

Evaluating natural reserve design efficacy in the Canadian boreal forest using time series AVHRR data

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Abstract

This research evaluates the efficacy of candidate reserves in boreal ecosystems with respect to a long term record of remote sensing derived productivity based on the dynamic habitat index (DHI) generated using Advanced Very High Resolution Radiometer (AVHRR) data (1987-2007) and compared differences related to reserve location (stratified by land cover, ecozone and gross primary productivity (GPP)) and reserve size. Effectiveness of candidate reserves was assessed by how productivity values differed from the initial conditions (2000-2005 baseline). Results indicate that small reserves (<1000 km²) at high elevations, high latitudes, intermittent environments (wetlands) or dominated by open shrub experienced the greatest amount of inter-annual variability. Alternately, larger reserves (≥ 1000 km²; <10000 km²) were stable under these same conditions. Results also indicate that reserves located in highly productive areas (>700 kgC m⁻² yr⁻¹) experienced greater inter-annual variability than low productivity areas. This approach provides an objective and consistent means of evaluating reserve efficacy across different geographic areas and through time. By highlighting uncertainty associated with change impacts, this approach also offers opportunities to develop more robust long-term conservation targets in new reserves and to test potential mitigation strategies prior to implementation.

1. Introduction

Protected areas are a vital component of biodiversity conservation and ecological sustainability. Recognition of the uniqueness of the Canadian boreal forest, in terms of both its ecological value and high remaining conservation potential (Powers et al., 2013a, Andrew et al., 2012a), has triggered a number of initiatives to expand current protected areas in this region (e.g., Far North Plan, 2011; Plan Nord, 2011; Canadian Boreal Initiative, 2005). As such, the present challenge is to design a more extensive protected area network that is realistic given the nature of the landscape, while complementing those protected areas that already exist. Systematic conservation planning (Margules and Pressey, 2000) is commonly used to develop plans that (i) help guide where (spatially) conservation investment (e.g., reserves) should be placed to efficiently meet conservation objectives, and (ii) to help prioritize candidate locations. Systematic planning is not restricted to a particular spatial scale and is typically used to guide conservation decisions both regionally and nationally (e.g., Klien et al., 2009; Rayfield et al., 2008; Leroux et al., 2007). However, even though many advances in techniques have been developed, the methods and data (e.g., conservation features) employed by most systematic conservation plans are largely based on a static view of biodiversity (Pressey et al., 2007).

Given the degree of anticipated changes in climate and disturbance regimes for the boreal forest (Dale et al., 2001; Fleming et al., 1998; Kurz et al., 1995), it is becoming more important to better understand (i) how changes in landscape properties can impact the effectiveness of candidate reserves, and (ii) what reserve design (e.g., reserve compactness and connectedness) or adaptation considerations better accommodate climate and disturbance impacts and enable more effective long-term conservation (e.g., representation) of species and ecosystems? For example, reserve size represents an important reserve design consideration for incorporating natural disturbances (Baker, 1992), which, over time, can potentially alter the landscape structure and function of reserves. 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. Additionally, an important adaptation consideration is the preferential conservation of areas in locations likely to contain climate change refugia (Game et al., 2011), areas where current environmental attributes closely resemble anticipated future conditions (Saxon et al., 2005). To address the above questions, one approach would be to evaluate the effectiveness (e.g., ability to maintain initial conditions) of a range of candidate reserves before they are implemented.

A key requirement for evaluating reserve design traits is understanding how biodiversity varies both spatially and temporally. When biodiversity monitoring is required over large areas, characteristics such as species richness cannot be obtained by detailed field based measures alone and there is benefit to proxy measures that can be more easily captured for large areas and multiple time periods. Remotely sensed measures of vegetation productivity, and hence available energy, have been shown to be strong predictors of biodiversity (Waide et al., 1999; Mittelbach et al., 2001; Hawkins et al., 2003a,b; Hurlbert and

Haskell, 2003; Evans et al., 2005; Coops et al., 2008, 2009a,b; Latta et al., 2009; St-Louis et al., 2009) as well as useful for providing reliable estimates of broad scale biodiversity patterns and community composition (Kerr and Ostrovsky, 2003; Turner et al., 2003; Pettorelli et al., 2005; Buchanan et al., 2008). In principle, the amount of available energy and energy pathways in a system increases with productivity; thus, highly productive areas typically support greater species richness and diversity (Walker et al., 1992). While current research that utilize such remotely sensed measures generally support the species-energy hypothesis (Bonn et al., 2004; Storch et al., 2005; Waring et al., 2006; Rowhani et al., 2008), the mechanisms that give rise to its positive relationship are still not fully understood and have inspired debate (Currie et al., 2004; Evans et al., 2005; Storch et al., 2005). Another classic hypothesis is the humped-back model (HBM), where taxonomic richness peaks at intermediate productivity and declines at low and high productivity (Grime, 1973). Again, research both supports (e.g., Fraser et al., 2015; Cornell and Karlson, 2000) and contests (e.g., Tredennick et al., 2016; Adler et al., 2011) this unimodal relationship between productivity and species richness. Despite this lack of consensus, however, there is widespread agreement that productivity measures are a major determinant of biodiversity (Hawkins et al., 2003a; b; Field et al., 2009).

Remote sensing offers an efficient means of monitoring and assessing the state of vegetation productivity over large extents in a consistent and repeatable manner (Foody and Cutler, 2003; Kerr and Ostrovsky, 2003; Turner et al., 2003). For instance, Normalized Difference Vegetation Index (NDVI) and fraction of Photosynthetically Active Radiation (fPAR) are two examples of remotely derived vegetation metrics for monitoring and modeling vegetation dynamics over time. Time series of the widely used NDVI (Rouse et al., 1973), an empirical-based measure of “greenness” (Coops et al., 2008), have been applied in a variety of studies to assess trends in productivity since the early 1980s (e.g., Myneni et al., 1997; Kawabata et al., 2001; Slayback et al., 2003; Tateishi and Ebata, 2004; Pouliot et al., 2009). fPAR is a physically-based measure of photosynthetic activity and, while not as widely used as NDVI, provides a link to the energy used during photosynthesis, and is more directly associated with vegetation productivity. In the past decade, fPAR has been used to construct an integrated index called the dynamic habitat index (DHI) applied, to date, in Australia (Mackey et al., 2004; Berry et al., 2007), Canada (Coops et al., 2008), and the United States (Coops et al. 2009b) to assess habitat and forage conditions. This integrated index comprises three annual fPAR metrics (cumulative greenness, seasonality, and minimum cover) based on ecological theory, and provides more comprehensive description of the vegetation dynamics than a single remote sensing metric (Coops et al., 2014). In the Canadian context, DHI metrics, derived from freely available Moderate-resolution Imaging Spectroradiometer (MODIS) (Justice et al., 1998), are effective at representing broad-scale biodiversity patterns (Andrew et al., 2012b; Coops et al., 2009a; b) and community composition (Andrew et al., 2011a) as well as useful for evaluating potential productivity biases and productivity trends in existing protected areas (Andrew et al., 2011b; Coops et al., 2014). For example, Coops et al. (2009 a; b) examined the effectiveness of DHI as a predictor of breeding bird species richness in the United States and Ontario. Results indicated that DHI was able to successfully estimate bird species richness, explaining as much 75% of the variation for certain guilds. In Ontario, Michaud et al., (2014) showed that DHI metrics significantly contributed to moose [*Alces alces*] occurrence and abundance.

MODIS data is available from 2000 onward and can be integrated with longer data archives available from the Advanced Very High Resolution Radiometer (AVHRR; Cracknell, 1997), whose data record begins in 1981, with operational considerations typically resulting in an initiation date of post-1985 (Pouliot et al., 2009; Fontana et al., 2012). The AVHRR-derived NDVI has been applied in both regional (Tucker et al., 2001) and global (Kidwell, 1990; Tucker et al., 2001; De Jong et al., 2012) studies on vegetation dynamics, and the utility of AVHRR NDVI time-series data have been well established (Myneni et al., 1995; Tucker et al., 2001; Zhou et al., 2001; Nemani et al., 2003; Fontana et al., 2012). Many studies that applied this remote sensing index to the assessment of vegetation changes have found differences in the way regional climate trends affect vegetation dynamics over a marked range of ecosystems and spatial scales (Myneni et al., 1995; 1997; Nemani et al., 2003; Zhao & Running, 2010; De Jong et al., 2012; Chen et al., 2014). For example, Myneni et al. (1997) utilized AVHRR remotely derived estimates of productivity to predict global plant growth in northern high latitudes. The authors identified a general increasing trend in photosynthetic activity in the region, with the northwestern portion

of Canada experiencing the largest NDVI increase in North America. AVHRR NDVI trend analysis by de Jong et al. (2011) also indicates greening in the Northern Hemisphere, particularly in the boreal forests. In a review of long-term AVHRR NDVI vegetation studies, Pouliot et al. (2009) developed a new 1 km data record for the years 1985-2007 to evaluate and compare NDVI trends across Canada. The comparison of trend analysis supported the positive greening trend in the north, but also found some inconsistencies, particularly in the south of the country due to land cover change. The results from these studies indicate that AVHRR data sets are uniquely suited for monitoring long-term vegetation trends in the boreal forest based on its high latitude and level of intactness (~80% intact).

The goal of this study is to explore the capacity of DHI productivity metrics derived from a long time-series AVHRR dataset (1987-2007) to assess how reserve design configurations (size and location) impact the efficacy of candidate reserves based on mid-2000 conditions. AVHRR measures were initiated from 1987 due to fragmented AVHRR data coverage for the years 1981-1984 (Fontana et al., 2012) and poor data coverage over large portions of western Canada during 1985 and 1986. These gaps prevented consistent data processing at a continental scale for these periods. To focus our analysis we utilize a series of previously generated reserve designs (Powers et al., 2013a) that are based on MODIS productivity data from 2000 to 2005 representing mean conditions in the early to mid 2000's, and other biodiversity data. This 2000 to 2005 epoch formed the baseline period for the analysis. We then assess the ability of the reserves to maintain the DHI baseline levels during this time period across various boreal ecozones, GPP productivity strata (low productivity ($\leq 3000 \text{ kgC m}^{-2} \text{ yr}^{-1}$), productive ($>3000 \text{ kgC m}^{-2} \text{ yr}^{-1}$; $\leq 7000 \text{ kgC m}^{-2} \text{ yr}^{-1}$), and highly productive ($>7000 \text{ kgC m}^{-2} \text{ yr}^{-1}$)), and land cover types (open shrubland, evergreen needleleaf, and mixed forest). Specifically, we compared the stability of the longer-term AVHRR DHI metrics from 1987-2007, to the averaged 2000-2005 AVHRR DHI values to establish how often, and under what conditions, reserves differed from baseline productivity conditions. We hypothesize that over the 21 year period that (i) larger reserves will be more stable than small reserves ($< 1,000 \text{ km}^2$); (ii) reserves located in productive environments will experience more variability; (iii) predominately forested reserves will be more stable than reserves dominated by shrub land cover, and (iv) predominately evergreen forested reserves will be more stable than reserves dominated by mixed forest land cover.

2. Methods

2.1. Study area and data

2.1.1. Study area

The study area consists of the entire Canadian boreal forest (~5.37 million km^2) as described by Brandt (2009) excluding the southern transitional hemiboreal subzone (includes much of British Columbia), which is considered temperate in North America and not formally recognized as boreal (Brandt, 2009). Situated in northern latitudes, the primarily forested region (~58% forested) 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 common throughout the boreal forest (Wulder et al., 2008). Stand replacing fire and insect infestation are the dominant natural disturbances on the landscape (Kurz et al., 1992; Fleming et al., 1998).

2.1.2. Remotely sensed data: time series of DHI productivity

The fPAR based DHI was computed from remotely sensed imagery to assess vegetation productivity and identify changes in habitat and forage conditions within candidate reserves. For this research the AVHRR archive (1987-2007) over Canada (see Latifovic et al., 2005) was used to derive the index components for each year at a 1 km spatial resolution. The AVHRR data record comprised of overlapping observations from all satellites of the NOAA series and were processed using a new methodology developed by Fontana et al. (2012) to enable improved geolocation and ortho-rectification accuracy (efficiency rate $>90\%$). DHI was calculated based on the April to September period to avoid very low fPAR values associated with northern hemisphere seasonality and snow contamination.

The index has three fPAR components representing different aspects of vegetation productivity: (a) the cumulative annual fPAR; (b) the annual minimum greenness; and (c) seasonal variation of the greenness. Cumulative annual fPAR or annual cumulative greenness provides an indication of the annual productive capacity of a landscape (Berry et al., 2007) and is strongly associated with species richness (Coops et al.,

2009b; Connell and Orias, 1964). This integrated annual estimate of greenness was calculated by summing monthly fPAR observations for each year. Annual minimum greenness describes a site's base level of cover within a year and provides a measure of the landscape's ability to sustain sufficient levels of greenness and permanent resident species year-round (Coops et al., 2009b). Positive values indicate that some degree of vegetation was maintained over the year, while predominately snow-covered areas, for example, will have values near or equal to zero (Coops et al., 2008, 2009b). Seasonal variation of greenness is an integrated measure linked to local climate, topography, and land use (Coops et al., 2014) and relates information about a site's annual variation in productivity. Annual variation in productivity is calculated as the coefficient of variation (CV) of fPAR estimates. High CV values indicate extreme seasonal changes in vegetation cover or climate conditions, and typically characterize habitats at high elevations or areas with seasonal winter snow cover and spring vegetation green-up. Areas with low CV values indicate habitats with less variation in seasonal vegetation cover, such as irrigated pastures, barren land or highly productive evergreen forests.

2.1.3. Boreal forest stratification

Three different datasets were used to stratify the boreal forest at a 1 km spatial resolution: land cover, ecozone, and productivity (Fig. 1; Table 1) and were chosen to represent boreal conditions in early to mid 2000's that coincide with the MODIS and AVHRR temporal overlap. Land cover data for Canada's boreal were obtained from the MODIS global land cover product (MOD12Q1), and includes five categorical maps derived from observations collected over a period of a year (NASA Land Processes Distributed Active Archive Center, 2010). We selected the University of Maryland (UMD) classification, which was based on data from 2004 and consists of 14 general biome types such as evergreen needle-leaf forest, savanna, and grassland. The three main land cover classes were used to stratify the boreal forest: mixed forest, evergreen needle-leaf, and open shrubland.

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The Ecozone stratification of Canada (Ecological Stratification Working Group, 1995) represents the highest level of a nested ecoregion hierarchy and defines large discrete regions based on similar geology, soil, topography, vegetation, climate, land use, hydrology, and wildlife. The majority of the boreal forest is located within eight of Canada's 15 terrestrial ecozones (Wulder et al., 2008); these were used for stratification: Boreal Cordillera, Taiga Cordillera, Taiga Plains, Southern Artic, Boreal Plains, Boreal Shield, Hudson Plains, and Taiga Shield.

Lastly, the productivity strata was defined using the annual MODIS gross primary productivity (GPP) product MOD17A3 (Zhao and Running, 2010; LP DAAC, 2011). Because there are inter-annual variation and long-term trends present within the dataset (Zhao and Running, 2010), an average of the GPP products was taken instead of a single year. GPP estimates of a single year are unlikely to produce an accurate representation of long-term forest productivity (Bolton et al., 2013). The 11-year average of annual GPP (2000-2011) was compiled (available at ftp://ftp.ntsg.umd.edu/pub/MODIS/NTSG_Products/MOD17/MOD17A3/) and then stratified into three relative productivity classes of low productivity ($\leq 3000 \text{ kgC m}^{-2} \text{ yr}^{-1}$), productive ($> 3000 \text{ kgC m}^{-2} \text{ yr}^{-1}$; $\leq 7000 \text{ kgC m}^{-2} \text{ yr}^{-1}$) and highly productive ($> 7000 \text{ kgC m}^{-2} \text{ yr}^{-1}$).

2.2. Candidate reserves based on mid-2000 conditions

Candidate reserves were generated in a previous study (Powers et al., 2013a) by partitioning the boreal forest into $5 \times 5 \text{ km}$ grids and using the freely available spatial conservation prioritization tool Marxan (Ball and Possingham, 2000) to identify potential areas for prioritization. Conservation targets were set using 15 environmental domains based on remotely derived boreal specific biodiversity indicators (Powers et al., 2013b) and 16 at-risk species to represent biodiversity. A long-term DHI index representing an average of the three components for the years 2000-2005, derived from MODIS fPAR data, was used in constructing the environmental domains. Environmental domains, typically labelled as coarse filters, ecological regionalizations, ecoregions, or clusters, are associated with unique combinations of environmental conditions, which in theory should be representative of species diversity

(Belbin, 1993, 1995; Mackey et al., 1988; Trakhtenbrot and Kadmon, 2005). The 6-year DHI index was used to establish a vegetation productivity baseline of DHI differences between varied sized candidate reserves located in a number of land cover, productivity, and ecozone strata. Reserve size and compactness levels were adjusted using the boundary length modifier (BLM) parameter, whereby a larger BLM places greater emphasis on reserve compactness than cost efficiency (Ball and Possingham, 2000). In total, we used 738 individual reserves, which were categorized by size: small ($\leq 1,000 \text{ km}^2$), medium ($> 1,000 \text{ km}^2; \leq 4,000 \text{ km}^2$), and large ($> 4,000 \text{ km}^2; \leq 10,000 \text{ km}^2$).

2.3. Statistical analysis

The three AVHRR DHI metrics were resampled to a $5 \times 5 \text{ km}$ cell to match the reserve planning units (cell) and then aggregated to individual reserves using simple averaging. To account for the internal variability, the spatial coefficient of variation (standard deviation / mean) of the DHI metrics were also calculated, making six DHI values in total for each reserve. The calculated coefficient metrics show the extent of variability of each reserve in relation to the mean of all reserves within its size and stratification grouping. We then assessed whether the reserves experienced any major changes in DHI values from their baseline means (2000-2005) over the 21 year period. Significant differences between annual DHI values and baseline means were assessed per reserve size and stratification because each might respond differently to changes (e.g., disturbances and climate change impacts). In total there were 252 assessments made (six DHI values \times three reserve sizes \times 14 distinct stratifications). Here, significant differences were defined as annual DHI values ($\pm 3 \text{ SD}$) outside the baseline means ($\pm 3 \text{ SD}$). Significant annual DHI differences were then summed for each reserve size and stratification to indicate the reserves' ability to maintain conservation targets (i.e., initial conditions). Stratums and reserve sizes with large sums indicated high temporal variability. Descriptive statistics for each reserve size and strata per DHI index is provided in the appendix (Tables A1 to A6). Lastly, one-way ANOVA was conducted to evaluate whether annual differences, with respect to the baseline, significantly differed based on the three reserve sizes (Table A7).

3. Results

3.1. Ecozone strata

Analysis confirmed that over the 21 year period there were many instances where the six DHI components were statistically different ($\pm 3 \text{ STD}$) from the base-line means (2000-2005). Half of the eight ecozones contained reserves that experienced moderate to high temporal variability; however, there were distinct differences in the proportion of variability between the reserve sizes and ecozone. Figure 2 and Table 2 provide an overview of the reserve temporal variability stratified by ecozone and size.

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The DHI productivity metrics indicate that small reserves ($\leq 1,000 \text{ km}^2$) in the Southern Arctic and Taiga Cordillera had relatively high levels of temporal variability in annual minimum greenness, annual minimum greenness (CV), cumulative annual fPAR and seasonal variation. Likewise, the Hudson Plains had a moderate amount of variability in seasonal variation and annual minimum greenness for small reserves. Both Boreal Plains and Taiga Shield experienced minor temporal variability. The Boreal Shield had moderate temporal variability for cumulative annual fPAR, seasonal variation, and annual minimum greenness for all reserve sizes. Large reserves ($> 4,000 \text{ km}^2; \leq 10,000 \text{ km}^2$) within the Boreal Cordillera experienced the greatest temporal variability in seasonal variation (CV) and a moderate amount in cumulative annual fPAR. It is also important to note that all reserve sizes in the Taiga Plains, an area dominated by low-lying plains, remained stable throughout the 21 year period for all DHI productivity metrics. Lastly, results from the one-way ANOVA (Appendix A7) show that, for each strata (ecozone, productivity, or land cover), there is no significant difference in reserve interannual variability based on size.

3.2. Productivity strata

The most productive stratum ($> 7000 \text{ kgC m}^{-2} \text{ yr}^{-1}$) extends across the southern boreal border. Overall, reserves located in this stratum were the most variable over the 21 year period (Table 3; Fig. 3). Reserves

that are contained within the productive stratum ($>3000 \text{ kgC m}^{-2} \text{ yr}^{-1}$; $\leq 7000 \text{ kgC m}^{-2} \text{ yr}^{-1}$) experience moderate variability for the DHI metrics (Table 3). Situated in the northernmost boreal extent and in the northern portions of the Rocky Mountains, the least productive stratum ($\leq 3000 \text{ kgC m}^{-2} \text{ yr}^{-1}$) has long and cold winters and short and cool summers. Very low temperatures and low precipitation (e.g., $\sim 250 \text{ mm}$ per year) combine to reduce vegetation development and encourages only smaller plants. The large greening that occurs in the majority of this stratum during the spring and summer also acts to increase the cumulative annual fPAR and results in a high seasonality. All reserves located in this stratum experience a moderate to high amount of variability related to seasonal variation and cumulative annual fPAR, with the highest amount occurring within small reserves (Table 3).

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3.3. Land cover strata

The variability of DHI metrics for each of the reserve sizes of the land cover classes (mixed forest, evergreen needle-leaf and open shrubland) is described in Table 4, and indicates that open shrub typically had the highest levels of variability. Specifically, small reserves ($\leq 1,000 \text{ km}^2$) dominated by open shrub land cover had the highest variability for the cumulative annual fPAR and seasonal variation (Fig. 4). Overall, reserves that were dominated by evergreen needle-leaf forests were slightly less variable in the DHI metrics over the 21 year period than both the open shrub and mixed forest land cover types. However, large reserves ($> 4,000 \text{ km}^2$; $\leq 10,000 \text{ km}^2$) in the evergreen needle-leaf stratum experience a high amount of variability in cumulative annual fPAR and annual minimum greenness. Similar to what was observed with the ecozone and productivity strata, all reserves had a relatively low amount of variability for the annual minimum greenness, cumulative annual fPAR (CV) and seasonality (CV) DHI metrics.

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4. Discussion

The Canadian boreal can be differentiated along a north/south latitudinal gradient, with five ecozones relating northern conditions (i.e., Taiga Cordillera (2); Taiga Plains (3); Southern Artic (4); Hudson Plains (6) and Taiga Shield (8)) and three relating conditions in the south (i.e., Boreal Cordillera (1), Boreal Plains (5) and Boreal Shield (7)). Our results indicate that only small reserves ($\leq 1000 \text{ km}^2$) within the two most northerly ecozones (ecozones 2 and 4) experienced a notable amount of temporally variability (>10 years of 21 outside ± 3 STD of baseline) with respect to seasonality, cumulative annual fPAR, minimum annual greenness and minimum annual greenness (cv), suggesting that reserve size is particularly important for maintaining overall productivity levels in these regions. In particular for minimum annual greenness since it affects both seasonality and cumulative annual fPAR. The numerous and large deviations from the DHI baseline mean indicate that these small reserves are likely to experience substantial changes in productivity, and medium and large reserves would constitute as a less risky conservation investment in these areas. Similarly, small reserves within the Hudson Plains (ecozone 6), an area that is poorly drained and has an extensive wetland component, experienced some moderate temporal variability related to annual seasonal greenness. In this case, wetlands such as bogs, fens, swamps and marshes represent a diverse range of landscape conditions (e.g., treed, shrubby, mossy etc.) depending on the state of local moisture, nutrient and hydrodynamic regimes (Smith et al., 2007). Given the influence of these fluctuating regimes (e.g., water availability is often variable) over landscape conditions and variable snow and ice conditions, it is expected that there would be some variability in the reserve DHI productivity over time.

In the context of the southern boreal, large reserves ($> 4,000 \text{ km}^2$; $\leq 10,000 \text{ km}^2$) within the mountainous Boreal Cordillera (ecozone 1) had a high degree of temporal variability related to seasonal annual greenness (cv), but maintained a consistent seasonal annual greenness. This indicates that collectively, the overall production of vegetation in large reserves was consistent over time, but had large differences in the level of production within the reserves themselves. Overall, bigger reserves (i.e., $>1000 \text{ km}^2$; $\leq 10,000$

km²) typically have a greater range of DHI productivity values than small reserves; thus these reserves are less likely to significantly deviate (± 3 STD) from baseline conditions in intermittent environments (Fig. 5). Generally, reserves large enough to accommodate periodic natural disturbances tend to be more resilient to disturbances and better able to maintain biodiversity (Carroll et al., 2010). Furthermore, such large reserves can also provide more area for habitat-specialist species by supporting a wide range of seral stages (Berg et al., 1994; Bradshaw et al., 2009). Mammal diversity and abundance, for example, varies considerably between successional stages (Fisher and Wilkinson, 2005), thus including many different stages represents an important reserve design consideration for boreal conservation.

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Our results demonstrate that out of the three land cover strata, small reserves dominated by *open shrub*, areas primarily in the northern mid latitude boreal regions and in the mountainous areas within the southern Yukon and British Columbia (e.g., ecozones 1, 2, 4, 6, and 8), had the greatest amount of temporal variability in DHI values. These findings suggest that small reserves in this stratum have an inconsistent level of vegetation production, which will likely affect the ability of these reserves to continuously support species food supply and habitat. As such, large and medium reserves would represent a less risky conservation investment in these areas. We have shown that reserves dominated by mixed forests, specifically large reserves, are slightly more temporally variable in DHI than those reserves dominated by evergreen needle-leaf. This was not surprising since evergreen needle-leaf forests maintain foliage cover throughout the year, thereby allowing them to sustain a consistently high level of productivity that typically results in a higher cumulative annual fPAR and low seasonality (Coops et al., 2008). It is likely that greater differences would be observed if the annual DHI metrics were calculated using the November-March months.

Our results also confirmed that reserves located in highly productive (>7000 kgC m⁻² yr⁻¹) areas experienced greater temporal variability in DHI productivity than reserves located in less productive environments (≤ 3000 kgC m⁻² yr⁻¹). In low productive areas (e.g., high latitudes and elevations), vegetation productivity is constrained by very cold annual temperatures and plant available moisture, which results in a limited growing period (Kimball et al., 2006). In the southern, more productive boreal regions a longer, yet still variable, growing period allows for greater vegetation development and a higher annual cover, which, depending on environmental conditions, can potentially lead to greater annual variation in DHI between years than less productive regions.

It is important to note that the candidate reserves used in this study were based partly on MODIS DHI productivity data (2000-2005) and not data derived from the AVHRR satellite sensor. While the timeframe of the baseline is only six years, it is consistent with the datasets used in current remote sensing efforts related to biodiversity monitoring or highlighting unique geographical areas across Canada and the Canadian boreal landscape with similar ecological features (e.g., Coops et al., 2009a; Andrew et al., 2011b; Powers et al., 2013a). Compared to AVHRR, the MODIS sensor provides better spatial and spectral resolution (Gallo et al., 2005), and improved atmospheric corrections and geo-registration. As a consequence, MODIS products, such as NDVI and DHI, have been regularly used since the 2000s to assess spatial and temporal changes in vegetation condition. However, the overall agreement of productivity indices between AVHRR and MODIS is high (e.g., van Leeuwen, 2006; Ji et al., 2008). Here, a newly processed historical AVHRR data set by Fontana et al. (2012) was used to derive DHI across Canada's boreal. The improved geometric accuracy of this new data set is in agreement with the standards outlined by the Global Climate Observing System (GCOS) (WMO, 2006; 2011); thus, facilitates a more precise examination of changes between years and better cross-sensor (AVHRR) continuity. It should also be noted that processed NDVI data using this AVHRR data set were shown to be highly correlated to NDVI MODIS for spatially and temporally (2001 to 2005) overlapping areas across a variety of biomes and ecoregions (Fontana et al., 2012). As such, these results lend credence to the processing approach of this novel AVHRR data set and highlight its usefulness as a source of information for climate and vegetation-related research in Canada and portions of northern United States.

The problem of evaluating the effectiveness of protected areas is complex, and made more challenging by climate change. Addressing this challenge will necessitate the use of accessible, spatially explicit and long-standing information sources or models. As such, inherent uncertainties will arise when assessing protection, be it from estimated species distribution models, climate change models, emission projections or observations derived from biodiversity proxies. Using temporal variability in DHI productivity as a measure of conservation effectiveness relies on the assumption that protected areas that remain constant through time will experience less severe ecological and biodiversity changes and constitute a better conservation investment. This assumption may not always be the case. It is wholly possible that protected areas that undergo large changes in DHI productivity may retain their conservation value, or even become more important, but different with respect to what habitats and species they are able to support. Incorporating reserve design considerations that facilitate consistent productivity values does not always guarantee a better investment from a biodiversity perspective, but it does represent a less risky one. Sites with stable vegetation productivity, and hence stable energy, generally maintain similar habitat conditions and resources (e.g., food supply and biomass), and are likely to support similar levels of biodiversity. Moreover, sites with stable productivity and predictable environments may contain important conditions for the occurrence of high species diversity (Fjeldså et al., 1997; Rowhani et al. 2008). Remote sensing based results by Rowhani et al. (2008), for example, offer some credence to this hypothesis. Specifically, Rowhani et al. (2008) observed a decrease in avian richness across the conterminous U.S. with decreasing energy availability and increasing energy variability, which suggests that a greater amount of avian species reside in more stable and productive environments. In essence, conservation of sites with low variability in productivity or energy can help reduce uncertainty in achieving long-term conservation goals. The immense size and remoteness of Canada's boreal forest provides a unique conservation opportunity and unprecedented flexibility in potential reserve designs. Therefore, given the current and anticipated dynamism of Canada's boreal forest (Price et al., 2013), it seems sensible that boreal conservation planning aim to reduce uncertainties associated with change impacts if possible.

It is becoming clear in the literature that reserves do not remain static through time, and that their environmental conditions will likely undergo changes (e.g., Dockerty et al., 2003; Lovejoy and Hannah, 2005; Gaston et al., 2006; Araújo et al., 2004; Lemieux et al., 2011a), ultimately resulting in altered vegetation composition or density. This is particularly important for the relatively intact boreal forest, since it still experiences an active natural disturbance regime such as large-area stand replacing wildfire and insect outbreaks (Price et al. 2013). However, determining the timing, location and manner in which boreal reserve conditions will be impacted by anticipated climate variability and changing disturbance regimes is not straight forward (Lemieux et al., 2011b) and remains, in general, a major challenge for systematic conservation planning (Margules and Pressey, 2000; Scott et al., 2001; Gaston et al., 2002, Carvalho et al., 2011). Nonetheless, steps can be taken to evaluate the effectiveness of candidate reserves and identify current shortfalls and possible future vulnerability; thereby enabling better informed conservation planning (e.g., Leroux et al., 2007; Rayfield et al., 2008).

A key advantage of evaluating reserves using remotely derived data like vegetation productivity is that it addresses a major limitation in evaluating the effectiveness (e.g., changing condition) of reserves by enabling objective and consistent assessments across sites and through time. Vegetation metrics like DHI and NDVI from long time-series earth observation datasets can be used to assess how well reserves maintain conservation targets under current and past conditions. As such, this approach could be useful for developing more robust long-term conservation targets by, for example, highlighting potential uncertainty in reserve designs associated with change impacts and testing potential mitigation strategies before implementation.

5. Conclusion

In this paper we presented and assessed a remote sensing approach for evaluating the efficacy of candidate reserves in boreal ecosystems. Specifically, we used a long-term AVHRR data record to evaluate reserve inter-annual variability in the dynamic habitat index (DHI), which is closely linked to habitat and forage conditions. Understanding how reserve design characteristics influence the dynamics of vegetation variability across different geographic areas and through time can provide important information for decision makers and conservation planners when developing robust long-term

conservation targets. Although preferentially prioritizing sites with stable vegetation and predictable environments does not guarantee a better conservation investment, it does represent a less risky one. Here we gauged reserve efficacy by how well initial DHI conditions (2000-2005 baseline) of various reserve sizes stratified by ecozone, productivity, and land cover were maintained through time. Reserves that consistently deviate (± 3 STD) from the DHI baseline means over the 21 year period likely experienced highly variable habitat and food supply, which can impact the species distribution and abundance within the reserves. Overall, we found that there were many differences in DHI variability between the three stratifications (ecozone, productivity, and land cover) and three reserve sizes (small, medium, large), with largest DHI variability occurring in small reserves ($<1000 \text{ km}^2$). The approach presented provides an objective and consistent means of evaluating reserves over large areas, which could be useful for aiding conservation planning at regional and national scales and/or testing potential mitigation strategies prior to implementation.

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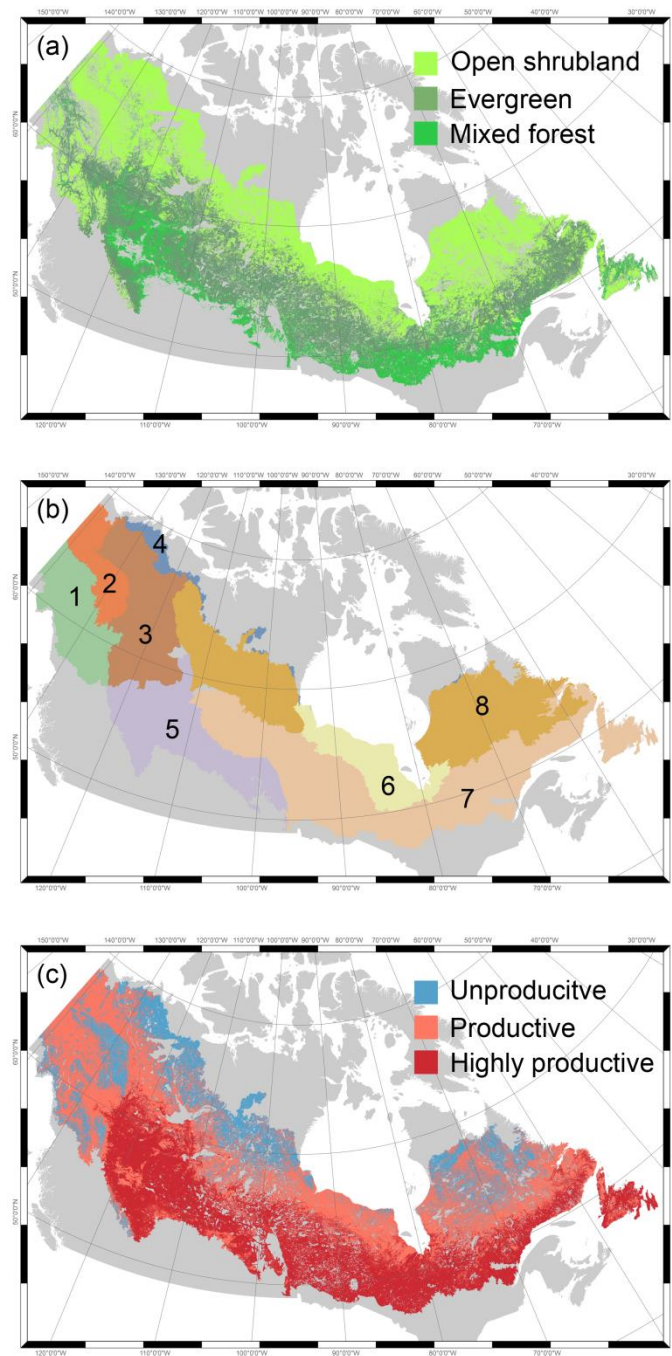


Fig 1. Map of (a) MODIS UMD land cover classes with open shrubland in yellow green, evergreen needleleaf in dark green, and mixed forest in lime green; (b) ecoregions, numbered as 1. Boreal Cordillera, 2. Taiga Cordillera, 3. Taiga Plains, 4. Southern Arctic, 5. Boreal Plains, 6. Hudson Plains, 7. Boreal Shield, and 8. Taiga Shield; (c) relative MODIS GPP productivity classes with low productivity (≤ 3000 $\text{kgC m}^{-2} \text{yr}^{-1}$) in blue, productive (>3000 $\text{kgC m}^{-2} \text{yr}^{-1}$; ≤ 7000 $\text{kgC m}^{-2} \text{yr}^{-1}$) in pink, and highly productive (>7000 $\text{kgC m}^{-2} \text{yr}^{-1}$) in red.

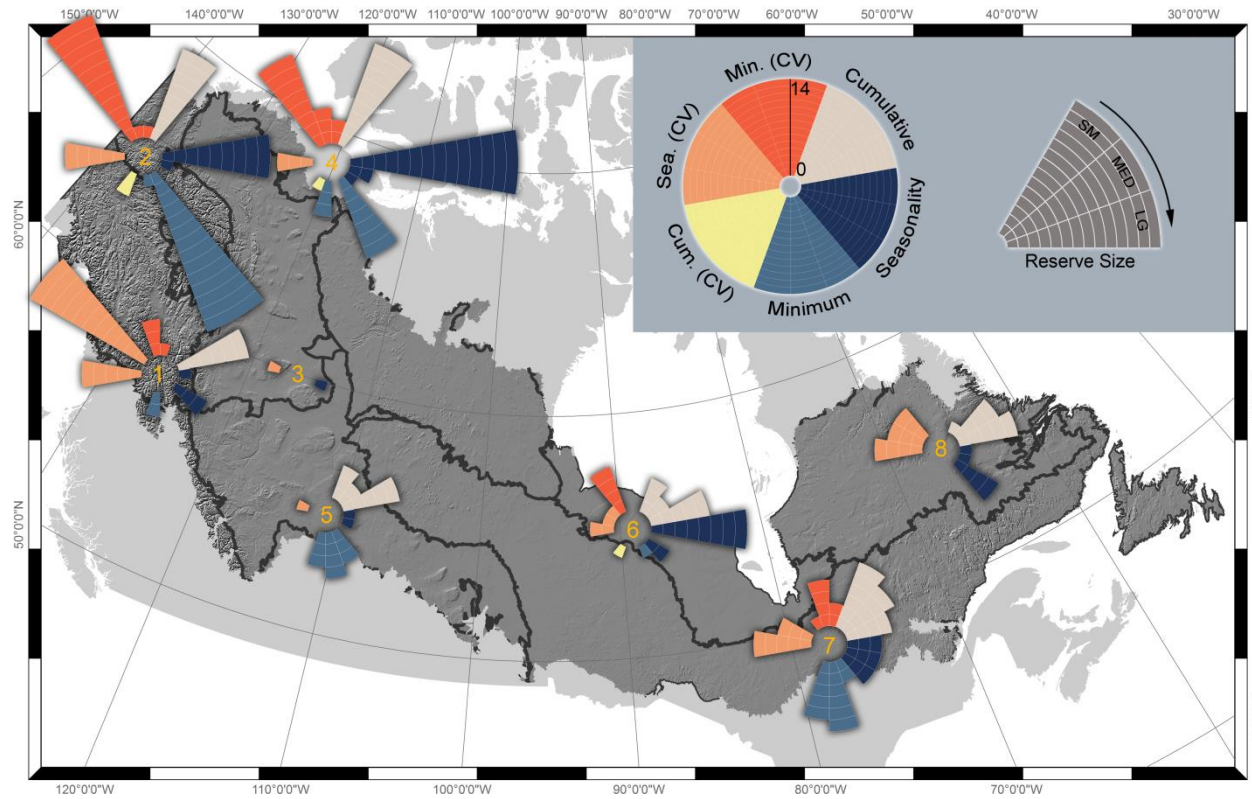


Fig. 2. Reserve size (small, medium and large) score of the occurrence of major deviations (± 3 STD) from the ecozone baseline means for the six dynamic habitat metrics for the years 1987-2007. Numbered ecozones are 1. Boreal Cordillera, 2. Taiga Cordillera, 3. Taiga Plains, 4. Southern Arctic, 5. Boreal Plains, 6. Hudson Plains, 7. Boreal Shield, and 8. Taiga Shield.

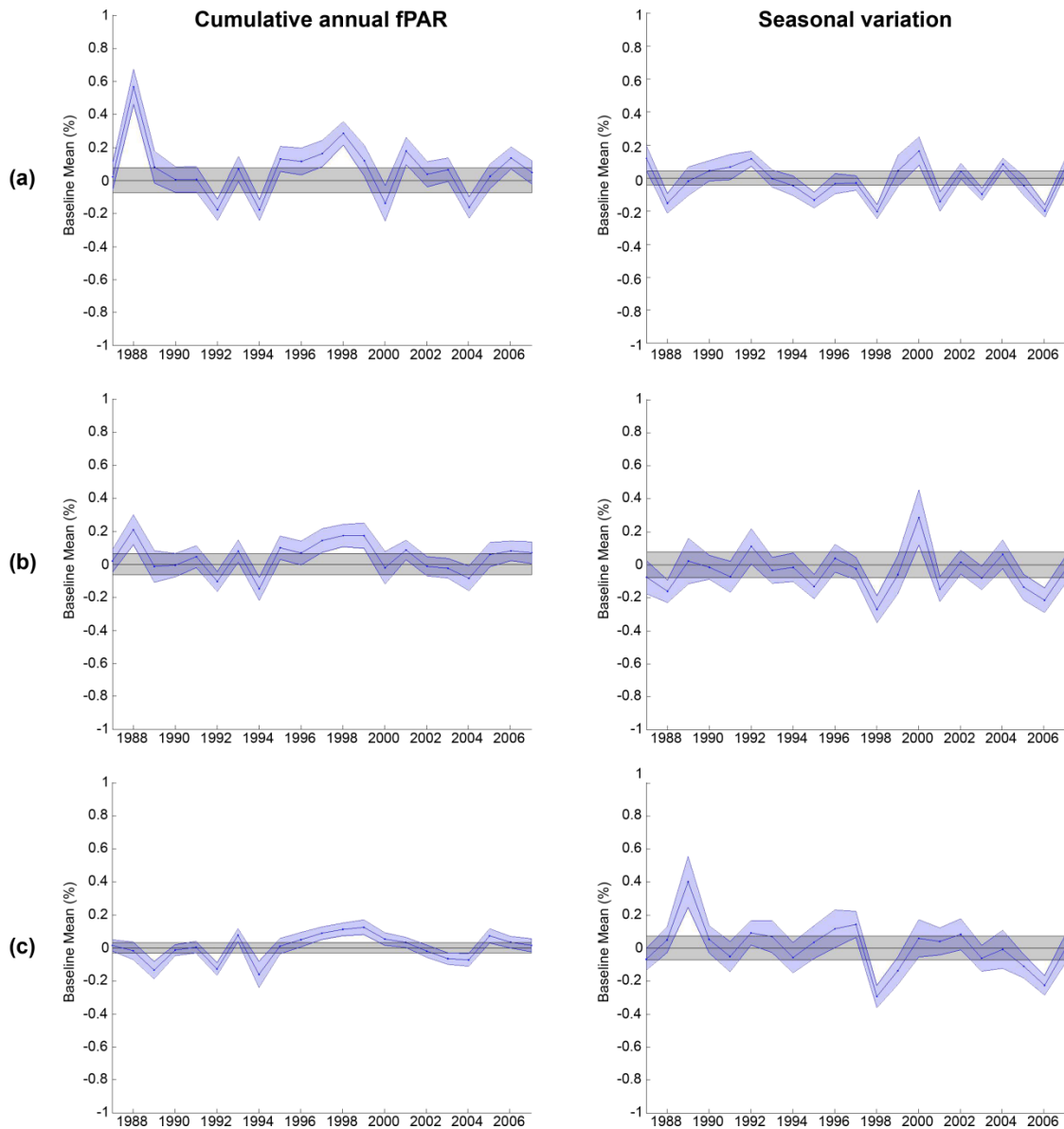


Fig. 3. Comparison of 1987 to 2007 mean AVHRR cumulative annual fPAR and seasonal variation to baseline means of small reserves (<1000 km²) at (a) low productivity (≤ 3000 kgC m⁻² yr⁻¹), (b) productive (>3000 kgC m⁻² yr⁻¹; ≤ 7000 kgC m⁻² yr⁻¹) and (c) highly productive (>7000 kgC m⁻² yr⁻¹) sites. The shaded area shows the ± 3 standard deviation for the AVHRR DHI components (blue) and baseline (grey).

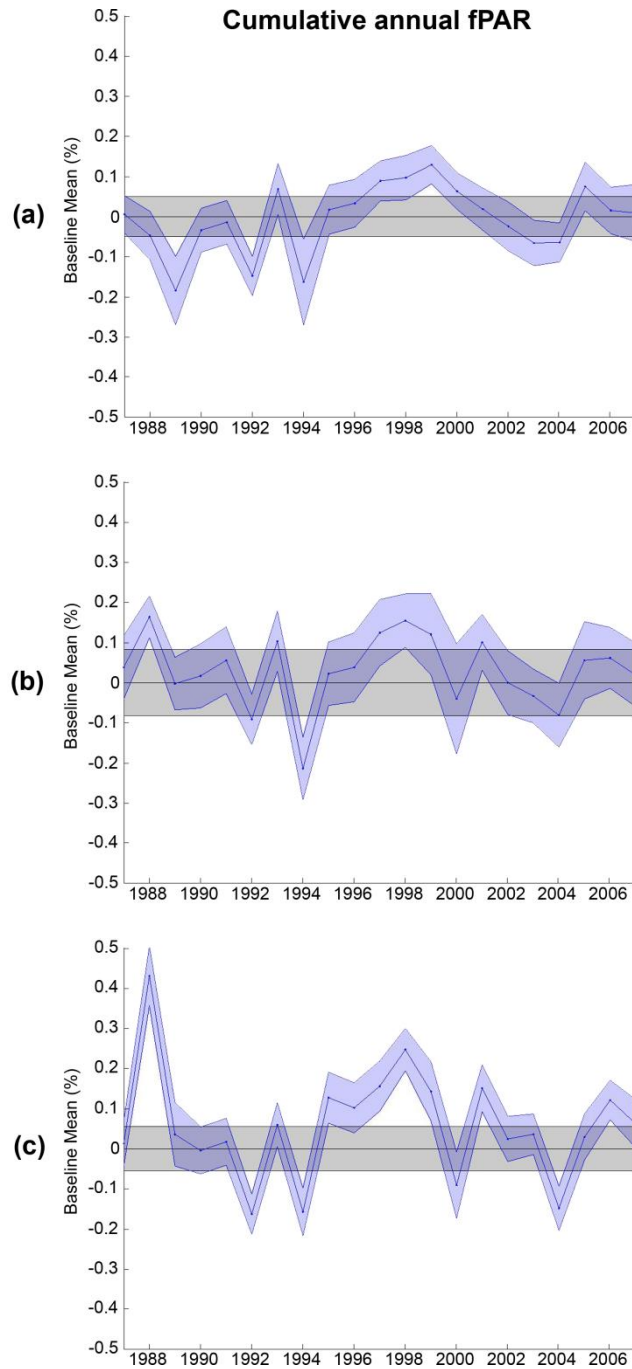


Fig. 4. Comparison of 1987 to 2007 mean AVHRR cumulative annual fPAR to baseline land cover means of small reserves (<1000 km²) at (a) mixed forest, (b) evergreen needleleaf and (c) open shrubland sites. The shaded area shows the ± 3 standard deviation for the AVHRR DHI component (blue) and baseline (grey).

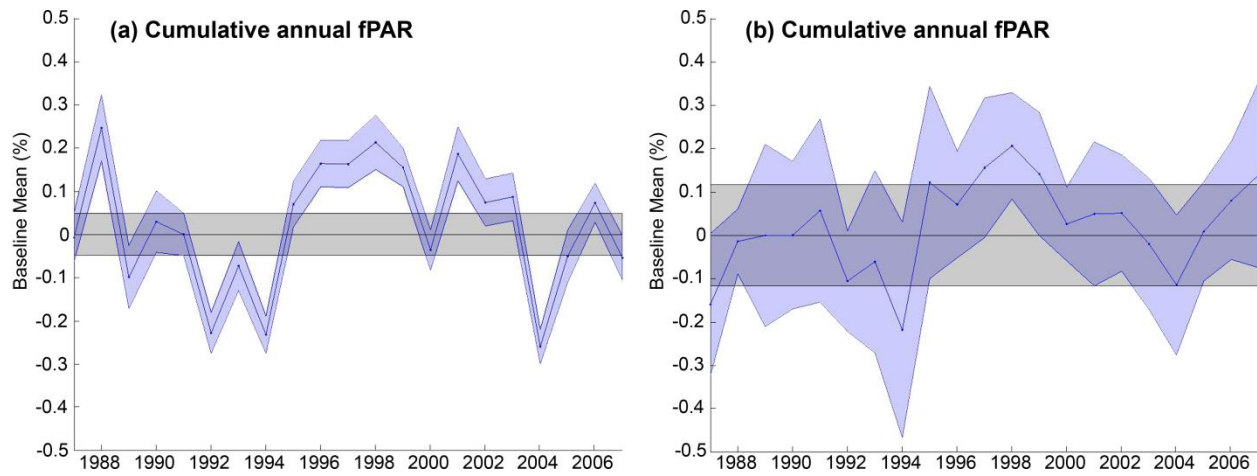


Fig. 5. Comparison of 1987 to 2007 mean AVHRR cumulative annual fPAR to baseline South Arctic ecozone means of (a) small reserves (<math><1000 \text{ km}^2</math>), and (b) large reserves (> 4,000 km^2 ; $\leq 10,000 \text{ km}^2$). The shaded area shows the ± 3 standard deviation for the AVHRR DHI component (blue) and baseline (grey).

Table 1: Strata and data sources for the stratification of the Canadian boreal

Strata	Dataset	Reference
Land cover	MODIS MOD12Q1 1 km land cover product	Friedl et al., 2010; LP DAAC, 2010
Ecological Units	Canadian Ecozones	Ecological Stratification Working Group, 1995
Productivity	MODIS MOD17A3 1 km product	Zhao and Running, 2010; LP DAAC, 2011

Table 2: Number of years that DHI metrics significantly differ (± 3 STD) from the ecozone baseline over a 21 year period. Larger values indicate higher temporal variability.

Ecozone	Reserve Size	Cumulative	Seasonality	Minimum	Cum. (CV)	Sea. (CV)	Min. (CV)
Boreal Cordillera (1)	Small	0	1	0	0	5	0
	Medium	0	0	0	0	0	3
	Large	6	3	2	0	11	1
Taiga Cordillera (2)	Small	8	9	14	2	5	11
	Medium	0	1	1	0	0	1
	Large	0	0	0	0	0	1
Taiga Plains (3)	Small	0	0	0	0	0	0
	Medium	0	1	0	0	1	0
	Large	0	0	0	0	0	0
Southern Arctic (4)	Small	9	14	7	1	3	8
	Medium	0	2	0	0	0	3
	Large	0	1	3	0	0	2
Boreal Plains (5)	Small	3	1	3	0	0	0
	Medium	2	1	4	0	1	0
	Large	5	0	3	0	0	0
Hudson Plains (6)	Small	0	8	1	1	2	4
	Medium	0	0	0	0	1	0
	Large	0	2	0	0	1	0
Boreal Shield (7)	Small	6	3	2	0	5	1
	Medium	5	3	6	0	3	4
	Large	4	3	5	0	0	2
Taiga Shield (8)	Small	1	1	0	0	4	0
	Medium	4	1	0	0	3	0
	Large	5	4	0	0	3	0

Table 3: Number of years that DHI metrics significantly differ (± 3 STD) from the productivity strata baseline

Productivity Strata	Reserve Size	Cumulative	Seasonality	Minimum	Cum. (CV)	Sea. (CV)	Min. (CV)
Low Productive	Small	7	9	4	0	2	4
	Medium	3	6	2	0	0	1
	Large	5	6	1	0	0	1
Productive	Small	5	4	2	1	0	3
	Medium	5	5	4	0	0	4
	Large	4	2	3	0	0	4
Highly Productive	Small	8	3	6	0	4	1
	Medium	10	7	10	2	0	9
	Large	10	3	9	0	0	3

Table 4: Number of years that DHI metrics significantly differ (± 3 STD) from the land cover strata baseline

Land Cover Strata	Reserve Size	Cumulative	Seasonality	Minimum	Cum. (CV)	Sea. (CV)	Min. (CV)
Mixed Forest	Small	4	1	2	0	2	0
	Medium	6	4	4	0	0	0
	Large	9	5	7	0	0	2
Evergreen Needle-leaf	Small	3	1	3	0	0	4
	Medium	6	2	6	1	0	5
	Large	3	1	1	0	0	0
Open Shrubland	Small	10	9	6	1	2	5
	Medium	2	5	1	1	0	1
	Large	5	2	1	0	0	1

Appendix A

Table A1: Descriptive statistics of cumulative annual fPAR for each reserve size (small, medium, large), land cover, productivity and ecozone.

	Small			Medium			Large		
	N	Mean	Std.	N	Mean	Std.	N	Mean	Std.
Mixed Forest	28	9380	802	26	10277	767	24	10312	820
Evergreen Needleleaf	42	8281	721	63	8721	756	35	8700	748
Open Shrubland	154	5437	709	70	6503	576	55	6646	648
Low Productivity	117	4991	783	31	5525	593	29	6015	684
Productive	72	7052	629	64	7471	629	37	7324	665
Highly Productive	54	9446	745	83	9701	735	55	9825	774
Boreal Shield	48	9217	795	50	9272	746	23	9455	789
Boreal Plains	17	9018	803	24	9567	791	16	9509	769
Hudson Plains	28	5834	728	11	7839	884	9	7232	830
Taiga Shield	21	6060	801	25	5965	688	24	6242	756
Taiga Plains	12	6188	643	15	6622	609	10	7624	615
Southern Arctic	43	5524	792	12	6278	759	14	6377	676
Boreal Cordillera	16	5233	919	11	6480	923	9	6089	1229
Taiga Cordillera	16	7078	804	14	6964	745	12	7146	848

Table A2: Descriptive statistics of DHI seasonality for each reserve size (small, medium, large), land cover, productivity and ecozone.

	Small			Medium			Large		
	N	Mean	Std.	N	Mean	Std.	N	Mean	Std.
Mixed Forest	28	321	53	26	299	44	24	306	45
Evergreen Needleleaf	42	378	58	63	342	45	35	338	48
Open Shrubland	154	651	71	70	543	67	55	551	64
Low Productivity	117	698	76	31	653	79	29	642	70
Productive	72	489	61	64	453	50	37	449	59
Highly Productive	54	305	43	83	302	40	55	306	39
Boreal Shield	48	322	55	50	328	51	23	332	49
Boreal Plains	17	330	34	24	301	33	16	305	32
Hudson Plains	28	538	101	11	416	98	9	405	96
Taiga Shield	21	540	99	25	584	95	24	579	85
Taiga Plains	12	454	75	15	450	57	10	401	52
Southern Arctic	43	684	93	12	647	74	14	622	62
Boreal Cordillera	16	671	113	11	583	109	9	664	134
Taiga Cordillera	16	598	87	14	540	75	12	555	94

Table A3: Descriptive statistics of DHI minimum for each reserve size (small, medium, large), land cover, productivity and ecozone.

	Small			Medium			Large		
	N	Mean	Std.	N	Mean	Std.	N	Mean	Std.
Mixed Forest	28	201	48	26	235	51	24	232	54
Evergreen Needleleaf	42	157	37	63	177	46	35	189	42
Open Shrubland	154	17	12	70	48	17	55	38	18
Low Productivity	117	11	11	31	10	7	29	10	7
Productive	72	73	23	64	87	26	37	82	30
Highly Productive	54	212	48	83	224	49	55	226	49
Boreal Shield	48	192	49	50	191	52	23	194	51
Boreal Plains	17	197	42	24	230	41	16	238	39
Hudson Plains	28	33	24	11	93	54	9	88	58
Taiga Shield	21	38	22	25	26	16	24	21	14
Taiga Plains	12	58	23	15	79	24	10	92	34
Southern Arctic	43	2	1	12	4	5	14	6	8
Boreal Cordillera	16	43	23	11	58	24	9	39	22
Taiga Cordillera	16	16	24	14	35	26	12	40	31

Table A4: Descriptive statistics of cumulative annual fPAR (CV) for each reserve size (small, medium, large), land cover, productivity and ecozone.

	Small			Medium			Large		
	N	Mean	Std.	N	Mean	Std.	N	Mean	Std.
Mixed Forest	28	1360	100	26	1182	84	24	1126	88
Evergreen Needleleaf	42	1268	101	63	1408	131	35	1525	127
Open Shrubland	154	1061	84	70	1275	93	55	1322	100
Low Productivity	117	1042	81	31	1166	97	29	1189	102
Productive	72	1273	108	64	1411	113	37	1427	111
Highly Productive	54	1187	77	83	1312	94	55	1364	100
Boreal Shield	48	1184	79	50	1267	99	23	1248	93
Boreal Plains	17	1332	109	24	1423	102	16	1569	108
Hudson Plains	28	1104	130	11	1547	157	9	1338	143
Taiga Shield	21	975	106	25	1042	90	24	1012	95
Taiga Plains	12	1217	127	15	1187	112	10	1420	123
Southern Arctic	43	625	75	12	811	101	14	1151	106
Boreal Cordillera	16	1536	131	11	1879	183	9	2045	228
Taiga Cordillera	16	1117	146	14	1635	172	12	1822	190

Table A5. Descriptive statistics of DHI seasonality (CV) for each reserve size (small, medium, large), land cover, productivity and ecozone.

	Small			Medium			Large		
	N	Mean	Std.	N	Mean	Std.	N	Mean	Std.
Mixed Forest	28	50	15	26	49	6	24	51	6
Evergreen Needleleaf	42	69	14	63	72	16	35	78	25
Open Shrubland	154	78	17	70	84	17	55	85	17
Low Productivity	117	83	19	31	93	22	29	88	21
Productive	72	74	13	64	87	18	37	87	24
Highly Productive	54	46	9	83	55	6	55	63	7
Boreal Shield	48	46	11	50	52	8	23	58	9
Boreal Plains	17	56	9	24	62	9	16	75	11
Hudson Plains	28	43	16	11	58	15	9	56	13
Taiga Shield	21	56	15	25	69	19	24	65	14
Taiga Plains	12	62	15	15	77	19	10	63	9
Southern Arctic	43	52	9	12	65	13	14	68	10
Boreal Cordillera	16	127	65	11	169	78	9	200	106
Taiga Cordillera	16	59	15	14	102	18	12	121	24

Table A6. Descriptive statistics of DHI minimum (CV) for each reserve size (small, medium, large), land cover, productivity and ecozone.

	Small			Medium			Large		
	N	Mean	Std.	N	Mean	Std.	N	Mean	Std.
Mixed Forest	28	72	13	26	57	7	24	55	8
Evergreen Needleleaf	42	52	10	63	59	11	35	62	9
Open Shrubland	154	13	7	70	27	7	55	26	7
Low Productivity	117	9	7	31	11	5	29	11	5
Productive	72	35	9	64	43	9	37	40	10
Highly Productive	54	62	11	83	60	9	55	63	10
Boreal Shield	48	64	12	50	54	9	23	56	10
Boreal Plains	17	51	11	24	58	9	16	66	9
Hudson Plains	28	12	9	11	37	19	9	32	17
Taiga Shield	21	17	7	25	14	6	24	13	6
Taiga Plains	12	24	9	15	32	8	10	36	11
Southern Arctic	43	1	1	12	4	6	14	6	8
Boreal Cordillera	16	27	11	11	50	13	9	49	15
Taiga Cordillera	16	14	19	14	35	18	12	40	19

Table A7. Summary of p values from one-way ANOVA of inter-annual DHI differences (% of baseline mean squared) for each strata based on reserve size (small, medium and large). * Significant at the 0.05 level; ** Significant at the 0.01 level; n.s. – not significant).

	Cumulative	Seasonality	Minimum	Cum. (CV)	Sea. (CV)	Min. (CV)
Boreal Cordillera	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Taiga Cordillera	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Taiga Plains	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Southern Arctic	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Boreal Plains	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Boreal Shield	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Hudson Plains	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Taiga Shield	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Open Shrublands	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Evergreen Needleleaf Forest	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Mixed Forest	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Low Productive	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Productive	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Highly Productive	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.