

## ORIGINAL RESEARCH

# A conservation assessment of Canada's boreal forest incorporating alternate climate change scenarios

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## Abstract

Ecologically based strategies for climate change adaptation can be constructively integrated into a terrestrial conservation assessment for Canada's boreal forest, one of Earth's largest remaining wilderness areas. Identifying solutions that minimize variability in projected vegetation productivity may represent a less risky conservation investment by reducing the amount of anticipated environmental change. In this study, we assessed hypothetical protected area networks designed for future vegetation variability under a range of different climate conditions to provide relevant recommendations of conservation requirements that support ongoing boreal conservation and land-use planning. We constructed a boreal conservation assessment using both a conventional (Marxan) and a new probabilistic site-selection approach (Marxan with probability) with projected 2080 vegetation variability probability (VVP) for least change (B1), business as usual (A1B) and most extreme change (A2) climate scenarios. We then assessed (1) reserve network performance (cost and area), (2) high conservation priority areas and (3) the influence and implications of VVP on reserve networks. We found that including VVP dramatically increased the relative cost and total area of reserve networks. Many low-cost sites with high VVP values were given higher conservation priority over fewer sites with low VVP values. Reserve networks designed for A1B and A2 climate scenarios contained more sites with very high VVP values. The ratio of sites with high and very high VVP values changes dramatically for reserve networks designed for current and least change (B1) climate scenarios when under more severe A1B and A2 conditions. We conclude that introducing additional complexity and realism into national or boreal-wide conservation assessments, that include, for example, elements of climate change, will increase the total area and cost of a reserve network. Moreover, reserve networks designed for current or least change (B1) climate scenarios will likely not achieve conservation targets when faced with more severe conditions, and will require additional sites. The adaptive strategies presented are well suited for a boreal conservation assessment and may improve long-term effectiveness of biodiversity conservation objectives.

## Introduction

The landscape of Canada's relatively intact boreal forest is dominated by an active natural disturbance regime driven by large-area stand-replacing wildfire and insect outbreaks (Price et al. 2013). Predictions of future climate, under varying climate change scenarios, largely agree that Canada's boreal forest ecosystems will experience substantial warming (Plummer et al. 2006), and face multiple direct and indirect effects, from more frequent large wildfires and extreme droughts to potential shifts in ecosystem state (Price et al. 2013). Climate change impacts that affect habitat, and subsequently species distribution, will have potentially important implications for boreal biodiversity and ecosystem integrity. However, determining the timing, location and manner in which present conditions will be impacted by anticipated climate variability and changing disturbance regimes is not straight forward (Lemieux et al. 2011). This uncertainty over the nature and alterations in comparison to present conditions of future habitats and distributions poses a considerable challenge to long-term biodiversity conservation planning in the region (Andrew et al. 2014; Lemieux et al. 2011). As such, proactive managing of uncertainty for future boreal biodiversity conservation necessitates the use of planning approaches that incorporate anticipated climate change impacts.

In general, the establishment of protected areas or reserves is the primary tool used for managing areas for conservation objectives (Margules and Pressey 2000), and will likely play a central role in any future boreal biodiversity conservation effort. However, climate change impacts to boreal forests, such as changes in vegetation productivity, can affect the ability of these reserves to maintain current levels of food supply and biomass, which may affect long-term conservation targets, and will likely influence their efficacy. Thus, to be effective in supporting the long-term persistence of boreal biodiversity, updated conservation planning approaches will need to consider the impact of these impending changes, as well as include measures of uncertainty, and incorporation of boreal forest dynamics, when formulating new and expanded reserve designs. In essence, a risk-averse approach would entail targeting areas with high conservation value and low uncertainty for conservation (Moilanen et al. 2006).

Systematic conservation planning (Margules and Pressey 2000) is a framework for guiding where (spatially) conservation efforts should be directed to meet conservation objectives at the least cost, and is typically employed to identify the location of areas that should be targeted for conservation (i.e. protected areas or reserves). Costs

associated with conservation can be defined in a variety of ways, financial or otherwise, including area in reserve or costs related to acquisition, management, transaction, damage or forgone opportunities (Naidoo et al. 2006).

At present, most methods and data used by conventional systematic conservation planning approaches have stemmed from a static interpretation of biodiversity (Pressey et al. 2007). However, existing planning tools and emerging methods are increasingly being used to incorporate broad-scale ecological processes and account for the dynamic nature of ecosystems as well as anticipated climate change impacts. As highlighted in a review by Leroux and Rayfield (2014), these advanced approaches include spatially explicit simulation models (e.g. Leroux et al. 2007a; Rayfield et al. 2008), spatial optimization algorithms (e.g. Lourival et al. 2011) and spatial probabilistic theory (e.g. Drechsler et al. 2009; Game et al. 2011; Tulloch et al. 2013).

In the context of conserving remaining boreal wilderness areas, Leroux et al. (2007a), for example, demonstrated how spatially explicit simulation models of patch dynamics and fire could be used to iteratively evaluate the ability of different competing hypothetical reserve designs to maintain their initial conservation targets over time. In a boreal-wide (Canada) study by Powers et al. (2013a), spatial prioritization algorithms (i.e. Marxan, Ball et al. 2000) were used to evaluate the trade-offs between different reserve design scenarios consisting of varied sized reserves and optimizations for both (i) wilderness/intact areas and (ii) areas with low human access. These hypothetical reserves were then evaluated in a later study (Powers et al. 2016) using time-series Earth observation data to determine, based on a comparison of different locations and reserve sizes, any sustained large deviations from the initial reserve productivity baseline, which could indicate a change in reserve species composition and diversity. Results demonstrated that landscape dynamics, as determined by variability in reserve productivity, could not only be accommodated by simply establishing large reserves, but that, in many locations, productivity in small- and medium-sized reserves also remained stable through time; thus, constitute a worthwhile (i.e. less risky) conservation investment. Using a 200-year simulation of boreal forest dynamics, Rayfield et al. (2008) examined static and dynamic (i.e. floating; updated/relocated every 50 years) protected areas for the conservation of American Martins (*Martes americana*) habitat within boreal Québec (Canada). Results indicated that, over the 200-year period, the dynamic protected areas safeguarded more high-quality home ranges than static reserves.

Combining probability theory with site-selection approaches (i.e. spatial conservation prioritization) is

particularly helpful for allowing planners to proactively incorporate ecosystem dynamics and anticipated effects of climate change impacts at the onset of the planning process (Game et al. 2008, 2009, 2011; Lourdival et al. 2011). For example, in a climate change adaptation study by Game et al. (2011), probabilities based on differences between current and future conditions were used to preferentially select/identify protected areas in locations likely containing climate change refugia (i.e. areas where current environmental attributes closely match those of their projected future conditions; Saxon et al. 2005). The probability theory combined with site-selection tools have been singled out as being particularly adept at accounting for the boreal forest's dynamism (Leroux and Rayfield 2014), and can provide previously unavailable insights over this important and under-assessed region with respect to addressing boreal-wide conservation planning in Canada.

Over the last decade, researchers have provided many solutions and recommendations for incorporating system dynamics and/or climate change adaptation into conservation planning (e.g. Scott and Lemieux 2005; Heller and Zavaleta 2009; Game et al. 2010; Lemieux et al. 2011; Groves et al. 2012). Large and connected reserves, for example, are commonly prescribed as key reserve design components for protecting shifting patterns of biodiversity under both climate change and landscape dynamics (Bradshaw et al. 2009; Heller and Zavaleta 2009; Andrew et al. 2014; Powers et al. 2013a). Using these recommendations as a guideline, we focus on three strategies for accounting for system dynamics and climate change effects that are well suited for a boreal-wide (Canada) conservation assessment and likely to meet long-term biodiversity conservation objectives: strategy (1) conserving large inaccessible/wilderness areas (>6480 km<sup>2</sup>), strategy (2) protecting environmental connectivity and strategy (3) protecting stable habitat (low productivity variability).

The creation of large protected areas from naturally functioning ecosystems that are largely without anthropogenic activity (strategy 1) is viewed as an important option for maintaining the persistence of biodiversity and for allowing natural ecological and evolutionary processes to continue (Burkey 1995; Ferraz et al. 2003). Such large reserves are possible in the Canadian boreal forest, one of the few remaining places on Earth that still possesses large tracks of remote intact areas with minimal anthropogenic disturbance (Andrew et al. 2012, 2014). Furthermore, the creation of large reserves that are environmentally diverse (i.e. provide connectivity between habitats) and robust to change may help alleviate or buffer against some of the conservation uncertainty associated with climate change such as changing habitat conditions and species distributions (Andrew et al. 2014). Specifically, reserves based on

strategies (2 and 3) could prove more robust to climate change impacts and have sufficient environmental heterogeneity to accommodate changing habitats within the reserves.

Using the entire Canadian boreal forest as a case study, our objective is to demonstrate how these three adaptive strategies can be constructively integrated with site prioritization that accounts for uncertainty to provide a proactive boreal conservation assessment. Here, we ask the questions: (1) where are high priority areas and how are they characterized?; (2) how is the overall productivity variability in sites within reserve networks influenced by different climate conditions and what are the implications for reserve networks designed for one estimated climate scenario should another occur? To answer these questions, we use a probabilistic prioritization method to design a reserve network using predicted productivity variability (2080) based on a range of different climate scenarios incorporating varying climate change outcomes (A1B, B1 and A2) to maximize future representation of environmental conditions in locations that are stable under climate change and large enough to accommodate the Canadian boreal forest's dynamism.

## Materials and Methods

### Study area

The study area is the entire Canadian boreal forest (~5.37 million km<sup>2</sup>) as described by Brandt (2009). The southern transitional hemiboreal subzone (includes much of British Columbia) was excluded as it is considered temperate in North America and not formally recognized as boreal (Brandt 2009). Canada's boreal is primarily forested (~58%) and is dominated by cold tolerant forest types within the genera *Larix*, *Abies*, *Picea* or *Pinus* as well as *Betula* and *Populus* (Brandt 2009). Water features such as lakes and rivers, as well as wetlands are also prevalent throughout the region (Wulder et al. 2008). The dominant natural disturbances on the landscape are stand-replacing fire and insect infestation (Kurz et al. 1992; Fleming and Candau 1998; Brandt et al. 2013).

### Planning unit and cost surrogate

The Canadian boreal forest was partitioned into 10 × 10 km grids/planning units. Each of the 50,529 sites was assigned an average cost based on its accessibility, as accessible protected areas are typically more costly. Furthermore, prioritizing areas with limited human activity offers an advantage of fewer land-use conflicts (Naidoo et al. 2006), higher social acceptance and a greater likelihood of being implemented. Access was calculated using

distance to roads and human settlements across a 1 km spatial grid (Wulder et al. 2011) derived from Statistics Canada's 2008 road network (Statistics Canada, 2008) and the circa 2000 Version 2 DMSP-OLS Nighttime Lights Time Series cloud-free composites (NOAA, 2011). The inverse of these distances was summed, and then rescaled to a cost surrogate ranging from 0 to 1000 for ease of interpretation. Lower values were assigned to areas further away from human influence (e.g. road or settlement); thus, encouraging the preferential prioritization of more remote, low-cost areas.

### Quantifying vegetation variability probability

Conservation of areas with low variance in productivity or energy can help reduce uncertainty in achieving long-term conservation goals as these areas generally maintain the habitat conditions and resources, such as food supply and biomass, required to sustain similar levels of biodiversity. In this study, variance in productivity was determined by the spatial and temporal variability in an area's vegetation productivity over a given time. To quantify productivity variance, we used modelled future productivity maps by Nelson et al. (2014) briefly described below. These mapping and productivity predictions were carried out using boreal ecodistricts as the spatial unit (592 polygons in all, with a minimum size of about 100,000 ha). Ecodistricts represent the lowest level of a nested ecoregion hierarchy and define discrete regions based on similar soil, geology, vegetation climate, land use, hydrology and wildlife (Ecological Stratification Working Group, 1995).

Future vegetation productivity maps were produced using three sources of data: (1) a vegetation productivity index, dynamic habitat index (DHI), derived from the historical record of Advanced Very High Resolution Radiometer (AVHRR) satellite data, (2) historical climate data and (3) differing scenarios of future climate. Here, the recently processed 1-km spatial resolution AVHRR DHI time-series data were used (Fontana et al. 2012). There are three DHI productivity metrics (see Coops et al. 2008): (1) the cumulative annual fPAR, provides an indication of the annual productive capacity of a landscape and is strongly associated with species richness; (2) the annual minimum greenness describes the base level of cover at a location and gives insight into the landscape's potential to continuously sustain permanent resident species year-round and (3) seasonal variation in the greenness (represented by the coefficient of variation in fPAR estimates).

Historical climate data (represented as grid points separated by 32 km) were derived from climate datasets

(1987–2007) supplied and modelled by the Pacific Climate Impacts Consortium (PCIC) and the National Centers for Environmental Protection (NCEP) North American Regional Reanalysis (NARR), respectively. NARR climate variables (precipitation, maximum temperature, minimum temperature and mean annual growing season index) were (1) interpolated (1 km) to spatially integrate with the DHI data, and (2) summarized annually. Lastly, three future climate scenarios from the Intergovernmental Panel on Climate Change (IPCC) were used: B1, A1B and A2. These scenarios represent a range of possible climate change outcomes from *least extreme change* (B1) to *business as usual* (A1B) and *most extreme climate change* (A2).

To map future vegetation productivity, Nelson et al. (2014) utilized random forest-derived regression trees from boot-strapped samples to quantify the relationship between historical climate and the AVHRR DHI components. Three 1987–2007 climate productivity models were produced, one for annual cumulative greenness, seasonal variation in greenness and minimum annual cover, respectively. Model fits were then used with the IPCC climate change scenarios (A1B, A2, B1) to forecast DHI values for the years 2020, 2050 and 2080 (Nelson et al. 2014). In total, there were 27 future vegetation productivity maps created (3 climate change scenarios  $\times$  3 DHI components  $\times$  3 different future dates). Random forest model fits for each forecasted DHI component were assessed by the mean square error and the percentage of variance explained. Furthermore, the random forest models were validated by applying data from 1987 to 2006 to predict the three DHI components in 2007. Here, the 2007 observed and predicted DHI maps were compared using a fuzzy numerical map comparison (Hagen-Zanker 2006). Both model variance explained and model performance were quite high, 72.0–74.0% and a mean of 0.6–0.9, respectively (see Nelson et al. 2014 for full description).

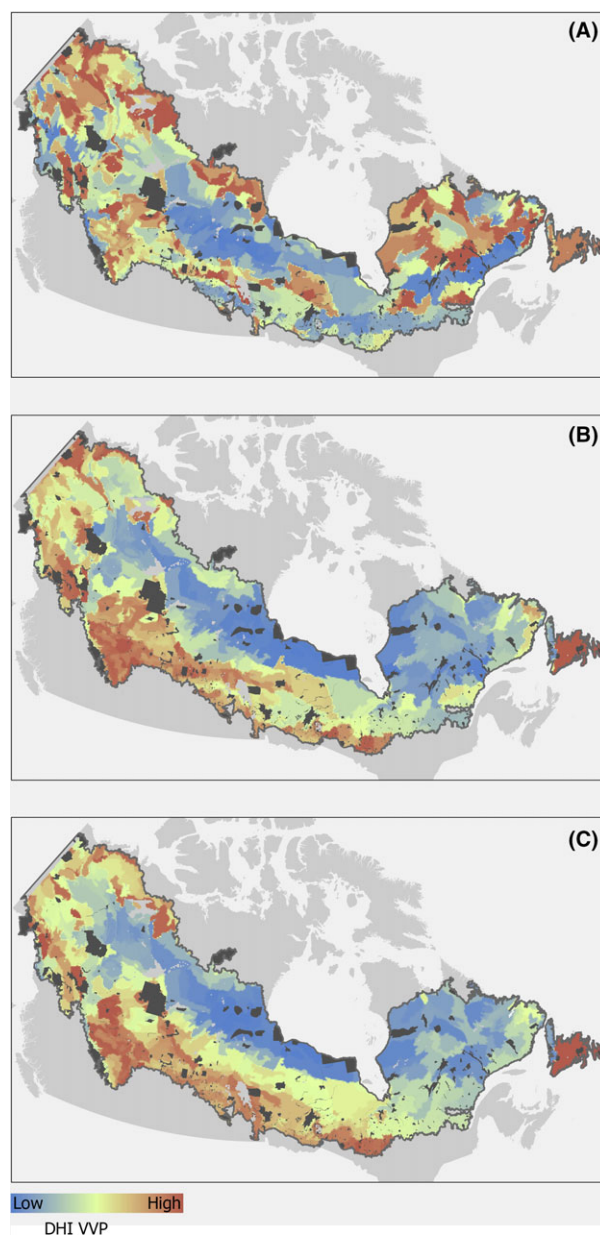
We used these future productivity maps to assess productivity variance associated with climate change and its impact on the productivity variability. The 2020, 2050 and 2080 modelled DHI values (27 maps) were used to calculate and map the temporal productivity variability or stability (S) of each "ecodistrict" up to 2080. One productivity variability map was created for each DHI component, where temporal stability was defined as  $S = \text{mean} / \text{standard deviation}$  (Tilman 1999; Lehman and Tilman 2000). For example, the "mean estimated DHI cumulative productivity for 2020, 2050 and 2080 of each ecodistrict" polygon was divided by the "standard deviation of the three cumulative productivity values of the same ecodistrict" polygon. Larger values of S represent greater stability and less change in DHI through time, whereas smaller

values of  $S$  represent greater variability and more change in vegetation productivity through time. The three 2080 ecodistrict DHI productivity variability maps (A1B, A2 and B1) were then averaged across each planning unit. For each climate scenario, the DHI 2080 variability components were normalized to a scale from 0 to 1 and inverted. These composites were then collectively scaled again, with 1 representing values above the 90th percentile of the DHI component (i.e. based on all scenarios for each DHI component), to place greater emphasis on the preferential selection of low variability areas. Lastly, a composite (average) of the DHI was created, representing the combined DHI variability in boreal vegetation. A low probability indicates a greater likelihood of a planning unit's productivity being less variable through time (Fig. 1). Hereafter, we refer to this probability as vegetation variability probability (VVP). By using a composite of the DHI components, it was possible to identify how their combined vegetation variability was expressed spatially.

Maps of predicted VVP (Fig. 1) clearly indicate a north/south gradient, which is in agreement with the observed and experienced temperature increase north of  $40^\circ$  latitude (Serreze et al. 2000). Mid-to-high latitudes have experienced diurnal decreases in temperature ranges and the boreal forest's northern extent has experienced a 10% decrease in snow cover attributed to increases in autumn and winter precipitation (IPCC, 2016). Forecasted DHI from 1990 and 2080 also indicate that vegetation productivity will be most impacted by the increased seasonality in the north and a combination of greenness and minimum cover in the south (Nelson et al. 2014).

### Conservation features

Conservation features included (1) environmental domains and (2) distributions for 16 at-risk species. Environmental domains were generated in a previous study (Powers et al. 2013b) by classifying the boreal forest into 15 domains based on productivity, seasonality (snow cover) and land-cover similarity. Seasonal greenness (Coops et al. 2008), a vegetation productivity metric, was found to be the most important indicator for discriminating between the environmentally distinct domain groups. Differentiation of domains occurred along a latitudinal gradient, and their spatial and attribute detail is appropriate for large-area conservation planning (Coops et al. 2009). The eight southern domains are dominated by coniferous and mixed forest and are characterized as having low seasonality and high productivity. In contrast, the five northernmost domains experience high seasonality and low productivity environments and are dominated by open shrub vegetation. The two central domains have relatively moderate seasonality and productivity and are



**Figure 1.** Map of 2080 vegetation variability probability (VVP) for Intergovernmental Panel on Climate Change (IPCC) climate change scenarios (A) B1 least extreme change, (B) A1B business as usual and (C) A2 most extreme change. DHI, dynamic habitat index.

dominated by coniferous forest and open shrubland vegetation. Species data were also considered to avoid missing or under-representing at-risk species, which is possible if reserve prioritization relies exclusively on environmental domains (Margules and Pressey 2000). Here, we used 16 species of fauna (Table 1) based on threat status, data availability and geographic distribution. Many of these species are widespread across Canada's boreal and require large habitat patches; thus, their conservation will likely

**Table 1.** Priority species based on threat status, geographic distribution and data availability.

Common Name	Scientific name	Status (COSEWIC)
American Marten	<i>Martes americana atrata</i>	Threatened
Wolf	<i>Canis lycaon</i>	Special Concern
Wolverine	<i>Gulo gulo</i>	Special Concern
Woodland caribou	<i>Rangifer tarandus</i>	Endangered; Threatened; Special Concern
Grey fox	<i>Urocyon cinereoargenteus</i>	Threatened
Barrow's Goldeneye	<i>Bucephala islandica</i>	Special Concern
Chimney Swift	<i>Chaetura pelagica</i>	Threatened
Harlequin Duck	<i>Histrionicus histrionicus</i>	Special Concern
Rusty Blackbird	<i>Euphagus carolinus</i>	Special Concern
Sprague's Pipit	<i>Anthus spragueii</i>	Threatened
Yellow Rail	<i>Coturnicops noveboracensis</i>	Special Concern
Whooping Crane	<i>Grus americana</i>	Endangered
Peregrine Falcon	<i>Falco peregrinus anatum/tundrius</i>	Special Concern
Burrowing Owl	<i>Athene cucularia</i>	Endangered
Piping plover	<i>Charadrius melodus circumcinctus/melodus</i>	Endangered
Ferruginous Hawk	<i>Buteo regalis</i>	Threatened

benefit a variety of other species. The target representation, area weighted for both the 16 at-risk species and 15 environmental domains, was set at 15% and 25% of the Canadian boreal forest's extent.

### Prioritization approach and analysis

To test the influence of different VVP on site prioritization, we compared the outcomes of reserve planning scenarios with and without the inclusion of VVP, using the conservation planning software Marxan 2.43 (Ball et al. 2000). Marxan aims to minimize the objective function, a combination of the cost of reserves and the boundary length (a penalty that is applied using the boundary length modifier [BLM]), subject to meeting representation targets. We used the same parameters (representation targets, cost and BLM across all scenarios [Table 2]). In all scenarios, sites that reside (>50% overlap) in protected areas (IUCN status I–IV) were not considered for prioritization; however, their contribution towards biodiversity targets was accounted for. To help ensure that reserves were likely to accommodate the boreal forest's dynamism (conservation strategy 1), the BLM was set to 2.3, resulting in reserves much larger than the suggested 3000 km<sup>2</sup> (~10 times the size of the average disturbance event; Wiersma et al. 2005) or 6480 km<sup>2</sup> (accommodates the largest expected disturbance event; Leroux et al. 2007b) minimum dynamic reserve size. Each scenario had 200 runs or separate sets of reserve design solutions.

**Table 2.** List of scenarios identifying the method, software, probability and targets used. In total there were eight assessments (4 scenarios × 2 representative targets).

Scenario	
1	Baseline scenario, Marxan, 15% as well as 25% representative targets
2	Probabilistic; MarProb; B1 VVP; certainty target of 0.9; 15% and 25% representative targets
3	Probabilistic; MarProb; A1B VVP; certainty target of 0.9; 15% and 25% representative targets
4	Probabilistic; MarProb; A2 VVP; certainty target of 0.9; 15% and 25% representative targets

VVP, vegetation variability probability.

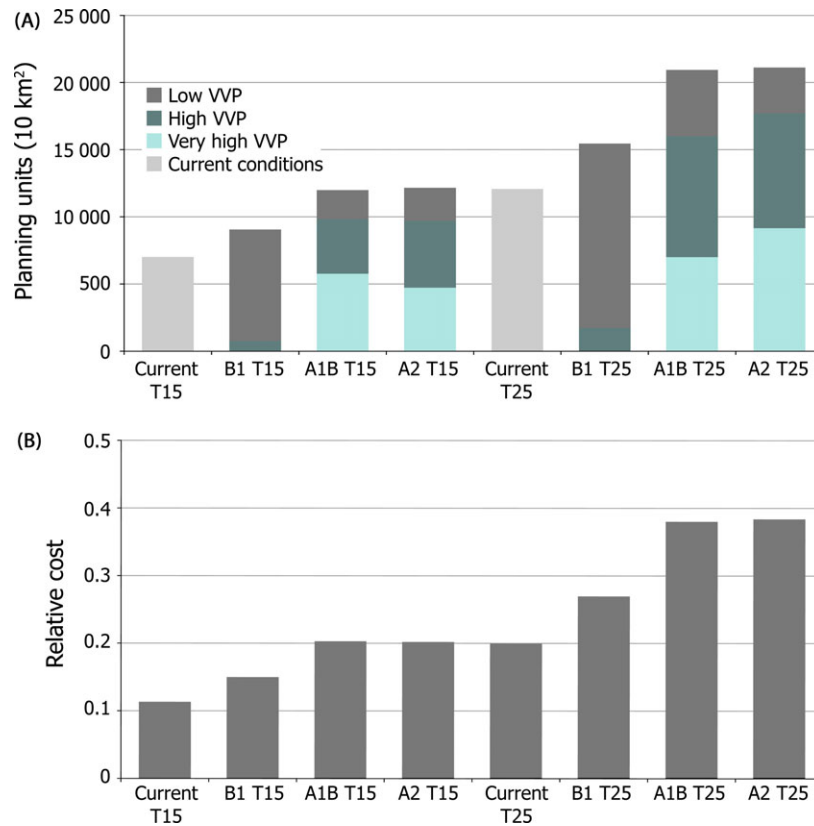
We used conventional Marxan, which assumes there is no uncertainty in the input data, to provide baseline reserve solutions for comparison, and did not include VVP. Marxan with probability (hereafter referred to as MarProb; Ball et al. 2000; Game et al. 2011) is a modified version of Marxan that can account for uncertainty, which was used in the B1, A1B and A2 scenarios to include probabilities on vegetation variability. VVP values (A1B, A2 and B1) were used as inputs in MarProb to identify protected area network solutions that minimize productivity variability. In MarProb, the certainty target was set to 0.9 or 90% confidence that the representative targets protected within the reserve network solution will still be protected in 2080.

To explore the trade-offs associated with each scenario's efficiency and performance, we used the best solution (lowest objective function score out of 200 runs) of each scenario to evaluate relative cost and the amount variability. Best solutions and selection frequencies were also used to identify common high-priority areas between the scenarios. Lastly, we tested how a reserve network designed for one climate scenario performs under different climatic conditions by examining the changes in the best solution VVP values. Specifically, we examined changes in the proportion of VVP values (low, mid and high). This will tell us, for example, the how proportion of VVP values for sites designed for the B1 scenario change under A1B and A2 climate conditions.

## Results

### Reserve efficiency, total area and proportion of VVP values

All eight best solutions from the scenarios with and without VVP values (Fig. 2B) were able to meet representative target requirements (15% and 25%) at the certainty target of 0.9 (B1, A1B and A2 scenarios). In general, there were



**Figure 2.** Number of prioritized sites (A) and relative cost (reserve cost/total reserve cost) of best scenario solutions (B) for three different scenarios with vegetation variability probability (VVP) and the one scenario based on current conditions. T15 and T25 represent the 15% and 25% representative targets, respectively. In (A) the proportion of the reserve network's VPP values was determined using natural breaks, where very dark teal represents low VPP sites ( $\leq 0\%$ ), or locations in 2080 likely containing similar levels of productivity as current conditions, and medium and light teal represent high ( $\geq 40\%$ ) and very high ( $\geq 45\%$ ) VVP, respectively.

very minor differences in reserve efficiencies, determined by relative reserve cost of management, between A1B (business as usual) and A2 (most extreme) scenarios. The most efficient lowest-cost solution was achieved by the baseline scenario, where probabilities were not included. In contrast, A1B and A2 scenarios, which included VPP values, had the least cost-efficient best solutions. The B1 scenario, which includes VPP for the least change climate scenario, was approximately 26% and 30% less expensive than A1B and A2 scenarios for the 15% and 25% targets, respectively. Overall, the inclusion of VPP resulted in a less cost-efficient solution. Compared to the baseline scenario, the B1 scenario represented a moderate 25% and 26% increase in relative reserve cost for the 15% and 25% targets. Most notably, in this case very large cost differences were observed between A1B and A2 scenarios, which were approximately 45% and 48% more expensive than the baseline scenario for the 15% and 25% targets, respectively.

Similar to what was observed in the reserve efficiency comparison, there were few area differences between A1B and A2 scenarios (Fig. 2A). However, with respect to the proportion of VPP values, the A2 scenario contained approximately 10,320 km<sup>2</sup> (18%) and 21,550 km<sup>2</sup> (24%) more high VPP sites than the A1B scenario. In addition, the A2 scenario also contained 16,980 km<sup>2</sup> (20%) more high VPP sites than the A1B scenario for the 15% target. Together, A1B and A2 scenarios represented the largest total priority areas with 121,560 km<sup>2</sup> and 119,860 km<sup>2</sup> for the 15% target and 209,410 km<sup>2</sup> and 211,140 km<sup>2</sup> for the 25% target, respectively. Comprising of mainly low VPP sites, the B1 scenario contained approximately 30,000 km<sup>2</sup> (25%) and 56,000 km<sup>2</sup> (27%) less total priority area than A1B and A2 scenarios for the 15% and 25% targets, respectively. Likewise, the baseline scenario represented the fewest priority sites of all scenarios with approximately 50,000 km<sup>2</sup> (42%) and 90,000 km<sup>2</sup> (43%) less area than A1B and A2 scenarios for the 15% and 25% targets, respectively.

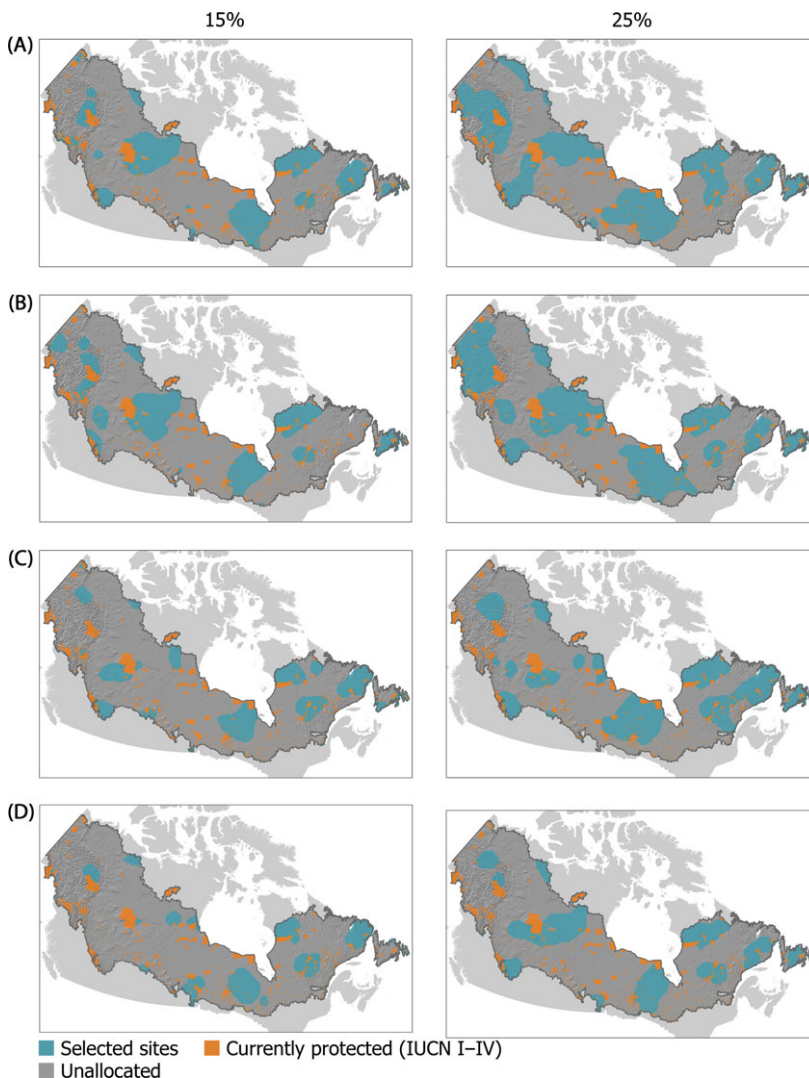
### Spatial prioritization and site-selection frequency

We assessed the prioritization distribution by comparing the selection frequency and best scenario solutions for each target level (Figs 3 and 4). In general, solutions for the baseline and B1 scenarios consisted of reserves that were smaller than A1B and A2 scenarios (Fig. 3). As illustrated in Figure 4, the frequency distributions between scenarios with VVP (scenarios 2–4) were very similar. The main differences in frequency distribution occurred between the baseline scenario and those that included VVP (scenarios 2–4), whereby more sites were selected at greater frequencies in and around the western boreal forest, Hudson Bay lowlands and Newfoundland.

Our results show the overlapping locations for the best solutions (B1, A1B, A2 scenarios) at the 25% target

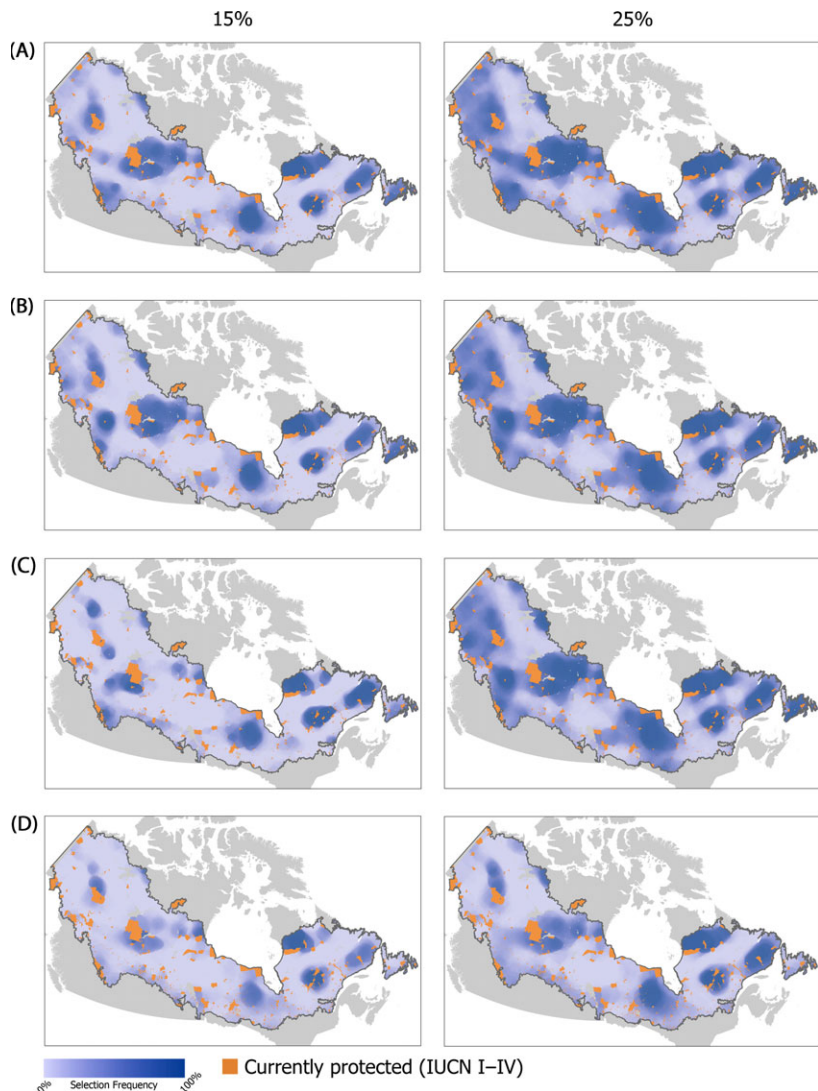
(Fig. 5A). These overlapping sites span across the boreal forest, encompassing a portion of each regionalization and represent a collection of sites selected under a range of forecasted climate/productivity conditions. Similarly, we found seven sites that were frequently selected ( $\geq 95\%$ ; over the 200 runs) in the B1, A1B and A2 scenarios (Fig. 5) and are described in Table 3. It should be noted that there is a 100% overlap between frequently selected areas for the 15% (Fig. 5B) and 25% (Fig. 5C) targets.

Overall, the seven frequently selected areas primarily consisted of sites with medium-to-high DHI productivity variability under A1B and A2 climate conditions (Table 3). However, under B1 climate conditions many of these seven areas contained low DHI productivity variability. Based on the summary provided in Table 3, it is likely that the selection frequency is related to the site's low cost (accessibility) and species richness.



**Figure 3.** Best scenario solutions for different targets (15 and 25%) using the same compactness level and planning unit cost. (A) A1B vegetation variability probability (VVP) incorporated. (B) A2 VVP incorporated. (C) B1 VVP incorporated. (D) Prioritization based on current conditions without VVP.





**Figure 4.** Blue gradient maps represent selection frequencies for different targets (15 and 25%) using the same compactness level and planning unit cost. (A) A1B vegetation variability probability (VVP) incorporated. (B) A2 VVP incorporated. (C) B1 VVP incorporated. (D) Current conditions without VVP. Selection frequency is used to determine how often a specific planning unit or site (i.e. 10 km<sup>2</sup> grid) is selected over the 200 runs, and provides an indication of its relative importance for an efficient reserve design.

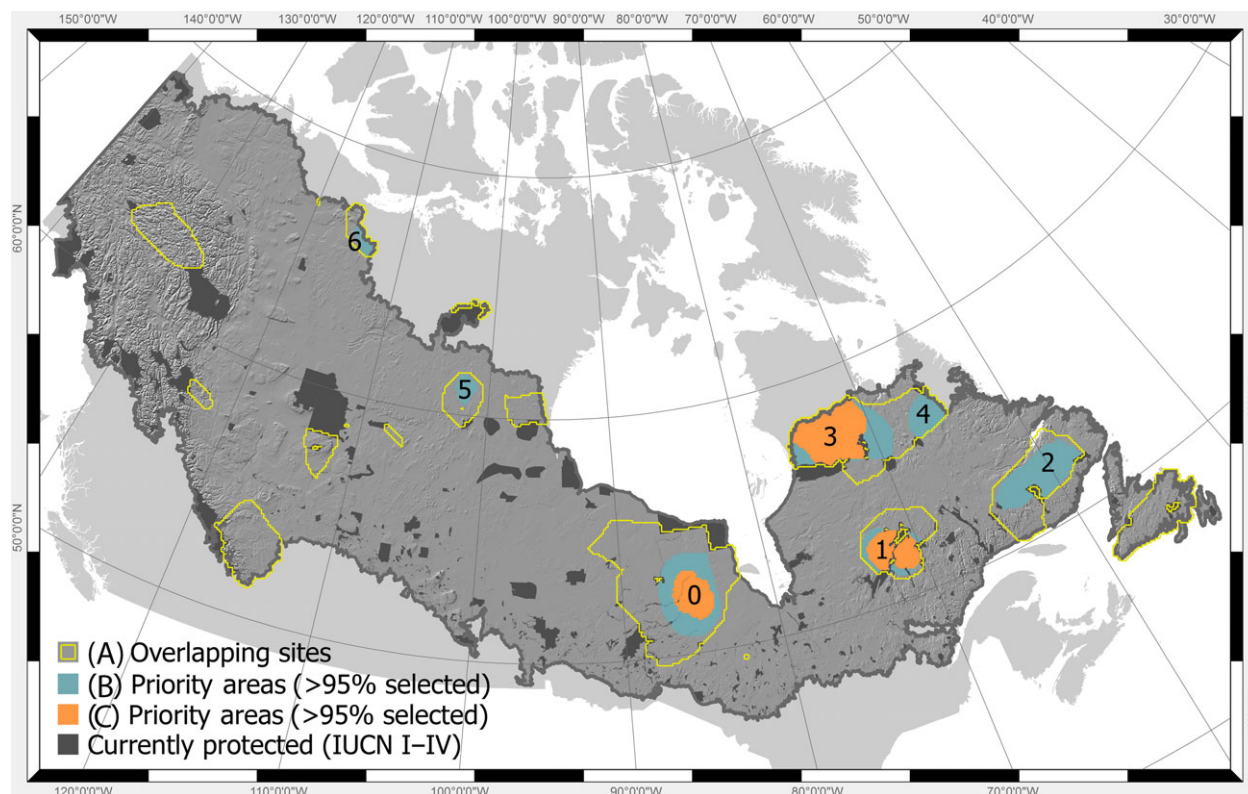
### Comparison of the proportion of VVP values under different climate/productivity conditions

The number of prioritized sites and the proportion of VVP values for those sites differed markedly depending on the scenario (Fig. 6). The proportion of low VVP values dramatically increases under B1 (least change) conditions (Fig. 6A, B), resulting in a very small proportion of sites with high and very high VVP values. Specifically, under B1 conditions the overall proportion of low VVP sites increased by 64% and 40% in the A1B reserve network (Fig. 6A), and by 65% and 69% in the A2 reserve network (Fig. 6B) for the 15% and 25% targets, respectively.

When the A1B reserve network is under A2 conditions, there was a moderate 15% increase in the overall

proportion of high VVP sites and a slight 7.5% overall decrease in low and very high VVP sites for the 15% target (Fig. 6A). For the 25% target, there was a moderate 21% and 14% increase in the overall proportion of high and very high VVP sites and a moderate 35% overall decrease in low VVP sites (Fig. 6A). There were only minor changes (~10%) between the overall proportions of VVP values for the A2 reserve network under A1B conditions (Fig. 6B).

Under A1B and A2 conditions, there was a large increase in the overall proportion of B1 sites with high and very high VVP and, subsequently, a substantial decrease in the proportion of low VVP sites (Fig. 6C). Specifically, the overall proportion of low VVP B1 sites decreased by approximately 68% and 69% under A1B conditions and by 79% and 75% under A2 conditions for 15% and 25% targets, respectively.



**Figure 5.** Sites commonly prioritized for scenarios with vegetation variability probability (VVP). (A) Overlapping best solutions for the 25% target. (B) Areas frequently selected (>95%) in the 200 MarProb runs for the 15% target in scenarios 2, 3 and 4. (C) Areas frequently selected (>95%) in the 200 MarProb runs for the 25% target in scenarios 2, 3 and 4. There is 100% overlap between (A) and (B). Numbers correspond to area description in Table 3.

Regardless of the representation target, reserve networks based on current conditions contained less than 18% of high VVP sites prioritized under B1 conditions. In contrast, very large amounts (up to 85%) of high and very high VVP sites prioritized under A1B and A2 conditions are contained within reserve networks based on current conditions.

## Discussion

### Location and characterization of high-priority areas

Overall, results indicate that the inclusion of VVP in the site-prioritization process greatly increases the cost and size of reserves. In other words, to meet conservation targets with 90% certainty under modelled productivity levels will require much larger and less efficient (costly) reserve networks. Others have also found that more area is typically required to meet boreal conservation targets when additional design criteria (e.g. connectivity, minimum reserve

size and wilderness areas) are incorporated into prioritization approaches (e.g. Beazley et al. 2005; Leroux et al. 2007a; Powers et al. 2013a). Furthermore, these findings are supported by the literature suggesting that rapid climate change will likely necessitate the protection of more area than required under static conditions to reduce the risk of under-representing current and future conservation targets (Hannah et al. 2007; Andrew et al. 2014).

In general, our assessment of the trade-offs between site VVP and cost implies that it is expensive to conserve low-risk or low VVP areas. Findings show that it is more efficient to conserve many sites with higher VVP, but lower cost. Under business as usual A1B and extreme A2 climate change conditions, there were fewer low VVP sites available for selection, explaining why more planning units were required (as compared to the baseline and least extreme B1 scenarios), to achieve conservation targets with a 90% certainty. However, similar costs and total areas of the networks chosen in the A1B and A2 scenarios were unexpected. Specifically, it was anticipated that the A2 scenario would produce a larger and more costly reserve network as it included VVPs that

**Table 3.** Description of the commonly selected areas.

Commonly selected areas	Ecoregion locations	Annual cumulative greenness variability	Annual minimum cover variability	Seasonal greenness variability	Species richness	Cost	UMD land cover (vegetation type)
0	James Bay Lowlands	B1: Med A1B: Med A2: Med	B1: Med A1B: High A2: Med	B1: High A1B: High A2: High	Med	Med	Evergreen Needle leaf forest; Open Shrublands
1	Riviere Rupert Plateau	B1: Med A1B: High A2: High	B1: Med A1B: High A2: High	B1: High A1B: High A2: High	Med	Med	Evergreen Needle leaf forest; Open Shrublands
2	Mecatina River	B1: Low A1B: High A2: High	B1: Med A1B: Med A2: High	B1: High A1B: High A2: High	Med	Med	Evergreen Needle leaf forest
3	Southern Ungava Peninsula & New Quebec Central Plateau	B1: Medium A1B: High A2: High	B1: Low A1B: High A2: High	B1: Med A1B: High A2: High	Med	Low	Open Shrublands
4	Ungava Bay Basin	B1: Low A1B: High A2: High	B1: Low A1B: Med A2: Med	B1: Med A1B: High A2: High	Med	Low	Open Shrublands
5	Selwyn Lake Upland & Kazan River Upland	B1: Low A1B: Med A2: High	B1: Low A1B: High A2: High	B1: High A1B: High A2: High	Med	Low	Open Shrublands
6	Coppermine River Upland	B1: Low A1B: Med A2: Med	B1: Low A1B: Med A2: High	B1: Med A1B: High A2: High	Med	Low	Open Shrublands

Feature rankings were derived from median indicator values from 27 "DHI" variability maps, species richness (Powers et al. 2013b), accessibility cost and defined by the natural breaks (jenks) classification scheme.

represented the greatest change. While similar in cost and area, the proportion of high and very high VVP sites within the A2 scenario reserve network was moderately greater than the A1B scenario. In spite of this difference in overall reserve VVP, representation targets were still met by the A2 scenario, which is likely attributed to its large total area (compared to the baseline scenario).

That there were only a few frequently selected regions with low DHI variability also implies that low-cost wilderness areas are relatively important for reserve design solutions. Frequently selected regions (as in Fig. 5) for scenarios with VVP, despite having moderate-to-high DHI variability values, are primarily located in wilderness areas (low cost) containing a moderate amount of species richness. Given that all these scenarios share the same cost and conservation features per planning unit, supports the likelihood that these areas were frequently selected.

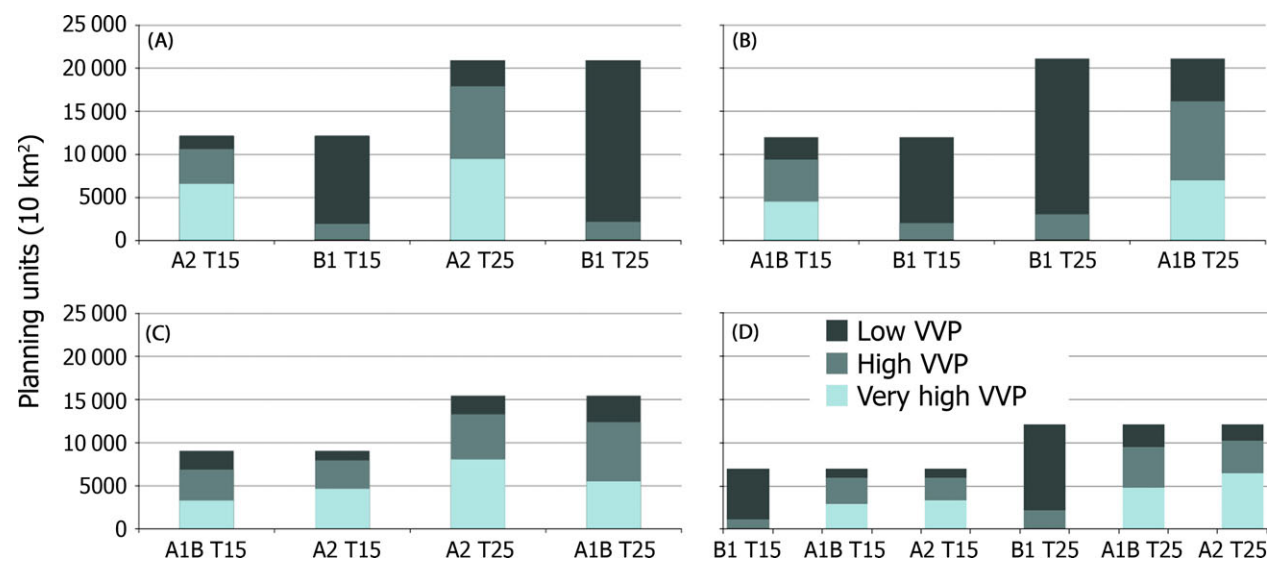
### Influence and implications of different climate conditions on reserve VVP

Reserve networks designed for current climatic conditions may not perform well under different climate conditions. Findings from the comparison of the proportion of VVP values suggest that reserve networks based on current conditions or incorporate projected B1 VVP may not be

adequate to achieve representative targets under the influence of A1B and A2 conditions. In essence, the substantial increase in the relative variability in sites that make up these reserve networks may influence their overall efficacy. Subsequently, additional planning units are likely required to compensate for the large increase in the reserve network's proportion of high and very high VVP sites.

### Climate change adaptation considerations

Conserving climate refugia (places less affected by anticipated climate impacts) can be considered an important hedging strategy against climate impacts by protecting species and habitats marginalized by ecological changes in other areas. However, this form of climate change adaptation is by no means entirely comprehensive. One concern is that this approach relies upon the assumption that areas with relatively constant climate-induced impacts will experience less severe ecological changes (Game et al. 2011). That said, how important an area is for biodiversity may not necessarily be reduced if greatly impacted by climate change, but rather it could retain its importance or become even more important, but different with respect to the habitats and species it supports (Groves et al. 2012). The protection of climate refugia alone, while it can certainly assist some ecosystems' ability adapt to



**Figure 6.** Comparison of the number of prioritized sites and the proportion of vegetation variability probability (VVP) values. T15 and T25 represent the 15% and 25% representative target, respectively. The proportion of the reserve network's VVP was determined using natural breaks, where very dark teal represents low VVP sites ( $\leq 30\%$ ), or locations in 2080 likely containing similar levels of productivity as current conditions, and medium and light teal represent high ( $\geq 40\%$ ) and very high ( $\geq 45\%$ ) VVP, respectively. (A) Reserve network designed for A1B VVP under A2 and B1 conditions. (B) Reserve network designed for A2 VVP under A1B and B1 conditions. (C) Reserve network designed for B1 VVP under A1B and A2 conditions. (D) Reserve network designed for current conditions without VVP under B1, A1B and A2 future 2080 conditions.

changes, will not guarantee its viability (Groves et al. 2012). Hence, it seems wise that climate change adaptation approaches include other strategies and criteria, such as those proposed here, when identifying important conservation areas.

Likewise, an inherent limitation with this adaptation approach is its reliance on modelled climate change projections, in this case projections of expected DHI productivity conditions and the inherent uncertainties associated with those projections. Such models, therefore, are not viewed as literal truth, but as a means of providing spatial and categorical insight into potential trends (Andrew et al. 2014). Based on this rationale, assessing a range of potential conditions will provide otherwise unavailable insights and be of value for aiding scenario development and planning exercises. Another important consideration is that this approach, or any approach that imposes analogous criteria, will typically introduce additional costs into conservation decisions, thus these costs should be justifiable.

Despite the mentioned concerns and limitations, however, there is an important distinction/advantage between the site selection with probabilities (e.g. climate projections) approach used here and other climate change adaptation approaches (e.g. model simulations). Specifically, unlike the other approaches, reserve design solutions are not guided solely by climate projections, but also meet conservation targets and are optimized for efficiency

(minimize cost). Thus, reserve solutions, while likely less efficient, are no worse and potentially much better than solutions produced using a conventional site-selection approach that does not consider climate change impacts (Game et al. 2011). Although this may constitute as a 'no-regret' conservation strategy (Game et al. 2011), limited funds and resources are a reality in the conservation planning process and will likely necessitate trade-offs (Stewart and Possingham 2005). For example, it might not be feasible to develop conservation solutions that incorporate all the various elements related to climate change. It should also be noted that the flexibility of systematic conservation planning approaches, such as the one used in this study, can be applied and adapted to address a host of local-to-regional and national-level priorities. For example, spatial prioritization algorithms (e.g. Marxan) have already been used to identify or include climate change refugia as part of national/broad conservation assessment for Papua New Guinea (Game et al. 2011; Groves et al. 2012), Australia (Klein et al. 2009) and the continental Iberian Peninsula (Carvalho et al. 2011).

## Canadian Context

Canada is globally unique with large tracts of lands that remain to function largely following natural ecosystem processes (Andrew et al. 2012, 2014). Approximately 50 to 80% of the Canadian boreal is found to have

characteristics that, while not under protection, resemble areas that are either by landscape structure or paucity of anthropogenic infrastructure. Distance to markets and lower productivity environments result in most industrial activity having regional and latitudinal concentration. Regardless, natural resources development is placing pressure upon terrestrial biodiversity (Venier et al. 2014) as more southern areas are more complex and it could be argued that protection is more important. Furthermore, climate change is expected to have diverse impacts across Canada's boreal (Price et al. 2013), with the complexities that would be related to possibly longer growing seasons, moisture deficits and subsequent stress on vegetation as a result. Values-based versus area-based conservation remains important as a consideration in the planning of protected areas. A focus on area could result preferentially in protection of locations with a bias protection towards lower productivity (and diversity) northern environments at the expense of southerly sites (Andrew et al. 2014).

The Canadian boreal is uniquely suited for data-driven conservation planning. With a large area of land both under and possibly eligible for protection, various scenarios can be envisioned and tested. Competitive uses for land, or existing development, reduce the likelihood of subsequent protection (Andrew et al. 2014). Conservation planning activities can benefit from the unique capacity present using spatial data and modelling to best incorporate as many of the known consideration, to offer near- and long-term protection functions to be offered (Powers et al. 2013a).

In Canada based on the unique situation of de facto protection communicated by Andrew et al. (2012), the creation of formal reserve networks is not a requirement for protection. That is, formal reserves may not be required due to the lack of access and minimal industrial activity present over much of the northern boreal in Canada. While protection may be a desired outcome for de facto protected lands, it may be an indication that there are other areas with a greater priority for protection (e.g. those with values or features that are rare or at risk). In terms of the protection mix present and offering potential for the future in Canada, are revisiting of IUCN categories with regards to Canadian imperatives, incorporation of private conservation initiatives, cultivating connectivity between protected areas and establishment of Indigenous Protected Areas (e.g. Ross et al. 2009).

## Conclusion

Adaptive strategies, which correspond to ecological theory, can be applied in conservation planning approaches to help increase the reliability, robustness and long-term

effectiveness of conservation solutions. Here, we use a probabilistic method that incorporates adaptive strategies and future vegetation variability to provide a proactive boreal conservation assessment. The resultant conservation solutions revealed that many sites with low cost or high wilderness were given higher priority over fewer sites with low vegetation variability probability (VVP). Also demonstrated by this research is a steep trade-off between incorporating VVP and reserve design efficiency, where the relative cost and total area of reserve networks with VVP were considerably greater than those without VVP. Findings also revealed a greater amount of sites with high VVP values in reserve networks optimized for moderate change (A1B) and most change (A2) climate scenarios. Moreover, the proportion of sites with high VVP values was found to dramatically increase for reserve networks based on current conditions or least change (B1) scenarios when under more severe A1B and A2 climate conditions, and suggests that additional sites may be required under these scenarios to meet long-term conservation targets.

Establishing priorities capable of addressing the complexities of conservation planning in Canada's boreal forest (e.g. biological systems, anticipated climate change, system dynamics and limited/realistic funding and resources) remains a critical challenge (Lemieux et al. 2011) and represents a major avenue for continued research. Results from this research could benefit adaptive planning for climate change in the region, and may provide a useful framework for determining how to best expand existing protected areas in Canada's boreal forest. Specifically, introducing elements of climate change impacts like future VVP and ecologically driven criteria (large reserves, wilderness and representativeness) with this approach may allow for less risky conservation that, in the long run, will likely have important implications for conservation investment and help improve the persistence of boreal biodiversity and ecological systems. Furthermore, our methods are well suited to be applied and adapted to other broad conservation assessments that are interested in incorporating climate change impacts.

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