

Preliminary scenarios of climate-driven changes in boreal forest vegetation and bird populations in Alberta considering topo-edaphic constraints and future disturbance

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Preface:

The Alberta Biodiversity Monitoring Institute (ABMI) is an arm's-length, not-for-profit scientific organization. The primary goal of the ABMI is to provide relevant scientific information on the state of Alberta's biodiversity to support natural resource and land-use decision making in the province.

In the course of monitoring terrestrial and wetland ecosystems across the province, the ABMI has assembled a massive biodiversity database, developed reliable measurement protocols, and found innovative ways to summarize complex ecological information.

The ABMI undertakes focused projects to apply this capacity to specific management challenges, and demonstrate the value of the ABMI's long-term monitoring data to addressing these challenges. In some cases, these applied research projects also evaluate potential solutions to pressing management challenges. In doing so, the ABMI has extended its relevance beyond its original vision.

The ABMI continues to be guided by a core set of principles – we are independent, objective, credible, accessible, transparent and relevant.

This report was produced in support of the ABMI's Biodiversity Management and Climate Change Adaptation project, which is developing knowledge and tools to support the management of Alberta's biodiversity in a changing climate. The views, statements, and conclusions expressed in this report are those of the authors and should not be construed as conclusions or opinions of the ABMI.

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Introduction

The global climate is expected to undergo profound changes during the 21st century (IPCC 2013). Over long periods, ecological communities should generally track these changes, as occurred throughout most of the Holocene (Prentice et al. 1991, Huntley et al. 1993). Based on this premise, bioclimatic models are widely used to project biotic responses to climate change, but their assumption of equilibrium is likely to be violated for a number of species with slower life-history characteristics (e.g., longer lifespans and lower reproductive rates) and specialized habitat requirements. In the short term, disequilibria between climate and biota are likely to arise because of lags in biological response (Svenning and Sandel 2013, Wu et al. 2015).

Although climate factors are strong predictors of avian distributions at broad spatial scales (Jiménez-Valverde et al. 2011, Cumming et al. 2014, Stralberg et al. 2015), wide-ranging boreal bird species are distributed locally according to upland vs. lowland vegetation preferences, as well as forest structure, composition, and age class (Hobson and Schieck 1999, Drapeau *et al.* 2000). Forest understory characteristics, which are largely driven by moisture and nutrient status in addition to climate, are also important components of avian habitat suitability (Bayne et al. 2010). In some cases, local vegetation patterns resulting from topo-edaphic conditions and land-use history may exceed those due to climatic gradients. Thus, given the high mobility of birds, and the widespread distributions of forest tree and shrub species, the potential for boreal birds to track climate change in the short term is likely to be limited more by local topo-edaphic (terrain- and geology-driven) conditions, disturbance regimes, and plant growth and successional processes, rather than plant or bird dispersal. Understanding the future of suitable avian habitat in the boreal biome therefore requires consideration of what changes in forest structure are likely to occur, and at what rate.

Within the next century, soil moisture deficits are projected to increase in frequency and severity throughout the southern boreal region of western Canada (Price et al. 2011, Price et al. 2013), where increased drought-induced tree mortality (Allen et al. 2010, Michaelian et al. 2010) may cause relatively rapid conversion of forest to grassland or open woodland (Hogg and Hurdle 1995, Schneider et al. 2009). Climate-related increases in fire (Flannigan et al. 2005, Balshi et al. 2009, Boulanger et al. 2014) and insect outbreaks (Hogg and Bernier 2005) may hasten these

transitions. Within the core of the boreal mixedwood region, which comprises a large portion of Alberta, warmer temperatures and increased disturbance frequencies could encourage competitive shifts from conifer-dominated to deciduous-dominated stands (Soja et al. 2007, Johnstone et al. 2010), and increased drought-induced tree mortality where moisture becomes limiting (Allen et al. 2010, Zhang et al. 2015). Peatland systems, in contrast, may persist longer than upland forests due to strong negative feedback loops (Waddington et al. 2015, Schneider et al. submitted). Thus it is important to consider underlying moisture and nutrient constraints on vegetation change and associated wildlife responses. In Alberta, for example, large peatland complexes are not likely to give way to upland deciduous forests within the next century. Meanwhile, drought and increased disturbance may result in rapid grassland encroachment on upland mixedwood forests, placing a near-term “squeeze” on these ecosystems.

An increase in disturbance may facilitate ecosystem shifts, reducing the mismatch between climate and vegetation. It would also create a much younger forest, however—a trend that will be exacerbated by continued timber harvest and other industrial development activities, especially along southern boreal margins (Schneider et al. 2003, Cyr et al. 2009, Hauer et al. 2010). Generalist and early-seral bird species may benefit from increased rates of natural disturbance, but late-seral species may be particularly dependent on *in situ* climate refugia: areas of relatively greater projected habitat stability in spite of climate change (Ashcroft 2010, Keppel et al. 2012). Thus, a decrease in average forest age could cause a near-term reduction in suitable habitat for species associated with late-seral forest, as well as lags in bird response due to delays in successional processes (Stralberg et al. in press). Ultimately, such changes in vegetation composition and age structure may be enough to limit populations of some bird species. Thus, it is critical to understand decadal-scale dynamics of vegetation succession in response to climate and land-use change. Although such dynamics are complex, simple simulations based on data-rich regions (in this case, Alberta, Canada) may yield insights regarding limiting factors and conservation priorities in upcoming decades.

Bioclimatic model projections may overestimate near-term climate impacts on generalist and early-seral species that benefit from the creation of new habitat, while underestimating impacts on late-seral forest species that face a near-term double-whammy: loss of old-growth habitat coupled with declines in suitable climate conditions. These differential responses among species

should be identified and considered in species vulnerability assessments and conservation prioritization. Our objective was to identify decadal-scale risks of climate change on boreal passerine birds, considering (a) topo-edaphic constraints to vegetation change; (b) forest age habitat associations; and (c) changes in disturbance regimes. We simulated climate- and disturbance-related changes in vegetation composition and age structure, and estimated numerical avifaunal responses in order to identify potential population bottlenecks and assess species vulnerability to climate change.

To rein in the complexity associated with many future uncertainties, we took a bookend approach to scenario evaluation, concentrating on four key scenarios with increasing levels of complexity (and uncertainty):

Scenario	Climate change	Topo-edaphic constraints	Fire-modified forest age	Fire-dependent vegetation change
A. Climate only	X			
B. Topo-edaphic	X	X		
C. Age-modified	X	X	X	
D. Fire-dependent	X	X	X	X

For scenario A, we allowed vegetation to change with climate, irrespective of underlying topo-edaphic conditions. In scenario B, wetlands were fixed at current conditions and upland vegetation types were topo-edaphically constrained within each ecosite type (i.e., hierarchically defined). Scenario C simulated future changes in forest age, based on climate-altered wildfire regimes, while scenario D also restricted vegetation change to simulated burn areas. Scenarios C and D, which factor in wildfire, are more realistic than scenarios A and B, which do not include fire, but we do not necessarily view one as a better representation of reality. Although crown-renewing wildfire is certainly an important catalyst for forest regeneration and ecosystem change, slower successional processes and forest edge/gap dynamics, aided by drought and human footprint expansion, may also have a large influence on forest transitions.

Notably, we did not include land-use scenarios in this iteration, so disturbance-related results should be viewed as conservative. Land-use scenarios will be incorporated as a next step. Also,

for demonstration purposes, we have used a single general circulation model (MPI ECHAM5, Germany), identified as a typical, “middle-of-the-road” scenario for Alberta. We will later expand to include other models.

Methods

Study Area

Our study area consisted of the province of Alberta (total area 661,848 km²), with a focus on the interior transition zone from grassland to parkland to boreal mixedwood and finally boreal highlands and subarctic vegetation at northern high elevations (Downing and Pettapiece 2006) (Figure 1, natural subregions). We also included the Rocky Mountain and foothills natural regions to improve our models, as they also contain many boreal elements and species. Boreal Alberta is characterized by a strongly continental climate. Soil moisture deficits are common, and fire is the predominant natural disturbance. Geologically, the boreal region of Alberta primarily consists of the boreal plain, an area of deep marine sediments; there is just a small section of the Canadian Shield (eroded Precambrian rock) in the northeastern corner of the province. Upland forests are composed primarily of aspen (*Populus tremuloides*) and white spruce (*Picea glauca*) in various mixtures, with the former dominating on warm, exposed, and disturbed sites, and the latter dominating on cold, sheltered, and late-successional sites; extensive forested wetlands are also found, where sparse black spruce (*P. mariana*) and/or larch (*Larix laricina*) dominate on cold, poor wetland soils. Forests on the granitic expanse of the western Canadian Shield are composed mostly of black spruce and pine (*Pinus contorta*). Alberta’s wildfire regime is characterized by a fairly long season, starting early-April and ending late-September, and remains mostly natural, i.e., based on lightning ignitions. Most fire activity is in the boreal region, particularly in the northern part of the province; the Rocky mountain and foothill regions have little activity in comparison (Tymstra et al. 2005).

Modeling Overview

Due to the difficulty associated with disentangling the effects of climate and vegetation on birds, and the inevitable decoupling over time, our approach was to develop models that assume avian responses to climate change are completely mediated by vegetation. We modeled vegetation (i.e. dominant overstory component) as a function of climate and moisture/nutrient class (hereafter

ecosite). For scenario A, we allowed ecosite types to change with climate, but for scenarios B-D we fixed ecosite at current conditions, assuming that any changes in moisture regime that occur as a function of climate change (i.e., wetland drying) will occur over a time period greater than 100 years. Scenarios A and B ignored forest age and assumed equal avian habitat value within a given vegetation type, whereas scenarios C and D incorporated age explicitly, with forest age increasing over time until disturbed by simulated wildfire events. Finally, scenarios A-C assumed that, subject to associated ecosite constraints, vegetation change will occur solely as a function of climate, e.g., through drought-related mortality and gradual changes in overstory composition. In Scenario D we restricted vegetation transitions to switches driven by simulated wildfire events.

Ecosite and Bird Data

To develop these models, we used ground-based datasets rather than relying on mapped vegetation layers to avoid propagating mapping errors, and to be able to incorporate ecosite conditions and associated understory characteristics directly, without propagating prediction errors. That is, bird models were based only on sites with both bird and ecosite data. We primarily used the Alberta Biodiversity Monitoring Institute (ABMI) dataset, which includes avian point-count surveys as well as field-based ecosite type classifications at pre-determined sites arranged in a regular grid of 1656 sites across Alberta, each consisting of 9 points. Not all of the pre-selected sites in the grid have been surveyed yet, but the addition of “off-grid” sites, primarily in areas of high land-use intensity, gave us a total of 2343 points for analysis. To improve model power, we also included a dataset collected by Environment Canada in the oil sands monitoring region (Mahon et al. unpubl.) (n = 3776), as well as a University of Alberta dataset focused on boreal hill systems (Bayne and Stralberg 2015) (n = 114), for a total of 6233 unique point locations after dropping developed sites without ecosite classifications (Figure 1). Sites were classified in the field according to moisture and nutrient categories (hereafter ecosite), based on understory vegetation indicators, and by ecosite phase (hereafter vegetation) as determined by ecosite-specific overstory vegetation, as described in ABMI’s terrestrial field protocols (<http://www.abmi.ca/home/publications/1-50/46.html>). Ecosite classifications are based on the ecological land classification system of Alberta, as described in Archibald et al. (1996) and Beckingham and Archibald (1996), but without the natural subregion hierarchy

(Table 1). We omitted this hierarchy to ensure that future vegetation was constrained by current moisture/nutrient status, but not by current natural subregion boundaries, the contents of which will change in the future.

Bird data consisted of point-count surveys (Ralph et al. 1993) conducted by a combination of trained observers (Mahon et al. unpubl.), single 10-minute recordings post-processed by trained observers (ABMI), and automated recording units (Bayne and Stralberg 2015). Data were collected between 2003 and 2011, primarily from single surveys at unique locations separated by a minimum of 300 m (standard spacing for ABMI point-count grids). All surveys were unlimited-distance surveys conducted between sunrise and 10:00 am.

Climate and Terrain Data

Climate, terrain, geology, and wetland variables used as inputs to ecosite and vegetation models are listed in Table 1. Terrain metrics (Stolar and Nielsen, unpubl.) included indices of topographic ruggedness at various scales (VRM, vector ruggedness measure) (Sappington et al. 2007), slope, solar insolation, and terrain wetness (CTI, compound topographic index) (Gessler et al. 1995). Wetland classes were primarily based on the Alberta merged wetland inventory (AESRD 2014), supplemented by a vegetation map for the Wood Buffalo National Park (Jensen 2003) (Figure 2). Surficial geology was based on the surficial geology map of Alberta (map 601) by Alberta Geologic Survey (2013).

Interpolated climate data for the 1961-1990 normal period based on the parameter-elevation regressions on independent slopes model (PRISM) (Daly et al. 2008) were obtained from ClimateWNA at 500-m resolution (Hamann et al. 2013). We used derived bioclimatic indices relevant to vegetation distributions (Table 1). To represent potential future climates for three consecutive 30-year periods (2011–2040, 2041–2070, and 2071–2100), we used projections from the CMIP3 multi-model dataset, corresponding to the fourth IPCC assessment report (Meehl et al. 2007), also downscaled using ClimateWNA.

For future prediction purposes, we focused here on a single GCM, the German MPI-ECHAM5 model, identified as a median model for Alberta, in terms of future temperature and moisture characteristics (Stralberg 2012). Future work will incorporate multiple GCMs to assess uncertainty. For this analysis, we adopted a scenario of high and monotonically increasing

emissions (SRES A2, IPCC 2001), reflecting actual emissions during the decade elapsed since the scenario was defined (Raupach et al. 2007).

Fire Data

Fire data from the period 1981-2010 were obtained from the Canadian National Fire Database (<http://cwfis.cfs.nrcan.gc.ca/datamart>). Fires <200 ha were excluded, as they are inconstantly reported.

Ecosite Models

As a basis for identifying topo-edaphic constraints on future projections, we modeled natural subregion-independent ecosite type (i.e., moisture/nutrient class) as a function of terrain, climate, geology, and wetland class sampled at 100-m grid cell resolution ($n = 6233$). The influence of these variables can be viewed in a hierarchical manner. Regionally, surficial geology provides the parent material from which soils are created, and influences nutrient availability; climate determines rates of evapotranspiration and available moisture. At the landscape level, terrain features determine the flow of water and resulting moisture characteristics (Figure 3). Thus, we presumed that terrain, climate, and geology could be used to predict moisture and nutrient conditions at an accuracy level suitable for province-wide analysis. We used a modeling approach rather than relying on mapped products because remotely-sensed vegetation products have poor discrimination of wetland classes, particularly treed wetlands, and detailed, high-accuracy wetland maps are not yet available province-wide. However, we did include the Alberta merged wetland inventory, as covariates to help improve the predictive power of the model.

We used a random forest (Breiman 2001) classification-tree approach to develop predictive models for 16 ecosite types (Table 2). Random forest is a powerful ensemble approach based on bootstrap sampling of the data and subsequent averaging of the data. It is widely used in vegetation mapping (Evans and Cushman 2009) and species distribution modeling (Iverson et al. 2004, Rehfeldt 2006) due to its high predictive performance (Prasad et al. 2006, Syphard and Franklin 2009). Models were constructed in 64-bit R v. 3.1.3 (R Core Team 2014) using the ‘randomForest’ package (Liaw 2015).

For prediction purposes, we used 500-m resolution raster layers to improve speed and reduce storage requirements, given the provincial scale of the analysis and the focus on population-level estimation rather than prediction at individual grid cells. Terrain metrics were originally derived at 100-m resolution and resampled. Climate metrics were originally obtained from ClimateWNA at 500-m resolution given the general lack of relief in the boreal region. Surficial geology was derived from compiled vector maps with source scales ranging from 1:50,000 to 1:1,000,000 (Alberta Geology Survey 2013) and wetland class was derived from compiled vector polygon GIS layers with a minimum mapping unit of 0.09 ha (AESRD 2014).

For scenario A, we projected ecosite classes based on future climate conditions for three 30-year periods: 2011-2040, 2041-2070, and 2071-2100. Ecosite classes were held fixed for scenarios B-D.

Vegetation Models

Because we assumed ecosite classes would remain fixed over the next century (in scenarios B-D), we used random forest to develop separate climate-based vegetation (ecosite phase) models for each ecosite (moisture/nutrient) class, as predicted based on current conditions. Vegetation classes, consistent with the classification system developed for the Joint Oil Sands Monitoring project (Fiera Consulting 2013), were obtained from ground-based surveys rather than remotely-sensed data due to substantial discrepancies with ABMI's wall-to-wall landcover layer (Figure 4), particularly in the wetland classes (Table 3). Where available, ABMI's mapped upland classes were derived from the Alberta Vegetation Inventory (AVI), an aerial photo-based inventory that is generally considered to be the most reliable mapped vegetation product for Alberta. However, AVI does not cover the entire province and is generally less recent than ABMI's ground-based data. Given the large ground-based sample available, we chose to use this consistent, field-derived dataset even though it meant sacrificing available avian data without corresponding ecosite information.

Fire Models

As a preliminary investigation of the effects of climate-change related increases in wildfire on vegetation age and composition, we modeled total area burned as a function of climate during the 1981-2010 period, generated smoothed predictions for the current period, and then applied

regional change multipliers projected by Balshi et al. (2009) to develop projections of future area burned at a subregional scale. A hexagonal grid was generated over the province, excluding the grassland natural region (Figure 5). The hexagon size (216,506 ha) was selected to capture enough variability both in historical area burned and explanatory variables, while limiting chances of spatial-autocorrelation. For the 463 fires considered, the total area burned was 5.7 million ha. This represents the total extent burned by fires in the province and is not a cumulative burned area calculation, i.e., it does not consider areas burned more than once to avoid statistical overemphasis of areas with short fire return intervals. Of the 283 hexagons considered, 271 with at least 10% of their area within non-grassland Alberta were retained for modeling. We modeled square-root-transformed area burned as a function of bioclimatic variables from Climate WNA for 1981-2010 using generalized linear models with a quasi-Poisson distribution and log link function.

Predicted area burned based on this model was used to provide a climate-smoothed representation of fire activity in the current period. We used Balshi et al.'s (2009) projections to obtain multipliers for each future time period examined: 1.5 for the 2011-2040 period, 3 for the 2041-2070 period, and 5 for the 2071-2100 period. Although spatial patterns of fire are far from random, we randomly sampled the number of non-water pixels equivalent to predicted area burned times the time-period-multiplier within each hexagon for each time period. For scenarios C and D, we reset the age of randomly-selected burn pixels to zero at each 30-year iteration. In scenario D, we updated only burned pixels to the climate-predicted vegetation type for the given time period.

We did this as a first-order approximation, but research indicates that forest flammability varies greatly according to fuel type (primarily conifer vs. deciduous) (Cumming 2001) and forest age (Héon et al. 2014), and that landscape features such as lakes serve as barriers to fire (Parisien et al. 2007), while topography can enhance or hinder fire spread. Thus, as a much more realistic next step we will use Burn-P3 simulation model, which simulates the spatial ignition and growth of fires over multiple stochastic iterations (Parisien et al. 2005). Burn-P3 models large fires (we will use a lower limit of 200 ha), as large fires are responsible for virtually all of the area burned in Canada (Stocks et al. 2002). Individual fires are simulated deterministically for one fire season using the Prometheus fire growth model (Tymstra et al. 2010), and this process is repeated for a

large number of iterations. The Prometheus model calculates the elliptical growth of each fire based on fuels and terrain according to the Canadian Fire Behaviour Prediction (FBP) System (Forestry Canada Fire Danger Group 1992) and fire spread mechanisms (Richards 1995). We will take advantage of newly-developed future daily fire weather projections (Wang et al. 2015) and a new method to convert potential to realized spread rates (Wang et al. 2014). Fuel inputs will be based on our ecosite vegetation model for Scenario C. For Scenario D, we will iteratively determine fuel type based on consecutive 30-year fire simulations.

Bird Models

Finally, we modeled bird abundance for 72 boreal-breeding passerine species according to ecosite, vegetation type, and age (36 factor levels) using a Poisson generalized linear model and detectability offsets determined according to methods defined in Sólymos et al. (2013). We used AIC to compare this full model with models lacking the age, ecosite, or vegetation and age variables. Although different models performed best for different species based on this dataset, we determined that for prediction purposes it was best to use the full model for consistency. When a larger avian dataset also containing points with no ecosite information was analyzed with respect to model-predicted ecosite and vegetation, the full model was more consistently the best model. However, we were reluctant to generate models based on multiple levels of predictions, and thus used the smaller, more conservative dataset for model-building and prediction.

Predicted density (males/ha) values were summed across the province. Because ecosite and vegetation classifications overlapped between foothill/mountain and boreal regions, we could not adequately separate them, despite major climatic differences (greater moisture availability and more moderate temperatures in the mountains). As a result, we found that models over-predicted the distributions of many species in the Rocky Mountains.

Results

Ecosite Models

Random forest models for 16 ecosite classes had an out-of-bag error rate of 39.72%. The lowest classification error (6%) was for alpine (AL) ecosites, followed by 10% for the medium mesic

(MM) upland ecosite type, which was predicted to comprise 50% of the province, including developed and agricultural areas (Table 4). The highest classification error (96%) was for marsh wetlands (VD), which had a very small sample size. The large majority of misclassified records were at least correctly classified by either moisture or nutrient status (i.e., half correct). The most important explanatory variable in terms of decrease in the Gini impurity index, a measure of how often a randomly chosen element would be incorrectly labeled, was the topographic position index for a 2-km window, followed by the annual heat:moisture ratio, and the vector ruggedness metric for a 1.1-km window (Figure 6). According to the prediction accuracy criterion, the wetland class variable was most important, followed by the summer heat:moisture ratio and mean cold month temperature (Figure 6). This can be interpreted to mean that the wetland variable provides the most overall explanatory power, but in terms of pixel-level classification success, the terrain position index was most useful. Predicted ecosite classes are shown in Figure 7.

Vegetation Models

Random forest models for vegetation type within ecosite had high classification success, with out-of-bag prediction error ranging from 0.75% for poor xeric ecosites (two vegetation classes), to 28.8% for medium mesic ecosites (five vegetation classes) (Table 5). Across ecosites, the most important explanatory variable according to the accuracy criterion was the annual heat:moisture ratio. A combined multi-ecosite model visualization with a single classification tree indicated that most of the climatic variation in vegetation type occurs within the medium mixed upland ecosite type. Annual heat:moisture ratio (AHM) determined the difference between grassland and forest vegetation, temperature difference (TD) determined the split between pine (mountains) and deciduous/mixed (boreal), and mean summer precipitation primarily determined the split between deciduous and mixedwood (Figure 8). Predicted vegetation classes are shown in Figure 9.

Fire Models

By the end of the century, applying the Balshi et al. (2009) future fire projections to our climatically-smoothed baseline, 38 of 283 hexagons, primarily in the northeast, were projected to be entirely burned over a 30-year period (Figure 10). The mean percent of projected area burned

per hexagon in the 2071-2100 period (not including current grasslands) was 38% (compared to 8% in the current period).

Bird Models

Ecosite/vegetation-bird models with and without forest age explained 24.8% and 19.2% of point-level variation in abundance, respectively, on average across species (SD = 16%) (Table 6). Models without ecosite explained 19.7% of variation on average, and models with only ecosite explained 11.4% on average. For the largest proportion (half) of species (36/72), AIC was lowest for the full model including vegetation, age, and ecosite (Table 6).

Scenario Evaluation – Vegetation

The constraining of vegetation by fixed ecosite conditions (Scenarios B/C and D) had a major influence on future projections, resulting in much less dramatic vegetation changes compared to Scenario A, especially toward the end of the century (Figures 11-13, Table 7). Scenario D, in which change was fire-dependent, was particularly subdued, with minimal noticeable vegetation change outside the northeastern portion of the province, even by the end of the century with fivefold increases in area burned.

With fire as the only disturbance considered, the median age of currently forested areas was projected to increase through mid-century, from 60 in the current period to 74 in 2011-2040, to 80 in 2041-2070. By end-of-century (2071-2100), there was a dramatic projected decrease to a median age of 30 years. Due to the large area of aging forest, however, the mean age was projected to increase over time, from 56 to 88 years (Figure 14).

Scenario Evaluation – Birds

Scenarios B and C did not differ greatly with respect to projected overall bird abundance, although by the end of the century, projections were generally lower for most mature-forest species (Table 8). 2071-2100 projected changes in suitable habitat for scenario B ranged from -87% (Brown Creeper) to +452% (American Goldfinch), with a mean of +11%. Scenario C projections ranged from -82% (Brown Creeper) to +455% (American Goldfinch), also with a mean of +11%. Scenario D projections ranged from -42% (Yellow-bellied Flycatcher) to +78% (American Goldfinch), with a mean of +5%. Because scenarios B-D were topo-edaphically

constrained, such that wetlands remained fixed, upland deciduous forest species such as Ovenbird were not projected to shift upslope, but rather experienced a projected shrinkage of current suitable habitat under scenarios B and C (Figure 14a,b). Because the areas with the highest projected area burned did not coincide with core mixedwood habitat, there was little change in these species under the disturbance-mediated change scenario (D) (Figure 14 c). This is likely unrealistic and will be addressed with the use of Burn-P3. In general, the largest projected decreases under scenarios B-D were for upland-conifer-associated species such as Bay-breasted Warbler and Cape May Warbler. Several wetland-associated species such as Palm Warbler and Olive-sided Flycatcher remained fairly stable or increased under scenarios B-D. Conversely, grassland-associated species had smaller projected increases under scenario D compared to the other scenarios.

Discussion

Our comprehensive analysis and simulation exercise addressed three major areas for which traditional bioclimatic models fall short: 1) topo-edaphic constraints on vegetation change; 2) changes in vegetation age structure, and 3) changes in disturbance regimes. Although much work remains in each of these areas, several interesting preliminary conclusions can be made.

Regarding topo-edaphic constraints, there is little consensus on the rate at which ecosite types may change in response to changes in available moisture, but conservative climate-change adaptation must assume that changes will occur slowly, especially within large peatland complexes that are maintained by negative feedbacks. Our consideration of this constraint, therefore, helps refine climate model predictions for mesic mixedwood forest species in particular, and identify potential climate refugia. As previous work indicates (Stralberg et al. in press), future refugia for most of these mixedwood species can be found in the central hill systems, as well as on the slopes of northern hills that hold permafrost peatlands at higher elevations. But our ecosite models also suggest some flat areas within the Athabasca and Peace watersheds that may also serve as refugia for deciduous and mixedwood forest. If wetlands do indeed persist in their current locations, as assumed by scenarios B-D in our models, we can expect to see a novel juxtaposition of peatlands surrounded by deciduous forest and eventually grasslands over the next century, as discussed by Schneider et al. (submitted).

Our simulation of future changes in age structure was incomplete, in that we only considered natural disturbances (i.e., wildfire), omitting anthropogenic disturbances (for now). By isolating wildfire, however, we observed that increases in fire alone may not result in younger-on-average forests until later in the century, or when area burned increases by five-fold. This may be partly due to current underestimation of forest age (Cumming et al. 2000) and partly due to the relatively young current forest age that has resulted from decades of timber harvest (in addition to wildfire), and the natural aging that would occur in the absence of additional new harvest. It also suggests that the addition of timber harvest and other anthropogenic activities would certainly reduce mean forest age substantially, resulting in potential population bottlenecks for old forest species.

Our bird models were improved by the inclusion of forest age information for a majority species, but it is difficult to say to what extent the relatively weak influence of age-specific simulations was due to lack of model discrimination potential vs. lack of importance vs. underestimated projected future change in age structure. Spatially-explicit estimates of wildfire dynamics that incorporate changes in fuels should greatly improve estimates of future forest age. Burn-P3-generated fire probabilities in the southern boreal region of Alberta are likely to be higher than our estimates in the next half century, as fire weather increases and fuels are plentiful, but lower towards the end of the century as fuels diminish. With better fire projections, it will be more fruitful to also start adding anthropogenic land-use change scenarios into the mix, in order to identify the relative influences of natural and anthropogenic disturbance on future vegetation change.

Although more work is needed to better estimate future fire extent and spatial patterns, our simulations did highlight that even with high future rates of wildfire, vegetation change could be substantially delayed if disturbance catalysts are necessary for vegetation transitions to occur. Fuel-dependent wildfire simulations may reveal a negative feedback process by which a warmer climate and more frequent near-term fires leads to an aspen-dominated landscape that in turn leads to fewer long-term fires due to its relatively low flammability. However, drought conditions may also result in vegetation transitions through increased tree mortality. In contrast with the traditional paradigm of faster rates of climate-change response on the leading edge of species' distributions—as individuals colonize previously unsuitable climates without significant

interspecific competition—the situation may be reversed in the Alberta boreal region. That is, northern and high-elevation shifts are constrained by wetlands that are likely to persist longer than upland habitats. Meanwhile, southern margins along the boreal-grassland ecotone are most vulnerable to changes in available moisture and associated tree mortality. Thus, retreats along the southern edge may happen faster than advances along northern margins. Long-term monitoring projects are critical to evaluating these rates of change.

In light of continued uncertainty, species near-term vulnerability remains difficult to assess. Quantification of inter-annual variability in individual species' abundance, as well as better quantification of variability across GCMs and vegetation models, should help improve species' vulnerability assessments.

Next Steps

Ecosite and Vegetation Models

We will obtain peer review on ecosite and vegetation models to determine areas of potential discrepancies. Initial review suggests an overestimation of deciduous forest and an underestimate of pine (Beaudoin et al. 2014). We expected to see a stronger latitudinal gradient from deciduous to mixedwood to coniferous forest composition, although our deciduous-conifer patterns do appear to be fairly consistent with ABMI's wall-to-wall vegetation product. The absence of a gradient may be a product of the relatively coarse thematic resolution that we used, particularly within the large medium-mesic upland category. We will consider also modeling canopy composition (% conifer/deciduous) to better discriminate among upland forests, with the potential inclusion of an age variable to account for successional changes in forest composition. Our original inclusion of age in the full model resulted in suspicious future projections, resulting in its ultimate exclusion, but it may still make sense to include it for the medium-mesic vegetation model.

As models are only as good as their inputs, we will also evaluate additional potential ecosite data sources and revisit the Alberta Ecological Site Information dataset, which was excluded from initial models. The lack of improvement in discrimination potential with this dataset was imprecise spatial coordinates, resulting in mismatches with fine-scale terrain information. However, we are in the process of identifying which subset of the dataset may be appropriate to

include. We are also updating our ABMI dataset to reflect the most recent surveys (through 2014).

Finally, we plan to evaluate multiple GCMs to better capture the range of uncertainty contained in projections.

Fire Models

Our simulations are based directly on current broad-scale spatial patterns of fire, which may shift in the future as fire weather changes, altering burn probabilities on the landscape. Furthermore, our simple simulation ignored landscape spatial patterns of fire spread, and equally importantly, fuel availability. We are currently parameterizing Burn-P3 for the boreal region of Alberta, using our vegetation projections as fuel inputs, to develop mechanistic predictions of future area burned. We suspect that near-term burn probability may increase in the central part of the province, where fuels are ample and extreme fire weather days will increase, and that burn probability is likely to decline throughout toward the end of the century as fuels diminish. These fuel-related dynamics are not captured in our current approach. Furthermore, we will utilize the stochastic element of Burn-P3 to evaluate a sample of alternative realizations, in order to quantify fire-related uncertainty.

Land-use change

Perhaps more importantly, in order to focus on core modeling components, we have temporarily ignored future industrial development activities, which may be an even larger contributor to forest change and loss. By incorporating available land-use scenarios for at least the Alberta-Pacific forest management area, we will get a better handle on the relative importance of fire, human land use and climate change as drivers for changes in bird populations.

Bird models and simulations

Our simulations project relatively moderate age-related changes in the most conservative scenarios C and D, potentially due to lack of model power to adequately differentiate habitat values of different age classes and forest types. We will evaluate a two-stage modeling approach that allows us to utilize the entire avian dataset for the forest type and age component of the model, while using field-mapped ecosites only. In addition, the reduced differentiation between

boreal and mountain regions, and the lack of latitudinal gradient in predicted forest cover, means that we have likely underestimated climatic spatial variation, in contrast to previous bioclimatic modeling efforts, which may have overestimated its near-term influence (Stralberg et al. 2015, Stralberg et al. in press). Thus, we will evaluate ways to improve the representation of climatic gradients within the bird models while still retaining a focus on vegetation-mediated change. We will also evaluate bootstrap uncertainty to develop error bounds on estimates, in conjunction with estimates of GCM uncertainty.

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Tables

Table 1. Climate, terrain, geology, and wetland variables included in random forest models for ecosite and vegetation.

Variable	Definition
ahm	annual heat:moisture ratio
shm	summer heat:moisture ratio
mwmt	mean warm month (Jul) temperature
mcmt	mean cold month (Jan) temperature
msp	mean summer (May-Sep) precipitation
td	temperature difference (summer – winter)
emt	extreme minimum temperature
slope	slope
slpasp	slope / aspect solar radiation index
tpi2km	topographic position index (2-km radius)
tpi300m	topographic position index (300-m radius)
tri	topographic ruggedness index
vrms5x5	vector ruggedness measure (5 x 5 cells)
vrms11x11	vector ruggedness measure (11 x 11 cells)
cti	compound topographic index (wetness)
geol_surf	surficial geology (parent material)
wetlands	wetland type

Table 2. Ecosite types modeled based on climate, terrain, geology, and wetland layers (see Table 1), and vegetation types (ecosite phases) modeled based on ecosite and climate. Alpine habitats, though not an ecosite type, were also included in the model.

Ecosite	Phase	Definition
AL	AL	alpine
MD	MDSB	medium-hydric black spruce
MD	MDSH	medium-hydric shrubland
MG	MGD	medium-hygric deciduous forest
MG	MGG	medium-hygric grassland
MG	MGSB	medium-hygric black spruce
MG	MGSW	medium-hygric white spruce
MM	MMD	medium-mesic deciduous forest
MM	MMG	medium-mesic grassland
MM	MMM	medium-mesic mixedwood forest
MM	MMP	medium-mesic pine forest
MM	MMSW	medium-mesic white spruce
MX	MXD	medium-xeric deciduous forest
MX	MXG	medium-xeric grassland forest
MX	MXP	medium-xeric pine forest
MX	MXSW	medium-xeric white spruce
PD	PDSB	poor-hydric black spruce bog
PD	PDSH	poor-hydric shrub bog
PG	PGSB	poor-hygric black spruce
PM	PMG	poor-mesic grassland
PM	PMSB	poor-mesic black spruce
PM	PMP	poor-mesic pine forest
PX	PXG	poor-xeric grassland
PX	PXP	poor-xeric pine forest
RD	RDG	rich-hydric grass fen
RD	RDSB	rich-hydric treed fen
RD	RDSH	rich-hydric shrub fen
RG	RGD	rich-hygric deciduous forest
RG	RGP	rich-hygric pine forest
RG	RGSH	rich-hygric shrubland
RG	RGSW	rich-hygric white spruce
RM	RMG	rich-mesic grassland
VD	VDG	very rich hydric grassland (marsh)
OW	OWNA	open water

Table 3. Correspondence between ABMI wall-to-wall vegetation map categories and ecosite classifications, as determined by field visits between 2003 and 2014. Mapped vegetation (columns) according to EC bird habitat classification. Ecosite codes represent a combination of nutrient-moisture-overstory type. Nutrient codes: M = medium, P = poor, R = rich, V = very rich. Moisture codes: X = xeric, M = mesic, G = hygric, D = hydric. AL = alpine. Overstory codes: SH = shrub, SB = black spruce / larch, D = deciduous, G = grassland, SW = white spruce, P = pine, M = Mixedwood. Corresponding classes highlighted in bold.

	Shrubland	Grassland	Deciduous	Mixedwood	WhiteSpruce	Pine	BlackSpruce	LarchFen	Bog	Fen	Swamp	Marsh
AL	0	0	0	0	4	0	0	0	0	0	0	0
MDSB	2	0	0	2	2	3	31	56	3	11	16	0
MDSH	0	1	0	0	0	0	12	13	2	7	3	0
MGD	1	4	38	34	8	3	0	1	0	1	21	0
MGG	1	20	0	0	0	0	0	0	0	0	1	0
MGSB	0	1	5	3	7	9	6	5	0	0	17	0
MGSW	0	0	4	7	16	2	3	4	0	0	32	0
MMD	6	11	549	134	83	15	5	6	0	1	18	5
MMG	6	98	8	0	0	0	0	0	0	0	0	8
MMM	5	1	315	184	68	52	20	20	0	0	37	0
MMP	0	0	2	7	13	60	2	2	0	0	8	0
MMSW	0	0	20	27	54	18	4	8	0	0	30	0
MXD	2	2	17	4	1	2	0	0	0	0	1	0
MXG	0	14	0	0	0	0	0	0	0	0	0	0
MXP	0	1	0	2	5	16	1	0	0	1	3	0
PDSB	5	1	2	0	10	8	141	79	12	13	49	0
PDSH	0	0	0	0	1	0	0	0	6	0	3	0
PGSB	2	0	0	4	8	7	7	1	0	0	4	0
PMG	0	15	0	0	0	0	0	0	0	0	0	0
PMP	12	0	10	12	19	59	14	16	0	5	29	0
PMSB	0	2	17	8	17	35	50	43	2	3	77	0
PXG	7	16	1	0	0	0	0	0	0	1	0	1
PXP	5	0	0	2	2	86	2	7	0	3	1	0

	Shrubland	Grassland	Deciduous	Mixedwood	WhiteSpruce	Pine	BlackSpruce	LarchFen	Bog	Fen	Swamp	Marsh
RDG	0	3	1	0	1	0	0	0	0	1	6	1
RDSB	0	0	7	1	6	1	34	55	3	7	33	0
RDSH	1	2	8	0	0	1	9	41	6	21	24	2
RGD	0	2	212	148	53	5	12	2	1	0	47	0
RGP	0	0	0	2	3	11	0	1	0	0	0	0
RGSH	0	0	0	0	0	0	0	0	0	0	0	0
RGSW	0	0	5	3	21	4	2	5	0	0	39	0
RMG	1	18	0	0	0	0	0	0	0	0	0	0
VDG	0	1	0	0	0	0	0	1	0	2	1	0

Table 4. Confusion matrix for ecosite classification model. See Table 2 for ecosite code definitions.

	PX	PM	PG	PD	MX	MM	MG	MD	RM	RG	RD	VD	OW	AL	Class Error
PX	71	28	0	4	5	88	0	1	1	2	4	0	1	0	0.65
PM	21	211	21	66	7	224	7	17	0	7	19	0	1	0	0.65
PG	1	22	193	26	0	94	4	59	0	11	12	0	0	0	0.54
PD	5	58	37	253	1	125	6	30	0	8	18	0	0	0	0.53
MX	5	11	0	2	66	29	1	0	0	0	1	0	0	1	0.43
MM	17	77	14	31	10	2264	22	7	1	80	10	0	1	0	0.11
MG	0	14	8	14	3	119	65	6	16	20	15	0	0	0	0.77
MD	2	22	47	38	0	40	2	149	0	1	38	0	0	0	0.56
RM	0	0	0	0	0	1	16	0	2	0	0	0	0	0	0.89
RG	1	7	9	11	1	401	11	2	0	252	10	0	0	0	0.64
RD	0	20	18	29	0	57	16	45	0	9	167	0	0	0	0.54
VD	0	0	10	3	0	4	0	1	0	0	6	1	1	0	0.96
OW	1	1	0	0	0	9	1	2	0	0	2	0	44	0	0.27
AL	0	0	0	0	1	0	0	0	0	0	0	0	0	14	0.07

Table 5. Classification accuracy, top predictor variable, proportion of province, and number of ecosite phases modeled for each ecosite class.

Ecosite	Out-of-bag error	Top predictor variable	Proportion of province	Number of classes
PX	0%	AHM	0.011	2
PM	9.66%	AHM	0.049	3
PG	0%	N/A	0.020	1
PD	0.61%	MCMT	0.044	2
MX	13.83%	MWMT	0.014	3
MM	28.64%	AHM	0.502	5
MG	17.72%	MSP	0.010	4
MD	10.37%	AHM	0.018	2
RM	10.37%	AHM	0.0001	2
RG	7.09%	MSP	0.009	3
RD	23.64%	SHM	0.060	3
SD	N/A	N/A	N/A	1
VD	0%	N/A	0.0001	1
AD	N/A	N/A	N/A	1
OW	N/A	N/A	0.015	1
AL	N/A	N/A	0.017	1

Table 6. Pseudo-R² (proportion of deviance explained) and delta AIC values for each species' model. The most explanatory model is the model for which Pseudo-R² is greater. The most parsimonious model is the one for which delta AIC = 0.

Species	Pseudo-R ²				Lowest AIC (model #)
	1. Full Model	2. Without age	3. Without ecosite	4. Without veg/age	
Alder Flycatcher	0.22	0.13	0.19	0.10	1
American Crow	0.20	0.17	0.15	0.05	2
American Goldfinch	0.25	0.20	0.19	0.02	3
American Redstart	0.18	0.14	0.13	0.10	1
American Robin	0.08	0.04	0.06	0.04	1
Black-and-white Warbler	0.17	0.13	0.14	0.10	1
Bay-breasted Warbler	0.24	0.18	0.15	0.13	1
Black-capped Chickadee	0.17	0.11	0.13	0.06	1
Brown-headed Cowbird	0.42	0.36	0.37	0.11	1
Blue-headed Vireo	0.13	0.07	0.10	0.02	3
Blue Jay	0.19	0.11	0.11	0.05	3
Blackpoll Warbler	0.24	0.13	0.17	0.08	3
Boreal Chickadee	0.12	0.07	0.07	0.03	3
Brown Creeper	0.23	0.09	0.20	0.07	3
Black-throated Green Warbler	0.22	0.16	0.18	0.16	1
Canada Warbler	0.16	0.10	0.11	0.06	3
Clay-colored Sparrow	0.34	0.32	0.29	0.11	1
Cedar Waxwing	0.08	0.05	0.04	0.03	2
Chipping Sparrow	0.12	0.09	0.07	0.04	1
Cape May Warbler	0.13	0.08	0.09	0.04	3
Common Grackle	0.31	0.22	0.15	0.08	4
Connecticut Warbler	0.16	0.14	0.16	0.12	3
Common Raven	0.06	0.02	0.04	0.03	3
Common Yellowthroat	0.16	0.10	0.08	0.07	1
Dark-eyed Junco	0.17	0.15	0.13	0.12	2
Eastern Phoebe	0.42	0.36	0.29	0.17	4
Evening Grosbeak	0.16	0.10	0.10	0.06	3
Fox Sparrow	0.29	0.19	0.21	0.16	3
Golden-crowned Kinglet	0.30	0.19	0.28	0.20	1
Gray Jay	0.10	0.08	0.08	0.03	1
Hermit Thrush	0.14	0.11	0.08	0.07	1
Horned Lark	0.69	0.69	0.68	0.16	2
House Wren	0.60	0.57	0.53	0.19	2
Le Conte's Sparrow	0.35	0.31	0.24	0.24	2
Least Flycatcher	0.08	0.05	0.04	0.02	1
Lincoln's Sparrow	0.11	0.08	0.06	0.05	1
Magnolia Warbler	0.15	0.11	0.09	0.07	1

Species	Pseudo-R ²				Lowest AIC (model #)
	1. Full Model	2. Without age	3. Without ecosite	4. Without veg/age	
Mourning Warbler	0.19	0.14	0.14	0.10	1
Northern Waterthrush	0.16	0.09	0.10	0.06	1
Orange-crowned Warbler	0.16	0.07	0.09	0.06	1
Olive-sided Flycatcher	0.26	0.19	0.14	0.13	2
Ovenbird	0.34	0.31	0.33	0.26	1
Palm Warbler	0.33	0.26	0.27	0.24	1
Philadelphia Vireo	0.21	0.17	0.15	0.10	3
Pine Siskin	0.12	0.07	0.11	0.07	1
Purple Finch	0.32	0.21	0.27	0.17	3
Red-breasted Grosbeak	0.14	0.12	0.11	0.08	1
Red-breasted Nuthatch	0.15	0.08	0.14	0.09	3
Ruby-crowned Kinglet	0.30	0.27	0.27	0.17	1
Red-eyed Vireo	0.30	0.28	0.29	0.20	1
Rusty Blackbird	0.27	0.22	0.19	0.12	2
Red-winged Blackbird	0.35	0.32	0.30	0.14	1
Savannah Sparrow	0.72	0.71	0.68	0.23	2
Song Sparrow	0.26	0.24	0.21	0.11	2
Swamp Sparrow	0.38	0.34	0.23	0.31	2
Swainson's Thrush	0.17	0.13	0.12	0.07	1
Tennessee Warbler	0.26	0.24	0.26	0.17	1
Tree Swallow	0.16	0.09	0.10	0.07	3
Varied Thrush	0.48	0.27	0.51	0.46	3
Veery	0.43	0.43	0.38	0.22	4
Vesper Sparrow	0.82	0.81	0.79	0.25	2
Warbling Vireo	0.17	0.13	0.18	0.15	1
White-breasted Nuthatch	0.23	0.15	0.21	0.12	4
White-crowned Sparrow	0.54	0.34	0.38	0.24	3
Western Tanager	0.15	0.10	0.11	0.07	1
Western Wood-pewee	0.17	0.09	0.10	0.02	3
Wilson's Warbler	0.21	0.12	0.13	0.07	3
Winter Wren	0.19	0.13	0.15	0.09	1
White-throated Sparrow	0.22	0.18	0.19	0.12	1
White-winged Crossbill	0.12	0.08	0.08	0.04	1
Yellow-bellied Flycatcher	0.24	0.13	0.14	0.09	1
Yellow-rumped Warbler	0.18	0.14	0.18	0.08	1

Table 7. Projected changes in vegetation (km²) over the next century based on scenarios A (unconstrained), B/C (topographically constrained) and D (disturbance-limited). See Table 1 for vegetation type definitions.

VegType	Current	A2020	A2050	A2080	B/C2020	B/C2050	B/C2080	D2020	D2050	D2080
ALSH	16,375	15,942	12,026	7,115	16,375	16,375	16,375	16,375	16,375	16,375
MDSB	12,806	9,552	5,732	114	12,806	12,806	12,806	10,119	10,460	10,856
MDSH	2,426	311	14	-	2,426	2,426	2,426	2,662	2,612	2,567
MGD	2,772	13,981	22,041	10,626	2,772	2,772	2,772	5,188	4,832	4,444
MGG	639	2,116	3,274	23,267	639	639	639	1,057	1,057	1,057
MGSB	440	948	1,465	835	440	440	440	922	924	930
MGSW	1,885	438	1,047	18	1,885	1,885	1,885	2,382	2,292	2,159
MMD	139,657	150,880	118,268	30,166	144,414	105,244	28,857	171,294	170,673	153,974
MMG	42,461	60,983	135,957	293,285	60,512	138,534	258,045	45,006	47,127	68,094
MMM	65,653	40,493	19,432	41	38,124	17,189	32	34,070	32,914	29,258
MMP	26,291	28,266	7,098	1,549	28,728	5,387	159	26,446	26,137	25,676
MMSW	13,406	13,268	20,882	710	15,690	21,115	375	15,771	15,421	14,845
MXD	1,111	3,258	4,675	3,848	1,277	1,068	1,069	1,278	1,279	1,279
MXG	1,741	299	318	1,892	1,741	2,012	2,024	1,126	1,158	1,175
MPX	6,745	3,434	1,999	8	6,578	6,516	6,503	4,022	4,033	4,066
OW	22,446	22,446	22,446	22,446	22,446	22,446	22,446	24,336	24,329	24,320
PDSB	32,437	28,641	26,893	15,019	32,437	32,437	32,437	35,033	34,548	34,056
PDSH	4,534	157	-	-	4,534	4,534	4,534	3,426	3,714	3,957
PGSB	17,107	1,755	22	-	17,107	17,107	17,107	5,675	6,641	7,875
PMG	522	488	517	38,277	579	2,784	22,959	1,095	1,912	9,012
PMSB	17,810	21,717	21,973	15,868	25,925	28,714	15,337	11,997	13,476	9,729
PXG	551	710	2,468	16,614	1,650	6,689	8,430	2,497	3,115	4,413
PXP	7,976	1,881	1,952	208	6,877	1,838	97	3,202	3,098	2,215

VegType	Current	A2020	A2050	A2080	B/C2020	B/C2050	B/C2080	D2020	D2050	D2080
RDG	184	46	5	-	184	184	184	575	567	561
RDSB	15,750	3,168	264	10	15,750	15,750	15,750	12,540	12,795	13,184
RDSH	30,118	63,717	62,262	11,990	30,118	30,118	30,118	35,832	35,115	34,357
RGD	4,408	10,202	7,784	2,137	4,408	4,408	4,408	6,904	6,641	6,290
RGP	1,568	1,024	991	42	1,568	1,568	1,568	909	932	958
RGSW	2,014	913	1,109	402	2,014	2,014	2,014	1,896	1,891	1,887
RMG	53	62	188	1,885	-	55	-	65	65	65
VDG	34	10	2	-	34	19	34	28	28	28
PMP	22,517	13,327	11,331	16,064	14,344	10,394	2,552	29,038	26,657	23,224
CULT	141,555	141,555	141,555	141,555	141,555	141,555	141,555	141,555	141,555	141,555
URB	4,829	4,829	4,829	4,829	4,829	4,829	4,829	4,829	4,829	4,829

Table 8. Current estimated number of millions of pairs of birds in Alberta, and projected percent changes in potential habitat for scenarios B (topographically constrained), C (topographically constrained and age-adjusted), and D (topographically constrained, age-adjusted, and disturbance-mediated).

Species	Current	B2020	C2020	D2020	B2050	C2050	D2050	B2080	C2080	D2080
ALFL	13.25	-6.4%	-9.3%	-2.3%	-23.5%	-18.1%	1.3%	-53.8%	-48.8%	-10.8%
AMCR	5.51	8.6%	4.5%	2.1%	36.7%	32.4%	2.4%	84.8%	82.0%	13.8%
AMGO	1.65	22.6%	19.7%	3.9%	175.5%	176.3%	12.2%	451.5%	455.3%	77.5%
AMRE	4.80	18.8%	-1.4%	7.7%	10.5%	-6.7%	3.4%	-6.5%	-13.4%	1.2%
AMRO	9.27	-14.2%	1.4%	3.0%	-6.0%	12.1%	7.8%	14.9%	32.4%	17.0%
BAWW	2.54	1.0%	-5.9%	4.9%	-17.0%	-19.0%	5.6%	-48.2%	-50.3%	-4.8%
BBWA	1.50	-21.9%	-5.7%	-13.6%	-40.1%	-27.5%	-14.8%	-70.2%	-61.3%	-22.0%
BCCH	3.29	-14.6%	-3.5%	-1.0%	-18.2%	-6.8%	2.0%	-21.2%	-17.7%	-3.1%
BHCO	5.77	3.4%	9.5%	8.9%	67.2%	71.7%	14.1%	202.3%	204.3%	51.6%
BHVI	1.87	-20.5%	-1.4%	-4.6%	-38.7%	-29.6%	-5.7%	-68.4%	-71.1%	-12.7%
BLJA	0.85	-4.0%	3.4%	10.9%	-7.7%	-2.4%	8.3%	-9.8%	-8.7%	5.0%
BLPW	0.89	11.0%	-12.7%	-1.5%	2.3%	-25.3%	-16.5%	-13.8%	-25.0%	-7.4%
BOCH	1.99	-5.0%	1.5%	-5.7%	-11.4%	0.4%	-1.9%	-29.7%	-6.2%	1.6%
BRCR	1.42	-39.2%	2.9%	17.0%	-56.6%	-24.3%	21.3%	-87.2%	-81.6%	5.8%
BTNW	1.21	-29.8%	0.1%	12.1%	-49.7%	-29.9%	10.9%	-82.7%	-78.5%	2.4%
CAWA	1.37	-3.5%	6.4%	20.6%	-30.0%	-27.7%	15.4%	-75.6%	-77.4%	6.2%
CCSP	15.33	4.9%	8.4%	7.9%	60.1%	65.3%	12.8%	171.1%	175.6%	41.4%
CEDW	3.43	-4.8%	-1.3%	4.9%	2.4%	7.4%	7.6%	16.7%	22.4%	12.5%
CHSP	23.02	2.2%	-3.4%	-2.8%	-12.3%	-16.8%	-3.7%	-38.5%	-43.8%	-12.8%
CMWA	1.49	-2.3%	-5.5%	-1.3%	-23.7%	-26.9%	-2.7%	-65.2%	-72.6%	-14.2%
COGR	0.06	16.5%	13.6%	35.7%	-2.7%	-11.1%	29.0%	-45.4%	-48.7%	15.4%
CONW	3.59	-10.9%	-5.3%	2.3%	-34.8%	-33.1%	0.8%	-75.8%	-77.9%	-9.3%
CORA	6.85	3.2%	3.4%	1.2%	31.2%	29.4%	0.8%	73.9%	70.8%	9.5%
COYE	5.59	6.7%	-3.2%	2.1%	10.6%	5.9%	1.5%	16.5%	13.2%	-2.5%
DEJU	7.76	1.7%	-5.0%	-3.0%	-6.7%	-12.9%	-2.9%	-21.5%	-29.5%	-11.0%
EAPH	0.09	-12.5%	4.6%	3.2%	8.0%	21.9%	2.5%	15.1%	26.3%	6.0%
EVGR	0.63	-20.3%	-5.1%	-4.4%	-41.2%	-38.4%	-6.0%	-69.6%	-78.6%	-11.8%
FOSP	1.39	20.1%	-8.7%	-1.1%	16.3%	-7.8%	0.3%	-3.5%	-4.3%	5.1%
GCKI	1.81	-42.7%	-3.0%	-13.9%	-55.2%	-18.8%	-11.7%	-75.7%	-51.3%	-18.7%

Species	Current	B2020	C2020	D2020	B2050	C2050	D2050	B2080	C2080	D2080
GRAJ	13.85	6.6%	-4.7%	-2.7%	-8.3%	-19.4%	-3.9%	-36.9%	-49.1%	-15.1%
HETH	14.87	11.8%	-0.7%	0.1%	1.6%	-8.8%	-1.8%	-14.5%	-21.3%	-7.9%
HOLA	4.86	16.9%	16.9%	2.8%	138.5%	138.5%	8.0%	352.5%	352.5%	58.1%
HOWR	4.37	11.5%	11.8%	6.6%	92.9%	92.6%	11.6%	246.0%	245.5%	52.6%
LCSP	1.89	9.6%	0.9%	5.3%	8.3%	-2.5%	2.2%	4.4%	-9.0%	0.5%
LEFL	6.13	15.3%	2.3%	7.4%	22.5%	11.4%	6.9%	40.4%	32.4%	10.9%
LISP	12.32	-9.7%	-7.0%	-3.0%	-19.3%	-11.6%	0.3%	-36.2%	-29.4%	-5.4%
MAWA	5.63	-5.6%	-7.9%	-2.4%	-19.9%	-21.4%	-2.3%	-40.5%	-39.3%	-2.5%
MOWA	3.34	11.0%	-6.7%	2.5%	-13.2%	-18.5%	4.8%	-57.0%	-55.3%	-11.2%
NOWA	2.39	4.3%	21.4%	8.2%	-1.4%	-11.3%	2.0%	-11.4%	-21.8%	0.4%
OCWA	2.25	22.6%	4.6%	4.8%	15.2%	-4.3%	6.7%	21.7%	10.4%	12.7%
OSFL	0.81	5.8%	-10.6%	-2.7%	-5.1%	-9.8%	0.4%	-16.8%	-26.2%	-11.6%
OVEN	37.92	-2.0%	5.4%	8.0%	-24.9%	-26.3%	6.3%	-67.1%	-70.6%	-4.1%
PAWA	5.59	25.8%	4.7%	1.9%	19.9%	-8.6%	-4.5%	10.3%	-9.4%	1.6%
PHVI	0.36	27.9%	28.4%	12.1%	12.5%	-9.0%	6.9%	-17.7%	-25.6%	0.4%
PISI	6.30	-10.7%	-4.7%	-3.9%	-24.7%	-12.8%	1.0%	-51.2%	-44.9%	-10.3%
PUFI	0.13	-6.6%	-3.7%	-6.2%	-20.1%	-22.0%	-4.4%	-40.3%	-41.0%	-6.6%
RBGR	5.36	14.0%	5.2%	0.1%	-7.2%	-20.6%	3.0%	-46.0%	-49.1%	-6.9%
RBNU	4.71	-19.5%	0.1%	1.9%	-34.3%	-25.3%	3.2%	-59.1%	-59.8%	-2.8%
RCKI	17.13	12.7%	-2.4%	-4.2%	2.3%	-10.7%	-7.6%	-22.5%	-34.0%	-14.1%
REVI	16.54	5.3%	4.6%	3.5%	-15.0%	-19.4%	7.2%	-51.9%	-53.0%	-4.7%
RUBL	0.78	11.2%	3.7%	3.6%	50.1%	42.2%	1.5%	104.6%	96.6%	14.7%
RWBL	10.96	5.1%	9.1%	5.3%	36.3%	35.6%	1.8%	103.5%	101.8%	17.8%
SAVS	8.94	7.3%	7.3%	1.4%	74.3%	75.4%	1.1%	192.3%	194.2%	29.1%
SOSP	3.32	1.3%	2.7%	1.4%	1.7%	1.0%	1.2%	2.2%	1.8%	0.6%
SWSP	2.33	4.9%	19.1%	13.1%	4.1%	-2.8%	5.0%	1.9%	-8.8%	2.5%
SWTH	25.65	0.0%	-0.9%	-1.4%	-19.8%	-24.2%	1.5%	-53.8%	-57.3%	-7.5%
TEWA	46.65	0.4%	-0.1%	0.2%	-21.1%	-24.9%	3.0%	-59.6%	-62.5%	-8.9%
TRES	2.80	-14.6%	6.0%	3.2%	-14.0%	10.7%	6.9%	-14.9%	11.2%	10.8%
VATH	0.77	-63.0%	5.8%	18.0%	-69.0%	6.5%	25.1%	-81.5%	-23.4%	15.9%
VEER	0.05	15.0%	58.7%	29.4%	124.8%	124.8%	17.3%	308.7%	308.7%	54.2%
VESP	6.22	19.8%	14.4%	9.3%	158.1%	157.6%	3.6%	442.7%	442.5%	76.0%
WAVI	4.13	-3.8%	5.3%	5.0%	-8.1%	-9.0%	12.4%	-3.4%	-5.4%	6.4%

Species	Current	B2020	C2020	D2020	B2050	C2050	D2050	B2080	C2080	D2080
WBNU	0.05	-27.0%	21.7%	14.1%	-36.3%	-21.3%	12.3%	-50.8%	-48.7%	8.5%
WCSP	0.32	-70.5%	-11.7%	-16.8%	-22.7%	25.8%	-23.2%	57.3%	126.6%	31.1%
WETA	3.94	-21.7%	-2.0%	-5.1%	-38.9%	-30.7%	5.6%	-64.3%	-63.9%	-3.8%
WEWP	1.38	-9.8%	-4.0%	-5.9%	-19.6%	-8.6%	-7.2%	-35.4%	-38.1%	-12.0%
WIWA	0.93	-2.5%	13.4%	10.7%	-7.5%	-6.2%	-0.2%	-17.3%	-24.9%	1.1%
WIWR	5.63	-22.0%	0.5%	3.0%	-40.0%	-22.9%	9.5%	-70.9%	-65.6%	-0.7%
WTSP	45.19	1.7%	1.2%	1.1%	-16.7%	-19.0%	3.3%	-49.6%	-49.9%	-6.1%
WWCR	4.25	-9.5%	-0.4%	-2.5%	-21.9%	-14.1%	-1.4%	-51.0%	-46.8%	-8.9%
YBFL	0.88	93.0%	-33.6%	-24.4%	68.5%	-41.6%	-41.7%	28.1%	-49.5%	-42.2%
YRWA	28.53	0.2%	-4.8%	-3.2%	-15.8%	-18.5%	-4.2%	-45.6%	-49.2%	-11.1%

Figures

Figure 1. Data locations

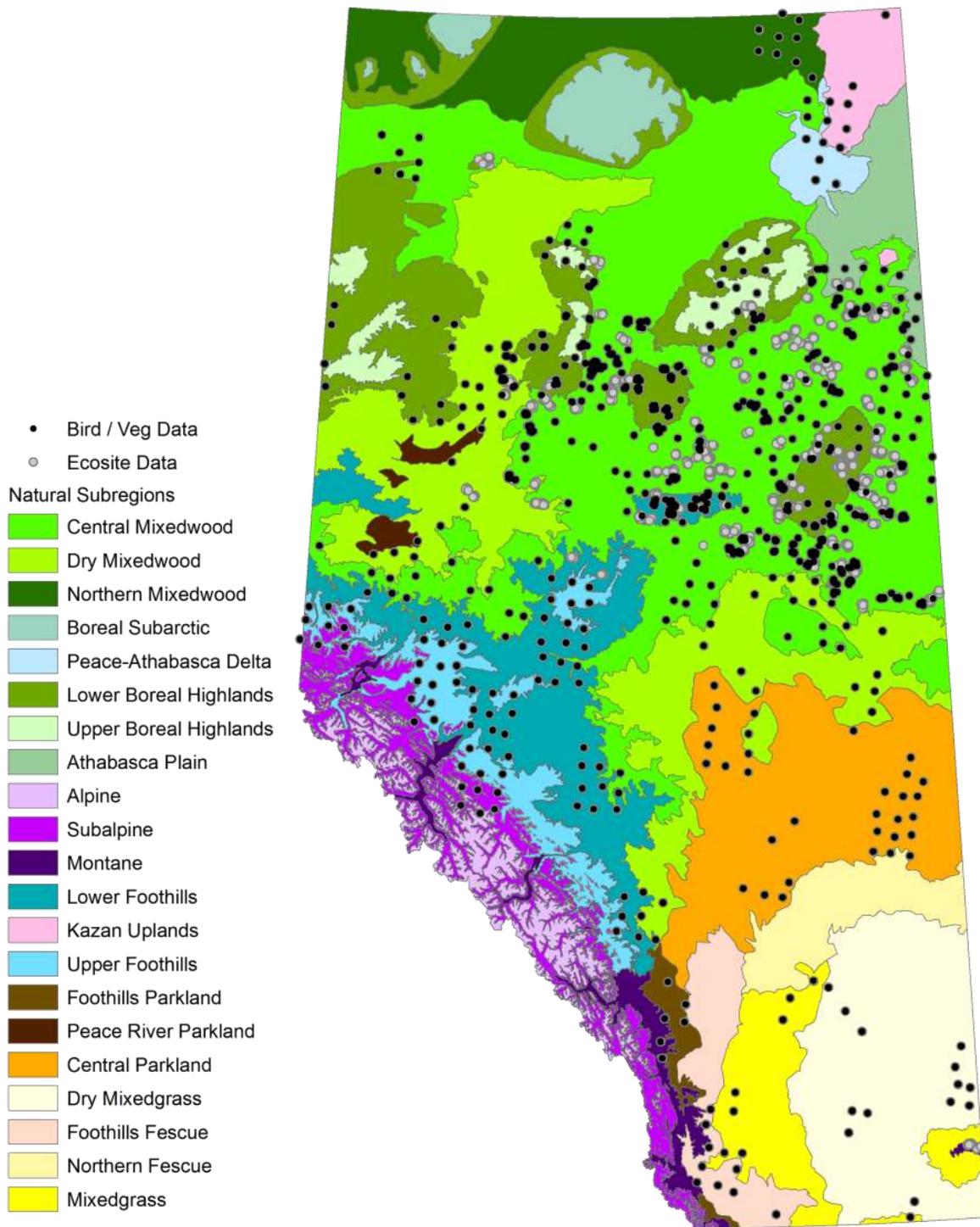


Figure 2. Wetland data used to develop ecosite models. From Alberta ESRD (2014) and Jensen (2003).

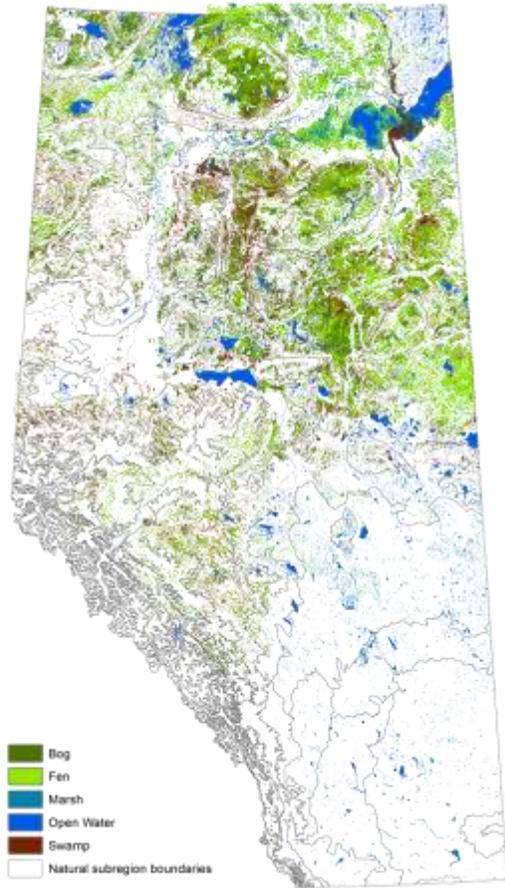


Figure 3. The influence of terrain on ecosite type and phase, as exemplified in (a) poor and (b) medium-rich nutrient conditions within the boreal region of Alberta, reproduced from Beckingham and Archibald 1996.

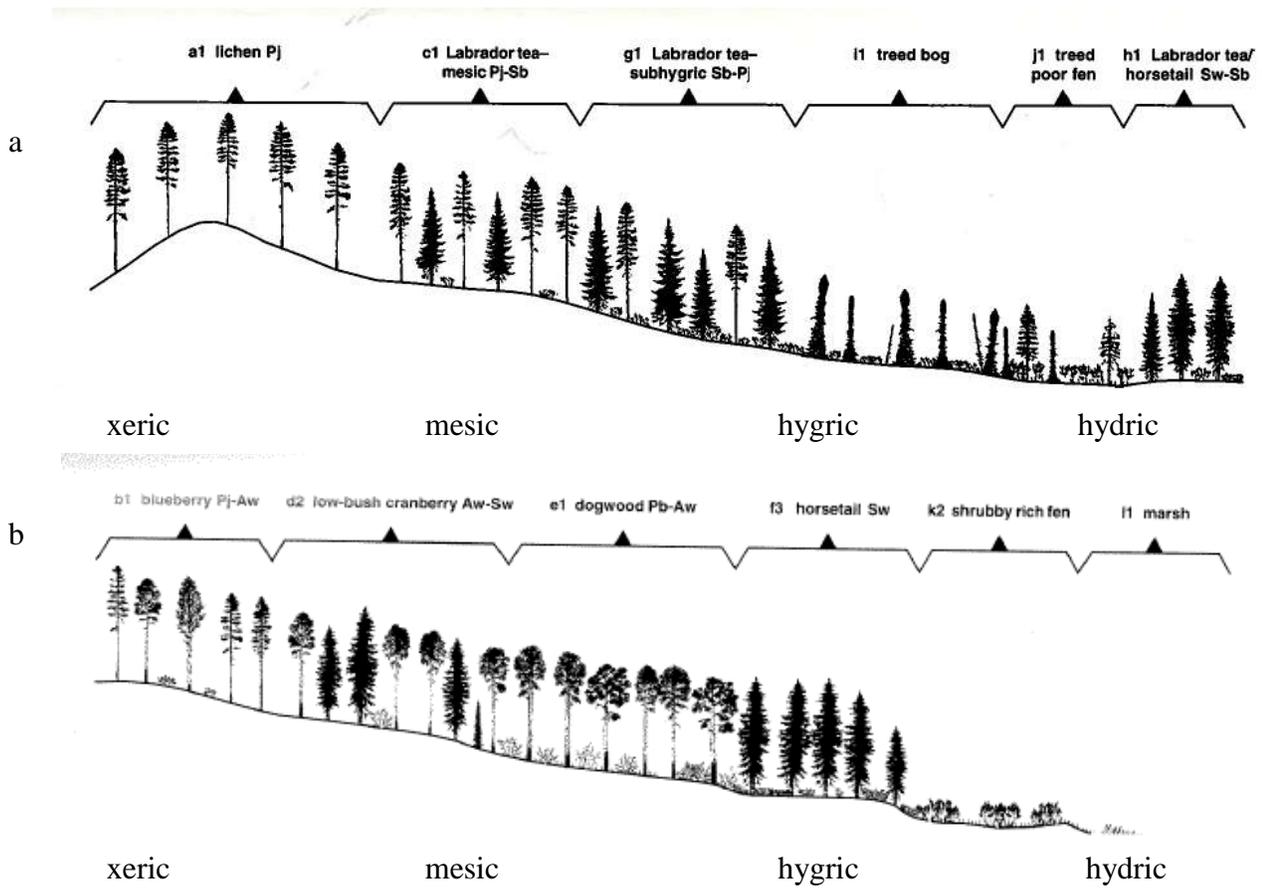


Figure 4. ABMI wall-to-wall landcover layer

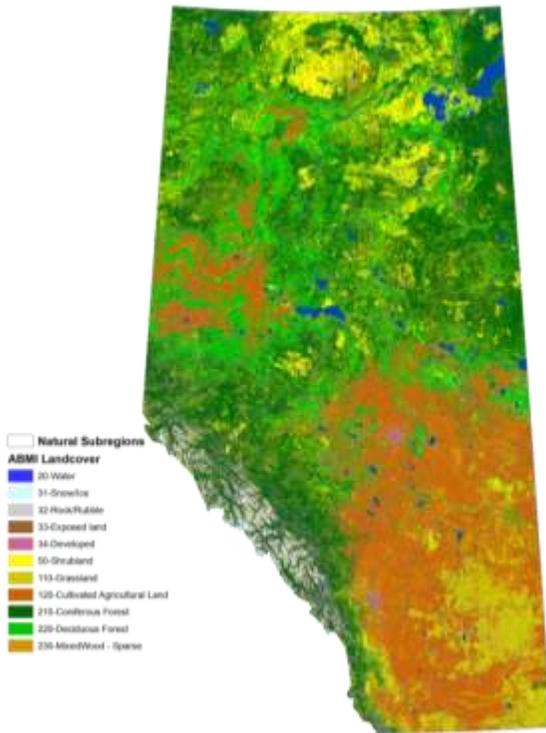


Figure 5. Large fire perimeters (1981-2100) and hexagons used to develop fire models. From the National Large Fire Database.

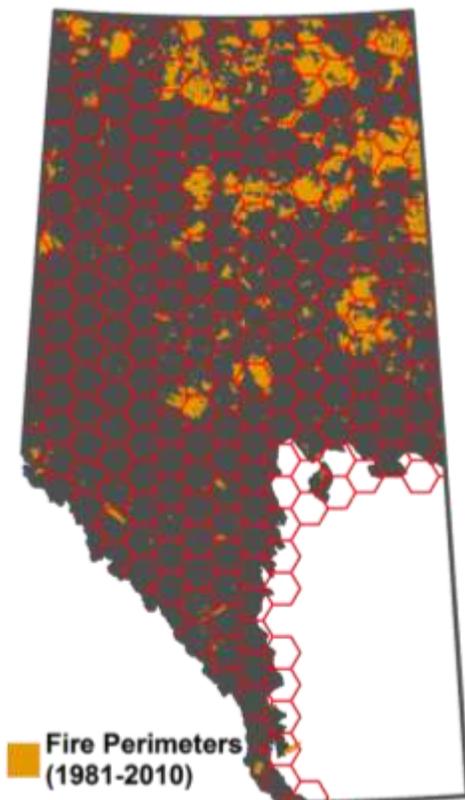


Figure 6. Random forest variable importance plot for ecosite (moisture/nutrient combination) based on the mean decrease in accuracy (left) and Gini coefficient (right) that results from removing the variable from the model. See Table 2 for variable definitions.

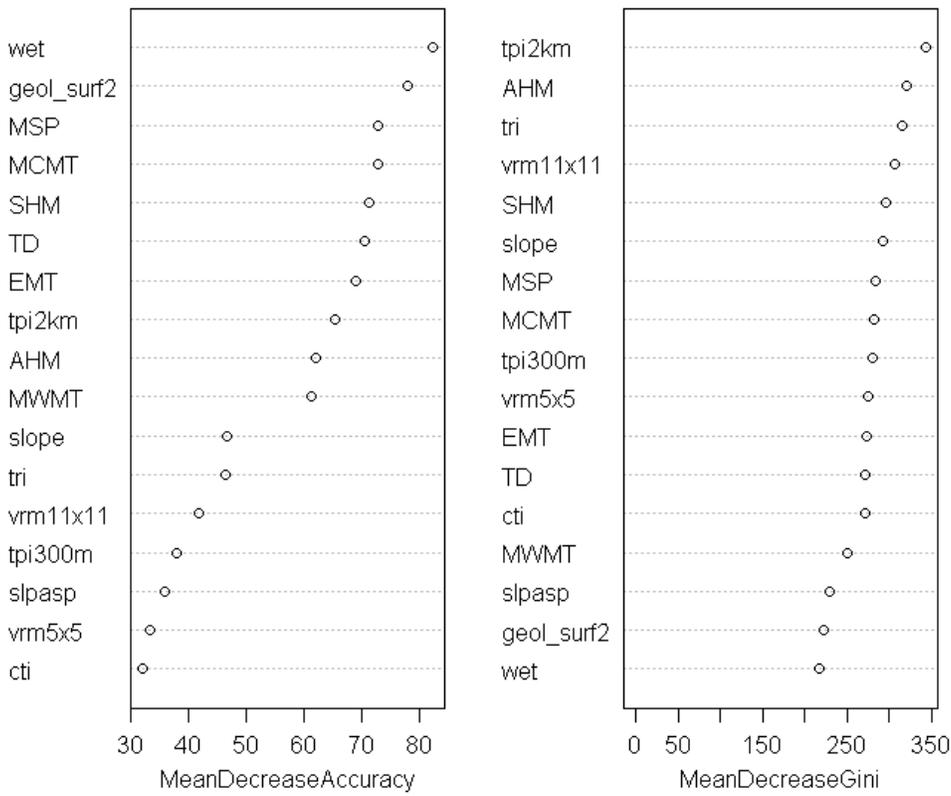


Figure 7. Predicted ecosite type (moisture/nutrient combination).

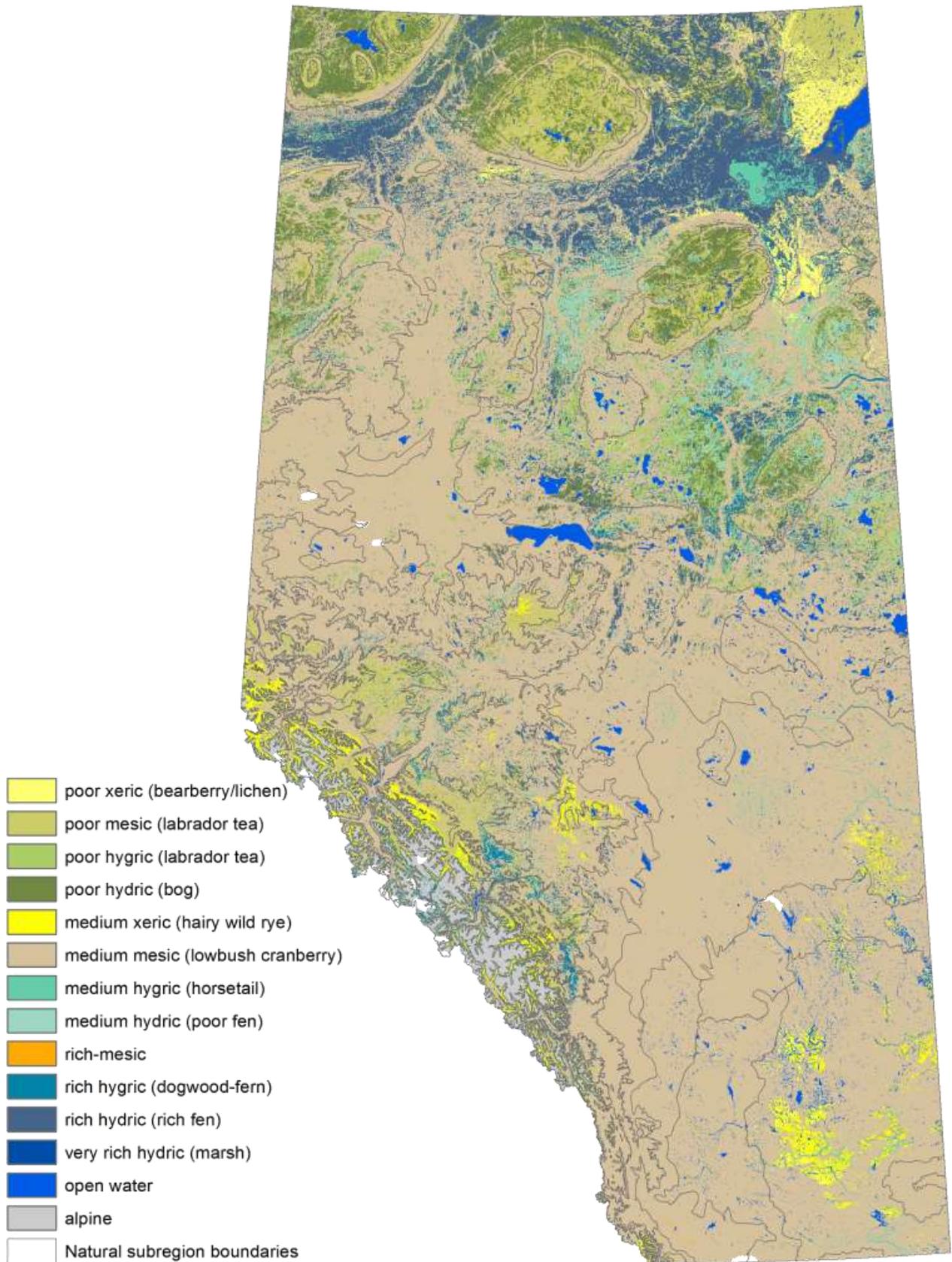


Figure 8. Classification tree model for ecosite phase based on climate and ecosite (moisture/nutrient class).

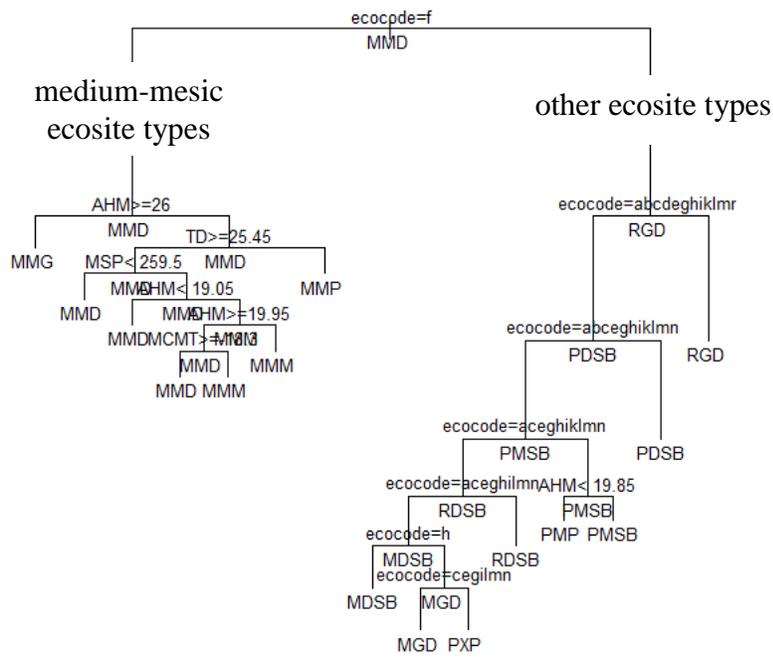


Figure 9. Predicted current vegetation type as a function of ecosite, climate, and age.

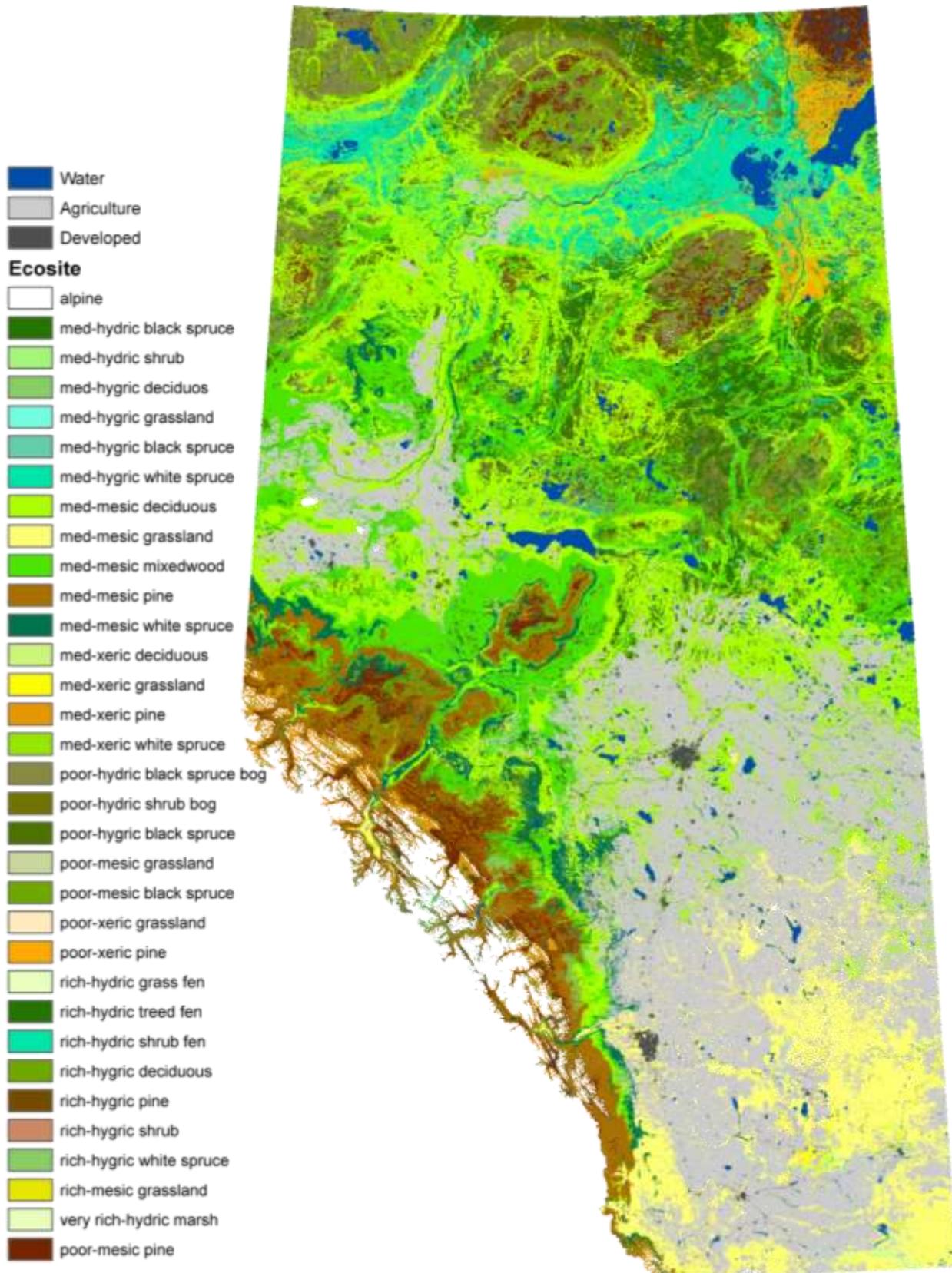


Figure 10. Simulated current and future area burned based on fire multipliers from Balshi et al. (2009).

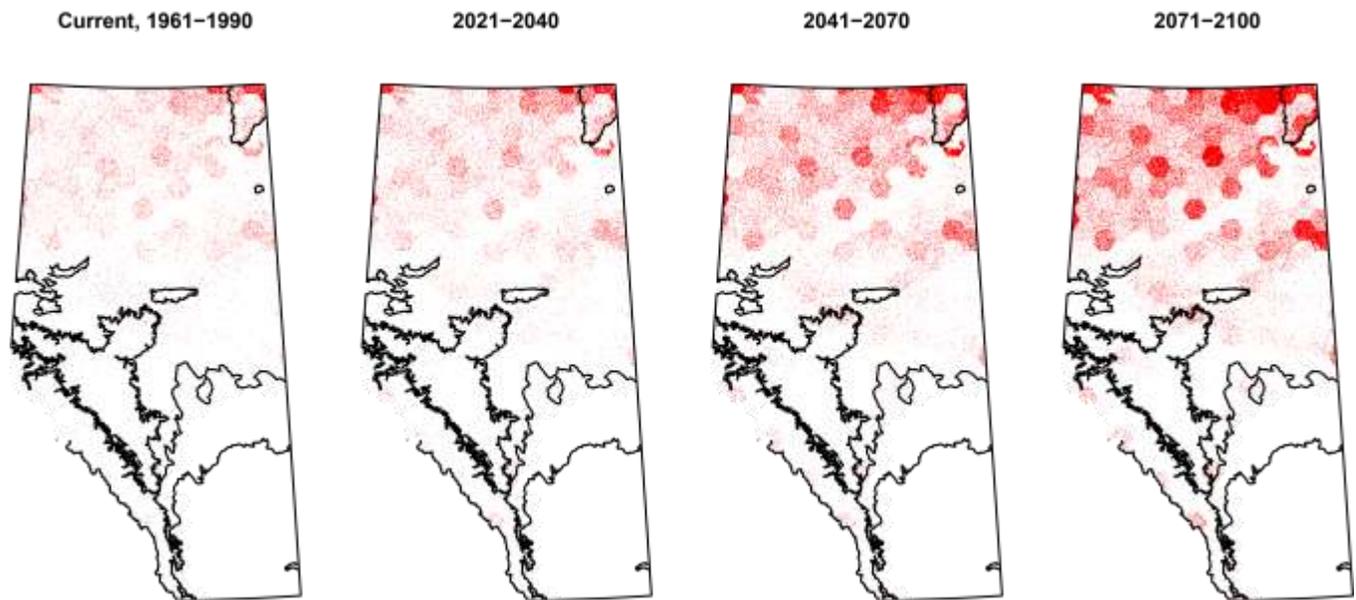


Figure 11. Projected vegetation changes according to scenario A (unconstrained).

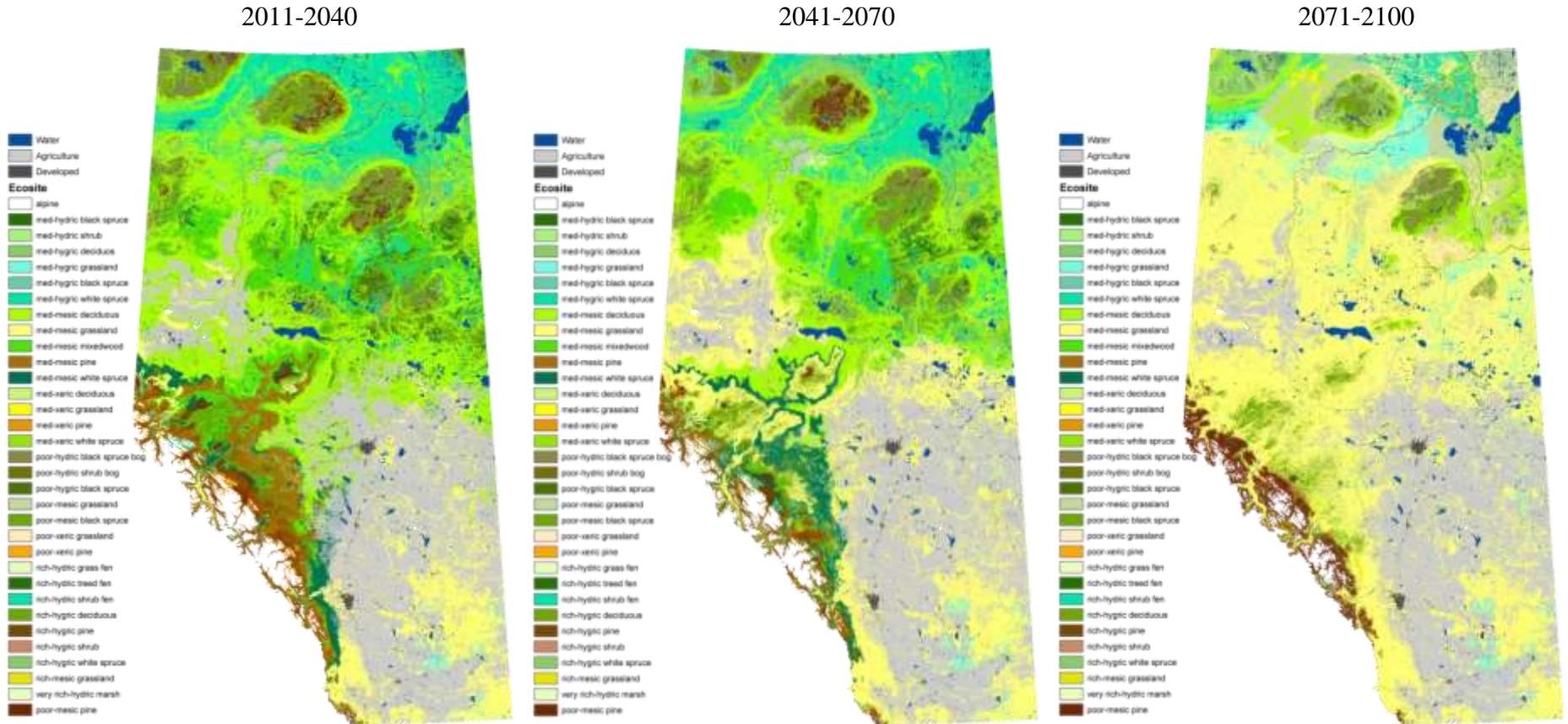


Figure 12. Projected vegetation changes for the 2041-2070 period according to scenarios B/C (topographically constrained).

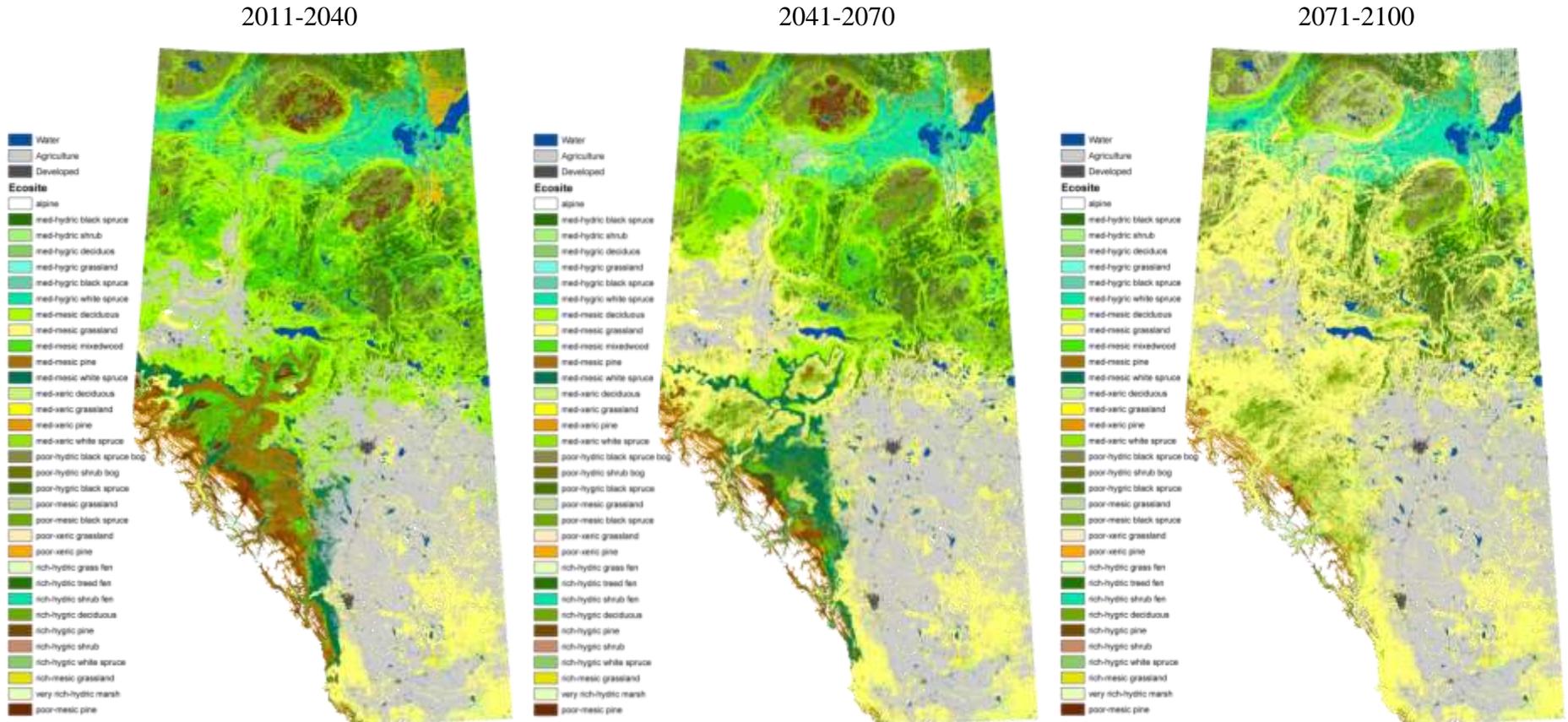


Figure 13. Projected vegetation changes for the 2071-2100 period according to scenario D (disturbance mediated).

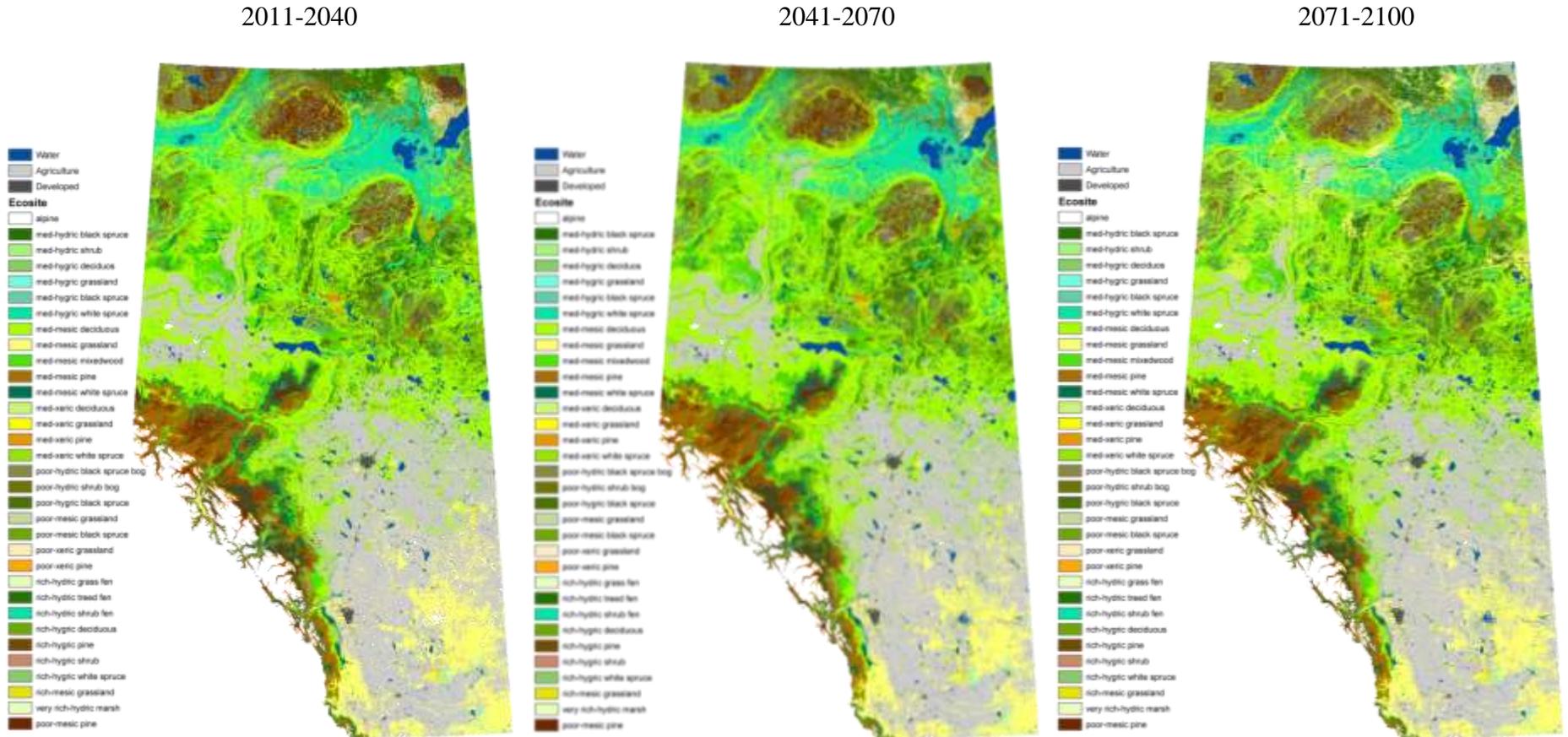


Figure 14. Estimated forest age based on fire as only disturbance (no new development).

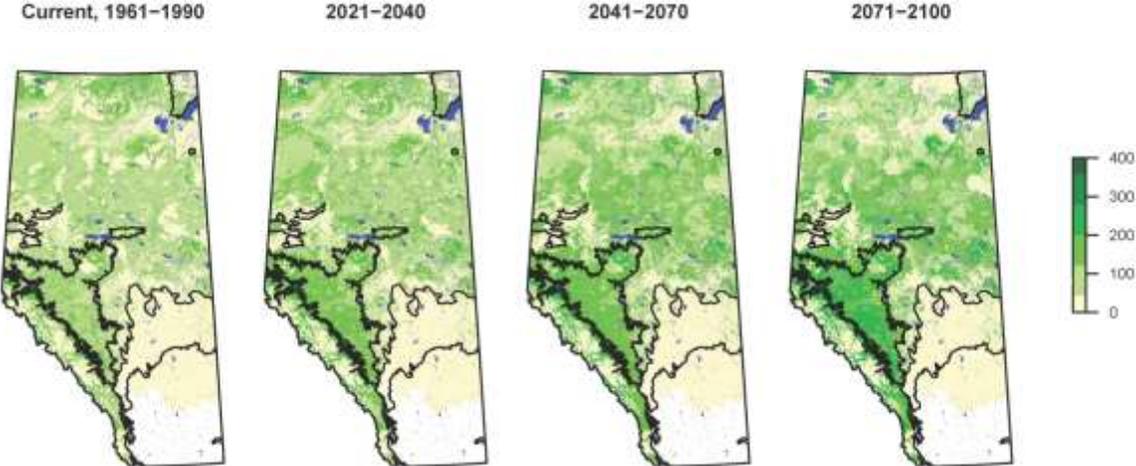
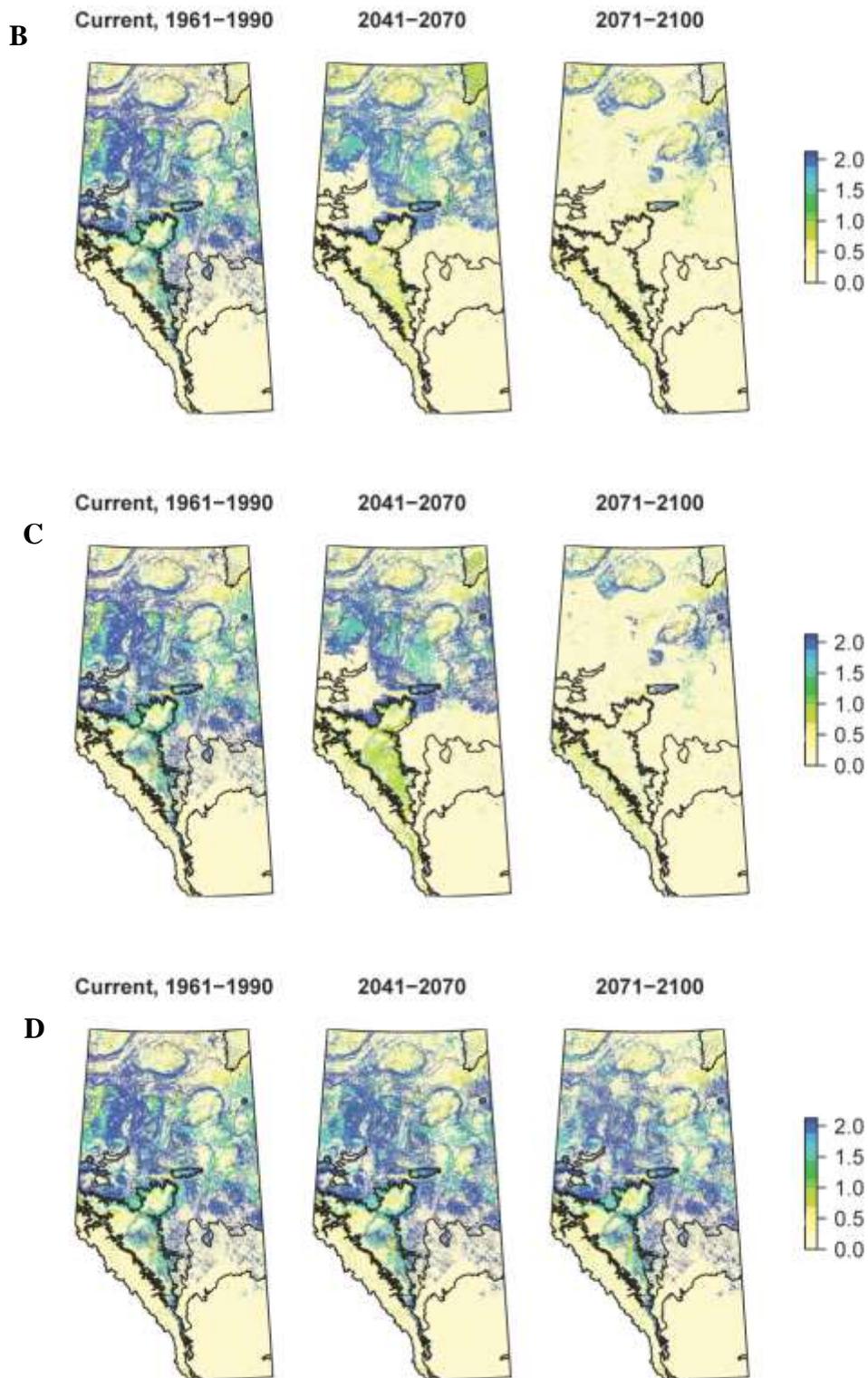


Figure 15. Projected changes in potential density for an example upland mixedwood forest species, Ovenbird, under scenarios B (topographically constrained), C (topographically constrained and age-adjusted), and D (topographically constrained, age-adjusted, and disturbance-mediated).



References

- AESRD. 2014. Alberta Merged Wetland Inventory. *in* A. E. a. S. R. Development, editor., Edmonton, AB. Alberta Geological Survey. 2013. Surficial Geology Map of Alberta *in* A. G. Survey, editor., Edmonton, Alberta.
- Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J.-H. Lim, G. Allard, S. W. Running, A. Semerci, and N. Cobb. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *Forest Ecology and Management* **259**:660-684.
- Archibald, J. H., G. D. Klappstein, and I. G. W. Corns. 1996. Field guide to ecosites of Southwestern Alberta. Natural Resources Canada, Canadian Forest Service, Edmonton, Alberta.
- Ashcroft, M. B. 2010. Identifying refugia from climate change. *Journal of Biogeography* **37**:1407-1413.
- Balshi, M. S., A. D. McGuire, P. Duffy, M. Flannigan, J. Walsh, and J. Melillo. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. *Global Change Biology* **15**:578-600.
- Bayne, E. M., S. Haché, and K. A. Hobson. 2010. Comparing the predictive capability of forest songbird habitat models based on remotely sensed versus ground-based vegetation information. *Canadian Journal of Forest Research* **40**:65-71.
- Beaudoin, A., P. Y. Bernier, L. Guindon, P. Villemaire, X. J. Guo, G. Stinson, T. Bergeron, S. Magnussen, and R. J. Hall. 2014. Mapping attributes of Canada's forests at moderate resolution through kNN and MODIS imagery. *Canadian Journal of Forest Research* **44**:521-532.
- Beckingham, J. D. and J. H. Archibald. 1996. Field guide to ecosites of Northern Alberta. Natural Resources Canada, Canadian Forest Service, Edmonton, AB.
- Boulanger, Y., S. Gauthier, and P. J. Burton. 2014. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Canadian Journal of Forest Research* **44**:365-376.
- Breiman, L. 2001. Random Forests. *Machine Learning* **45**:5-32.
- Cumming, S. 2001. Forest type and wildfire in the Alberta boreal mixedwood: what do fires burn? . *Ecological Applications* **11**:97-110.
- Cumming, S. G., F. K. A. Schmiegelow, and P. J. Burton. 2000. Gap dynamics in boreal aspen stands: Is the forest older than we think? *Ecological Applications* **10**:744-759.
- Cumming, S. G., D. Stralberg, K. L. Lefevre, P. Sólomos, E. M. Bayne, S. Fang, T. Fontaine, D. Mazerolle, F. K. A. Schmiegelow, and S. J. Song. 2014. Climate and vegetation hierarchically structure patterns of songbird distribution in the Canadian boreal region. *Ecography* **37**:137-151.
- Cyr, D., S. Gauthier, Y. Bergeron, and C. Carcaillet. 2009. Forest management is driving the eastern North American boreal forest outside its natural range of variability. *Frontiers in Ecology and the Environment* **7**:519-524.
- Daly, C., M. Halbleib, J. I. Smith, W. P. Gibson, M. K. Doggett, G. H. Taylor, J. Curtis, and P. P. Pasteris. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. *International Journal of Climatology* **28**:2031-2064.
- Drapeau, P., A. Leduc, J.-F. Giroux, J.-P. L. Savard, Y. Bergeron, and W. L. Vickery. 2000. Landscape-scale disturbances and changes in bird communities of boreal mixed-wood forests. *Ecological Monographs* **70**:423-444.
- Evans, J. and S. Cushman. 2009. Gradient modeling of conifer species using random forests. *Landscape Ecology* **24**:673-683.
- Fiera Consulting. 2013. Landbird Monitoring under the Joint Canada/Alberta Implementation of Plan for Oil Sands Monitoring.
- Flannigan, M., K. Logan, B. Amiro, W. Skinner, and B. Stocks. 2005. Future Area Burned in Canada. *Climatic Change* **72**:1-16-16.

- Forestry Canada Fire Danger Group. 1992. Development and structure of the Canadian Forest Fire Behavior Prediction System. Forestry Canada, Information Report ST-X-3 (Ottawa, ON).
- Gessler, P. E., I. D. Moore, M. N.J., and R. P.J. 1995. Soil-landscape modeling and spatial prediction of soil attributes. *International Journal of GIS* **9**:421-432.
- Hamann, A., T. Wang, D. L. Spittlehouse, and T. Q. Murdock. 2013. A comprehensive, high-resolution database of historical and projected climate surfaces for western North America *Bulletin of the American Meteorological Society* **94**:1307–1309.
- Hauer, G., S. Cumming, F. Schmiegelow, W. Adamowicz, M. Weber, and R. Jagodzinski. 2010. Tradeoffs between forestry resource and conservation values under alternate policy regimes: A spatial analysis of the western Canadian boreal plains. *Ecological Modelling* **221**:2590-2603.
- Héon, J., D. Arseneault, and M.-A. Parisien. 2014. Resistance of the boreal forest to high burn rates. *Proceedings of the National Academy of Sciences of the United States of America* **11**:13888–13893.
- Hobson, K. A. and J. Schieck. 1999. Changes in bird communities in boreal mixedwood forest: harvest and wildfire effects over 30 years. *Ecological Applications* **9**:849-863.
- Hogg, E. H. and P. Y. Bernier. 2005. Climate change impacts on drought-prone forests in western Canada. *Forestry Chronicle* **81**:675-682.
- Hogg, E. H. and P. A. Hurdle. 1995. The aspen parkland in western Canada: A dry-climate analogue for the future boreal forest? *Water, Air, & Soil Pollution* **82**:391-400.
- Huntley, B., R. A. Spicer, W. G. Chaloner, and E. A. Jarzembowski. 1993. The use of climate 815 response surfaces to reconstruct palaeoclimate from Quaternary pollen and plant 816 macrofossil data [and discussion]. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* **341**:215-224.
- IPCC. 2001. *Climate Change 2001. Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.
- IPCC. 2013. Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.
- Iverson, L. R., M. W. Schwartz, and A. M. Prasad. 2004. How fast and far might tree species migrate in the eastern United States due to climate change? *Global Ecology and Biogeography* **13**:209-219.
- Jensen, O. 2003. Wood Buffalo National Park Vegetation Classification Final Report.
- Jiménez-Valverde, A., N. Barve, A. Lira-Noriega, S. P. Maher, Y. Nakazawa, M. Papeş, J. Soberón, J. Sukumaran, and A. T. Peterson. 2011. Dominant climate influences on North American bird distributions. *Global Ecology and Biogeography* **20**:114-118.
- Johnstone, J. F., T. N. Hollingsworth, F. S. Chapin, and M. C. Mack. 2010. Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology* **16**:1281-1295.
- Keppel, G., K. P. Van Niel, G. W. Wardell-Johnson, C. J. Yates, M. Byrne, L. Mucina, A. G. T. Schut, S. D. Hopper, and S. E. Franklin. 2012. Refugia: identifying and understanding safe havens for biodiversity under climate change. *Global Ecology and Biogeography* **21**:393-404.
- Liaw, A. 2015. Package 'randomForest'. Available on-line at <http://cran.r-project.org/web/packages/randomForest/index.html>.
- Meehl, G. A., C. Covey, T. Delworth, M. Latif, B. McAvaney, J. F. B. Mitchell, R. J. Stouffer, and K. E. Taylor. 2007. The WCRP CMIP3 multi-model dataset: a new era in climate change research. *Bulletin of the American Meteorological Society* **88**:1383-1394.
- Michaelian, M., E. H. Hogg, R. J. Hall, and E. Arseneault. 2010. Massive mortality of aspen following severe drought along the southern edge of the Canadian boreal forest. *Global Change Biology* **17**:2084–2094.
- Parisien, M., D. R. Junor, and V. G. Kafka. 2007. Comparing landscape-based decision rules for placement of fuel treatments in the boreal mixedwood of western Canada. *International Journal of Wildland Fire* **16**:664-672.

- Parisien, M. A., V. G. Kafka, K. G. Hirsch, J. B. Todd, S. G. Lavoie, and P. D. Maczek. 2005. Using the Burn-P3 simulation model to map wildfire susceptibility. Information Rep. NOR-X-405. Edmonton, AB: Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre. 36 p. .
- Prasad, A. M., L. R. Iverson, and A. Liaw. 2006. Newer classification and regression tree techniques: bagging and random forests for ecological prediction. *Ecosystems* **9**:181-199.
- Prentice, I. C., J. Bartlein, and W. Thompson. 1991. Vegetation and climate change in eastern North America since the last glacial maximum. *Ecology* **72**:2038-2056.
- Price, D. T., R. I. Alfaro, K. J. Brown, R. A. F. M. D. Flannigan, E. H. Hogg, T. L. M. P. Girardin, M. Johnston, D. W. McKenney, J. H. Pedlar, T. Stratton, R. N. Sturrock, I. D. Thompson, J. A. Trofymow, and L. A. Venier. 2013. Anticipating the consequences of climate change for Canada's boreal forest ecosystems. *Environmental Reviews* **21**:322-365.
- Price, D. T., D. W. McKenney, L. A. Joyce, R. M. Siltanen, P. Papadopol, and K. Lawrence. 2011. High resolution interpolation of IPCC AR4 GCM climate scenarios for Canada. Natural Resources Canada, Northern Forestry Centre, Edmonton, Alberta, Canada.
- R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>.
- Ralph, C. J., G. R. Geupel, P. Pyle, T. E. Martin, and D. F. DeSante. 1993. Handbook of field methods for monitoring landbirds. PSW-GTR-144. Pacific Southwest Research Station, Corvallis, OR.
- Raupach, M. R., G. Marland, P. Ciais, C. Le Quéré, J. G. Canadell, G. Klepper, and C. B. Field. 2007. Global and regional drivers of accelerating CO₂ emissions. *Proceedings of the National Academy of Sciences* **104**:10288-10293.
- Rehfeldt, G. L. 2006. A spline model of climate for the Western United States. Gen. Tech. Rep. RMRS-GTR-165. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 21 p.
- Richards, G. D. 1995. A general mathematical framework for modeling two-dimensional wildland fire spread. *International Journal of Wildland Fire* **5**:63-72.
- Sappington, J. M., K. M. Longshore, and D. B. Thompson. 2007. Quantifying Landscape Ruggedness for Animal Habitat Analysis: A Case Study Using Bighorn Sheep in the Mojave Desert. *The Journal of Wildlife Management* **71**:1419-1426.
- Schneider, R., E. Bayne, and K. DeVito. submitted. Moving beyond bioclimatic envelope models: integrating upland forest and peatland processes to predict ecosystem transitions under climate change in the western Canadian boreal plain.
- Schneider, R. J., B. Stelfox, S. Boutin, and S. Wasel. 2003. Managing the cumulative impacts of land uses in the Western Canadian Sedimentary Basin: a modeling approach. *Conservation Ecology* **7**:8.
- Schneider, R. R., A. Hamann, D. Farr, X. Wang, and S. Boutin. 2009. Potential effects of climate change on ecosystem distribution in Alberta. *Canadian Journal of Forest Research* **39**:1001-1010.
- Soja, A. J., N. M. Tchebakova, N. H. F. French, M. D. Flannigan, H. H. Shugart, B. J. Stocks, A. I. Sukhinin, E. I. Parfenova, F. S. Chapin Iii, and J. P. W. Stackhouse. 2007. Climate-induced boreal forest change: predictions versus current observations. *Global and Planetary Change* **56**:274-296.
- Sólymos, P., S. M. Matsuoka, E. M. Bayne, S. R. Lele, P. Fontaine, S. G. Cumming, D. Stralberg, F. K. A. Schmiegelow, and S. J. Song. 2013. Calibrating indices of avian density from non-standardized survey data: making the most of a messy situation. *Methods in Ecology and Evolution* **4**:1047-1058.
- Stocks, B. J., J. A. Mason, J. B. Todd, E. M. Bosch, B. M. Wotton, B. D. Amiro, M. D. Flannigan, K. G. Hirsch, K. A. Logan, D. L. Martell, and W. R. Skinner. 2002. Large forest fires in Canada, 1959–1997. *Journal of Geophysical Research: Atmospheres* **107**:FFR 5-1-FFR 5-12.
- Stralberg, D., E. M. Bayne, S. G. Cumming, P. Sólymos, S. J. Song, and F. K. A. Schmiegelow. in press. Conserving boreal forest birds in a rapidly changing climate: a modified refugia approach. *Diversity and Distributions*.

- Stralberg, D., S. M. Matsuoka, A. Hamann, E. M. Bayne, P. Sóllymos, F. K. A. Schmiegelow, X. Wang, S. G. Cumming, and S. J. Song. 2015. Projecting boreal bird responses to climate change: the signal exceeds the noise. *Ecological Applications* **25**:52–69.
- Svenning, J.-C. and B. Sandel. 2013. Disequilibrium vegetation dynamics under future climate change. *American Journal of Botany* **100**:1266-1286.
- Syphard, A. D. and J. Franklin. 2009. Differences in spatial predictions among species distribution modeling methods vary with species traits and environmental predictors. *Ecography* **32**:907-918.
- Tymstra, C., R. Bryce, B. Wotton, and O. Armitage. 2010. Development and structure of Prometheus: the Canadian wildland fire growth simulation Model. Northern Forestry Centre.
- Waddington, J. M., P. J. Morris, N. Kettridge, G. Granath, D. K. Thompson, and P. A. Moore. 2015. Hydrological feedbacks in northern peatlands. *Ecohydrology* **8**:113-127.
- Wang, X., M.-A. Parisien, M. D. Flannigan, S. A. Parks, K. R. Anderson, J. M. Little, and S. W. Taylor. 2014. The potential and realized spread of wildfires across Canada. *Global Change Biology* **20**:2518-2530.
- Wang, X., D. Thompson, G. Marshall, C. Tymstra, R. Carr, and M. Flannigan. 2015. Increasing frequency of extreme fire weather in Canada with climate change. *Climatic Change* **130**:573-586.
- Wu, D., X. Zhao, S. Liang, T. Zhou, K. Huang, B. Tang, and W. Zhao. 2015. Time-lag effects of global vegetation responses to climate change. *Global Change Biology*:DOI: 10.1111/gcb.12945.
- Zhang, J., S. Huang, and F. He. 2015. Half-century evidence from western Canada shows forest dynamics are primarily driven by competition followed by climate. *Proceedings of the National Academy of Sciences* **112**:4009-4014.