ES	0.88	0.80	0.87	0.86	0.57	0.57
INM-CM4	0.90	0.90	0.86	0.87	0.56	0.56
IPSL-CM5A-MR	0.89	0.88	0.87	0.86	0.56	0.56
MPI-ESM-LR	0.86	0.90	0.87	0.87	0.56	0.57

In general, even under the scenario of greatest increase to greenhouse gas concentrations (RCP8.5), caribou range did not shift dramatically on a basin-wide scale. Using boreal woodland caribou as an example, areas of highest relative rate of occurrence under historical climate conditions (**Figure 2.2**) are generally similar to those under future climate change (**Figure 2.3**). This can be explained simply by the fact that we modeled our future emission scenarios out to mid-century, at which point projected radiative forcing is not highly different than present conditions, even under RCP8.5 (**Figure 2.1**). These same patterns hold true for the mountain woodland and barren-ground caribou (**Appendix 5, 6**).

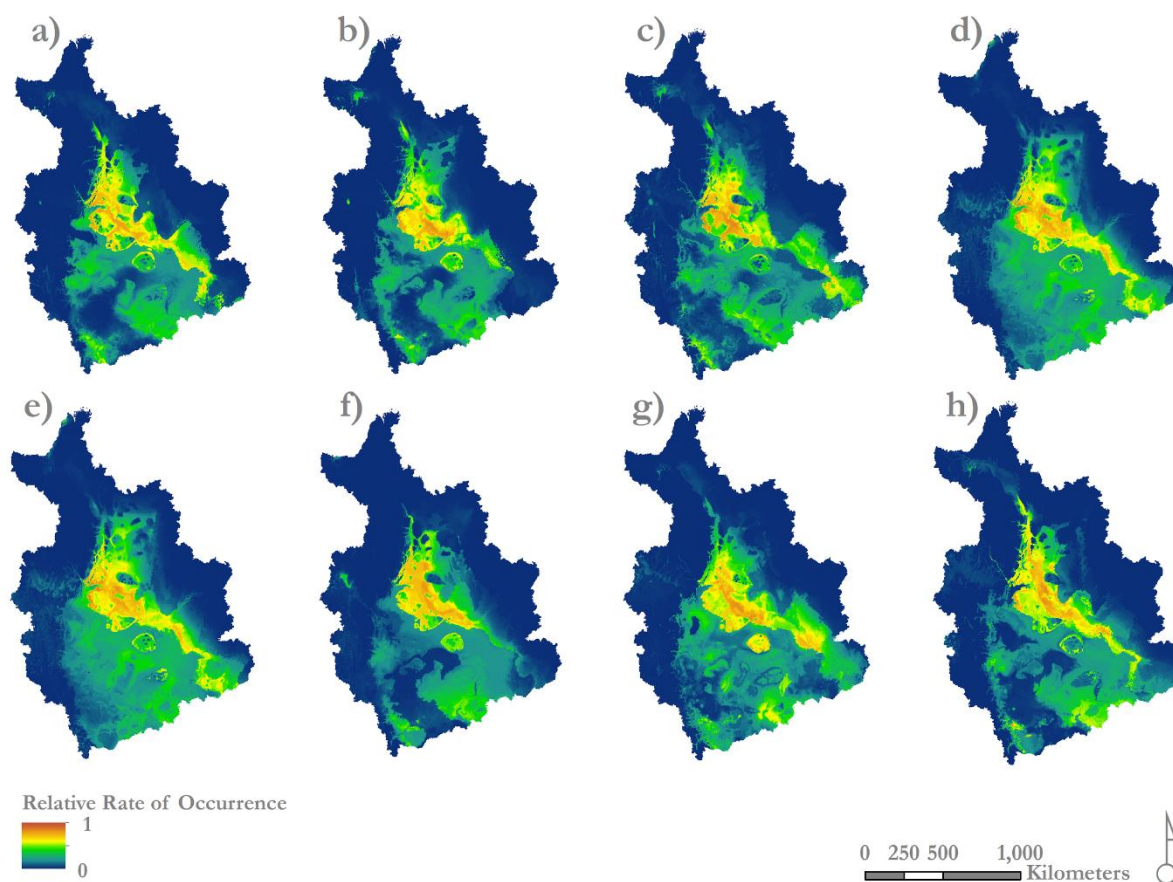


Figure 2.3. MaxEnt model outputs for boreal woodland caribou for eight Atmosphere-Ocean General Circulation Models (AOGCM) projected to mid-century under RCP8.5. Warmer colors represent areas of higher relative rate of caribou occurrence, while cooler colors represent lower relative rate of occurrence. Lowercase letters above individual maps indicate different AOGCMs and are as follows: a) CCSM4, b) CNRM-CM5, c) CanESM2, d) GFDL-CM3, e) HadGEM2-ES, f) INM-CM4, g) IPSL-CM5A-MR, h) MPI-ESM-LR.

Despite these largely similar patterns for caribou relative rate of occurrence, it is important to recognize that there are minor differences in model output—particularly for boreal woodland caribou. Visual comparison between relative rate of occurrence maps is difficult. For this reason, relative rates of occurrence were reclassified in ArcGIS suite version 10.4 into binary suitability maps using the “Maximum Training Sensitivity Plus Specificity” logistic threshold from MaxEnt. For boreal woodland caribou, some AOGCMs under RCP8.5 (i.e. GFDL-CM3 and INM-CM4) show an increase in suitability in the southern portions of the MRB, while others (i.e. HadGEM2-ES, IPSL-CM5A-MR) show these same areas shrinking in size (**Figure 2.4**). It should be noted that the number of presence points for boreal woodland caribou ($n = 276$) is drastically lower than for mountain woodland ($n = 3,359$) and barren-ground caribou ($n = 65,354$), and could explain much of the variability in model prediction.

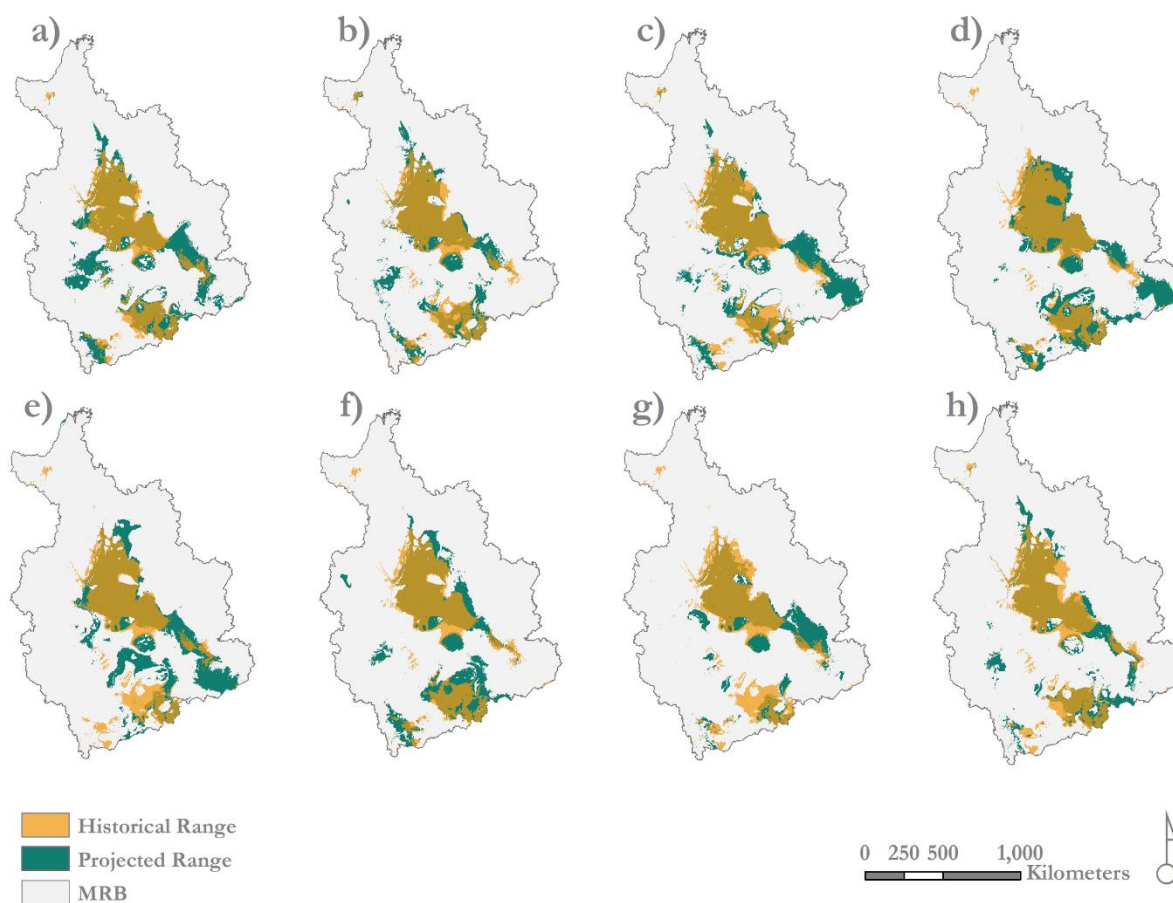


Figure 2.4. Binary climate suitability ranges based on MaxEnt model outputs for boreal woodland caribou using historical bioclimatic variables and eight Atmosphere-Ocean General Circulation Models (AOGCM) projected to mid-century under RCP8.5. Historical range is shown in orange, while projected range under each AOGCM is shown in teal. Lowercase letters above individual maps indicate different AOGCMs and are as follows: a) CCSM4, b) CNRM-CM5, c) CanESM2, d) GFDL-CM3, e) HadGEM2-ES, f) INM-CM4, g) IPSL-CM5A-MR, h) MPI-ESM-LR.

III

Resource Valuation



Chapter 3. Resource Valuation

Overview

Effective conservation in large regions such as the MRB should consider the economic impacts of any conservation action (Margules & Pressey, 2000). To design a reserve that would account for economic forces within our study region, we estimated potential future revenues from three resource types within the MRB—timber, hydrocarbons (natural gas, oil, and bitumen), and minerals.

Table 3.1. Total 2015 GDP contributions of selected industries by province and territory. All figures reported in millions of Canadian dollars.

Province or Territory	Hydrocarbons and Minerals	Timber	Total
Alberta	\$63,322	\$4,896	\$68,220
Northwest Territories	\$972	\$21	\$992
Yukon	\$292	\$0.80	\$292
Total	\$64,580	\$4,910	\$69,502

The extraction of these resources contributes significantly to the GDP of each territory and province within our study area (**Table 3.1**), as well as the overall Canadian economy. Resource extraction across Canada of these three resources contributed nearly 7.3% of national GDP and over 50% of exports in 2015 (“Key Facts”, 2016). Although the abundance of each resource varies by province and territory, a large portion of these resources are in boreal forests. As of 2014, 67% of Alberta’s boreal forests, and 41% of Saskatchewan’s boreal forests, included or were overlaying at least one of these resources (Chang & Lee, 2014).

Methods

Data

Timber

Spatial and Volume - Timber resources were valued based upon price data and three types of spatial data. Spatial data include genus density, aboveground merchantable volume, and proximity to commercial sawmills. Genus density and aboveground merchantable volume data have been mapped by Canada’s National Forestry Inventory (NFI)—a collaborative effort between territorial, provincial, and federal agencies to identify fine scale (250m resolution) forest stand attributes for all of Canada’s forests. For more information on methods and other identified forest stand attributes, see Beaudoin et al. (2014). Commercial sawmill locations were provided by Atlas of Canada (2010). Price data were based on the three-month averages of stumpage rates—or price per stump of the species harvested—from the British Columbia Department of Farming, Natural Resources & Industry.

Commercially valuable tree species were identified for each province or territory within our study

region. The primary commercial timber trees in Yukon are white spruce (*Picea glauca*), black spruce (*Picea mariana*), lodgepole pine (*Pinus contorta* var. *latifolia*), trembling aspen (*Populus tremuloides*), balsam poplar (*Populus balsamifera*), and subalpine fir (*Abies lasiocarpa*) (Government of Yukon, 2016). The NWT commercial tree species include those within Yukon, with the addition of jack pine (*Pinus banksiana*), balsam fir (*Abies balsamea*) and tamarack (*Larix laricina*) (NWT Department of Environment and Resources, 1997). Commercial tree species in Alberta include those already identified in Yukon and the NWT (Government of Alberta, 2012). While individual tree species are not mapped, genus densities have been mapped by NFI at 250m resolution. Therefore, the commercial tree species of each province and territory were categorized into their respective genus groups.

Aboveground merchantable volume of timber has also been mapped by NFI at 250m resolution. Aboveground merchantable volume ($\text{m}^3/\text{hectare}$) is defined as the amount of timber which can be milled into lumber and sold. Typically, this is most a tree's trunk, minus the branches and a certain amount from the top and bottom. Aboveground merchantable volume was used instead of total forest volume because it represented a more accurate measure of true commercial value.

Forest stand locations were determined by proximity to registered commercial sawmills, which are defined by Natural Resources Canada as any mill capable of producing at least 10,000 m^3/year of timber. Data for locations of registered sawmills came from Natural Resources Canada's Atlas of Canada (2010) dataset. Correspondence with Madison Lumber Report, an organization responsible for providing monthly lumber prices to the Government of Alberta, suggested that no commercial harvest takes place beyond 200km of an operating mill (Keta Kosman, Personal Correspondence). To confirm this, we performed a spatial analysis on current commercial harvest parcels obtained from the governments of Yukon, the NWT, and Alberta. We found that 95% of all current operations within our study area did occur within 200km of commercial mills. The other 5% of plots were found to be adjacent to or less than 21km from another harvest plot. It was assumed that these more distant plots were within range of forest roads not publicly available through current datasets, thereby reducing the costs of access and transportation. No current plots were over 220km from a current sawmill.

Price - Stumpage rates for each commercial tree species were sourced from the British Columbia Department of Farming, Natural Resources & Industry website ("Interior Log Market Reports", 2017). These rates were used as a proxy for stumpage rates of harvested species in Yukon, the NWT, and Alberta due to lack of published and updated stumpage rates in those areas (Keta Kosman, Personal Correspondence). The British Columbia Government reports stumpage price per timber category (eg. Spruce, Fir, Pine) and product type (eg. sawlogs, pulpwood, peelers, etc.). We identified the commercially viable timber categories within the MRB study area as follows: Spruce-Pine-Fir, Douglas Fir-Larch, and Hemlock-Balsam Fir (Timber Pricing Branch, 2017; **Table 3.2**). The price used for each category was derived from the weighted average of products per species group for the three-month period between September 1 and November 30, 2016 (**Table 3.2**).

Table 3.2. Tree species and timber price group used to value timber resources throughout study area.

Timber Price Group ¹	Tree Species	Common Name	Price (US\$/m ³) ²
Spruce-pine-fir	<i>Abies balsamea</i>	Balsam fir	52.34
	<i>Abies lasiocarpa</i>	Subalpine fir	
	<i>Picea glauca</i>	White spruce	
	<i>Picea mariana</i>	Black spruce	
	<i>Pinus banksiana</i>	Jack pine	
	<i>Pinus contorta</i> var. <i>latifolia</i>	Lodgepole pine	
Douglas fir-larch	<i>Larix laricina</i>	Tamarack	61.35
Hemlock-Balsam fir	<i>Populus balsamifera</i>	Balsam poplar	49.84
	<i>Populus tremuloides</i>	Trembling aspen	

¹Timber price group taken from the British Columbia Department of Farming, Natural Resources & Industry "Interior Log Market Reports", 2017.

²Weighted average for prices between September 1 and November 30, 2016.

Hydrocarbons

Spatial and Volume - In this report, we define hydrocarbons as oil, natural gas, and bitumen. Each resource is harvested differently, and even the same resource can be extracted in different ways. In the oil sands, for example, bitumen is either mined or extracted in-situ (Natural Resources Canada, 2016). Both of these techniques have different cost structures, physical footprints, and environmental effects (Dyer & Huot, 2010) but these differences were not accounted for in this analysis.

Typically, oil and natural gas extraction methods are grouped into two categories: conventional or unconventional drilling. Conventional drilling uses vertical wells to tap directly into oil and natural gas reserves, while unconventional techniques use horizontal drilling and often hydraulic fracturing to access resources (Ministry of Natural Gas Development, 2016). Unconventional drilling techniques have become increasingly popular in the past few decades (National Energy Board, 2016) because they allow oil and natural gas to be harvested from stratigraphic layers that have been historically inaccessible. Unconventionally harvested resources include tight shale oil and natural gas and shale oil and natural gas. We report tight and shale resources together. Hydrocarbons were valued using either spatially explicit geologic formations or reserve pool volume estimates, depending on information availability, and commodity price data.

Bitumen reserves and volume information was obtained from the Alberta Energy Regulator (AER). Of the three oil sand operation areas—Cold Lake, Athabasca, and Peace River (**Appendix 9**)—only Athabasca and Peace River areas are located within our study region. Each oil sand production area is further divided into deposits. Bitumen deposit boundaries were delineated by bitumen pay depth—

the average thickness of an oil sand zone—and were found in AER Report ST98 (2017). Only the outer edge of each formation was used to represent that deposit, and estimated volumes were equally distributed across the formation. These deposits, and their estimated resources, are grouped by region in **Table 3.3**.

Table 3.3. Oil Sand bitumen deposits, organized by operational area. The Athabasca region has by far the most proven reserves compared to the Peace River region.

Operational Area	Deposit	Million Barrels
Athabasca	Upper Grand Rapids	1,612
	Middle Grand Rapids	602
	Lower Grand Rapids	356
	Wabiskaw-McMurray	42,241
	Nisku Figure	4,498
	Grosmont	17,884
Peace River	Bluesky-Gething	1,575
Total		68,767

Conventional oil and natural gas information was obtained from the provincial and territorial governments within our study area. In Alberta, conventional oil and natural gas information was obtained from AER. Natural gas and oil pools were identified and mapped using AER Map 90 and Map 94, which distinguish Designated Oil and Gas Fields (2016), and corresponding oil and natural gas reserve estimates came from AER records. For conventional oil, remaining established reserves per pool were used. For conventional natural gas, values for remaining estimated marketable gas were used. In Yukon, estimated conventional hydrocarbon resource estimates were obtained from the Yukon Oil and Gas Annual Report (2015). In the NWT, conventional hydrocarbon resource estimates were from the National Energy Board Report (2014). Spatial information for the corresponding geologic formations were sourced from Esri shapefiles (Alberta Research Council, 1994). It should be noted that there is significantly less conventional oil and natural gas production within the NWT and Yukon than in Alberta. This is primarily due to a lack of processing facilities, increased distance to markets and a lack of detailed subsurface exploration in these areas (Government of Yukon, 2015). Therefore, estimates in the NWT and Yukon are much broader spatially.

Unconventional oil and natural gas production has increased substantially each year for the past decade (National Energy Board, 2016). While hydrocarbon production using unconventional methods is rapidly expanding (National Energy Board, 2016), only some geologic formations have undergone detailed resource evaluations at the time of this analysis. Detailed assessments have been completed for the Montney formation in Alberta, and the Liard Basin, which spans small regions of British Columbia, NWT, and Yukon (**Table 3.4, Appendix 10**). Results of these explorations were provided by the National Energy Board (NEB). Broader unconventional volume estimates have

been reported by AER and Alberta Geological Services for the remaining geologic formations (Wilrich, North Nordegg, Muskwa, and Duvernay) within the Alberta portion of our study area (**Table 3.4, Appendix 10**). AER and Alberta Geological Services also provided unconventional oil estimates for the Montney formation, which were not included in the detailed assessment from NEB. The Liard Basin is the only region in Yukon that has been assessed for unconventional resources. In the NWT, two areas have been evaluated for unconventional resources: the NWT section of the Liard Basin, and the Central Mackenzie Valley (**Table 3.4, Appendix 10**).

Table 3.4. Unconventional oil (BBL) and natural gas (Tcf) by evaluated geologic feature. Basins without estimates have not yet been evaluated.

Province or Territory	Formation	Oil (BBL)	Natural Gas (Tcf)
Alberta	Duvernay	61.7	443
	Muskwa	115.1	419
	Montney	136.3	190
	North Nordegg	37.8	148
Northwest Territories	Liard Basin	-	44
	Mackenzie Valley	191.2	-
Yukon	Liard Basin	-	8.6
Total		542.1	1252.6

Price - The same price information (US\$53.07 per barrel) was used to value conventional oil, unconventional oil, and bitumen resources.¹ Similarly, the same price for natural gas was used to value both conventional and unconventional natural gas volumes. Prices for natural gas were calculated by averaging the monthly Natural Gas Exchange (NGX) Alberta Market Price indices from January 2016—December 2016. Saturated natural gas supply across North America and consecutive winters (2014–2016) of decreased energy demand have led to a surplus of natural gas supply (National Energy Board, 2016). Prices have responded accordingly, dropping from CAN\$4.20 per gigajoule in 2014 to CAN\$2.05 in 2016. At the time of this report, natural gas was selling for roughly CAN\$2.05 per gigajoule of energy produced.¹

Minerals

This report valued the most commonly mined minerals within the MRB—coal, precious and industrial metals (PIM), and diamonds. PIM include gold, silver, tungsten, copper, rare earth elements, zinc and lead.

¹ Value reported by the Bloomberg Index, January 27, 2017

Spatial and Volume - Mining leases collected from the Government of NWT and Global Forest Watch Canada's Industrial Tenures of Canada report (2013) were used to determine the location and volume of PIM and diamond resources. Each mineral lease is attributed to a leaseholder and a commodity. In cases where leases were actively being developed, leaseholders had submitted NI 43-101 reports² to the Government of Canada. These reports provide estimated proven mineral reserve volumes and, in some cases, estimated values for the proven reserves. Coal field locations and associated reserve values were sourced from the Alberta Geological Survey (Smith et al. 2008). The only coal fields currently in production within the MRB are in Alberta, along the foothills of the Rocky Mountains in the Southwest portion of our study area.

Price - Diamond valuation was dependent on whether average carat grade was provided in the NI 43-101 report. If so, the corresponding carat price was used to value the reserve. When average carat grade and price were not provided, average raw carat price was sourced from Dominion Diamond Corporation's Report on Diavik Diamond Mine (Yip & Thompson 2015; **Table 3.5**). For PIM and coal resources volume and value estimates from NI 43-101 reports were used for operations which had submitted them. When no report or value had been submitted for a mineral reserve, most often due to infancy of process, values were calculated for estimated reserves based on the most recent average mineral prices sourced from either Statista.com or InfoMine.com (**Table 3.5**).

Table 3.5. Average price per volume of commodities examined within the mineral extraction industry.

Commodity	Value per Volume (US\$)	Source
PIM	Rare Earth Elements	\$885/mt Avalon Advanced Materials, Inc. 2016
	Gold	\$1250.74/oz Newmont Mining Corp, 2016 (Statista.com)
	Silver	\$19/oz Mosher et al. 2016
	Lead	\$2,204/mt Siega & Gann 2014
	Zinc	\$2,094/mt Siega & Gann 2014
	Tungsten	\$24,380/mt Delaney & Bakker 2014
	Copper	\$5,889/t Copper Price Charts, n.d. (InfoMine.com)
Coal		\$45.53/t US Energy Information Administration
Diamonds	\$180.52/rough carat	Yip & Thompson 2015

² National Instruments 43-101 Reports are the Canadian standard of disclosure for mineral projects. Within these reports companies must disclose all of the scientific and technical information that exists on the minerals project they are developing (British Columbia Securities Commission, n.d.)

Analyses

Although the process for valuing each resource is unique, there are three assumptions which apply to all resources. When applicable, values were converted from Canadian to US Dollars (CAN\$ 1.33 = US\$1.00)³

First, costs associated with exploring for, harvesting, transporting, or refining/milling were not included in the valuation of any resources. Second, cost differences within industries were not considered. Within any given industry, different companies have different cost structures, and there are often different methods of harvesting a resource. For example, many different well types can be used to tap into a conventional oil pool. The main example of this comes from bitumen harvest, with in-situ harvesting being a more expensive process than open-pit mining. None of these costs were considered due to lack of publicly available data, differing cost structure across territories and provinces, and uncertainty about future costs as extraction and transportation technology improves. Third, we assumed equal distribution of a resource within its spatial extent (eg. forest stand, mining vein, gas pool, etc.) In the case where portions of a reported resource were found both inside and outside of our study area, then the total resource reserve was multiplied by the percentage of the reserve which was found within our study area. For example, if only 60% of a geologic formation with proven hydrocarbons was within the MRB, then the total reported volume estimate of that resource was multiplied by 0.6.

Timber

$$Value_t \sum_{i=1}^n = AMV_i * SGD_s * SR_s$$

Equation 3.1. Timber (t) was valued per spatial extent (i) based on the aboveground merchantable volume (AMV) and specific tree type density (SGD) per species (s). Once the volume of each tree type was determined, that volume was multiplied by the current stumpage rate (SR) for that species.

The value of timber present within our study area was calculated as the product of aboveground merchantable tree volume, species group density, and stumpage rate (**Equation 3.1**). Uniform distribution of species across a spatial extent was assumed for simplicity. Thus, the aboveground merchantable volume was assumed to be equally distributed amongst all tree species groups present. No areas further than 200km from a mill were considered commercially attractive. Thus, a buffer of 200km was applied to each reported sawmill, and all values outside these plots were given a value of zero. This analysis did not include other factors determining harvest areas, such as slope, distance to roads, and proximity to previous harvest areas (increased access).

³ Conversion factor as of 3/19/2017

Hydrocarbons

$$Value_h \sum_{i=1}^n = Volume_{ri} * Market Price_r * \rho_i$$

Equation 3.2. Hydrocarbons (h) were valued based on the volume of resource type (r) per proportion (ρ) of the spatial extent (i) that was within the MRB. Spatial extents (i) were determined by data resolution, ranging from geologic formations to individual pools. Resource types (r) included oil (barrels) and natural gas(ft.³).

Conventional and unconventional oil and natural gas was calculated as the product of their estimated volumes (barrels and trillion cubic feet, respectively) and their corresponding prices (**Equation 3.2**). Natural gas prices, as reported by the NGX Alberta Market Price indices, are in Canadian dollars per gigajoule of energy produced. Therefore, reserve estimates were converted to gigajoules using conversions provided by the NEB, Canada, before being multiplied by the value per gigajoule. Finally, total value was divided by feature area to determine value per square kilometer.

Minerals

$$Value_m[e] \sum_{i=1}^n = \begin{cases} Mass_{ri} * Market Price_r * \rho_i \\ (\frac{Value_o}{area_o}) * area_i * \rho_{extent} \end{cases}$$

Equation 3.3. Mineral value (m) depended on if an operation had published reserve estimates for their leased operation (e). If so, the top equation was used, and value was determined by the proportion (ρ) of a spatial extent (i) of a resource (r) within the MRB. If estimates weren't reported, per square kilometer values were found for similar operations (o) and used as proxies.

PIM and coal reserves were determined based on published reserve quantity or, if possible, value estimates. If only reserve quantities were available, the volume per resources was multiplied by the current market value of that mineral (**Equation 3.3**). Value per km² was estimated by dividing the total resource reserve value by the lease area.

In instances in which no mineral reserve estimates had yet been made by the leaseholder, values per km² were assumed to be equal to the value of the closest highest value leases of the same commodity. For example, for a gold lease with no reserve estimate near the northeastern arm of Great Slave Lake, we took the lease value of the highest value gold lease located in the same area but owned by a different leaseholder. When no lease of the same commodity occurred close by a lease with no reserve estimate, the lease was given the same value as the highest value lease of the same commodity occurring anywhere in the study area. While using these proxy values can introduce significant uncertainty, this was done to overvalue resources, and account for all mineral projects currently occurring within the region.

All Resources

We summed individual resources to combine each of our different resource values into a single number. We assumed that when resource locations overlapped they could be harvested sequentially (timber cleared to open the area for drilling or mining) or simultaneously. The primary issue with this assumption is that the huge footprint associated with some of these operations might not allow for simultaneous extraction. However, this assumption was made to overestimate, rather than underestimate, land value.

Results and Discussion

Timber

Based on the assumption that no commercial harvest takes place further than 200km from an existing commercial sawmill, nearly all timber value is found in Alberta (**Figure 3.1, Appendix 7**). Two commercial mills located in northern British Columbia allowed for values to be registered in the southern extents of Yukon and the NWT. Within Alberta, the highest value areas are in the central western portion of the province (**Figure 3.1**). The lack of commercial sawmills in Yukon and the NWT confirms that most timber harvest in these areas is for personal use, not commercial harvest. Total timber value for the areas within 200km of a sawmill was US\$45.9 billion. The average value per square kilometer was around US\$148 thousand, with a range from US\$1 to US\$535,000.

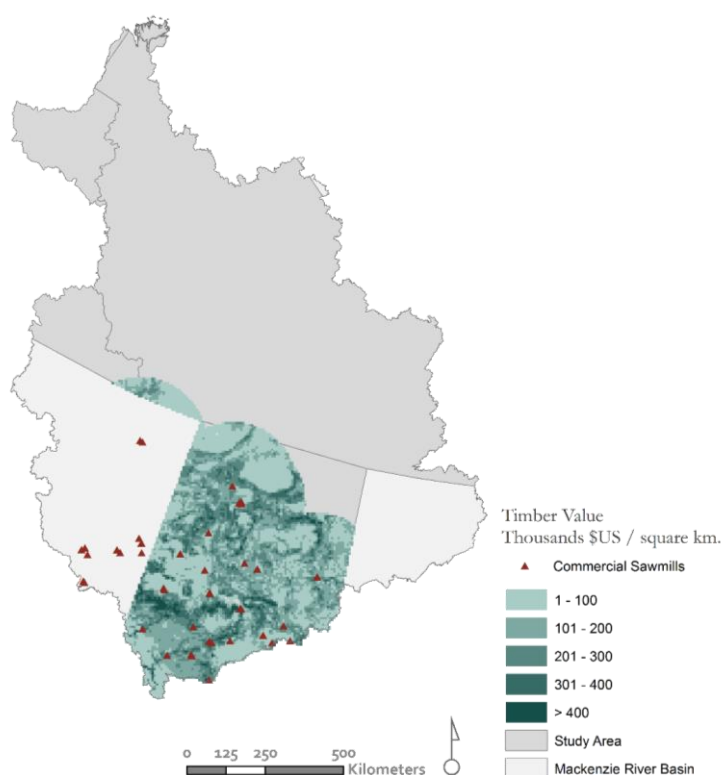


Figure 3.1. Distribution of timber value (green) within the MRB. Darker shades of green correspond to higher value areas. A buffer of 200km was applied to commercial sawmills (magenta triangles) to delineate commercially viable harvest areas from non-viable harvest areas.

Hydrocarbons

The highest value land for bitumen exists where deposits overlap, as the value of each deposit was summed to get total land value. This was especially apparent in the central portion of the Athabasca area, where multiple deposits overlapped (**Appendix 8, Table 3.6**). More so than our other studied resources, industry specific differences in cost structure could play a deciding factor in where operations are located. In this case, the location of the highest volumes might not correspond to the most attractive areas for development, and accounting for these could shift the most valuable lands from areas with the highest resource volume to the areas with the lowest cost of extraction.

Table 3.6. Reserve volume estimates and value for each bitumen deposit, organized by operational area.

Operational Area	Deposit	Volume (Million Barrels)	Value (Million US\$)	Value (Million US\$/km ²)
Athabasca	Upper Grand Rapids	1611.94	85,546	23
	Middle Grand Rapids	601.60	31,927	18
	Lower Grand Rapids	356.36	18,912	15
	Wabiskaw-McMurray	42240.19	2,241,687	44
	Nisku Figure	4498.02	238,710	29
	Grosmont	17883.75	949,091	54
Peace River	Bluesky-Gething	1575.07	83,589	8
Total		68766.93	3,649,461	-

For conventional oil and natural gas, specific reserve estimates and spatially explicit pools in Alberta allowed for more precise estimates, resulting in higher value per area than in the NWT and Yukon, where reserve estimates were applied across large geologic formations (**Appendix 9**). Total conventional hydrocarbon value throughout the study area was around US\$89.8 billion. Estimates within Yukon and the NWT reveal hydrocarbon resources worth US\$46.3 billion. Estimates within Alberta are valued at US\$43.5 billion, which is nearly equal to both Yukon and NWT combined. The average value per square kilometer was US\$850 thousand, and ranged from US\$351 thousand to US\$1.3 million dollars depending on the territory or province (**Table 3.7**).

Table 3.7. Conventional hydrocarbon (oil and natural gas) value by province and territory.

Province or Territory	Value (Million US\$)	Value (Million US\$/km ²)
Alberta	43,500	0.89
Northwest Territories	34,000	0.35
Yukon	12,300	1.31
Total	89,800	-
Average Value/km²	-	0.85

Unconventional drilling techniques allow significantly greater volumes of oil and natural gas to be recovered. Therefore, the land value overlaying unconventional hydrocarbon resources is greater on a per square kilometer basis than land over conventional resources. This can be demonstrated by comparing the unconventional marketable natural gas in the Liard Basin—219 trillion cubic feet estimated reserve—with the total consumption for the United States in 2015—27.3 trillion cubic feet (Energy Information Administration, 2017). The Liard Basin (Yukon, NWT) and Montney Formation (Alberta) are the highest value areas of unconventional resources within the MRB (**Appendix 10**). Both total and per square kilometer value for each basin are reported in **Table 3.6**. In total, the areas with estimated unconventional resources are the most valuable within the study area.

Table 3.8. Unconventional hydrocarbon (oil and natural gas) value by province and territory.

Province/ Territory	Formation	Oil Value (Billion US\$)	Natural Gas Value (Billion US\$)	Total Value (Billion US\$)
Alberta	Duvernay	3274	719	3993
	Muskwa	6108	680	6788
	Montney	7233	308	7542
	North Nordegg	2006	240	2246
Northwest Territories	Liard Basin	0	71	71
	Central Mackenzie Valley	10145	0	10145
Yukon	Liard Basin	0	14	14
Total		30084	2088	32172

Overall, the most valuable hydrocarbon areas are found in Alberta (**Figure 3.2**). Although the oil sands area is one of the largest oil deposits in the world, the portion of it that lies within our study area is actually less valuable on a square kilometer basis than the natural gas resources available in other parts of Alberta, NWT, and Yukon. Western Alberta is more valuable than the oil sands due to the vast amount of natural gas and oil which can be unlocked using horizontal drilling methods there (**Table 3.8**). In NWT and Yukon, the most valuable area was the Liard Basin (southeast Yukon, southwest NWT). British Columbia has already begun developing the portion of this deposit within their provincial border, which could incentivize NWT and Yukon to begin developing their portions of the basin as well. Although many areas further north do register high hydrocarbon values, production in these areas is close to none. However, a pipeline has been approved for construction, the Mackenzie Valley Pipeline, which would travel through these high value areas to connect them with southern markets.

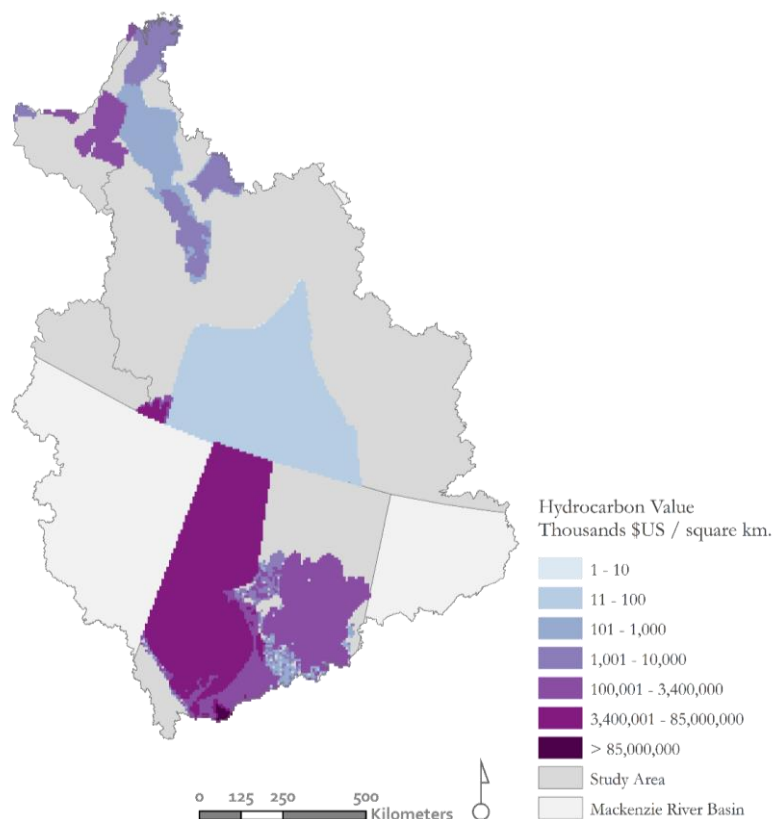


Figure 3.2. The most valuable hydrocarbon resources are in the southern portions of the study region (darkest purple). A history of oil and natural gas production and exploration in the south have yielded more specific reserve estimates and spatial extents. Therefore, the spatial resolution is higher in those areas, compared to northern section, in which estimates are applied uniformly across entire geologic formations.

Minerals

The highest value minerals in this analysis were diamonds, which primarily occur in the northeastern portions of the NWT (**Table 3.9, Appendix 11**). These Diamond leases are owned by some of the same companies (Dominion and Harry Winston) that own Ekati and Diavik Diamond Mines, Canada's largest diamond mines (Diavik Diamond Mine, n.d.). Coal was the second highest value mineral resource, and was concentrated near the southwestern edge of the Alberta portion of the study region (**Figure 3.3**). While the NWT has most PIM mining activity, these activities have a relatively small footprint, and lower total value than these other two mineral resources (**Table 3.9, Appendix 11**).

Table 3.9. Resource value estimates (in billion US\$) for each of the three mineral commodity types valued

Commodity	Total Value (Billion US\$)
PIM	79
Coal	269
Diamonds	867
Total	1,215

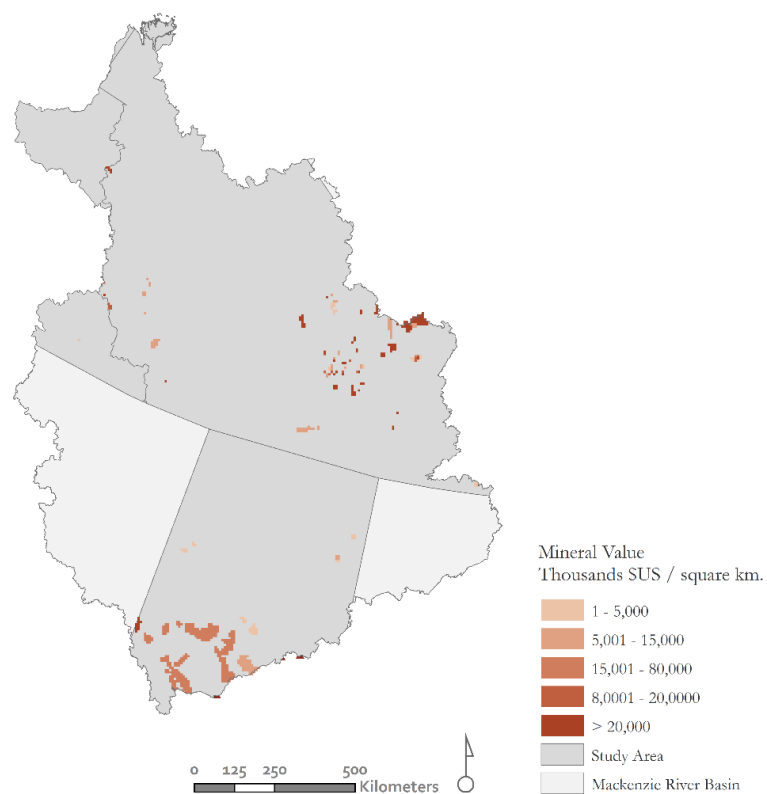


Figure 3.3. The most valuable mineral areas within the study region are the diamond mines in eastern Northwest Territories (darkest red), while the most contiguous deposits are the coal mines in southern Alberta (lighter red).

All Resources

The value of oil and natural gas combine with their enormous quantities to make hydrocarbons the most valuable resources within the MRB (**Figure 3.4**). The most valuable hydrocarbons were unconventional natural gas and oil deposits, followed by bitumen. Because the majority of conventional and unconventional oil and natural gas evaluations and all oil sand operations occur in Alberta, the southern portions of our study area are disproportionately more valuable than the northern portions. Interestingly, the single most valuable area within the MRB is the southern tip of the study region, in Alberta. This is one of the only areas where significant mineral reserves (coal), unconventional natural gas and oil, timber, and conventional oil and natural gas resources exist together (**Figure 3.4**).

Within the NWT, the highest value areas are the Central Mackenzie Valley (Western Central section of NWT), the diamond mining operations in the eastern portion of the territory, and the Liard Basin in the southwest corner of the NWT. The portion of Yukon which lies within the MRB has the lowest land value as judged by the resources evaluated in this study. The most valuable area within Yukon is the Liard Basin. The majority of valuable timber overlays hydrocarbon reserves, owing to the fact that no commercial sawmills were located in the NWT or Yukon.

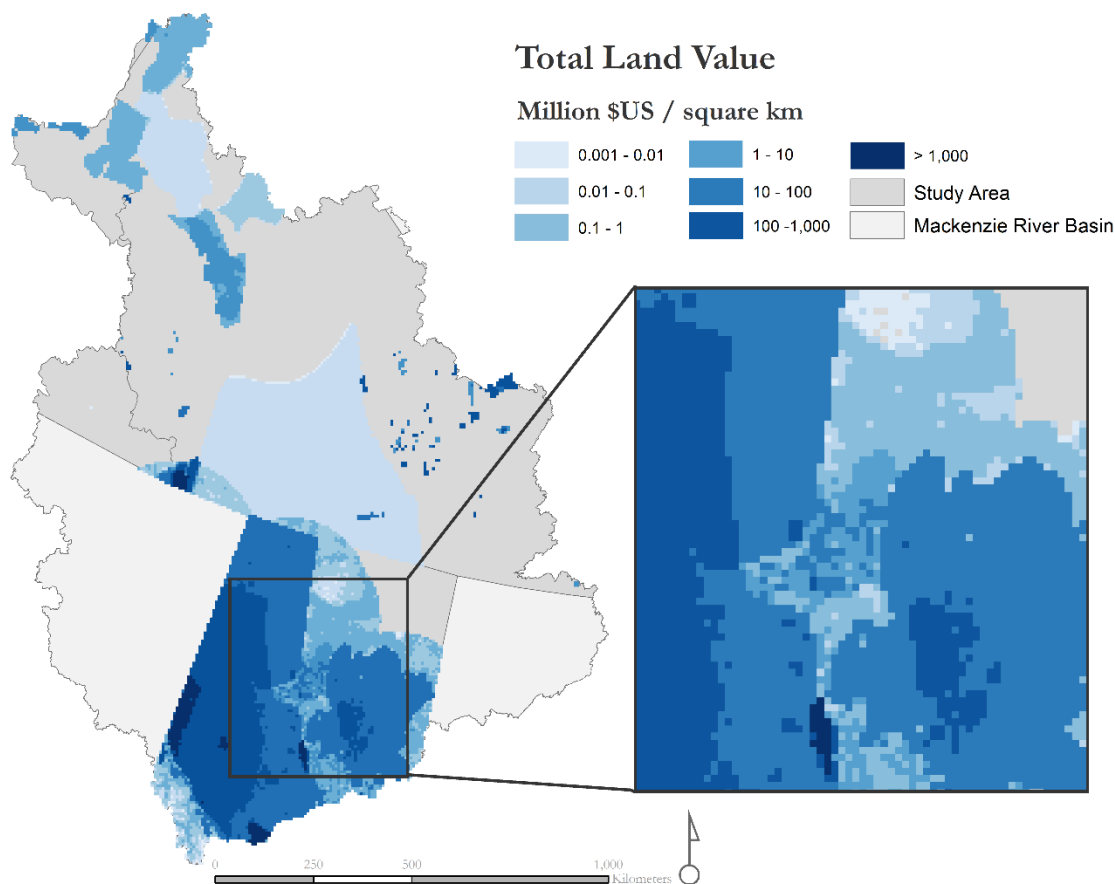


Figure 3.4. Total land values in million \$US per square kilometer. Total is the sum of timber, hydrocarbons, and mineral resources.



Reserve Design



Chapter 4. Optimal Reserve Design

Overview

A popular strategy for reserve creation is target-based conservation planning, where targets can be defined as minimum amounts of the distribution of species, vegetation type, or other biodiversity feature intended for conservation (Carwardine, Klein, Wilson, Pressey, & Possingham, 2009). In target-based planning, there are three main site selection formulations—mathematical methods to solve a problem—that are used to guide reserve design. These formulations are the minimum set, maximum coverage, and benefit function formulations (Moilanen, 2007)⁴. Our project utilizes the minimum set formulation, which attempts to achieve strict conservation targets at minimal costs. (Pressey, Possingham, & Day, 1997).

MARXAN is a conservation software designed to achieve a minimum ecological target at the lowest possible cost, and is a widely used tool for reserve planning using the minimum set formulation (Game, Watts, Wooldridge, & Possingham, 2008; Zhang, Laffan, Ramp, & Webster, 2011). The underlying basis for a minimum set reserve is that a less economically disruptive reserve is more likely to be implemented. MARXAN was primarily chosen due to its ability to address the class of conservation planning problems needed to meet our defined objectives. Furthermore, its popularity as a conservation planning software and ease of use will allow others to more easily interpret our results.

Methods

MARXAN comparatively selects an optimal solution using a mathematical objective function (**Equation 4.1**; Game & Grantham, 2008).

$$Score = \sum_{PU} Cost + BLM \sum_{PU} Boundary\ Length + \sum_{CV} SPF * Penalty$$

Equation 4.1. MARXAN objective function.

In this equation, cost refers to the land value placed on each unit of land—or planning unit (PU)—included within the reserve. For this analysis, this is the economic value for timber, hydrocarbons, and minerals (**Chapter 3**). This cost per PU is then added to the sum of the boundary lengths of each PU, and multiplied by the boundary length modifier (BLM). The BLM is a multiplier applied to the boundary length that gives reserves with less connected PUs (ie. a reserve with a larger boundary length) a higher, or worse, score. The boundary length is a measure of the perimeter of the reserve with less connected reserves having a larger perimeter. The final value refers to the sum of the penalties for not achieving a conservation value, summed over all conservation values and over all PUs. This

⁴The maximum coverage formulation attempts to achieve the maximum number of targets for a defined maximum cost. The benefit function formulation uses the set target more as a guideline, and values reserves based on how much over or under its targets the reserve is (Moilanen, 2007).

penalty is multiplied by a species penalty factor (SPF), which is user defined and forces MARXAN to reach species conservation targets. A higher SPF places greater emphasis on ensuring targets are met. These three variables are summed to produce an overall score. MARXAN runs repeated simulations to produce a reserve output with the lowest score as the ‘best’ reserve. For the MRB this would mean that restrictions to natural resource extractions have been minimized in a fashion that most effectively limits destruction to caribou habitat and thereby maximizes the conservation value of the reserve. This method thus designs a reserve that accounts for a diverse set of economic, social, and ecological pressures and is therefore more likely to be implemented. The necessary inputs to the objective function include a conservation layer, cost layer, and a determination of the optimal BLM, and SPF (Game & Grantham, 2008). For this analysis, we used MARXAN version 2.4.3 (Ball & Possingham, 2011).

Data

The data layers include a cost layer—our results in Chapter 3—and a conservation layer—our MaxEnt results from Chapter 2. Parameters such as the BLM and SPF were determined through sensitivity analyses, explained below. Additionally, MARXAN requires that the study region be divided into PUs. For our analysis, a grid of equal sized PUs (50km²) was created. This PU size reflects the low range of caribou home range sizes, allowing our reserves to better account for the scale at which caribou use the landscape (Faille et al., 2010).

Cost Layer

Using the estimated values of the timber, hydrocarbon and minerals industries in the MRB, we assigned cost values to each PU within the study region. Because our cost estimates were at a kilometer scale, we averaged all the costs per industry occurring within each PU. We then summed the costs/km² for each industry to produce a total cost/km²/PU. This method therefore assumed that timber harvesting, mineral and hydrocarbon extraction can occur simultaneously in the same PU.

Conservation Layer

To assign conservation value across the MRB, the MaxEnt model outputs (**Chapter 2**) were used to broadly define habitat as either suitable or unsuitable. Delineation of suitable and unsuitable habitat was determined using the “Maximum Training Sensitivity Plus Specificity” logistic threshold - a MaxEnt model output (Liu, Berry, Dawson, & Pearson, 2005; Phillips, Anderson, & Schapire, 2006). Using this threshold, a binary display was generated for the historical MaxEnt model and each of the eight AOGCMs MaxEnt models under our two projected emissions scenarios (RCP4.5 and RCP8.5). These binary outputs (eight for each the historical and the two emissions scenarios) were then added to the NWT and Alberta Government produced caribou ranges to create the final conservation layer (Environment Canada, 2012; COSEWIC, 2014).

Three main conservation layers were created; one for each emissions scenario and one for historical habitat. For the two emissions scenarios, the level of conservation value was based on model

agreement. Model agreement was the level of overlap between the binary MaxEnt model outputs for the eight AOGCMs, the binary MaxEnt model output using historical data, and the Government ranges. The level of overlap, or the consistency with which models reported a PU as suitable, was used to generate a conservation value. The conservation value ranged from 0-3. While the Government ranges and historical model binary outputs were both given a value of 1, each of the eight AOGCM model's binary outputs was given a value of $\frac{1}{8}$. Therefore, if all eight AOGCM climate models within a given emissions scenario agreed, a PU was valued at 1. If, in addition, the historical model agreed with these eight AOGCM models, a PU was given a 2. Finally, if the Government ranges agreed with the climate and historical models, the PU was given a value a total value of 3. These values were averaged and assigned to each PU. Therefore, each 50km² PU contained in the MRB was assigned a continuous value between 0-3. The emphasis was placed on historical habitat due to the uncertainty inherent in predicting future species ranges based on climate change projections.

The conservation layer for the historical habitat analysis was generated using the same method of model agreement. However, agreement was solely based on the Government ranges and the MaxEnt historical model. Therefore, the conservation values ranged from 0-2. An additional conservation layer was generated that used only the agreement between the eight AOGCM climate models under the RCP8.5 emissions scenario. This layer was created as a proxy for a reserve under an extreme emissions scenario. The conservation values for the only RCP8.5 emissions scenario ranged from 0-8 with each of the eight AOGCMs being equally weighted.

Planning Unit Status

MARXAN allows users to account for current land-use or status within PUs by always including or always excluding particular PUs. We chose to always include PUs within existing protected areas, and always exclude PUs occurring on private land or pre-existing industrial footprints. We chose to always include national parks under the assumption that it is easier to expand pre-existing national parks than it is to create new protected areas.

Analysis

Ecological Target Setting

Conservation targets are the requirement MARXAN must meet while generating the least cost reserve. Our objective was to determine the impacts and feasibility of a range of different reserve sizes based on these conservation targets. Therefore, we analyzed three conservation targets of 17%, 50% and 80% of the ranges of each of the three caribou ecotypes. The 17% caribou range target was set as the lowest target as Canada has committed to protecting 17% of its terrestrial lands and inland waters by 2020 (CPAWS, 2015). The 80% caribou range target was set as our highest target as some conservation proponents have suggested protecting up to 80% of the sensitive watersheds within the MRB (Protect the Peel, n.d.).

BLM and SPF Determination

To increase reserve connectivity, we chose a BLM that would allow MARXAN to prioritize reserve connectivity without jeopardizing reserve costs or conservation value. To determine our desired BLM we ran MARXAN with a range of BLM values and plotted the boundary length associated with the reserve outputs against the costs of the reserve (**Figure 4.1**). Based on the figure, a BLM value of 100 was chosen as it maximized reserve connectivity while minimizing costs.

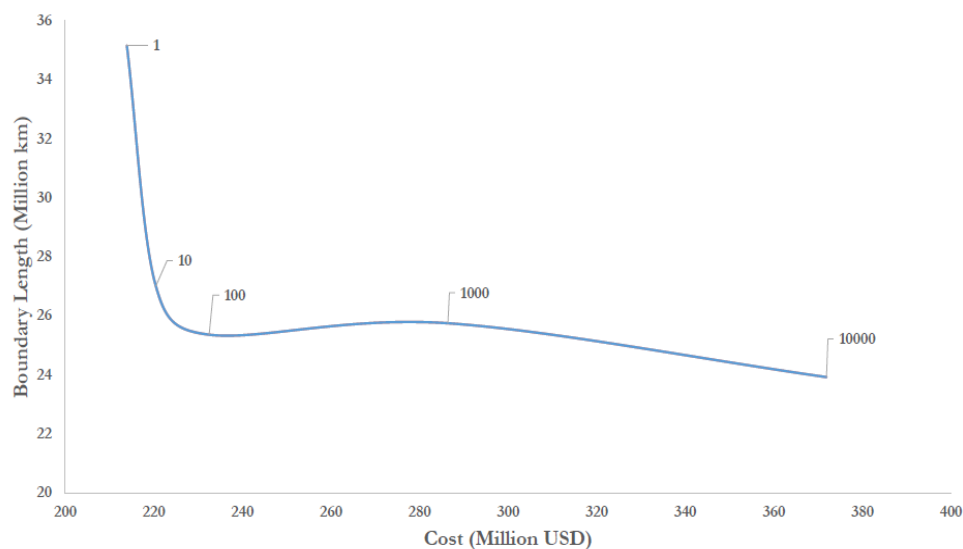


Figure 4.1. Exploratory analysis to determine the appropriate boundary length modifier (BLM) for MARXAN. Reserve cost (million \$US) is shown on the x-axis and total boundary length of reserve (million km) on the y-axis. Numbers above blue line represent BLM values used in exploratory analysis. A BLM of 100 was used as it was deemed an appropriate level of trade-off between reserve cost and total boundary length.

Much like the BLM, the SPF must be set high enough to achieve targets, but not so high that reserve costs are disproportionately high. The standard method to determine SPF is to iterate through a range of values until all targets are met at the lowest SPF (Game & Grantham, 2008). We therefore increased SPF values incrementally by factors of 0.1 starting at 0. The SPF can be utilized to place a higher relative importance on different conservation features. We chose to equate the three caribou ecotypes and therefore only used the SPF to ensure that all targets were met. We found that SPF values needed to be set differently across the three ecotypes, depending on the emission scenario and target set (**Appendix 12**).

We ran MARXAN once for each conservation target (17%, 50% and 80%) and emission scenario (historical, RCP4.5, RCP8.5, and only RCP8.5). Each MARXAN run included 1000 simulations of possible reserve outcomes.

Results and Discussion

The 17% reserves created using the three projected emission scenarios (RCP4.5, RCP8.5, Only RCP8.5) all looked highly similar, however all three differ slightly from the 17% reserves created using the historical climate scenario (**Figure 4.2**). The difference is most apparent in the northern portions of the study region as the reserves created under the three emissions scenarios appear to prioritize connectivity between the northern protected areas (**Figure 4.2**). The irreplaceability, which is a metric of how often a PU of land was chosen during each MARXAN run, is similar across all four scenarios. Few PUs had a high value of irreplaceability in the 17% reserves as the targets are low enough to allow MARXAN a great deal of flexibility in which PUs it chooses. Highest irreplaceability is in the protected areas across all scenarios as they were chosen in every MARXAN iteration (shown in dark red in **Figure 4.2**). These results indicate that at 17% protection of caribou range, a change in emissions scenarios does not have a drastic effect on reserve design.

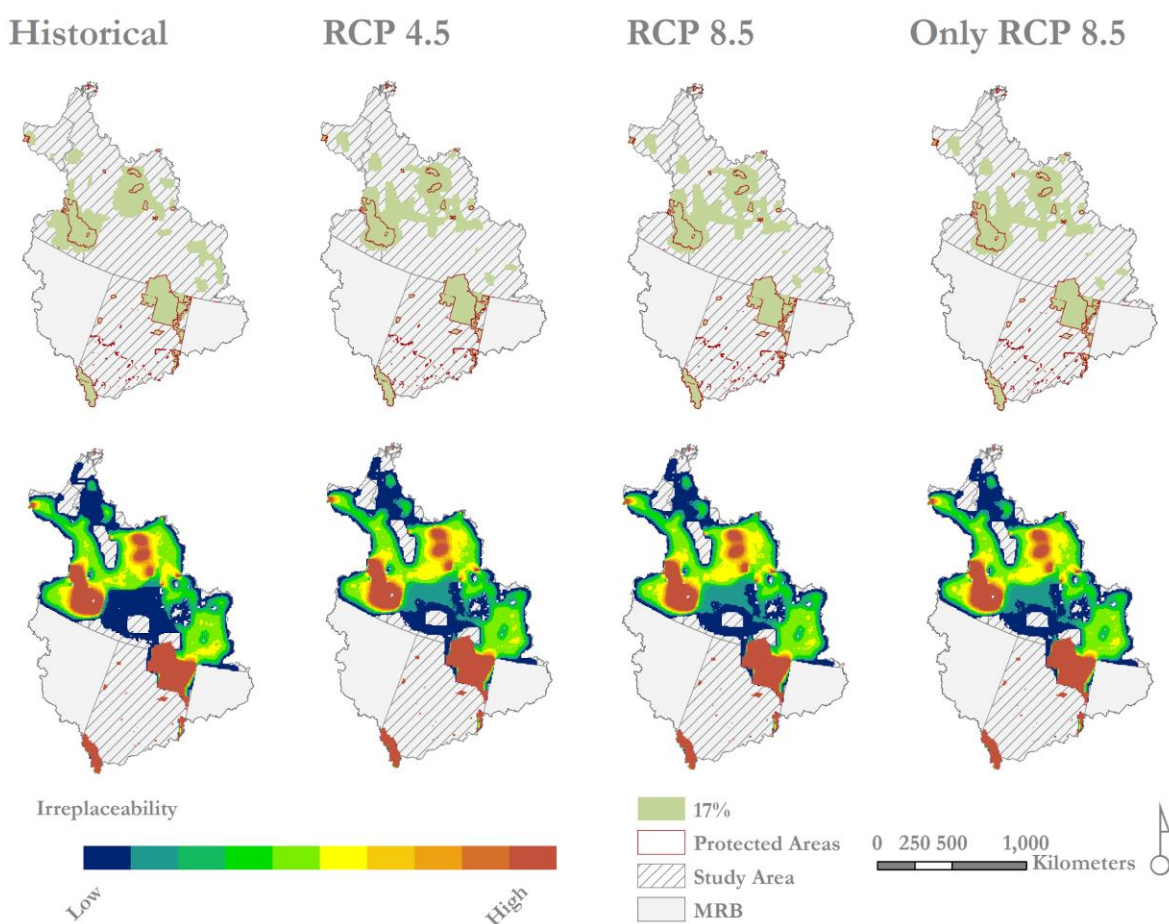


Figure 4.2. MARXAN reserve outputs for 17% conservation target under four emission scenarios—Historical, RCP4.5, RCP8.5, and Only RCP8.5. Only RCP8.5 refers to a conservation layer that only used outputs from the eight AOGCMs and did not include historical or government ranges. Top row: MARXAN ‘best’ solution in green and protected areas as red outlines. Bottom row: planning unit (PU) irreplaceability. Warmer colors are PUs that are chosen more often by MARXAN.

With the 50% reserves, there is a larger difference between the scenarios. Historical and RCP4.5 scenarios are similar to each other, but differ slightly from the RCP8.5 and the only RCP8.5 scenarios (**Figure 4.3**). Reserves created with 80% caribou range targets were the most similar between emission scenarios, as is highlighted by the increased number of PUs with high irreplaceability (**Figure 4.4**). All reserve outputs demonstrated how MARXAN used pre-existing protected areas as ‘seeds’ from which to build reserve outputs. In some instances, MARXAN is unable to build on the pre-existing protected areas as the land around these areas is too costly and therefore creates islands within the reserve network (eg. protected areas in the central and western regions of Alberta). In general, we find that the 50% reserves build off the 17% reserves and the 80% reserves build off of the 50% reserves (**Appendix 13**).

Conservation targets of 17%, 50%, and 80% resulted in variable degrees of total area protection in the study region, ranging from an average of 24.6% for the 17% caribou range targets to an average of 70% for the 80% caribou range targets (**Table 4.1**). The greatest variation in total area protected was observed between the four emissions scenarios at the 80% conservation target (**Table 4.1**). Despite this variation, however, it appears that the relationship between percent of caribou range protected and percent of total area protected is linear. Reserves built using the historical scenario and the extreme emissions scenarios (RCP 8.5 and only RCP 8.5) tended to cover most of the same areas, with a few regions being represented in only one emissions scenario (**Figure 4.5**). However, it is important to note that the emissions scenarios used do not take into account secondary impacts of a warming climate such as fire. Addition of potentially important secondary impacts of a warming climate may result in a more drastic difference between the reserves designed under the three emissions scenarios.

Table 4.1. Percent of study area protected under each conservation target (17%, 50%, 80%) and emission scenario (Historical, RCP4.5, RCP8.5, Only RCP8.5). Percent of region protected is based on MARXAN ‘best’ reserve out of 1000 iterations. Only RCP8.5 refers to a conservation layer that only used outputs from eight AOGCMs and does not include historical or government ranges.

Conservation Target (%)	Emission Scenario	Protected (%)
17	Historical	23.5
	RCP4.5	24.3
	RCP8.5	24.3
	Only RCP8.5	24.3
50	Historical	40.8
	RCP4.5	41.1
	RCP8.5	41.1
	Only RCP8.5	39.3
80	Historical	67.3
	RCP4.5	71.3
	RCP8.5	70.7
	Only RCP8.5	69.2

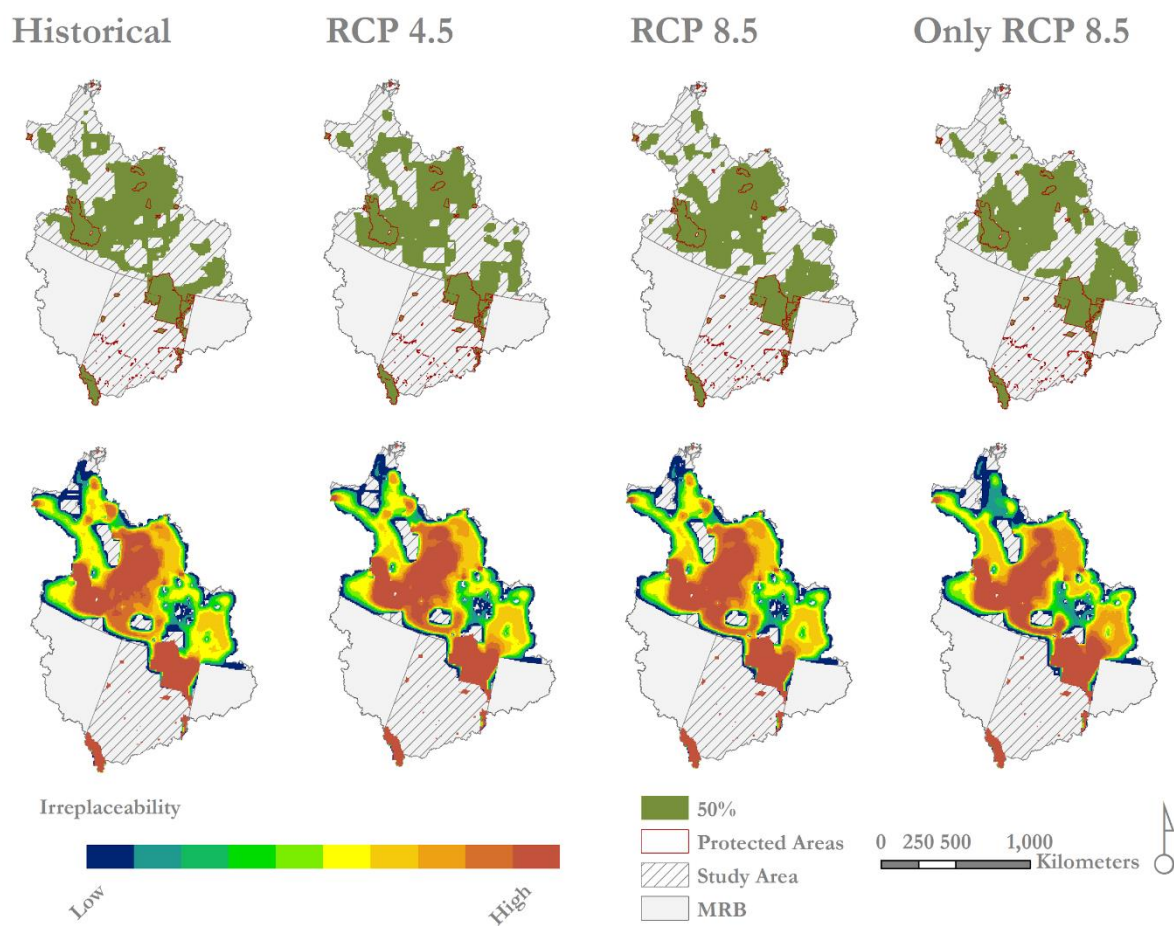


Figure 4.3. MARXAN reserve outputs for 50% conservation target under four emission scenarios—Historical, RCP4.5, RCP8.5, and Only RCP8.5. Only RCP8.5 refers to a conservation layer that only used outputs from the eight AOGCMs and did not include historical or government ranges. Top row: MARXAN 'best' solution in green and protected areas as red outlines. Bottom row: planning unit (PU) irreplaceability. Warmer colors are PUs that are chosen more often by MARXAN.

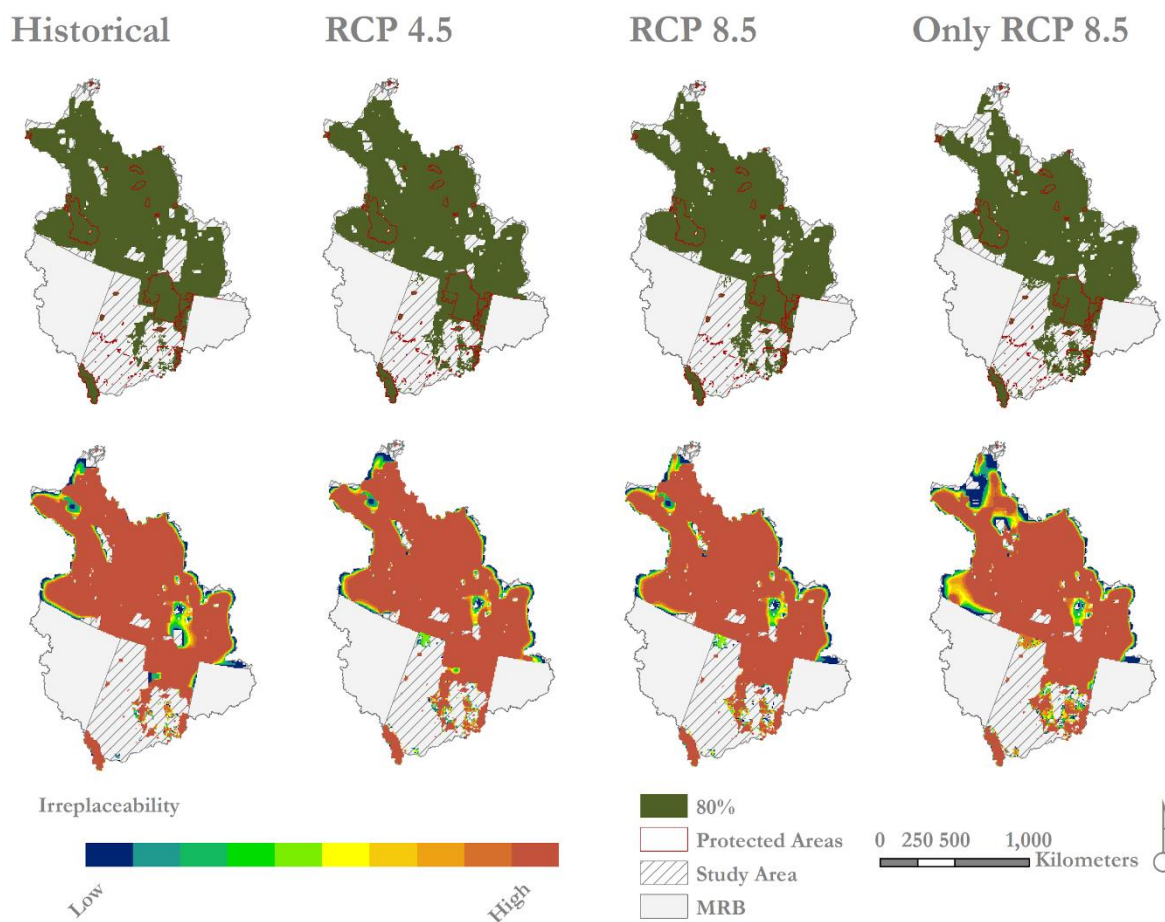


Figure 4.4. MARXAN reserve outputs for 80% conservation target under four emission scenarios—Historical, RCP4.5, RCP8.5, and Only RCP8.5. Only RCP8.5 refers to a conservation layer that only used outputs from the eight AOGCMs and did not include historical or government ranges. Top row: MARXAN 'best' solution in green and protected areas as red outlines. Bottom row: planning unit (PU) irreplaceability. Warmer colors are PUs that are chosen more often by MARXAN.

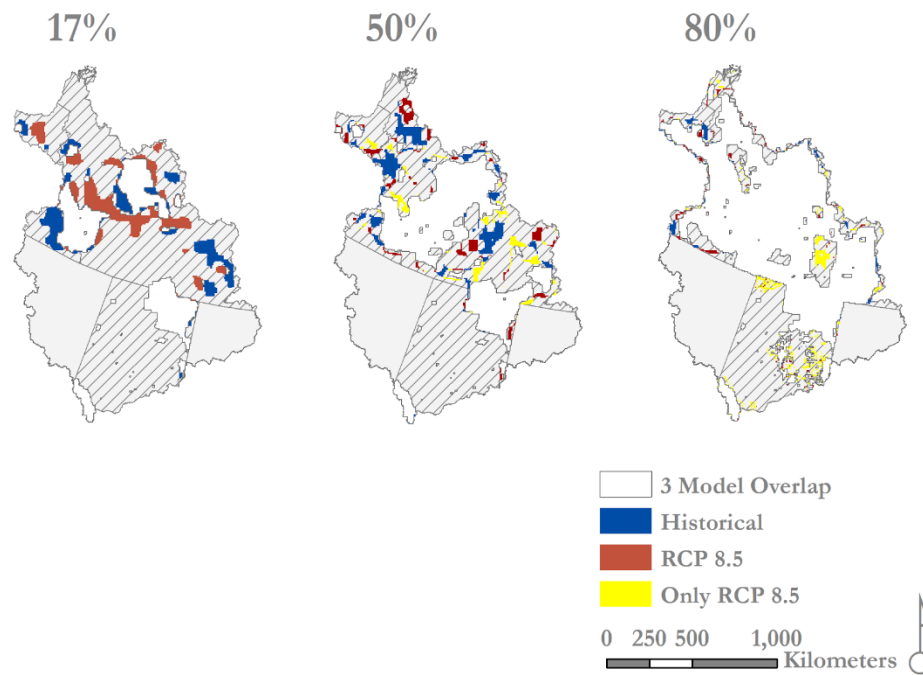


Figure 4.5. MARXAN 'best' reserve output comparison for each of the conservation targets. Reserve overlap is between historical, RCP 8.5, and only RCP 8.5 reserves shown in white. Blue represent unique areas in the historical reserves, red represent unique areas in the RCP8.5 reserves, and yellow represent unique areas in the only RCP8.5 reserves. Areas between two model overlap are not shown.



Reserve Design Effectiveness

Chapter 5: Reserve Design Effectiveness

Overview

Determining the least cost option to achieve set conservation objectives has become a popular method of reserve design as it incorporates the socioeconomic aspects of implementation into the conservation planning process (Pressey & Bottrill 2008). However, while these reserves may be more appealing to the stakeholders involved, their efficacy is dependent on their ecological representativeness, and not only on their cost (Margules & Pressey 2000). An optimal reserve would therefore have high ecological representativeness of the biodiversity present on the landscape, while also having low cost and equitable socioeconomic impacts. A quantitative analysis of the efficacy of our reserves depends on analyzing a multitude of ecological variables and conservation targets, making it beyond the scope of this project. However, to begin to explore whether our reserves were effective, we examined several proxies that are likely indicators of a reserve's ability to conserve biodiversity and ecosystem services. We studied four ecological indicators—ecozones, major river sub-basins, land cover types, and kilometers of major rivers—and one socioeconomic indicator—proportion of each territory and province covered by the reserve. These proxies, when compared to the cost of the reserve, can serve as a preliminary understanding of the ecological and socioeconomic impacts of reserve implementation in the MRB.

Methods

Data

Data used in this section of the analysis were results found in Chapter 4 and published data regarding ecozones, land cover, major river sub-basins, and rivers, as well as the territories and provinces of Canada. Ecozone spatial data came from the Government of Canada's National Ecological Framework database. Land cover data was from the North American Land Change Monitoring System (2010). Provincial and territorial boundaries and sizes were provided by Natural Resource Canada's Geopolitical Boundaries and Administrative Boundaries for Canada Lands dataset.

Analysis

Ecological Representativeness

The first indicator of ecological representativeness analyzed was ecozones. Ecozones are ecological zones classified by similar climate, habitats, and species assemblages, and therefore can be used as a proxy for the biodiversity of the MRB (Wiken, 1986). Using an umbrella species assumes that a single species, in our case caribou, adequately represents regional biodiversity within its range (Roberge & Angelstam 2004). In this case, we assume that the umbrella species protects the diversity within its range, regardless of which ecozone it is in. If the reserve effectively covers these broad biogeographic

divisions, it can be asserted that on a coarse scale, our reserve networks are protecting a large distribution of terrestrial organisms (Roberge & Angelstam 2004). Of the 15 ecozones in Canada, nine exist within the MRB, with the taiga plain, taiga cordillera, taiga shield, and boreal plain covering the most area (**Appendix 1**). The prairie ecozone is marginally present along the eastern edge of the study region. This ecozone covers so little area within the MRB study region that it only overlapped 11 planning units, and none of these planning units was included in any of the reserve outputs. Therefore, this ecozone was excluded from further analyses. The proportional cover of each ecozone type was determined for each of our reserves. These proportions were dependent on total ecozone area present within the study region.

The second ecological indicator we examined was land cover type. The original land cover dataset was reclassified from its original 15 categories to nine categories (**Table 5.1**). This was done to account for the broad habitat categories of interest within the Basin. Eight of the new categories created describe the natural system, while the ninth describes anthropogenic land-use features. Few, if any, of these anthropogenic features were included within our reserves as they were generally excluded as private land. We then determined the proportion of each natural land cover type available in the study region that was protected by each of our reserves. Land cover data was reported on a 250m resolution.

Table 5.1. Reclassified land cover dataset from 15 categories to nine categories.

Original Land Cover Type	Reclassified Land Cover Type
Temperate or Sub-polar Needleleaf Forest	Needleleaf Forest
Sub-polar Taiga Needleleaf Forest	
Temperate or Sub-polar Broadleaf Deciduous Forest	Deciduous Forest
Mixed Forest	
Temperate or Sub-polar Shrubland	Shrubland
Polar or Sub-polar Shrubland-lichen-moss	
Temperate or Sub-polar Grassland	Grassland
Sub-polar or Polar Grassland-lichen-moss	
Barren Land	Lichen-moss
Barren-lichen-moss	
Wetland	Wetland
Water	Water
Snow and Ice	Snow and Ice
Cropland	Anthropogenic Land-use
Urban and Built-up	

For our third ecological indicator, the degree to which our reserves protected freshwater ecosystems, we examined how well each of our reserves covered each of the 6 major river sub-basins within the

MRB (**Appendix 14**). This analysis was very similar to the ecozones analysis, in which we examined what proportion of each sub-basin present in the study region was included within each of the reserves. Finally, we calculated the number of kilometers of each major river included within our reserves as our fourth ecological indicator, in order to estimate how this protection translated to actual protection of each major river.

Socioeconomic Impacts

Reserve feasibility and socioeconomic impacts were assessed by examining how reserve outputs impacted the territories and provinces within the study region and also how they impacted each of the three natural resource extraction industries. Much like the ecozone analysis, the impact of the reserves on the territories and provinces was determined by examining how much of each territory and province within the MRB was included in the reserves.

Economic losses overall and to each industry were assessed by comparing the cost of the planning units included in the MARXAN reserve outputs. Losses to the individual industries were assessed by examining the industry's estimated value within each planning unit included in the reserve. Total dollar estimates were produced by multiplying the average per km² value by the size of the planning unit (i.e., 50km²). This generated a total value for each PU. For this analysis, we did not include the value of resources within pre-existing national parks as potential lost revenue to each of the major industries. This was done under the assumption that any current resource extraction occurring within National Parks (e.g., timber harvest in Wood Buffalo National Park) will continue.

To further examine how different conservation target setting schemes may result in various socioeconomic impacts, we investigated two different conservation target methods. In these analyses, we tried to equally represent each ecozone and major river sub-basin. To do this we set the same percentage targets (ie. 17%, 50% and 80%) of caribou range, but made these targets specific to caribou range lying within each of the eight ecozones or six major river sub-basins of the MRB. We then examined how the costs of reserves created using only caribou ranges compared to those created using caribou ranges and these additional ecological targets. The goal of this analysis was to estimate the relative cost of creating reserves with more ecological representativeness.

Results and Discussion

Ecological Representativeness

Ecozones - The majority of ecozones were well represented by the reserves created under each caribou range protection target (17%, 50% and 80%) and each emissions scenario (Historical, RCP4.5, and RCP8.5). At equal caribou range protection targets, there was little difference in the relative proportion of ecozones protected between the three emission scenarios (**Figure 5.1**).

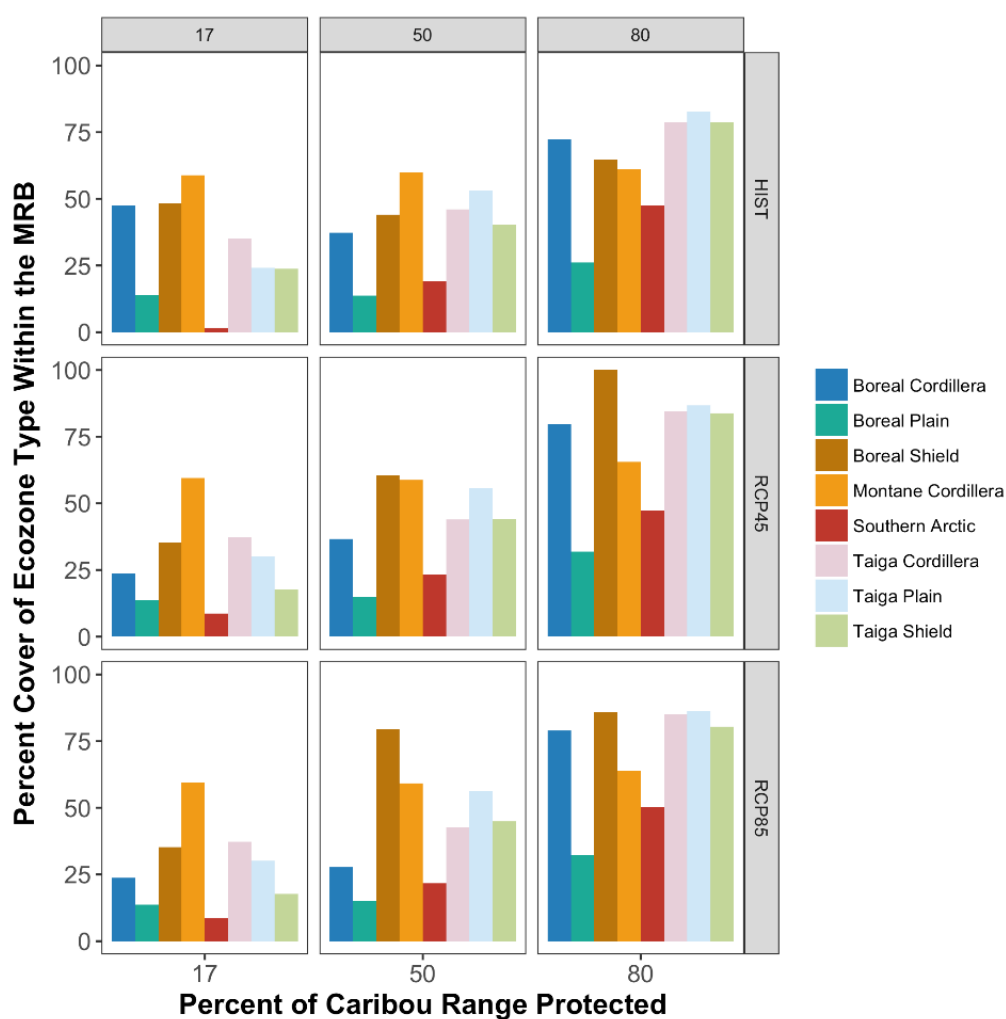


Figure 5.1. Percent cover of the eight ecozones within our study area under three emission scenarios (Historical (HIST), RCP4.5, RCP8.5) and the three protection targets (17%, 50%, 80%).

However, there was a consistent relationship between the proportions of each ecozone covered within the reserves at each level of caribou range protection assessed. Representative reserves would ideally protect proportions of the ecozone types present in the MRB that are equal to or greater than the conservation targets set. Our results show this to be the case, with many ecozones being protected at, or near, 17% in the reserves created using 17% caribou conservation targets. Notable exceptions include the boreal plains and southern arctic ecozones, which are significantly underrepresented within these reserves (**Appendix 1**). At 50% caribou range conservation, all but the same two ecozones and the boreal cordillera are well represented at, or close to, 50% coverage. At 80% caribou conservation this trend continues with all but the boreal plains and southern arctic ecozones being represented at, or close to, 75% cover. This trend therefore suggests that caribou is an effective umbrella species for the majority of the diversity present within the MRB.

The two consistent exceptions to this trend are the boreal plains and southern arctic ecozones, which are underrepresented in all reserve outputs. The boreal plains ecozone lies almost entirely within Alberta. Human activity within this ecozone has already resulted in four vertebrate species disappearing from the area—the plains grizzly, swift fox, black-footed ferret, and the greater prairie chicken (Wildlife of the Boreal Plains Ecozone, n.d.). According to the Status of Endangered Wildlife in Canada, at least an additional six species, including the whooping crane and woodland boreal caribou, are classified as endangered and threatened (Wildlife of the Boreal Plains Ecozone, n.d.; Alberta's Boreal Forest Region, n.d.). This is likely due to the presence of high value timber and hydrocarbon resources in this portion of Alberta (**Figure 3.4**).

Given the land value associated with the boreal plains, it is not particularly surprising that all reserves would under-represent this economically high value region. Furthermore, boreal caribou protection targets can be achieved by protecting more land to the north in the NWT, where their ranges tend to overlap with those of barren-ground caribou. We believe this overlap may also be a major contributing factor in the under-representation of the southern arctic ecozone. Given that PUs in which both ranges overlap have a higher cumulative conservation value for a relatively lower cost, MARXAN chooses to include these PUs within the reserves, reducing the total amount of reserve area. This highlights a shortfall of MARXAN's method of solving the minimum set problem, and of the umbrella species concept. While we assert that caribou are a generally good umbrella species for conservation at this scale, this result illustrates the fact that there are pieces of the system that may require additional protection than that afforded by a focus solely on caribou habitat.

Land cover - Reserves designed using each of the three emission scenarios resulted in similar land cover protection to the ecozone analysis (**Figure 5.2**). Of the available land cover types within the MRB, the 17% caribou conservation targets consistently represented the land cover types at, or above, 20%, while the 80% caribou conservation targets protected about 80% of most land cover types (**Figure 5.2**). Some land cover types (e.g., snow and ice, lichen-moss and deciduous forest) existed primarily in one province or territory; therefore, they were either consistently over— or under—represented according to how much of that province or territory was conserved within each reserve. Land cover types in Alberta were consistently under-represented in each reserve because of the extremely high value of the oil sands and natural gas industries in that province (**Figure 3.2**). Most deciduous forests exist within Alberta and are therefore less often protected within each of our simulated reserves.

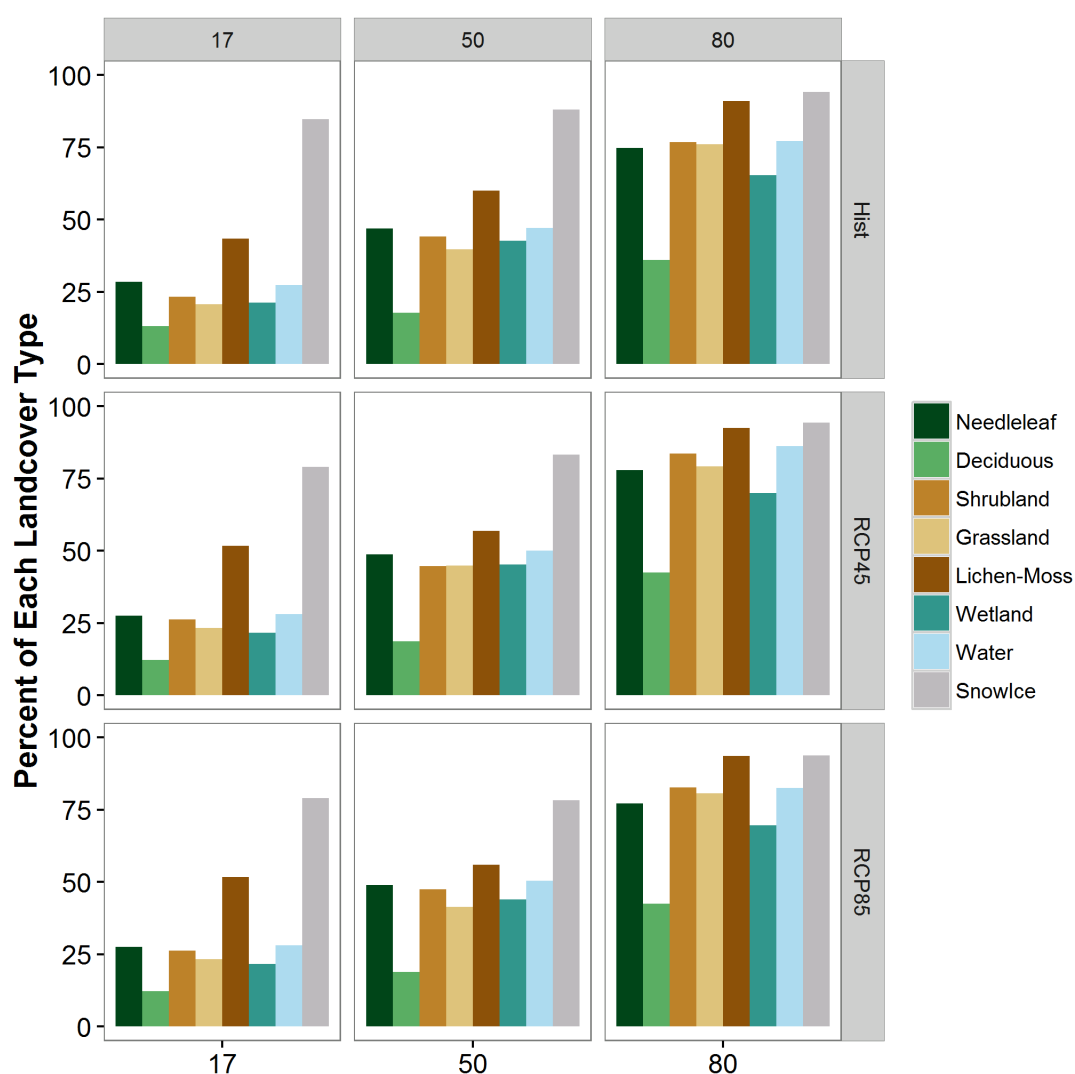


Figure 5.2. Percent cover of the eight land cover types, excluding urban built-up, within our study area under three emission scenarios (Historical (HIST), RCP4.5, RCP8.5) and the three protection targets (17%, 50%, 80%).

These deciduous forests are ecologically important: they make up the majority of the boreal plains ecozone, they are the greatest transition zone between grasslands and northern boreal forests in the world (Canadian Aspen forests and parklands, n.d.), and they have been defined by the World Wildlife Fund as an endangered habitat type (Canadian Aspen Forests and Parklands, n.d.). Additionally, they provide habitat for a high diversity of both plants and animals, namely songbirds, and waterfowl. However, caribou do not generally use deciduous forests, preferring instead to spend the majority of their time in needleleaf forests, wetlands, alpine, or barren-ground habitats (Environment Canada 2012). Because caribou don't prefer this land cover type, and because it exists within a high value region of the MRB study area, this area is consistently underrepresented in our reserves. This illuminates the need for habitat specific protection within Alberta, and suggests caribou habitat protection at the scale of the entire MRB is too coarse a method to properly protect certain highly sensitive habitats.

However, this analysis does show that increasing caribou conservation targets does substantially increase the protection of some land cover types with high ecosystem service values, such as needleleaf forests and wetlands. These two land cover types have some of the greatest ecosystem service values due to their potential for carbon sequestration and water filtration (DeGroot et al. 2012; Schindler & Lee, 2010; Dillon & Molot, 1996). Therefore, designing reserves based on caribou conservation targets protects some of the highest value ecosystem services in northern Canada.

An important consideration for the analyses described above is that they were completed using current ecozone and land cover classifications. These are based on current vegetation distributions; however, we have created reserves under two future emissions scenarios (ie. RCP4.5 and RCP8.5). Under these scenarios, vegetation ranges and assemblages are likely to shift. This is particularly true in far northern latitudes, where tree species range shifts have already been observed (e.g., Boisvert-Marsh et al. 2014). While modelling these species shifts is beyond the scope of this project, if any conservation actions are designed using reserves based on future caribou range predictions, potential vegetation range shifts will need to be taken into consideration.

Rivers and River Sub-basins - Another high value ecosystem service of the MRB is the provision of freshwater. We found that each reserve created under the three emissions scenarios protected similar amounts of each of the major river sub-basins in the MRB (**Figure 5.3**). However, we did find that, while 17% caribou conservation targets also protected nearly 17% of every major river sub-basin in the MRB, increasing protection to 50% had little effect on the overall protection of each of these sub-basins (**Figure 5.3**). The river sub-basins that were consistently under-represented were the Peace, the Athabasca, the Mackenzie and the Peel. The Peace and the Athabasca exist primarily in Alberta, the highest value portion of our study region; this is likely why they are consistently under-represented in each of the reserves (**Appendix 14**). Furthermore, the Peel river basin is found in the far northwestern corner of the MRB, where only northern mountain caribou ranges exist (**Appendix 14**). While this region also has few high value resources, it is likely that MARXAN reserves prioritize other portions

of the study region where more caribou ranges overlap. Furthermore, the Mackenzie river sub-basin is very large, and is therefore likely difficult to proportionally represent.

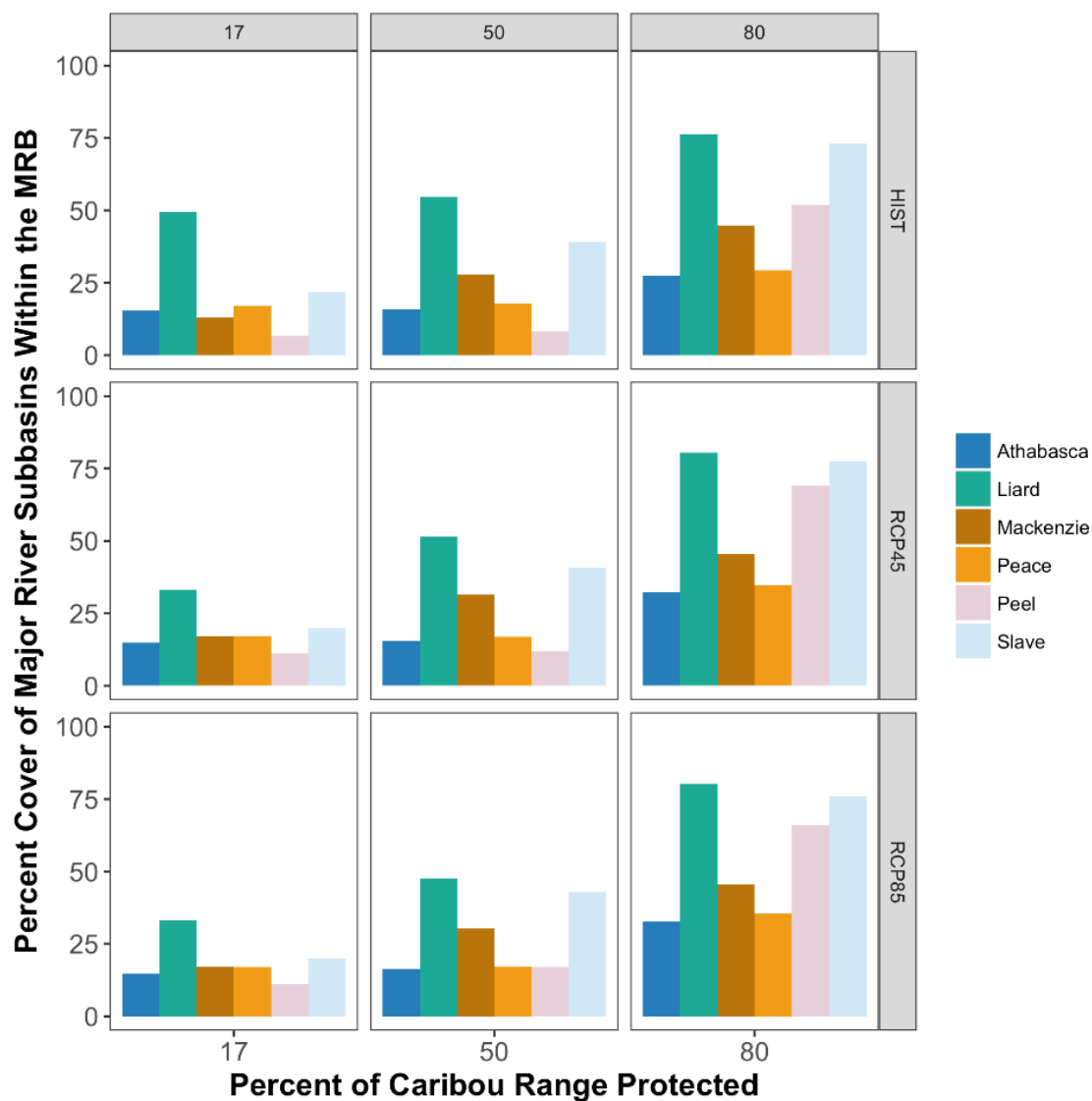


Figure 5.3. Percent cover of the six major river sub-basins within our study area under three emission scenarios (Historical (HIST), RCP4.5, RCP8.5) and the three protection targets (17%, 50%, 80%).

Analyzing how many kilometers of major rivers were protected within each of the reserves found that all reserves protected more than 60% of of major rivers within the MRB (**Figure 5.4**). This is significant as it suggests that while the major river sub-basins may be less well represented, the major rivers are generally well represented within each reserve. River systems are more than just water, as many are surrounded by high biodiversity riparian areas (Naiman et al. 1993).

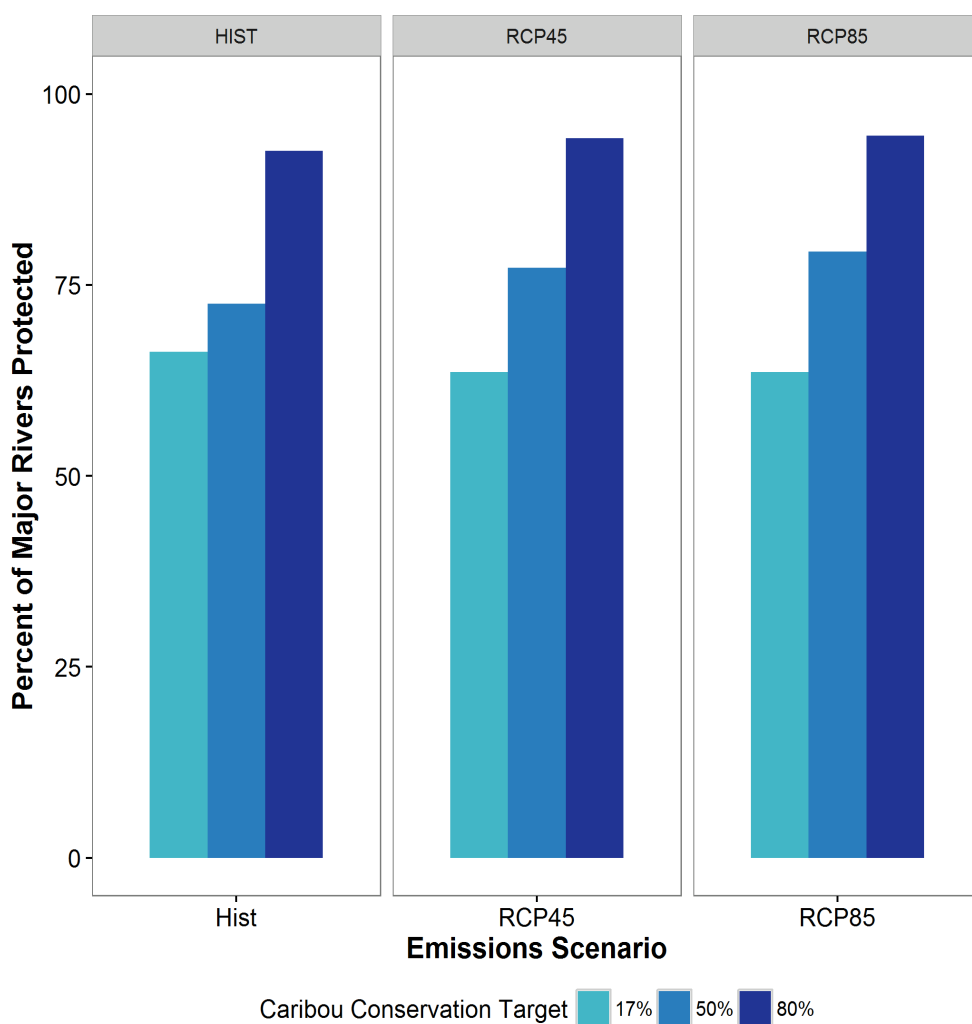


Figure 5.4. Percent cover of major rivers within our study area under three emission scenarios (Historical (HIST), RCP4.5, RCP8.5) and the three protection targets (17%, 50%, 80%).

Socioeconomic Impacts

Territories and Provinces - The design of our reserve was not restricted by provincial and territorial borders. Therefore, reserves could disproportionately represent the territories and provinces in the MRB. The primary result from this analysis showed that across the different percentages of caribou range protection, disproportionate amounts of the reserves lie within NWT (**Figure 5.5**).

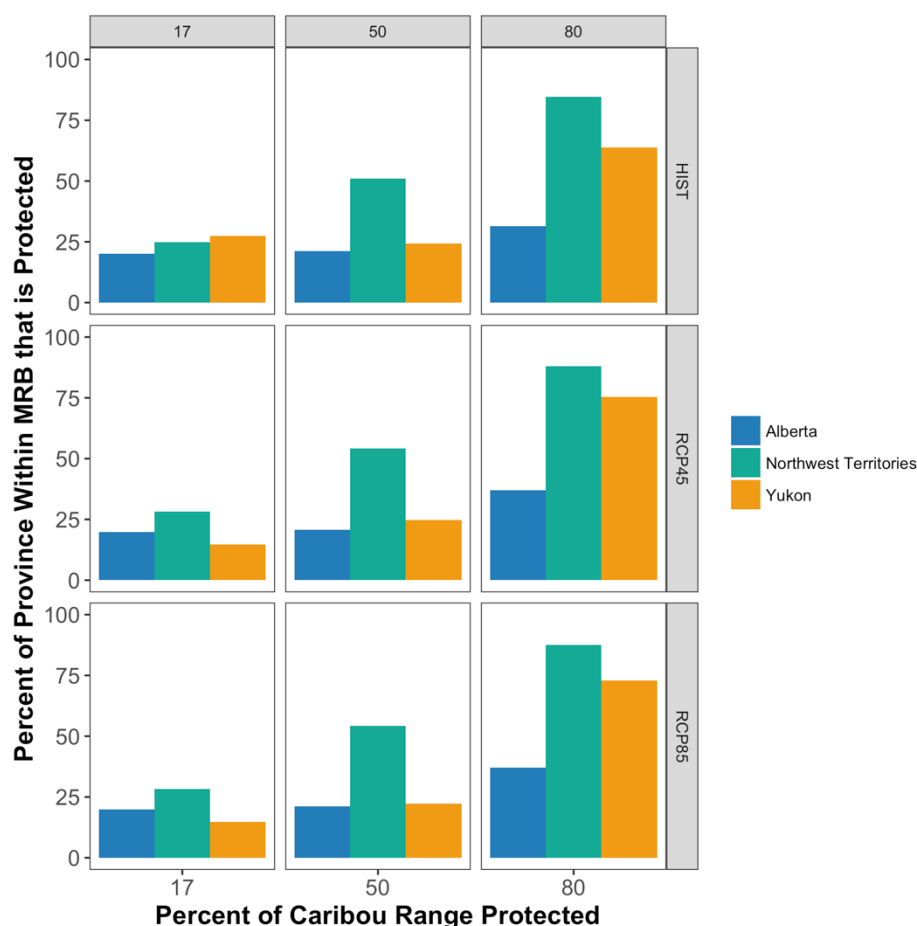


Figure 5.5. Percent cover of the provinces and territories within our study area under three emission scenarios (Historical (HIST), RCP4.5, RCP8.5) and the three protection targets (17%, 50%, 80%).

This is not particularly surprising for several reasons. First, the NWT occupies the majority of the MRB study region. Second, all three caribou ecotypes exist within the territory, giving it a higher conservation value. Finally, the NWT has relatively low natural resource values, which makes it a cost effective area to conserve. Alberta is consistently underrepresented in our reserve designs because of the presence of high value resources within it.

This result highlights potential challenges to reserve implementation in the NWT as the territorial government is less likely to support a reserve that hinders its economic growth to such a degree. However, in a survey of residents ($n = 456$) of the NWT, 90% said they supported the implementation of a protected area network that would limit timber harvest, as well as hydrocarbon and mineral resource extraction (Ekos Research, 2015).

Natural Resource Extraction - To account for the trade-offs between conservation and the economic development in the MRB, we valued the losses each reserve conferred on each of the three industries (**Table 5.2**). Most notably we found that increasing caribou range protection from 17% to 50% resulted in little substantial change in the revenue lost. Once protection was increased to 80% of caribou range, total revenue losses increased from an average of less than 0.1% to an average of 1.41% (a more than 14-fold increase in potential revenue lost). Furthermore, costs of reserves created using only caribou range remained relatively low until 70% conservation targets, beyond which costs increased exponentially. For all three caribou protection targets, the timber industry lost the greatest proportion of potential revenue (**Table 5.2**).

Reserves that focused on only protecting caribou ranges protected many, but not all, of the ecozones and river sub-basins within the greater MRB. To force these underrepresented areas into our reserves, conservation targets were set as percentages (17%, 50%, 80%) of caribou range and river sub-basins, and percentages of caribou range and ecozones. A comparison across reserves under the RCP 8.5 emissions scenario designed using only caribou conservation targets versus two alternative conservation target setting scenarios—inclusion of ecozones and major river sub-basins—revealed reserves incorporating protection of ecozones or river sub-basins were substantially costlier than those designed using only caribou range (**Figure 5.6**). Additionally, costs of reserves created using the two alternate conservation target setting scenarios increased exponentially starting at about 10%.

Table 5.2. Natural resource losses under each simulated reserve for each of the three industries—timber, hydrocarbons, and minerals.

Caribou Range Protected	Emission Scenario	Timber		Hydrocarbons		Minerals		Total	
		Million US\$	%	Million US\$	%	Million US\$	%	Million US\$	%
17%	Historical	7.69	0.77	1.74	<0.1	0	0.0	9.43	<0.1
	RCP4.5	5.13	0.51	.90	<0.1	0	0.0	6.03	<0.1
	RCP8.5	5.13	0.51	.90	<0.1	0	0.0	6.03	<0.1
50%	Historical	6.90	0.69	8.00	<0.1	0	0.0	614.9	<0.1
	RCP4.5	10.42	1.04	10.20	<0.1	0	0.0	20.62	<0.1
	RCP8.5	13.533	1.35	8.65	<0.1	0	0.0	22.18	<0.1
80%	Historical	165.72	17.0	10,726	0.97	70.40	0.11	10,962	0.94
	RCP4.5	233.57	23.36	18,984	1.72	96.54	0.15	19,314	1.65
	RCP8.5	239.94	23.99	20,403	1.85	96.54	0.15	20,739	1.77

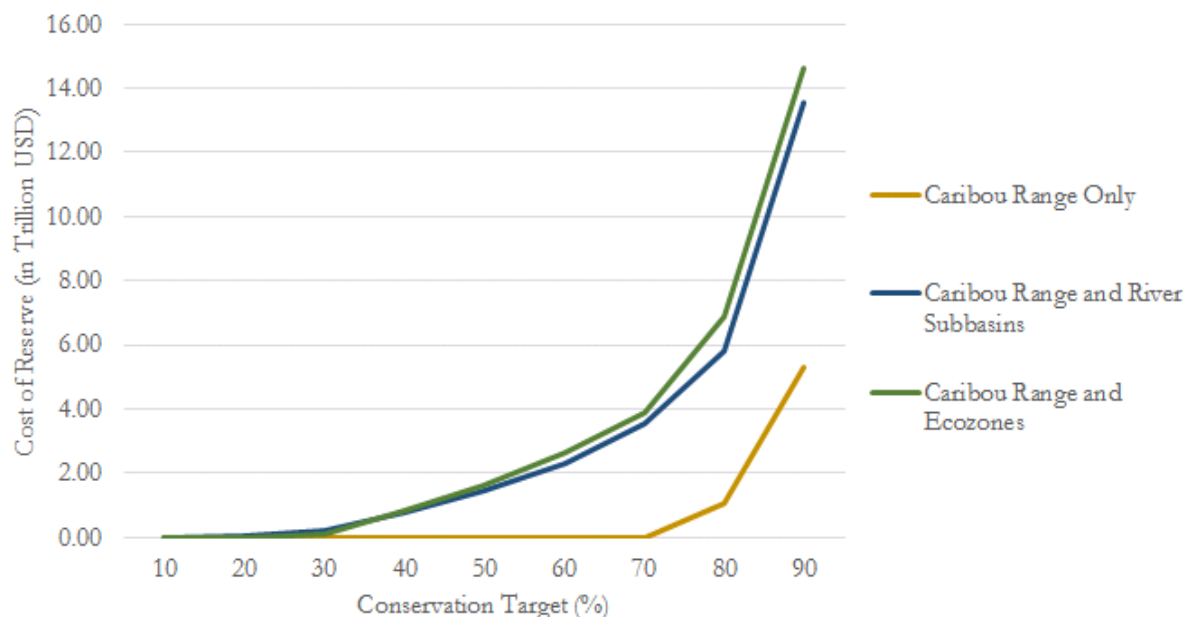


Figure 5.6. Costs of reserves created using the RCP 8.5 emissions scenario and with conservation targets set using only available caribou range (yellow line), caribou range and the six major river sub-basins of the MRB (blue line) and caribou range and the eight ecozones of the MRB (green line).

When we examined the difference between 50% reserves created under each of these three alternate conservation scenarios we found that the reserves created using ecozones or sub-basins for target setting looked very different from the reserve created using only caribou ranges (**Figure 5.7**). Setting conservation targets using ecozones or river sub-basins forces MARXAN to create reserves that are far more widespread across the study region. While all 3 of these reserves cover similar percentages of the total study region, they have vastly different costs (**Figure 5.6**). Therefore, forcing reserves to be more representative of the entire MRB may result in significantly costlier reserves. This is important as the southern portions of the MRB are at significant risk for biodiversity loss and water quality degradation. Water quality is of particular concern as water in the MRB flows from the southern, more industrialized, portions of the basin to the northern, more biodiverse, regions. The mining activities in the south can have particularly detrimental impacts on water quality, which could severely limit the functioning of the northern portions of the MRB, regardless of whether or not the north is well protected (*The Mackenzie River Basin*, 2013; Schindler, 2013).

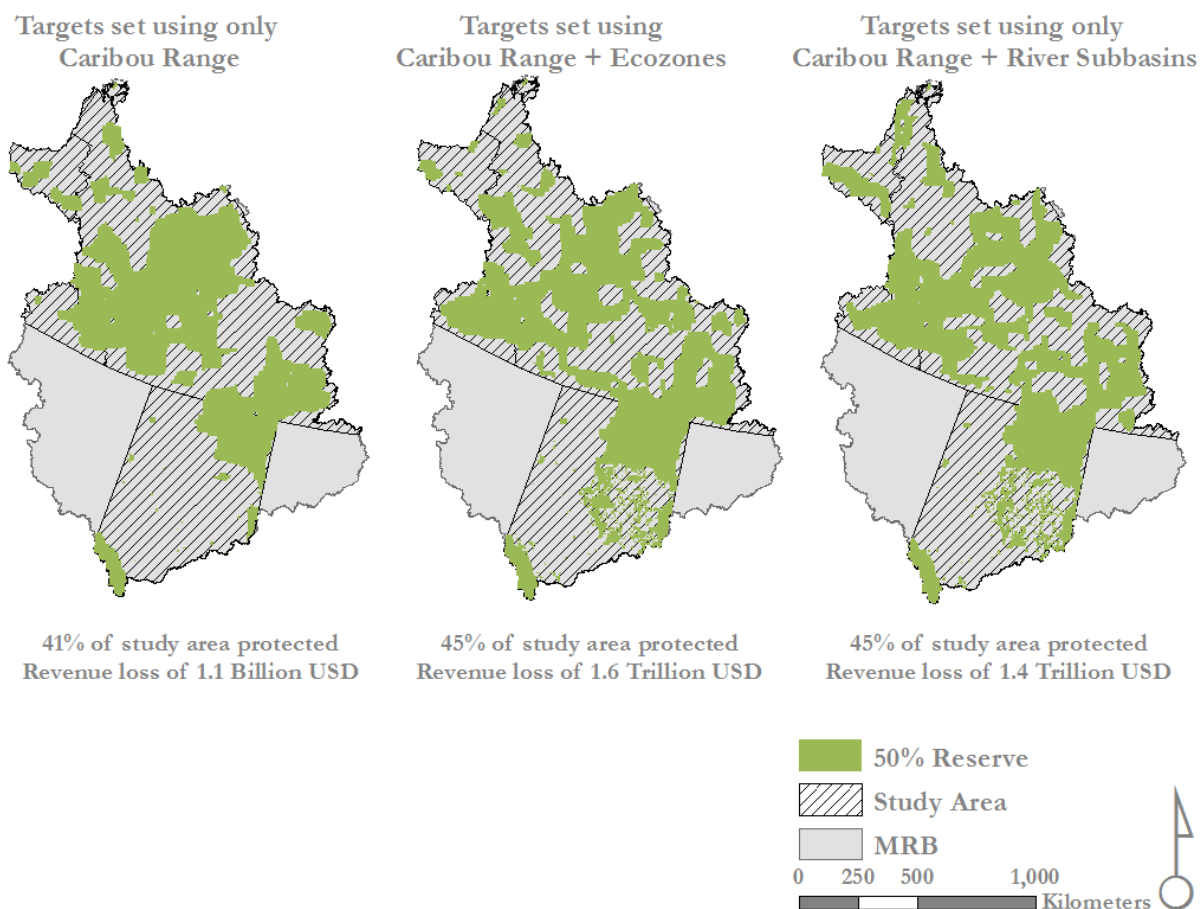


Figure 5.7. 50% reserves created using the RCP8.5 emissions scenario, and three different conservation target setting strategies. Targets were either set as 50% of caribou range (far left), 50% of caribou range falling within each of the eight ecozones in the MRB (center), or 50% of caribou range falling within each of the five major river sub-basins in the MRB (far right).

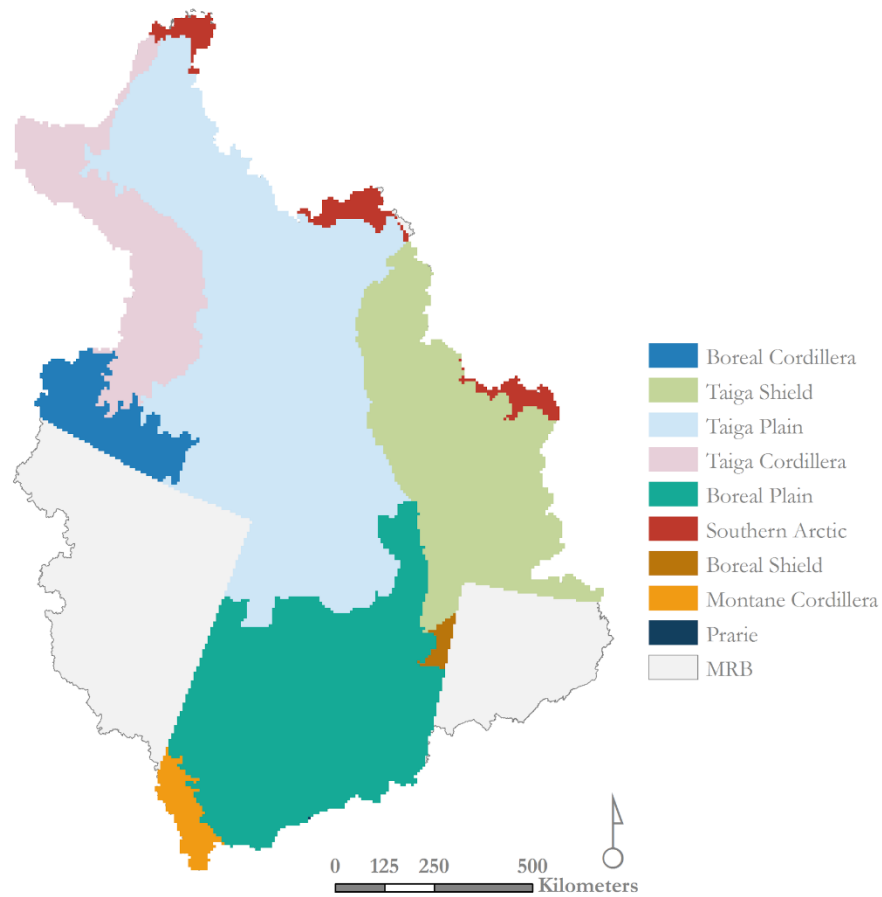
Conclusion

The reserve networks we designed generally represent the large scale biodiversity present in the MRB. Therefore, these reserves have great potential to protect the different landscape types, such as boreal forests, wetlands, and freshwater, that provide high value ecosystem services. However, because these reserves protect less of the southern portions of the study region, they may be less suited to account for the consequences of reduced biodiversity and water quality degradation that is occurring in the southern MRB. Reserves created using conservation targets of caribou range and river sub-basins, or caribou range and ecozones may be costlier but could better protect the ecological integrity of the region.

Nevertheless, for the costs we have calculated, we suggest that actions taken in the MRB focus on conserving 50% or more of caribou ranges. This would protect 40% of the entire region, and only reduce potential revenue to the three primary industries by 0.1%.

While our estimates do not incorporate the costs of implementing and maintaining reserves, we suggest that protecting 50% of caribou ranges could be a feasible target that would confer significant biodiversity protection for a marginal increase in costs. Our results can be used to support and influence the management of the MRB to promote the ecological integrity of the region while balancing economic interests. Ideally, they could be used to help inform the diverse set of stakeholders in the region to help Canada reach or exceed its goal of conserving 17% of its lands by 2020.

Appendices



Appendix 1. The nine ecozones within the Mackenzie River Basin displayed on the 50km² used in the analysis done in Chapter 5. There are nine ecozones, however the Prairie only covers 11 planning units and therefore was excluded from the analysis.

Appendix 2. Caribou presence-only data used as inputs for MaxEnt analysis.

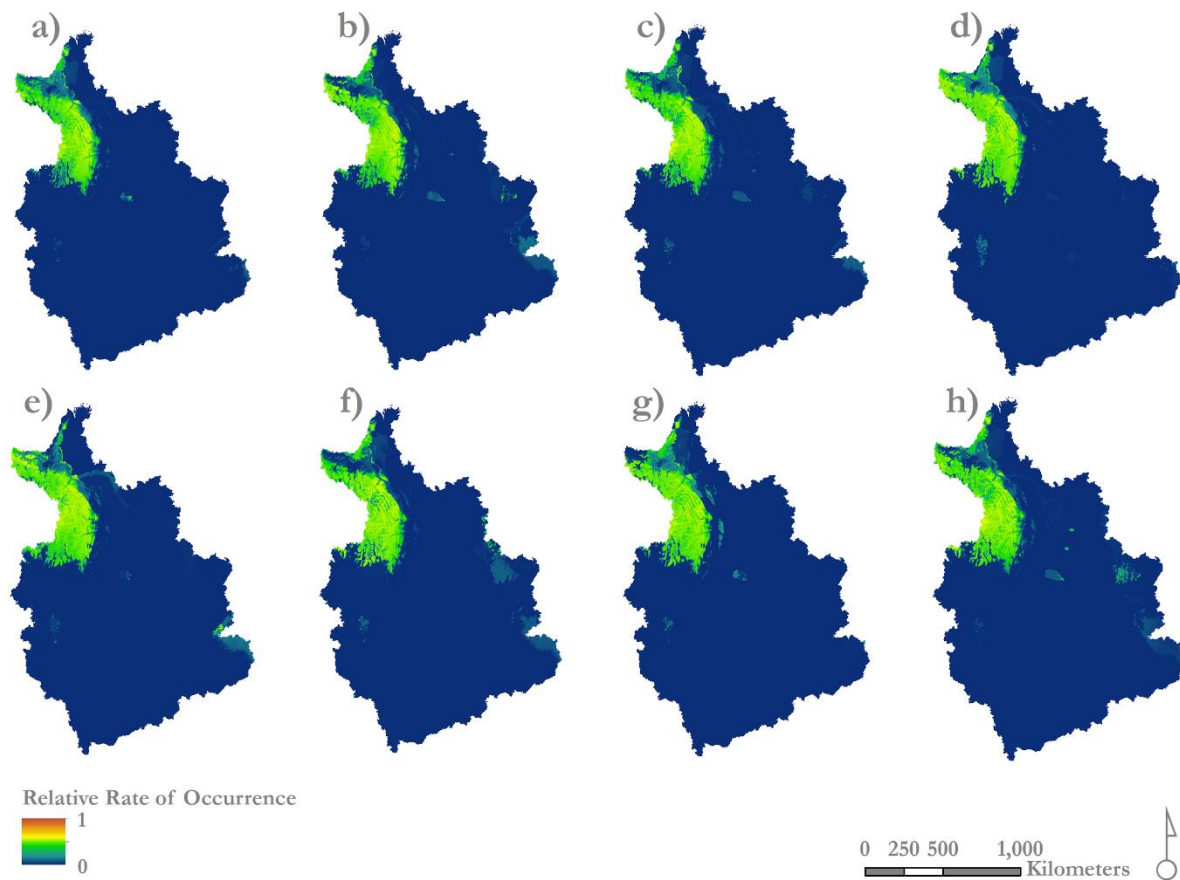
Caribou Type	Data	<i>n</i>	Data Source
Boreal Woodland	Incidental Vertebrate and Winter Snowtracking Data (2004-2014)	73	Alberta Biodiversity Monitoring Institute (ABMI)
	Southern Boreal Caribou Individual Home Ranges	203	
Mountain Woodland	Mountain Woodland GPS Collar Data	3,359	Government of the Northwest Territories
Barren-ground	Barren-ground Caribou GPS Collar Data	65,354	

Appendix 3 Atmospheric-Ocean General Circulation Models (AOGCM) chosen for modeling future climate scenarios (RCP4.5 and 8.5) in caribou MaxEnt models

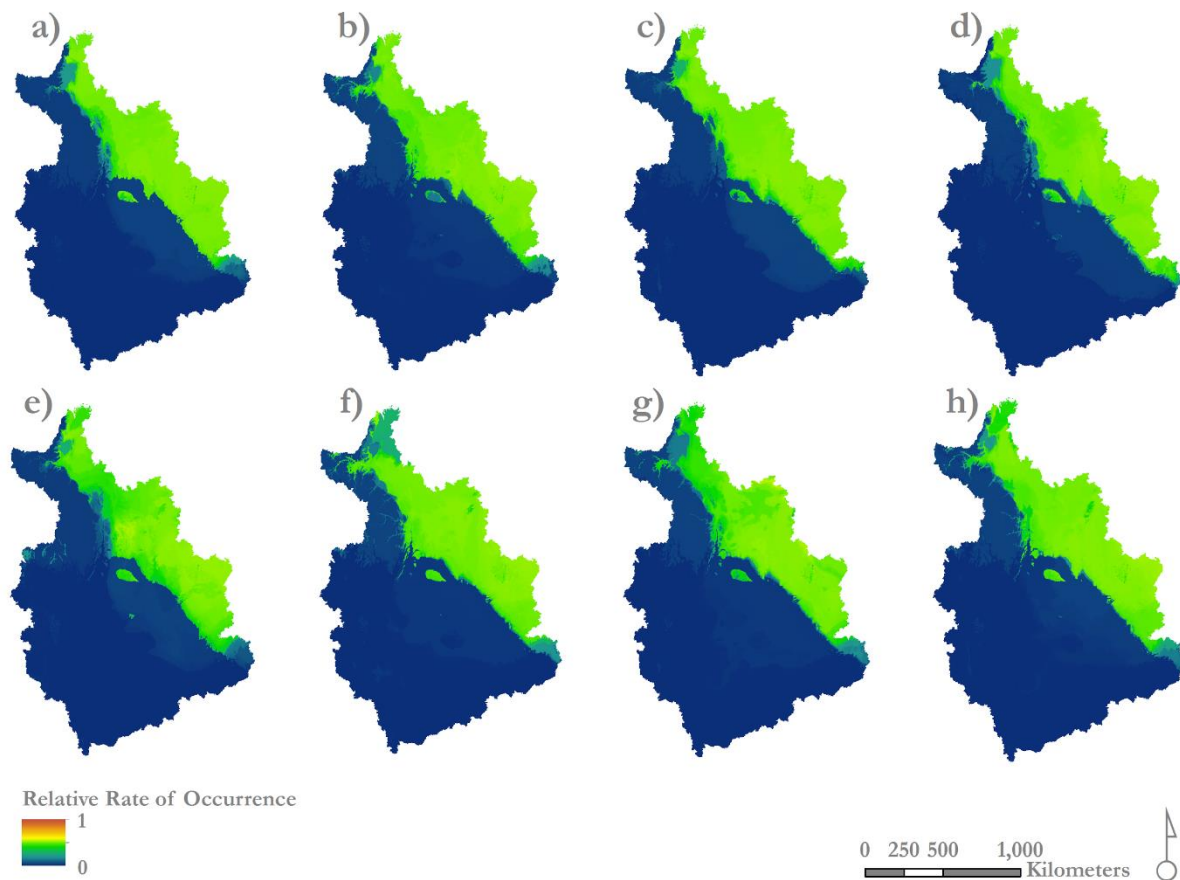
Model	Institution
CCSM4	National Center for Atmospheric Research, USA
CNRM-CM5	Centre National de Recherches Météorologiques, Météo-France, France
CanESM2	Canadian Centre for Climatic Modelling and Analysis, Canada
GFDL-CM3	NOAA Geophysical Fluid Dynamics Laboratory, USA
HadGEM2-ES	Met Office Hadley Centre, UK
INM-CM4	Institute for Numerical Mathematics, Russia
IPSL-CM5A-MR	Institute Pierre-Simon Laplace, France
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany

Appendix 4. Bioclimatic variables chosen as potential inputs into MaxEnt SDM for caribou and their ecological relevance.

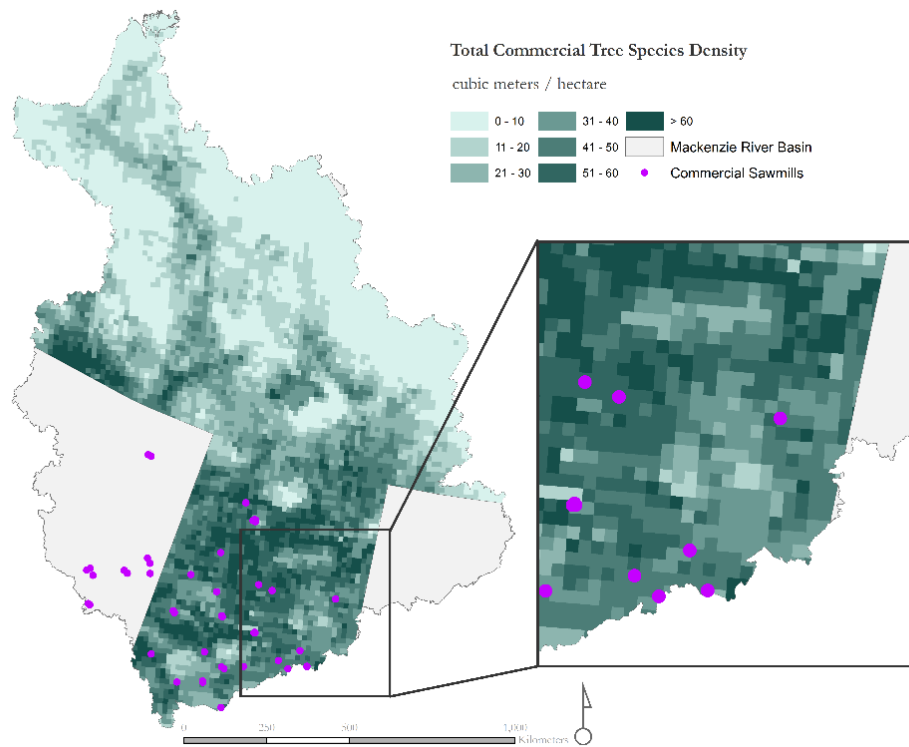
Bioclimatic Variable	Identifier	Ecological Relevance
The Julian date on which the frost-free period begins	bFFP	Length of growing season; Available forage; Increased insect harassment
Hargreave's climatic moisture index	CMD	Available forage
Degree-days above 5°C	DD5	Length of growing season; Available forage; Increased insect harassment
Hargreave's reference evaporation	Eref	Available forage
Mean annual precipitation (mm)	MAP	Available forage; Increased insect harassment
Mean annual temperature (°C)	MAT	Increased insect harassment; Immigration of white tailed deer
Mean temperature of the coldest month (°C)	MCMT	Severity of winter climate
Mean summer (May to Sep) precipitation (mm)	MSP	Available forage; Increased insect harassment; Increased severity of fires
Mean temperature of the warmest month (°C)	MWMT	Increased insect harassment; Increased severity of fires
Precipitation as snow (mm)	PAS	Length of growing season; Severity of winter climate; Difficulty finding winter forage
Summer (Jun to Aug) precipitation (mm)	PPT_sm	Available forage; Increased insect harassment; Increased severity of fires
Winter precipitation (mm)	PPT_wt	Available forage; Severity of winter climate



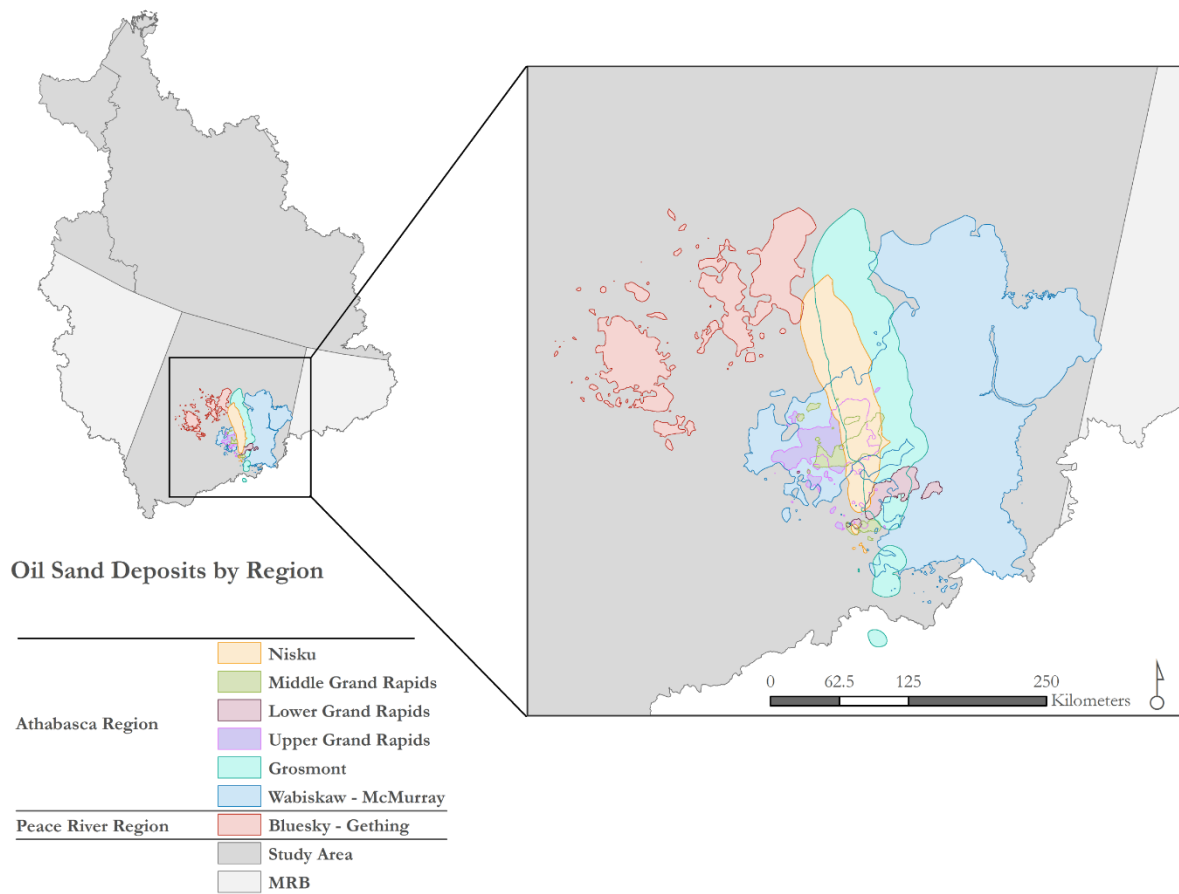
Appendix 5. MaxEnt model outputs for mountain woodland caribou for eight Atmosphere-Ocean General Circulation Models (AOGCM) projected to mid-century under RCP8.5. Warmer colors represent areas of higher relative rate of caribou occurrence, while cooler colors represent lower relative rate of occurrence. Lowercase letters above individual maps indicate different AOGCMs and are as follows: a) CCSM4, b) CNRM-CM5, c) CanESM2, d) GFDL-CM3, e) HadGEM2-ES, f) INM-CM4, g) IPSL-CM5A-MR, h) MPI-ESM-LR.



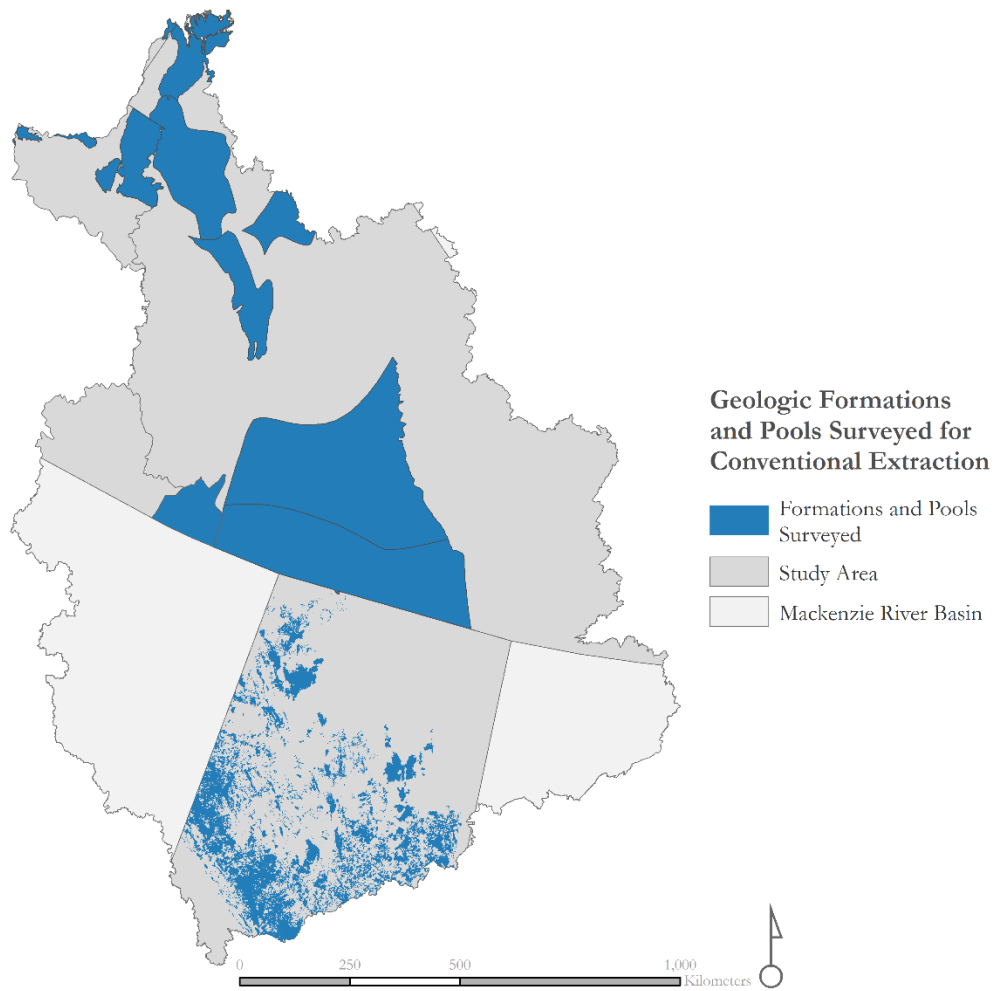
Appendix 6. MaxEnt model outputs for barren-ground caribou for eight Atmosphere-Ocean General Circulation Models (AOGCM) projected to mid-century under RCP8.5. Warmer colors represent areas of higher relative rate of caribou occurrence, while cooler colors represent lower relative rate of occurrence. Lowercase letters above individual maps indicate different AOGCMs and are as follows: a) CCSM4, b) CNRM-CM5, c) CanESM2, d) GFDL-CM3, e) HadGEM2-ES, f) INM-CM4, g) IPSL-CM5A-MR, h) MPI-ESM-LR.



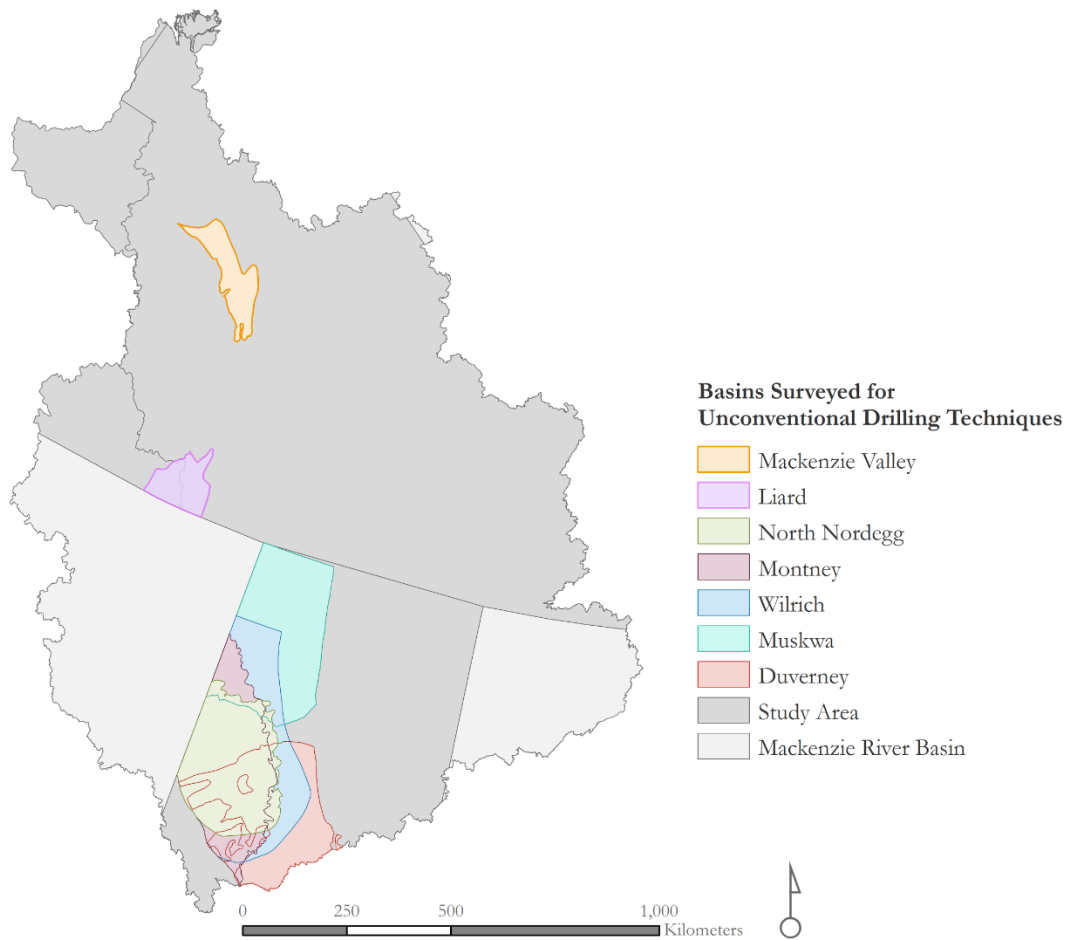
Appendix 7. Timber values within our study area. Darker shades of green correspond to more valuable areas. Sawmills (purple circles) from inside and outside of our study area were included because timber from within our study area could be transported outside of our study area.



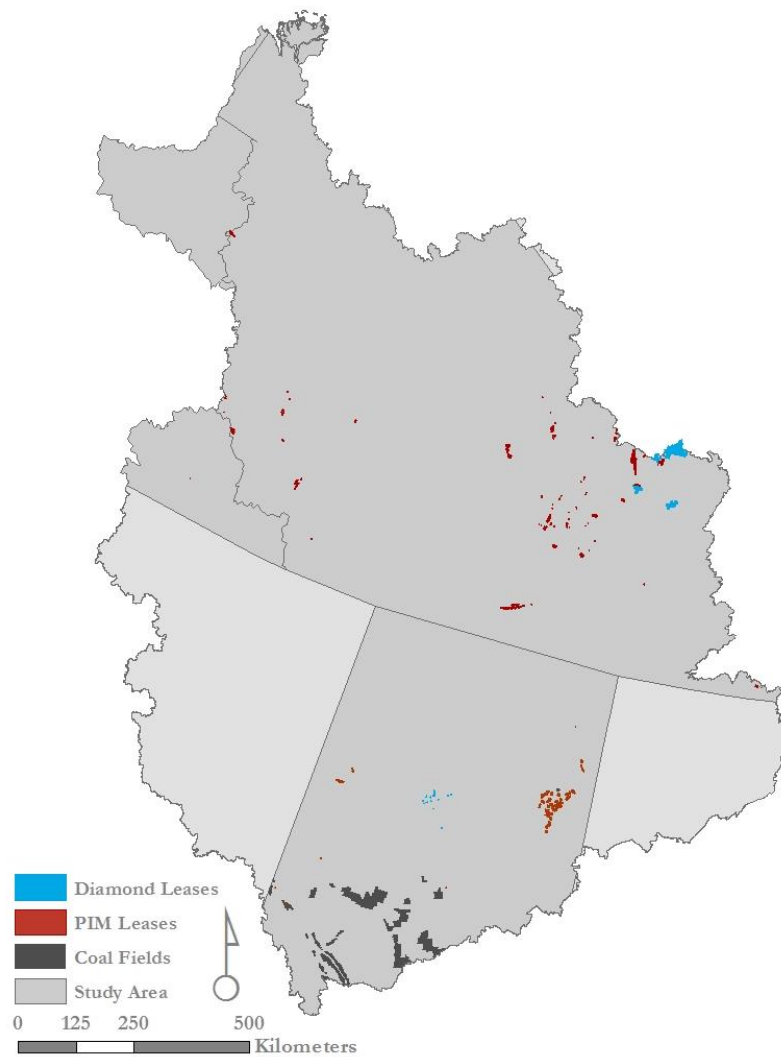
Appendix 8. Oil sand deposits by region which have been evaluated in the MRB.



Appendix 9. Geological and pools surveyed for conventional gas extraction in the MRB.



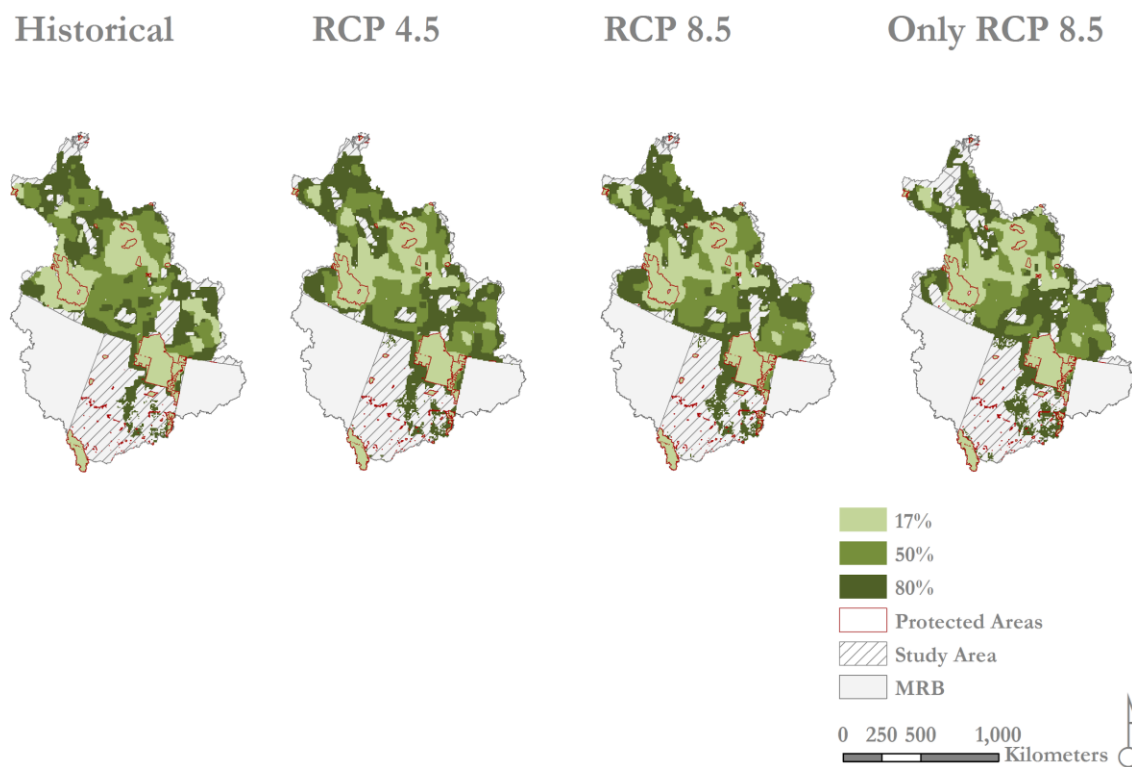
Appendix 10. Geologic formations of the MRB which have been evaluated for unconventional extraction of hydrocarbon reserves.



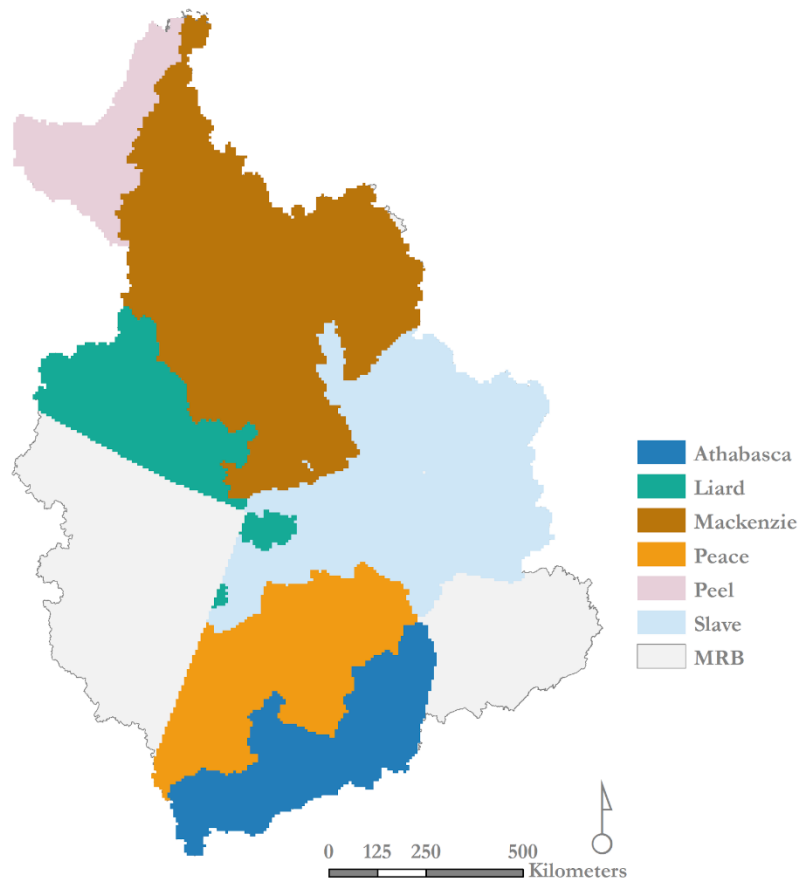
Appendix 11. Locations of the active PIM -precious and industrial metals -(red) and diamond (blue) leases and coal fields (black) of the MRB study region.

Appendix 12. SPF set for each of the four types of conservation layers (historical, RCP4.5, RCP8.5, only RCP 8.5) in conjunction with the protection targets (17%, 50%, 80%).

Caribou Type	Emission Scenario	Caribou Range Protected (%)		
		17	50	80
Woodland boreal	Historical	0.1	0.1	8
	RCP4.5	0.1	0.1	8
	RCP8.5	0.1	0.1	8
	Only RCP 8.5	0.1	0.1	8
Mountain boreal	Historical	0	0.1	0.1
	RCP4.5	0	0.1	0.1
	RCP8.5	0	0.1	0.1
	Only RCP 8.5	0	0.1	0.1
Barren-ground	Historical	0	0.1	0.1
	RCP4.5	0	0.1	0.1
	RCP8.5	0	0.1	0.1
	Only RCP 8.5	0	0.1	0.1



Appendix 13. MARXAN ‘best’ reserve outputs for all conservation targets under four emission scenarios — historical, RCP4.5, RCP8.5, only RCP8.5. Only RCP8.5 refers to a conservation layer that only used outputs from the eight AOGCMs and does not include historical or government ranges.



Appendix 14. The six major river sub-basins within the Mackenzie River Basin displayed on the 50km² used in the analysis done in Chapter 5.

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