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Application of land-use simulation to protected area selection for efficient avoidance of biodiversity loss in Canada's western boreal region

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ABSTRACT

Avoided ecological loss is an appropriate measure of conservation effectiveness, but challenging to measure because it requires consideration of counterfactual conditions. Land-use simulation is a well suited but under-utilized tool in this regard. As a case study for the application of land-use simulation to assess the impact of protected areas, we present a scenario analysis exploring conservation options in Canada's western boreal forest. The cumulative effect of multiple natural resource sectors, including oil and gas, forestry, and agriculture, have substantially altered the region's ecosystems in recent decades and elevated risk to wildlife. The evolving state of the region is such that managing risks to biodiversity requires consideration of not only today's but also tomorrow's conditions. We simulated the long-term (50-year) outcomes of land use and protection to caribou, fisher, fish, and resource production in each of 104 watersheds in the 693,345 km^2 study area. Simulated land use caused increased risk to wildlife in response to northwards expansion of resource extraction and expansion of agricultural lands. For each watershed, indicator performance with and without protection were compared to calculate the benefit (avoided ecological loss) and cost (lost opportunity for resource production) of protection. The capacity for protected areas to avoid disturbance varied substantially across watersheds, as did the potential loss of economic opportunity. Focusing protection on cost-effective watersheds made protected area expansion a more efficient strategy for reducing wildlife risk than reducing the overall rate of natural resource production. Heterogeneity in the cost-effectiveness of protection presents an opportunity to balance ecological integrity and economic growth.

1. Introduction

Protected areas provide a tool to conserve ecosystems in the face of growing development pressure. The term protection implies prevention of a disturbance that otherwise would have occurred and, in so doing, provides an avoidance of risk to sensitive ecosystem components. In practice, however, capacity to avoid disturbance is rarely considered during the design or evaluation of protected areas (Pressey et al., 2015; Visconti et al., 2015). Indeed, in an effort to balance socioeconomic and ecological objectives, conservation planners may avoid recommending areas with economically viable natural resource deposits for protection. For example, protected areas in Canada disproportionately occur in ecozones in remote northern or montane portions of the country where resource production and population expansion pressures are lower (Environment Canada, 2015). Specifically, with the exception of the Pacific Maritime ecozone, Canadian ecozones with protection exceeding 10% are limited to those at northern latitudes or high elevation (Arctic Cordillera, Southern Arctic, Taiga Cordillera, Boreal Cordillera, Montane Cordillera, and Hudson Plains). In contrast, protected areas in southern and low elevation regions such as the Mixedwood Plain, Boreal Plains, and Prairie ecozones are under-represented despite being exposed to greater development pressure. Focusing conservation efforts on landscapes that are unlikely to face land use pressures regardless of protection status is arguably an inefficient allocation of limited planning and management resources and can detract attention from the importance of conserving biodiversity within landscapes that face greater pressure.

Commonly used conservation prioritization software such as Marxan and Zonation are designed to identify reserve portfolios that efficiently (e.g., minimum area) represent conservation features (Ball et al., 2009; Moilanen et al., 2011). The analysis is completed by applying algorithms to spatial data that provide a snapshot of the distribution of conservation features. Although some applications of prioritization software incorporate estimates of future distribution of

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conservation features due to climate change (e.g., Stralberg et al., 2018; Loos, 2011) and availability of intact land cover due to land use (e.g., Tyson et al., 2016), consideration of landscape dynamics remains limited. As landscapes change in the future in response to anthropogenic and natural processes, so too will the capacity of a conservation strategy to achieve targets. Identification of resilient conservation strategies therefore requires consideration of potential future changes both within and outside of protected areas (Franklin and Lindenmayer, 2009; Rodewald, 2003). A related limitation of using a static representation of conservation features during conservation prioritization is that it does not assess the degree to which candidate protected areas avoid ecological loss that is otherwise likely to occur. As a result, there is a risk that conservation planning will prioritize areas that are unlikely to be degraded regardless of whether or not protection is implemented, and miss opportunities to protect areas that have the greatest opportunity to avoid ecological loss.

There is growing recognition that the conservation effectiveness of a protected area is best interpreted as the degree to which it avoids the loss of biodiversity and ecosystem function (Ferraro and Pressey, 2015). This measure, while logical, presents an analytical challenge because it requires consideration of counterfactual conditions (Pressey et al., 2015). Specifically, conservation outcomes with and without protection must be understood so that performance can be calculated as the difference between the two using an approach similar to that applied to calculate carbon dioxide emission reductions due to avoided loss of natural land cover (e.g., Ahlering et al., 2016). Scenario analysis is well suited to this task, whereby a variety of scenarios are evaluated to better understand the consequences of a range of potential futures (e.g., conservation decisions). By assessing future ecological and economic implications of candidate protected area options, scenario analysis can inform a key objective of conservation planning, which is to cost-effectively maximize avoided ecological loss (Ferraro and Pressey, 2015).

The utility of scenario analysis to land-use planning is well recognized (Peterson et al., 2003; Shearer, 2005) and numerous examples exist (e.g., Gounaridis et al., 2019; Daniel et al., 2016; Rempel et al., 2007). Given the complexity of assessing future outcomes of multiple overlapping land-use trajectories, such analyses frequently make use of computer models that simulate the implications of potential future land use. There has been limited use of land-use simulation models to forecast future landscape condition as part of a protected area impact assessment, however. Examples include consideration of future shifts in ecological communities due to climate change (e.g., Stralberg et al., 2015; Langdon and Lawler, 2015) and natural disturbance (e.g., Leroux et al., 2007), and assessment of the threat presented by future land-use to existing protected areas (e.g., Hamilton et al., 2013; Wilson et al., 2015). These examples, while valuable for exploring sensitivity of protected areas to stressors, do not evaluate potential future status of ecosystems with and without protection and are therefore not suited for assessing the impact of candidate protected areas. The use of simulation modeling to evaluate future effectiveness has been relatively narrow in scope, such as investigating a single set of candidate areas (e.g., Yemane et al., 2008) or comparing a relatively coarse set of conservation strategies (e.g., Wessely et al., 2017; Dorning et al., 2015; Visconti et al., 2015). Here, we expand the concept by demonstrating how scenario analysis can be used to compare the impact of a wider range of candidate protected area options, both in terms of the location of protected areas and the proportion of the landscape under protection. As well, we consider how scenario analysis can also be used to assess the future cost of protection in terms of forgone resource development opportunity, thereby providing information on the cost-effectiveness of protected area options.

As a case study for the application of land-use simulation to assess the impact of protected areas, we present a scenario analysis exploring conservation options in Canada's western boreal forest. The cumulative effect of multiple natural resource sectors, including oil and gas, forestry, and agriculture, have substantially altered the region's ecosystems in recent decades (Pickell et al., 2016; Hobson et al., 2002; Pickell et al., 2015). As disturbance has expanded, risk to sensitive species has increased. For example, with the exception of the Northwest Territories, the majority of boreal caribou range in the region exhibits levels of disturbance that make the persistence of caribou on the landscape highly unlikely (Environment Canada, 2012). Ongoing resource development, as well as natural disturbance such as fire, will continue to modify the landscape and impact the region's biodiversity. The evolving state of the region is such that managing risks to biodiversity requires consideration of not only today's but also tomorrow's conditions.

To explore future risks to biodiversity and opportunities to avoid risk, we applied the ALCES computer model (Carlson et al., 2010) to simulate landscape dynamics and biodiversity response over a 50 year time period from 2010 to 2060. The ALCES model (ALCES Landscape and Land-Use Ltd, 2017) was used due to its capacity to simulate the cumulative effect of multiple overlapping anthropogenic and natural processes that are active in the region, and to do so across large spatial (e.g., hundreds of thousands of km2) and temporal (i.e. decades) scales while also providing sufficient spatial resolution to inform the inherently spatial question of protected areas placement. While the capacity of ALCES to simulate cumulative effects has seen it used in a variety of planning contexts (e.g., Carlson and Stelfox, 2014; Carlson et al., 2015), the analysis presented in this paper is unique by way of its comprehensive consideration of the influence of protection on the future state of ecological indicators. This novel application of a land-use simulation model provides an additional tool for identifying strategies for cost-effective avoidance of ecological loss by allowing decision-makers to explore the following questions: 1) what is the capacity of protected areas to avoid future ecological risk; 2) where should protected areas be located to maximize their capacity to avoid future risk; and 3) what is the tradeoff between risk avoidance and lost opportunity for natural resource production?

2. Study area

The study area spans 693,345 km^2 of the Boreal and Taiga Plains Ecozones, including parts of Alberta, Saskatchewan, British Columbia, Northwest Territories, and Yukon (Fig. 1). This region is subject to the cumulative effects of energy and forestry development due to overlapping distribution of hydrocarbons (oil and gas) and forest. The vegetation of the study area is dominated by boreal forest composed of white spruce (*Picea glauca*), black spruce *Picea mariana*, jack pine (*Pinus banksiana*) and poplar (*Populus sp.*). Extensive peatlands are also present. Agricultural land covers 6% of the study area and other anthropogenic footprint (footprint by road, railway, transmission line, pipeline, seismic line, well site, industrial plant, oil sand mine, gravel pit, settlement, and rural residential) covers 2%. Fire and forestry are the dominant drivers of natural land cover disturbance and together determine forest age. Approximately 0.8% of the study area is available for timber harvest annually.

The region contains globally significant oil sand and shale gas deposits, hundreds of thousands of km^2 of forestry tenures, and thousands of km^2 of farmland. Although resource production has slowed in recent years in response to declining energy prices, the general trend has been one of rapid development (e.g., Schneider, 2002; Alberta Government, 2017). Resource development has driven strong economic growth but also loss and fragmentation of habitat (Lee and Cheng, 2014).

3. Methods

To evaluate the impact of conservation strategies on wildlife in Canada's western boreal region, we assessed the response of wildlife indicators to land use scenarios with and without protected areas (Fig. 2). The approach involved the following steps: i) establishing the region's current landscape composition; ii) simulating long-term (50-

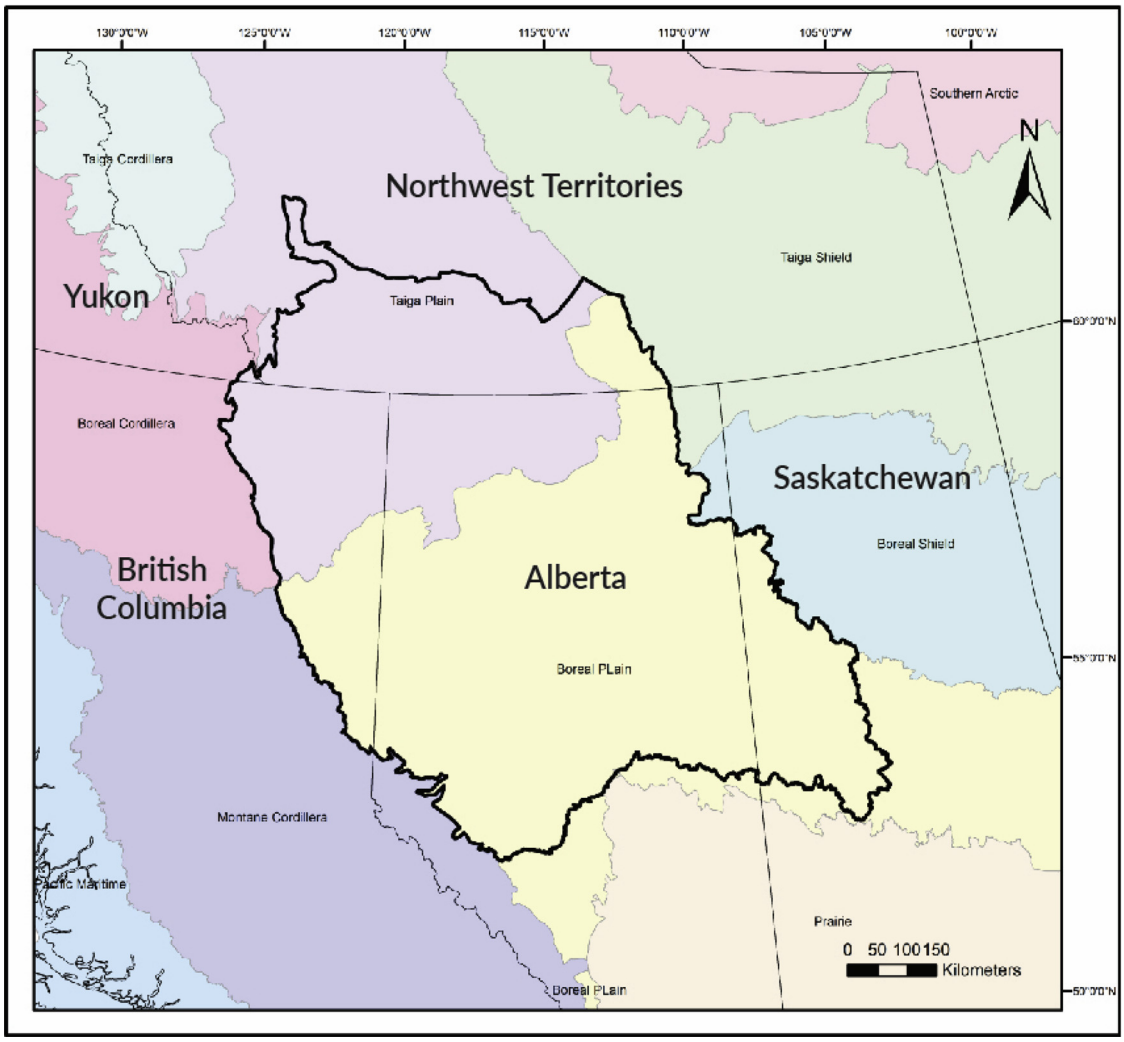

Fig. 1. Study area location (outlined in black) relative to western Canadian ecozones.

year) changes in landscape composition under alternative land-use and best practice scenarios as well as in the absence of land use to simulate a suite of protected area scenarios; iii) applying habitat models and economic coefficients to estimate future risk to wildlife and economic performance in the presence of alternative land-use scenarios and under a range of levels of protection; and iv) using the outcomes to quantify the trade-off between economic development and risk to wildlife at sequentially higher levels of protection. Full model parameterization and data layers are described in the methods for a broader study including data sources for landscape composition, assumptions for land use and fire, and coefficients for wildlife models (Carlson and Browne, 2015a).

3.1. Current landscape composition

The region's current landscape composition was characterized using land cover, forest age, and anthropogenic footprint inventories available publicly at the time of the analysis. This included Earth Observation for Sustainable Development land cover data (Centre for Topographic Information, 2009), National Hydro Network hydrology (Centre for Topographic Information (2004)), a national forest age layer (Chen et al., 2003), and numerous inventories from federal and provincial government and Global Forest Watch Canada for anthropogenic footprint data. A single land cover and anthropogenic footprint layer was created by integrating these spatial datasets (see Carlson and Browne, 2015a for full description of datasets). The layer described the proportion of each 25 km^2 cell covered by each of 12 land cover types and 14 footprint types.

3.2. Land-use simulations

Simulations using ALCES included the following land uses: energy (conventional oil and gas, bitumen mining, in situ bitumen, and shale gas), forestry, agriculture, and human settlements. ALCES operates by exposing a cell-based representation of today's landscape to a range of user-defined scenarios that incorporate key drivers of western boreal landscapes. Energy exploration is simulated by converting land cover to well sites, pipelines, seismic lines, and bitumen mines; forestry is simulated by creating cutblocks that change forest age to 0; agricultural expansion is simulated by converting land cover to cropland and pasture; settlement expansion to accommodate population growth is simulated by converting land cover to urban and rural residential areas; roads are created to access simulated footprints; fire is simulated by creating burns that change forest age to 0; and succession is simulated by aging the forest through time and returning temporary footprints (e.g., cutblocks, seismic lines) to natural land cover. For each of these drivers, the user defines the rate of disturbance and its spatial pattern as dictated by layers defining spatial variation in the relative likelihood of each driver and rules governing the size of individual events. The assumptions used for each driver are described below. The model tracks the cumulative effect of the drivers to the area, length, and age of natural and anthropogenic cover types using an annual time step.

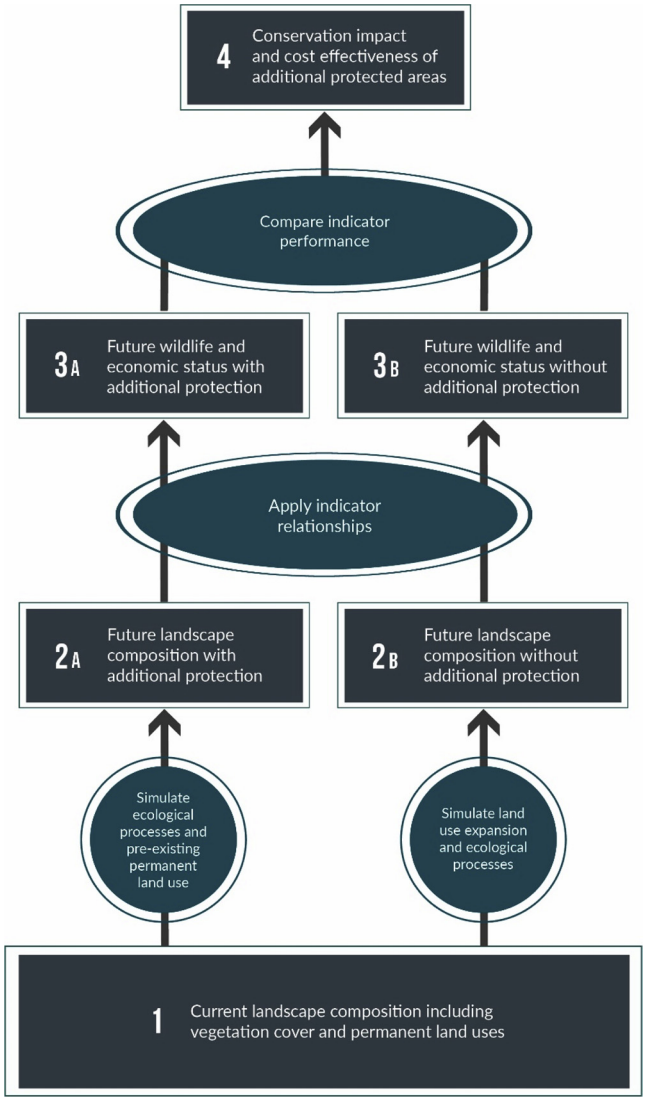

Fig. 2. An overview of the approach used to assess the conservation impact and cost-effectiveness of protected areas through scenario analysis: 1) establish current landscape composition; 2) simulate future landscape composition with and without protection; 3) apply indicator relationships to assess future wildlife and economic performance with and without protection; and 4) compare indicator performance with and without protection to assess the cost-effectiveness of protected areas.

Ecological and economic performance is then assessed by applying relationships to convert simulated future landscape composition to ecological indicators (e.g., wildlife habitat suitability) and to convert simulated natural resource production to economic indicators (e.g., GDP).

ALCES was applied to simulate multiple scenarios that explored the sensitivity of indicators to land use and conservation options. The first set of scenarios explored the sensitivity of landscape and wildlife outcomes to development rate. Three rates of resource development were explored: low, moderate, and high, representing 80%, 100%, and 120% of the projected trajectories based on industry estimates for each land use type and assuming business as usual environmental practices. The three development rates reflected: reduced or stagnant commodity prices, moderate commodity prices, and robust and sustained high commodity prices. A second scenario type explored the effectiveness of a suite of industry best environmental practices at mitigating ecological impacts by applying them to the moderate development rate scenario. This scenario was run to explore best practices as an alternative to protected areas for achieving wildlife conservation. Finally, a suite of scenarios explored the outcomes of zoning portions of the landscape for wildlife conservation while elsewhere applying the moderate development rate. In these scenarios, it was assumed that the intensity of land use outside of protected areas would not increase to offset the reduction in development caused by habitat protection. The model treated protected areas as zones within the landscape in which all future development was prevented but natural fires were simulated, permanent land uses were maintained, and existing anthropogenic disturbances were gradually reclaimed to natural condition.

Using an annual time step, the land cover components of each 25 km^2 cell belonging to various natural and anthropogenic cover types changed during a simulation in response to the rate and spatial pattern of land use, fire, and vegetation dynamics. Resource development was excluded from permanent protected areas (i.e., enacted by legislation) which covered 9% of the study area at the time of the analysis (Lee and Cheng, 2011). Energy development trajectories were informed by available projections (Energy Resources Conservation Board, 2012; National Energy Board, 2011; Natural Resources Canada, 2008; Millington and Mei, 2011) and allocated spatially according to the distribution of reserves. The intensity and lifespan of energy sector footprints (well sites, pipeline, seismic lines, mines, and industrial plants) were based on previous studies from the region (Wilson et al., 2008; Athabasca Landscape Team, 2009; Lee and Boutin, 2006; Nishi and Antoniuk, 2010). Under the best practices scenario, well site and well access road lifespan was reduced from 35 to 20 years in response to reforestation efforts, and directional drilling was assumed to double the number of wells per pad for bitumen and shale gas extraction (Athabasca Landscape Team, 2009). The lifespan of new seismic lines was reduced from 20 to 10 years in response to strategies to minimize soil disturbance and prevent motorized access (Schneider and Dyer, 2006).

The simulated timber harvest rate was based on the annual allowable cut of commercial forest tenures (Lee et al., 2004) and annual harvest data (Canadian Council of Forest Ministers, 2011). Forest harvest patterns and forest growth and yield were informed by detailed forest management plans from the two largest forest management areas in the region (Alberta-Pacific Forest Industries Inc (2008); Tolko High Level Lumber Division and Footner Forest Products Ltd (2003)) which were assumed to be representative of forest management in the study area.

Expansion of settlements was based on historical population growth rate by census divisions (Statistics Canada, 2006a). Simulations allowed farmland to expand into land with agricultural potential (Agriculture and Agri-Food Canada, 1998). Rates were based on an estimate of future deforestation due to agriculture in the region (ArborVitae Environmental Services, 2004).

Fire was included in the simulations due to its important role in boreal ecosystems. Fire was simulated to disturb 1% of forest area per year (Schneider et al., 2003); individual fire events followed the size distribution of fires in the region from 1959 to 1999 (Stocks et al., 2003) and were randomly distributed across forest within the study area.

The road network expanded at rates determined by the rate of growth in energy (well sites), forestry (cut blocks), settlement, and agricultural development. The length of additional road required for each new footprint (well sites, cut blocks, acreages, and farmland) was based on existing patterns occurring in the study area. Road requirements for overlapping forestry and energy developments were reduced by 34% under the best management practices scenario with coordinated road network design (Schneider and Dyer, 2006).

To estimate economic consequences of the scenarios, the simulated rates of natural resource production were translated into gross domestic product (GDP) using conversion factors of \$64.76/m^3 of timber, \$310.12/ha of farmland, \$0.1335/m^3 of gas, \$179.29/m^3 of conventional oil, and \$163.86/m^3 of bitumen. These conversion factors were

derived by dividing each sector's GDP in Alberta between 2000 and 2007 (PriceWaterhouseCoopers, 2009) by the province's timber production (Canadian Council of Forest Ministers, 2011), petroleum production (Canadian Association of Petroleum Producers (2011)), and agricultural land use (Statistics Canada, 2001, 2006b) during the same period.

3.3. Wildlife indicators

Indicator wildlife species were selected to be relevant to the public and decision-makers. Consequences of the land use scenarios were explored for the following species: i) boreal caribou (*Rangifer tarandus caribou*) a species at risk sensitive to broad-scale land cover change and the subject of significant regulatory effort; ii) fisher (*Martes pennanti*) a commercially harvested furbearer sensitive to forest age; and iii) the recreational fish community, including walleye (*Sander vitreus*), northern pike (*Esox lucius*), and arctic grayling (*Thymallus arcticus*) sensitive to human access density and stream fragmentation due to road crossings. Habitat change was tracked as change in forest age and change in anthropogenic footprint, where footprint was calculated as the total area of land cover converted to anthropogenic features excluding cut block area. To provide a common measure across the three wildlife indicators, outcomes for each were presented as risk levels (low, moderate, high) at the scale of watersheds, a suitable unit for conservation planning (Schindler and Lee, 2010). Tertiary watersheds were used instead of higher-order watersheds to obtain a larger number of planning units (n = 104).

Boreal caribou are threatened throughout their Canadian range and protected under the federal Species at Risk Act (Environment Canada, 2008). Habitat loss and alteration from broad-scale industrial development, including oil-and-gas exploration and extraction, forestry, and mining, has resulted in steep declines in boreal caribou populations (McLoughlin et al., 2003; Environment Canada, 2012). Linear disturbance associated with industrial activity such as roads and seismic lines have facilitated an increase in the distribution and movement of predators, leading to incidental predation of caribou (James et al., 2004; Wittmer et al. (2007); DeMars and Boutin, 2018). The response of the boreal caribou population to the land use scenarios was calculated using a model for finite rate of increase (λ) that assigns negative effects of anthropogenic disturbance (linear feature density) and young forest (forest < 30 years in age) based on the relationship between population parameters and range disturbance for 10 caribou herds in Alberta between 1993 and 2006 (Boutin and Arienti, 2008). This model is similar to the Canada wide model developed through a meta-analysis of boreal caribou demographic data from across Canada (Environment Canada, 2008, 2011). A λ value below 1.0 infers population decline due to mortality exceeding recruitment. The model's response variable (λ) was converted to risk by applying thresholds used to assess caribou in northeastern Alberta (Athabasca Landscape Team, 2009): low (> 0.99); moderate (> 0.95 and < = 0.99); and high (< = 0.95).

Fish community response was assessed using an Index of Native Fish Integrity (INFI) developed for northeastern Alberta (as described in Nishi et al., 2013) that attributes a negative impact to linear footprint disturbances due to increases in fishing access and fragmentation of stream habitat and the associated effects on species such as northern pike, walleye, and grayling (Post et al., 2002; Sullivan, 2003, and Alberta Sustainable Resource Development (2005)). The INFI ranges from 0 (highly disturbed fish community) to 1 (undisturbed fish community), with lower values indicative of increased risk to the native fish community. The INFI was interpreted using risk categories adopted in Alberta fish sustainability indices (MacPherson et al., 2014): low (> = 0.7); moderate (> = 0.5 and < 0.7); and high (< 0.5).

Fisher are often associated with intact, late-successional forests and avoid young successional forest stages (Weir and Harestad, 2003) and disproportionately use both stand sites and regional landscapes characterized by large diameter trees (Schwartz et al., 2013). Fisher response to simulated change in landscape composition was assessed using a habitat suitability model developed for northeastern Alberta that ascribes a positive effect to older forest and a negative impact to anthropogenic disturbance associated with human access (as described in Nishi et al., 2013). Fisher habitat suitability was converted to a risk index based on departure from natural condition using the same categories adopted for INFI, which are similar to IUCN red list population reduction criteria (International Union for Conservation of Nature (2001)). For example, an index of 0.5 was applied if habitat suitability was 50% that of natural conditions. Departure of habitat suitability from natural condition was assessed by dividing a watershed's simulated habitat suitability by its estimated natural condition. Natural condition was estimated by calculating the response of the fisher habitat suitability index to natural landscape dynamics as simulated by removing the anthropogenic footprint from the landscape and applying a natural fire rate of 1.1% per year (Armstrong, 1999), which is slightly higher than the 1% fire rate applied during land-use simulations due to the effect of fire suppression.

3.4. Impact of protection

Outcomes from protection and moderate development simulations were summarized at the scale of tertiary watersheds to derive estimates of wildlife risk and economic development for each watershed after 50 years with and without protection. The regional consequences of protecting a subset of watersheds was then assessed by assigning outcomes of the protection scenario to the protected watersheds and assigning outcomes of the moderate development scenario to the unprotected watersheds. In this manner, the implications to wildlife risk and GDP of incrementally protecting more watersheds was evaluated. Protected watersheds were incrementally and efficiently added by prioritizing protection of watersheds with the lowest cost of avoided habitat loss. A watershed's cost of avoided habitat loss was calculated as GDP ($) generated by resource development over 50 years divided by the reduction in anthropogenic footprint (km^2) at the end of the protection simulation as compared to the moderate development simulation. The environmental and economic impact of protected area expansion was then assessed based on the reduction in high-risk watersheds and GDP as successively more watersheds were zoned for protection. As an example of the type of decision-support scenarios that can be explored using a land-use simulation model, we compared outcomes between a protection scenario that resulted in the setting aside of 20% of potential GDP with the business as usual scenarios.

4. Results

Annual energy production grew more than twofold during the moderate development scenario from six billion to more than 14 billion GJ per year, almost exclusively due to continued expansion of bitumen development. Growth of the energy sector caused GDP to increase more than twofold. Timber production remained constant at almost 30 million m^3 per year and required, on average, the harvest of 1632 km^2 of forest. Agricultural land expanded by 14% over the 50-year simulation. Relative to the energy sector, however, forestry and agriculture made only small contributions to economic activity; 95% of natural resource GDP was driven by energy production. The high dependence of GDP on bitumen development resulted in economic growth being spatially aggregated near bitumen deposits in northeastern Alberta.

Resource development caused anthropogenic footprint to increase in coverage from 8% to almost 10% of the study area over the 50-year, moderate development rate simulation. Anthropogenic footprint expansion was greatest in the Peace Country in western Alberta due to forest conversion to cropland and pasture, and in the bitumen and shale gas regions of eastern Alberta and eastern British Columbia, respectively (Fig. 3). Conversion of forest to cropland and pasture accounted for 50% of the growth in anthropogenic footprint, followed by energy

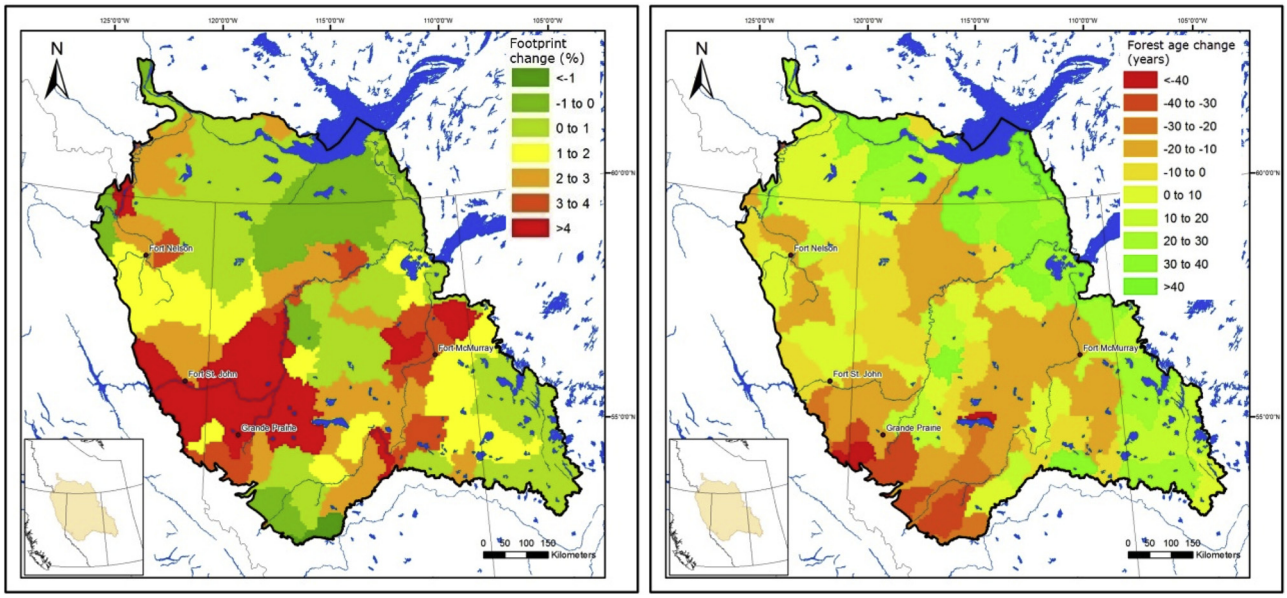

Fig. 3. Change in percent coverage by anthropogenic footprint (left map) and average forest age (right map) of tertiary watersheds during a 50-year simulation of potential future land use and fire under the business as usual, moderate development rate scenario.

(24%, excluding roads), roads (20%), and settlements (6%). Growth in anthropogenic footprint occurred in all scenarios, although the lower development rate and best management practices scenarios reduced the expansion of anthropogenic footprint by 69% and 15%, respectively, relative to the moderate development rate and business as usual practices. In addition to direct habitat loss, hunting and angling pressure is expected to rise due to a growing human population and an expanding network of linear features such as roads and seismic lines that can be used for access. During the moderate development scenario with business as usual practices, human population grew from ˜ 450,000 to ˜800,000 and total length of linear features increased by 27%.

Forest succession caused old forest (> 100 years) to grow from 23 to 36% of forest area under the business as usual, moderate development rate scenario. At the same time, forest disturbance (timber harvest and fire) caused young (< 20 years) and immature (20–60 years) forest to increase from 24 to 55% of forest area. These two processes were spatially distinct, with a decline in forest age evident to the south due to the additive disturbance of timber harvest and fire, and an increase in forest age evident to the north where forest management areas are absent or have lower harvest rates.

Watersheds in the high-risk category for boreal caribou, fisher, and INFI are currently concentrated in the southern portion of the study area but expanded northward with anthropogenic disturbance during the moderate development simulation (Fig. 4) resulting in an increase in high-risk watersheds for boreal caribou and fisher (Fig. 5). The proportion of high risk watersheds by the end of the simulation was greater for caribou (69% of the study area) than it was for fisher (45%) and INFI (42%) due to the sensitivity of caribou to footprint, but the general pattern of a north to south gradient in wildlife risk was consistent across indicators (see Carlson and Browne, 2015b for detailed indicator results). A 20% lower rate of development slowed but did not eliminate the increased risk to wildlife (Fig. 5). Best management practices also mitigated risk but the effect was relatively minor. In comparison to the moderate development scenario, best management practices reduced the proportion of watersheds that were at high risk by the end of the simulation from 69% to 63% for boreal caribou, 45% to 40% for fisher, and 41% to 36% for INFI.

The protection scenario resulted in 18,454 km^2 less anthropogenic footprint after 50 years as compared to the moderate development scenario with business as usual practices. The magnitude of this avoided loss was highest in northern Alberta and BC where the potential for agricultural and energy development was greatest. The cost of land protection in terms of foregone potential economic gains ($GDP) also differed substantially across the study area. Watersheds with bitumen reserves (northeastern Alberta) accounted for 82% of the region's simulated GDP, despite covering just 30% of the study area. Because the cost per km^2 of avoided loss was dramatically higher in the bitumen region than elsewhere, these watersheds were selected last during an efficient expansion of the protected areas network. Across watersheds, the economic cost of avoided habitat loss through protection ranged from $1.2 million to $959.3 million (for areas with minable bitumen) of foregone GDP per km^2 of avoided anthropogenic disturbance.

Wildlife risk declined as successively more watersheds were protected from development (Fig. 6). A rapid decline in risk was evident during protection of those watersheds representing the lowest economic cost options for protecting lands corresponding to 20% of the region's potential contribution to GDP. The steep initial reduction in risk to wildlife occurred because the lowest economic potential watersheds accounted for a much larger portion of the total area (66%) than total GDP potential (20%) due to the concentration of natural resource value in the oil sands region. At a large landscape level, under the example protection scenario corresponding to 20% of potential resource derived GDP, concentrating economic development in the oil sands region while protecting a large portion of the landscape (i.e., 66%) is a substantially more effective strategy for avoiding wildlife risk than is the strategy of reducing the rate of economic development everywhere by 20%, despite the two strategies having similar implications to overall GDP (Fig. 7). By the end of the simulation, the number of watersheds with two or more wildlife indicators at high risk under the protection scenario (19 watersheds) was less than half compared to the number of watersheds with two or more wildlife indicators at high risk under the scenario with the lower development rate (45 watersheds).

5. Discussion

Assessing the impact of protected areas requires comparison of outcomes with and without protection. Quantitative assessment of the impact of protected areas have typically been historical in their approach, for example comparing past rates of deforestation inside and outside of protected areas (e.g., Pfaff et al., 2017). Conservation planning, however, requires a forward-looking perspective, especially given the tendency for threats to vary in space and time (Haruna et al., 2014).

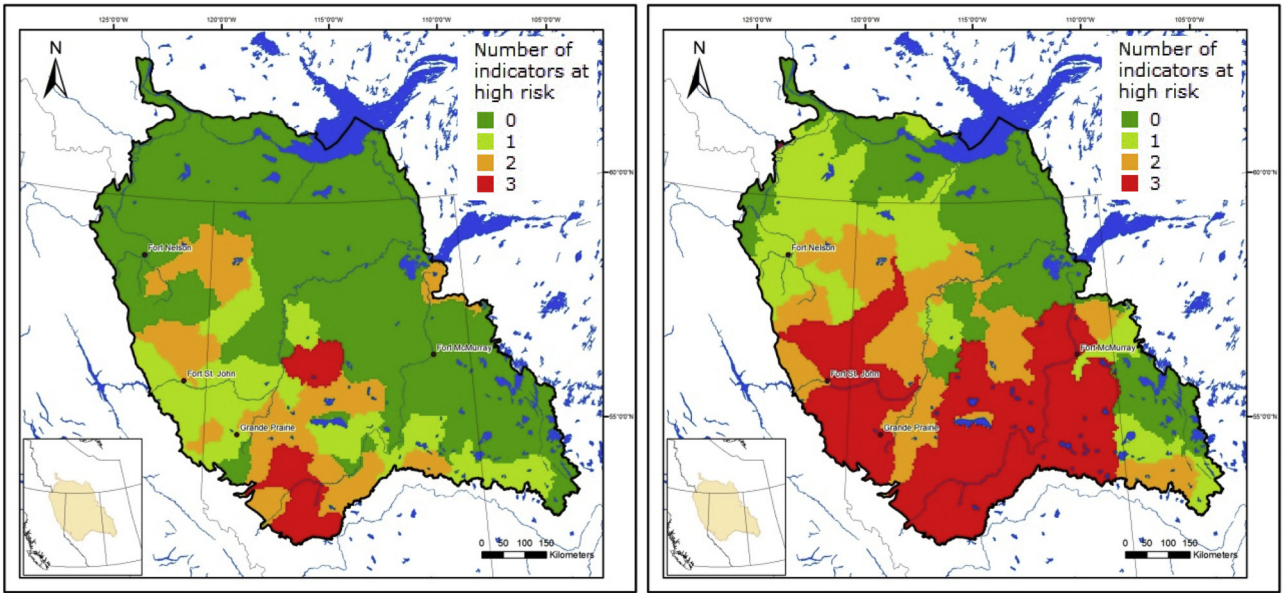

Fig. 4. Number of wildlife indicators (woodland caribou, fisher, fish community) assessed as high risk based on each tertiary watershed's current landscape composition (left map) and simulated landscape composition by the year 2060 in response to land use and fire (right map) under the business as usual, moderate development scneario.

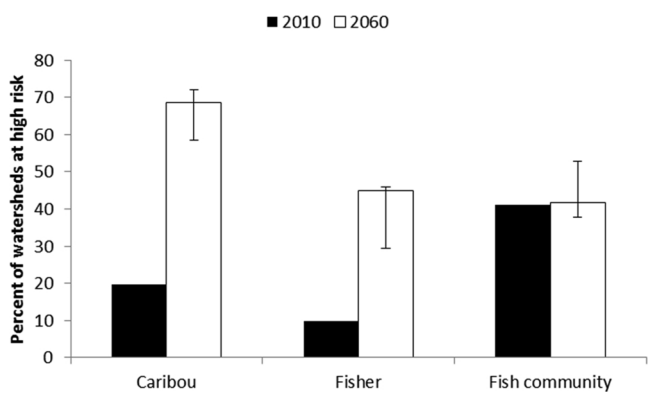

Fig. 5. Percent of tertiary watersheds assessed as high risk for wildlife indicators at the start and end of a 50-year simulation of potential future land use and fire. Upper and lower error bars indicate outcomes for scenarios where the simulated development rate is increased and decreased by 20%, respectively.

The capacity of simulation modeling to explore future conditions under a range of conservation strategies and threats makes it well suited as a tool for assessing the future impact of candidate protected areas. Simulation modeling is well utilized as a tool for evaluating the effectiveness of existing protected areas under alternative management strategies (e.g., Mairota et al., 2014) and in the face of future changes in climate or land use (e.g., Berteaux et al., 2018; Hamilton et al., 2013). The analysis presented in this paper demonstrates the utility of using simulation modeling to also consider the future effectiveness of candidate new protected areas.

Conservation strategies can differ substantially in their outcomes, making it important to assess tradeoffs among options (Dorning et al., 2015). In the simulations, capacity of protection to avoid disturbance varied substantially across watersheds. Watersheds with higher intactness and resource potential, such as are found in portions of northern BC and Alberta, tended to display the highest potential for avoided disturbance through protection. Given the range in simulated protected area effectiveness that was observed, failure to consider future landscape dynamics could result in protected areas with low potential to improve future conditions. We expect other landscapes display similar heterogeneity in capacity of protected areas to avoid impacts, due to the aggregated distribution of both development potential and ecological value. However, focusing protection efforts on areas with high potential to avoid future land use impact implies forgoing opportunities for future resource production. As such, protection comes at the cost of potential economic benefits from development. While this cost could be eliminated by protecting areas where future development is unlikely, such a strategy also ensures that protection is ineffective because it would not alter future land use patterns from the status quo. Instead, protection should focus on those areas that avoid the greatest amount of risk at the lowest economic cost. The land-use simulation model presented here allows stakeholders and decision-makers to set different protected area selection rules and explore broad scale outcomes for wildlife, habitat, and the economy. While the scenario analysis can inform stakeholders as to which watersheds are most cost-effective to protect, the total amount of protection and the amount of potentially foregone resource development remains a societal decision. As demonstrated by the lack of a strong inflection point in the relationship between protected resource potential and wildlife risk (Fig. 5), there is not a clear optimal level of protection. Rather, there are cost-effective options for achieving a desired balance between economic and environmental objectives.

Land-use simulation provides a means to explore possible outcomes of different decision models and inform protected area planning. It can help to identify the desired balance between conservation and development by quantifying the associated trade-off between environmental and economic values (Fig. 6). The simulation approach demonstrated in this paper can also minimize that trade-off by identifying opportunities for efficient avoidance of risk. Potential inefficiencies are substantial as demonstrated by the wide range in cost of avoided habitat disturbance across watersheds. Driving the large differences in cost of avoided disturbance was the high economic benefits of energy development relative to agriculture and timber harvest. Agricultural expansion has caused high rates of deforestation in portions of the boreal plains (Hobson et al., 2002), and forestry disturbs thousands of km^2 annually in Alberta, British Columbia, and Saskatchewan (Canadian Forest Service, 2016). The lower economic value (in terms of GDP) of agricultural and timber production made it possible to protect entire watersheds where these land uses were the dominant form of future development without substantially reducing regional economic growth. As a result, risk to wildlife initially declined at a faster rate than

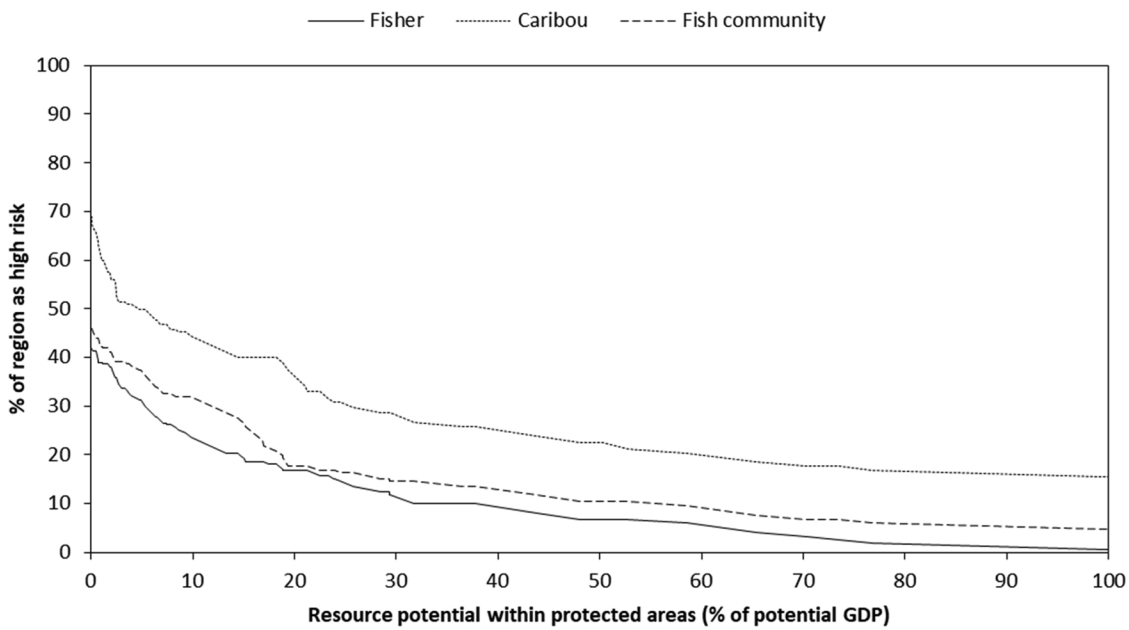

Fig. 6. Percent of the region covered by watersheds assessed as high risk for fisher, woodland caribou, and the fish community based on simulated landscape composition in the year 2060 in response to land use and fire under a range of protection levels (i.e., percent of potential GDP related to future resource production occurring within protected areas).

economic benefit as successively more watersheds were protected from development. The concentration of resource value in a small number of watersheds in the region is such that over 50% of the region's area can be protected while affecting only 20% of the region's simulated future GDP. From a strategic perspective that considers regional wildlife risk and GDP, the spatial aggregation of economic value presents an opportunity to balance ecological integrity and economic growth. As mentioned previously, we expect that other landscapes will exhibit heterogeneity in both the benefits of protection (i.e., capacity of to avoid future impacts) and the cost of protection (i.e., the value of foregone resource development).

An important caveat is that, while effective in reducing risk to wildlife and GDP, the strategy of focusing development on areas with a high abundance of hydrocarbons may not satisfy other environmental and socio-economic objectives. Perhaps most problematic is the substantial growth in greenhouse gas emissions that would accompany increased bitumen production in the region (Carlson and Browne, 2015b). Focusing development on a single sector could also violate economic objectives such as sectoral and geographic diversification of development. As well, achieving ecological objectives may require the protection of focal species habitat (e.g., boreal caribou ranges), rare features, underrepresented ecosystem types, and north-south gradients to capture variation in ecosystem productivity and to facilitate northward species migrations in response to climate change. Due to spatial variation in ecological values, achieving these objectives will not necessarily be achieved by protecting those areas that avoid future

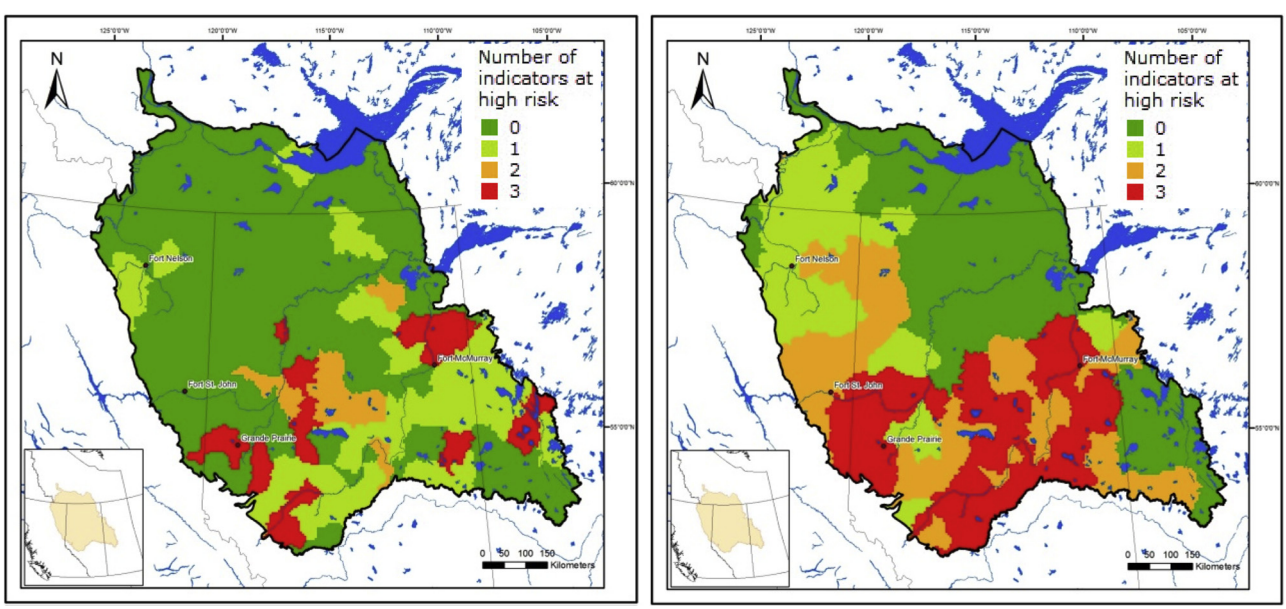

Fig. 7. Number of wildlife indicators (boreal caribou, fisher, fish community) assessed as high risk based on each tertiary watershed's simulated landscape composition by the year 2060 in response to land use and fire when the protected areas network is expanded to incorporate 20% of the study area's potential contribution to GDP from natural resource development (left map) and when the development rate is reduced by 20% (right map).

disturbance at minimum cost. These and other conservation objectives could be incorporated by integrating land-use simulation with conservation prioritization software such as Zonation and Marxan (e.g., Tyson et al., 2016). An important strength of such tools is their ability to consider a range of criteria concurrently when identifying protected area networks that satisfy multiple objectives (e.g., ecosystem representation, protection of special elements). Avoided risk as calculated through simulation modeling could be included as a layer in conservation prioritization software to be balanced with other conservation objectives such as ecosystem representation and economic objectives such as sub-regional economic growth.

Another important caveat is that the future rate of development is uncertain due to fluctuations in domestic and international markets, government policy, and technology. As such, simulations should not be interpreted as predictions but rather scenarios that are consistent with a specific set of assumptions regarding the future rate and spatial distribution of land use. We adopted two strategies to address this uncertainty. First, although we simulated land-use at a relatively high spatial resolution (25 km^2), we summarized consequences to wildlife at a coarser scale (tertiary watersheds with an average size of 6500 km^2) when evaluating protection options. As such, the sensitivity of outcomes to the specific location of land use is reduced; the general pattern of development is more influential than fine-scale details. Our second and more important strategy for addressing uncertainty was to simulate a range of scenarios to assess sensitivity to key assumptions. The three simulated development rates (low, moderate, high) were sufficiently diverse to encapsulate the downward shift in development projections that occurred due to the recent decline in the price of oil. The National Energy Board's more recent projection for bitumen production in 2040 is 278 million m^3/yr. (National Energy Board, 2016), which is slightly lower than what was assumed for the moderate development scenario (293 million m^3/year) but higher than the production rate assumed for the low development scenario (235 million m^3/year). Although development rate was positively correlated with wildlife risk, even the low development scenario resulted in increases in risk to caribou and fisher and continued high risk to the fish community. Risk also remained high when the simulation implemented management practices that shortened the lifespan and lowered the intensity of anthropogenic footprint. The high abundance of natural resources in the region is such that land use is likely to increase risk to wildlife under a range of plausible development trajectories. These findings are consistent with other studies that have explored the relationship between land use and wildlife risk in the region: the majority of western boreal caribou herds have been assessed as not self-sustaining (Environment Environment Canada, 2012); the sustainability of fish populations for species such as walleye and arctic grayling has been identified as low across much of Alberta (Alberta Environment and Parks, 2016); and future development has been projected to exacerbate impacts (Cumulative Environmental Management Association (2008)).

An uncertainty that was not addressed by the scenario analysis is climate change. Northern regions such as the boreal forest are expected to experience large changes in climate, with numerous implications such as higher rates of natural disturbance and loss of permafrost. Climate change was excluded from the scenario analysis to avoid obscuring differences in simulation outcomes that are attributable to land use. Fire, for example, is projected to increase by as much as 5.5 times by the end of the century (Balshi et al., 2009). An increase of this magnitude would dramatically alter forest demography and impact wildlife such as caribou that are influenced by forest age. Substantial uncertainty surrounds the response of boreal ecosystems to climate change. We recommend that the scope of future scenario analyses be increased to assess the effectiveness of conservation strategies under a range of assumptions regarding climate change and its impacts.

The western boreal region is vast and the fixed spatial distribution of resources imposes localized trade-offs between economic growth and ecological integrity. At a landscape level, the trade-offs do not imply, however, that policies must favour economic growth over ecological integrity, or vice versa. Economic growth is desirable, but so too are abundant wildlife and intact habitat. In the absence of a coherent land use strategy, continued expansion of development across the region will diminish options for balancing economic and environmental objectives. Opportunities for improving both environmental and economic outcomes remain and the scenario analysis presented here indicates that protected areas can improve environmental outcomes while maintaining opportunities for resource development in the remaining landscape. Land-use simulation can contribute to maximizing this opportunity through the identification of protected areas that reduce future environmental risk at minimum economic cost.

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