Protected areas in boreal Canada: a baseline and considerations for the continued development of a representative and effective reserve network[1]

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Abstract: Boreal forests maintain regionally important biodiversity and globally important ecosystem services, such as carbon storage and freshwater resources. Many boreal systems have limited anthropogenic disturbances and are preserved, in effect, to date largely by their harsh climates and remoteness. As of 2011, almost 10% of Canada is subject to some manner of formal protection, with 4.5% of this protected area found within the boreal zone. The management of existing parks and protected areas (PPAs) is shared amongst many federal, provincial, and territorial jurisdictions. Although there are currently low levels of anthropogenic development in some portions of the boreal zone (especially the north), if expansion of protected areas is of interest, there are challenges to traditional PPA networks that may be more prominent in the boreal zone than elsewhere: (1) the boreal zone is home to charismatic mammal species with area requirements much larger than typical PPAs; (2) the boreal zone is characterized by natural disturbance regimes that impact large areas; and (3) projected changes to climate for the boreal zone are among the greatest in the world, creating temporal considerations for conservation planning exercises. There is currently no PPA assessment specific to boreal Canada. To address this lack of an assessment, we developed a conservation gap analysis of the current PPA system with respect to a variety of environmental surrogates (ecozones, land cover, vegetation productivity, and landscape structure). The amount of formally protected land varied within each surrogate, with few commonly reported features meeting national or international conservation targets. Furthermore, few reserves met the areal requirements that have been previously recommended to protect large mammals or accommodate the disturbance regimes present. We also discuss considerations and implications of area-based versus value-based protection objectives. While recognizing that there are still scientific challenges around understanding and evaluating the effectiveness of PPAs, based upon our review and assessment, the following considerations should inform conservation options for the boreal zone: (1) representation of the distribution of natural features within the PPA network; (2) effective maintenance of habitat requirements and spatial resilience to both cyclical and directional changes in spatial patterns through large, connected reserves; and (3) implementation of sustainable forest management practices (where applicable) throughout the broader landscape, as traditional on-reserve protection is unlikely to be sufficient to meet conservation goals. The Canadian boreal is unique in possessing large tracts of inaccessible forested lands that are not subject to management interventions, thereby offering functions similar to protected lands. The question of how to more formally integrate these lands into the existing PPA network requires further consideration. Further, the important temporal role of landscape dynamics in designing an effective PPA needs to be further studied as well as development of a better understanding of design needs in the context of a changing climate.

Key words: climate change, gap analysis, remote sensing, landscape dynamics, prioritization, representation, wilderness.

Résumé : La forêt boréale maintient une importante biodiversité à l'échelle régionale et d'importants services écosystémiques à l'échelle globale, tels que le stockage du carbone et les ressources en eau douce. Plusieurs systèmes boréaux subissent des perturbations anthropiques limitées et sont dans les faits conservés jusqu'à maintenant par leurs climats rigoureux et leur éloignement. Depuis 2011, presque 10 % du Canada se voit, de diverses façons, soumis à une protection formelle; on retrouve 4.5 % de ces surfaces protégées dans la zone boréale. L'aménagement des parcs existants et des aires protégées (PAPs) se partage entre plusieurs juridictions fédérales, provinciales et territoriales. Il se peut que l'expansion des aires protégées soit un objectif souhaitable malgré de faibles niveaux actuels de développement anthropique dans certaines portions de la zone boréale (spécialement au nord). Cependant, il existe des défis pour les réseaux traditionnels de PAP qui pourraient s'avérés plus proéminents dans cette région qu'ailleurs, notamment : (1) dans la zone boréale vivent des espèces de mammifères charismatiques requérant des besoins beaucoup plus vastes en superficies que le sont les PAPs typiques; (2) la zone boréale se caractérise par des régimes de perturbation affectant de vastes superficies; et (3) les changements climatiques attendus pour la zone boréale se situent parmi les plus importants au monde, impliquant des considération temporelles dans les exercices de planification de la conservation. Il n'y a présentement aucune évaluation des PAPs spécifiques pour le Canada boréal. Pour faire face à ce manque

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d'évaluation, les auteurs ont développé une analyse des lacunes dans la conservation du système des PAPs actuel en relation avec des substituts (écozones, couverture des terres, productivité végétale et structure du paysage). La quantité de terres formellement protégées varie selon chaque substitut, avec peu de caractéristiques communes rencontrant les cibles nationales ou internationales de conservation. De plus, peu de réserves rencontrent les besoins en surfaces généralement recommandées pour protéger les grands mammifères ou accommoder les régimes de perturbations actuels. Les auteurs discutent également des considérations et des implications d'objectifs de protection basés sur les surfaces versus basés sur les valeurs. Tout en reconnaissant qu'il existe toujours des défis scientifiques au sujet de la compréhension et de l'évaluation de l'efficacité des PAPs, sur la base de cette revue et son évaluation, on soumet que les considérations suivantes devraient informer le développement des options de conservation dans; la zone boréale : (1) représentation de la distribution des caractéristiques naturelles dans le réseau des PAPs; (2) maintient effectif des besoins en habitats et résilience spatiale aux changements à la fois cycliques et directionnels dans les patrons spatiaux, par le maintien de vastes réserves interconnectées; et (3) mise en place de pratiques d'aménagement forestier durable (lorsqu'applicables) sur l'ensemble de paysages plus vastes, puisque la protection traditionnelle sur réserve ne suffira probablement pas pour rencontrer les objectifs de conservation. La forêt boréale canadienne est unique en ce qu'elle possède de grandes étendues de terrains forestiers inaccessibles n'étant pas soumises aux interventions d'aménagement, offrant conséquemment des fonctions similaires à celles de terres protégées. La connaissance plus formelle sur la façon d'intégrer ces terres dans le réseau PAP existant nécessite d'autres considérations. De plus, le rôle temporel important des dynamiques du paysage dans la conception de PAPs efficaces doit être davantage étudié, et une meilleure compréhension des besoins conceptuels doit être développée dans un contexte de changement climatique. [Traduit par la Rédaction]

Mots-clés : changement climatique, analyse des lacunes, télédétection, dynamique des paysages, priorisation, représentation, nature sauvage.

1. Introduction

Anthropogenic activities have caused unprecedented global changes (Cardille and Lambois 2010; Nelson et al. 2006), compromising the ability of many ecological systems to maintain biodiversity and provide ecosystem services (Ellis and Ramankutty 2008). Historically, habitat modification and over-exploitation of natural resources have been the primary drivers of the loss of biodiversity (Wilcove et al. 1998) and ecosystem services (Hassan et al. 2005). Parks and protected areas (PPAs) are an important conservation mechanism that specifically responds to these threats. Parks and protected areas strive to maintain functioning ecosystems with their complement of native species by restricting human uses within their boundaries (Wiersma and Nudds 2009).

Boreal forests (Brandt et al. 2013) contain globally important biodiversity (Venier et al., Manuscript in preparation) but are less species-rich and historically less threatened than many systems in the conservation spotlight (Bradshaw et al. 2009). Perhaps as a result, boreal forests have received relatively little conservation attention to date and are under-represented in the global PPA system (Mittermeier et al. 2003; Schmitt et al. 2009). However, increased risk to boreal species and ecosystems is anticipated, as a result of species traits of boreal organisms, such as large size and late onset of sexual maturity, that make them especially vulnerable to disturbance (Cardillo et al. 2006) and of geographic patterns of global warming (Lee and Jetz 2008; Kujala et al. 2011). Further, although relatively poor in biodiversity, boreal systems provide a wealth of important ecosystem goods and services, such as carbon storage, clean water, and fibre products (Anielski and Wilson 2009; Kurz et al. 2013).

In this paper, we review PPA system research in Canada, with an emphasis on the boreal zone. We first provide an overview of some of the compelling features of the boreal zone, as well as the current organizational framework for conservation in the boreal (section 2). The remainder of the paper is structured by elements presented in the scientific literature that are essential considerations for effective conservation of the boreal zone, structured into three broad, often related, themes: representation, effectiveness, and prioritization of PPA systems (sections 3–5). We evaluate the current PPA system in the context of these needs, supported by a gap analysis of the existing PPA system. This gap analysis is described in detail in Appendix A to support, but not disrupt, the overall goal of this work to review the current knowledge of PPA systems in Canada's boreal zone, the state of the PPA system itself, and needs and options for future opportunities.

2. Background

2.1. Select notable features of the boreal zone

Canada's northern boreal zone is one of the world's last repositories of large expanses of land having minimal anthropogenic disturbances (McCloskey and Spalding 1989; Sanderson et al. 2002; Mittermeier et al. 2003; Potapov et al. 2008). In an evaluation of forested landscape structure, Cardille et al. (2012) found that the characteristic landscapes most typical of Canada's boreal zone are notable for their general low level of conspicuous human activity, which is much more pervasive elsewhere in North America (Cardille and Lambois 2010) and globally (Ellis and Ramankutty 2008). In that evaluation, anthropogenic signatures on landscape structure were only relatively prominent in a few characteristic landscapes of southern boreal ecozones (Cardille et al. 2012). Wilderness, defined alternatively as an area that "exists in a natural state" (Canada National Parks Act 2000) or, more measurably, as a large area without anthropogenic infrastructure or industrial human activities (e.g., Andrew et al. 2012), is a globally scarce resource. Given its remoteness and harsh climate, many parts of Canada's boreal zone qualify as wilderness by these definitions (Andrew et al. 2012). Boreal wilderness is of local, regional, and global importance because it provides the large, unaffected areas necessary to maintain natural systems, ecological processes, and essential ecosystem services. For example, Canada supports some of the few large mammal migrations that remain worldwide (such as *Rangifer tarandus*) (Harris et al. 2009). Costs for acquiring land and offsetting existing land uses can often pose barriers to the designation of protected areas. Locations that have fewer competing interests to address, such as these northern boreal regions, can be cost-effective for protection. (Mittermeier et al. 2003; Andrew et al. 2012).

In addition to its widespread wilderness character, Canada's boreal zone provides exceptional freshwater resources (Webster et al., Manuscript in preparation). Water is a conspicuous part of the boreal zone: wetlands and open water, such as lakes and rivers, cover 12.4% (estimated from the Earth Observation for Sustainable Development of Forests (EOSD) land-cover classification, Wulder et al. 2008*a*) and 12.2% (estimated from the Canada-wide 1-km Water Fraction dataset, Fernandes et al. 2001) of the boreal zone, respectively. There are more than 600 000 lakes in the boreal ecozones; this represents 66% of Canada's lakes and 70% of the total lake area (Minns et al. 2008). Many boreal ecosystems are recognized to be important providers of water-related ecosystem services (Anielski and Wilson 2009). Canada has the 3rd highest

freshwater supply in the world; 55% of this runoff is generated in boreal drainage regions, which is proportionate to area (Statistics Canada 2010). Despite their abundance, these water resources are fragile and under threat from pollution, climate change, invasive species, and changes in land use (Schindler 2001; Croke and Hairsine 2006; Monteith et al. 2006; Kreutzweiser et al. 2008, 2013; Schindler and Lee 2010; Webster et al., Manuscript in preparation; Langor et al., Manuscript in preparation).

2.2. The protected area mosaic in the boreal zone

Legislative authority for protected areas and conservation is shared under the Constitution of Canada, which proclaims resource stewardship responsibilities a provincial jurisdictional matter. There are at least 75 pieces of legislation over various levels of government that relate to protected areas (Parks Canada 2004) and regulations, policies, and goals differ amongst PPAs of different jurisdictions. In the database we compiled of protected areas in Canada's boreal zone (Appendix A), there were 74 types of PPAs, spread among 38 federal and provincial management agencies. We reviewed the conservation goals and management actions of these park types to aggregate them into 16 generic PPA types (Table 1). Because of this diversity of PPAs, researchers typically use the categorization system developed by the International Union for the Conservation of Nature (IUCN; Dudley 2008) to describe variation in park management goals (Malcolm 2009). This system was developed specifically to harmonize the plethora of PPA types and agencies worldwide. All PPAs recognized by the IUCN must have the primary goal of nature conservation (Dudley 2008). IUCN categories I–IV refer to strict protected areas that restrict industrial activities. These are joined by categories V and VI, which are more permissive, "anthropogenic" PPAs that allow certain types of sustainable resource use. The International Union for the Conservation of Nature categories map out fairly cleanly between park types in the boreal zone (Table 1). However, IUCN categories are now assigned by the park management agencies; interpretations differ between nations (Chape 2004).

The number of management authorities involved in Canadian PPAs continues to expand as indigenous interests are increasingly considered during the establishment and management of PPAs (Environment Canada 2006; Dearden and Langdon 2009). For instance, many of the PPAs in the Yukon Territory were established in consultation with First Nations groups and are jointly managed by the Department of Environment and the relevant First Nations. The Gwich'in First Nation manages a number of PPAs in the Northwest Territories. In addition, traditional use rights are granted in many PPAs throughout the boreal zone and the preservation of aboriginal cultural heritage is often considered as a parallel conservation goal to environmental objectives.

Based upon the large areas and complex interactions, it is difficult to assess the impact of Canada's current approach to conservation. In theory, a range of protected area mechanisms can enhance PPA systems if they target different features and result in greater levels of protection and more even representation of biodiversity. For example, National Wildlife Refuges make substantial contributions to the United States' portfolio of protected areas because they tend to be located in productive, low-elevation environments that are often under-represented in other protected area types (Scott et al. 2004). In a portion of boreal Canada, Leroux et al. (2007a) found that sites identified as indigenous heritage priorities reflect a subset of the areas needed to meet biodiversity objectives. Thus, they may contribute to a comprehensive, regional PPA network but will need to be considered in conjunction with environmental objectives.

The capacity of different PPA types to complement each other and achieve overall regional conservation goals may be reduced by divergent objectives and management actions. To some degree, this seems likely. Wildlife reserves may be often designated to protect specific taxa (e.g., a particular endangered species or migratory waterfowl), whose requirements may pose potential conflicts with those of other biodiversity features. Provincial parks may place a strong emphasis on protection to provide outdoor recreation opportunities. Such conflicts between management goals and the broader needs of biodiversity are an especial concern for the implementation of PPAs to protect ecosystem services (e.g., Bullock et al. 2011).

The majority of the area protected in Canada's boreal zone corresponds to four classes of PPA. In descending order, provincial parks, national parks, wilderness areas, and wildlife reserves dominate the boreal protected area system, accounting for more than 85% of the total area protected, but just over half of the total number of reserves (Table 1). The concentration of PPA types into four broad categories greatly simplifies the conservation landscape in Canada, suggesting that PPA governance may not be as fragmented as first indicated by the large number of park types and agencies, although the heterogeneity of protection goals among provinces remains. This heterogeneity exists not only for provincial parks, but also for wildlife reserves and wilderness areas in provincial jurisdictions, and is likewise not reflected in the IUCN categories currently assigned to PPAs. Most government agencies managing protected areas in Canada have established the primary goal of completing and maintaining representative PPA networks (Parks Canada 1997; Environment Canada 2006), but management goals and activities prohibited in PPAs vary by jurisdiction. Yet our review of the relevant legislation indicates that it is not straightforward to determine how prohibitions vary, as the specific restricted activities are legislated in some jurisdictions, delineated in general PPA regulations in others, or determined on a park by park basis in regulations or management plans. Some jurisdictions also grant permits to allow activities that are generally restricted in PPAs, including some forms of natural resource extraction. The ultimate effect is that both the extent and the degree of protection may be quite variable regionally.

There are also a variety of other areas in the boreal zone that are subject to some form of protection, including lands that are set aside following forest management best practices. These include non-harvestable areas along streams, on steep slopes, or that are set aside to maintain old growth forests on the landscape, but because of their disjoint locations on the landscape and bias by type, make limited contributions to the conservation of biodiversity (Huggard et al. 2006). Moreover, such sites cannot be relied on for ongoing conservation. Streamside forest practices may change in response to new research, suggesting that forest harvest can supply important disturbance events to riparian forests (Kreutzweiser et al. 2012; Naylor et al. 2012). Additionally, sites that are currently under de facto protection (Andrew et al. 2012) because they lack access or economic motivations for harvest may lose this status as technology, market pressures, and access infrastructure change. Consequently, de facto protected areas are not considered further in this accounting of PPAs in the boreal zone, excepting some consideration in the discussion.

3. Extent of boreal PPAs and representation of natural features

A dominant theme of PPA system research in Canada is representation (Table 2). Representation refers to the extent to which all natural features of a planning region occur within the PPA system, often evaluated against quantitative targets. By natural features, we mean the various biological and physiological elements that are expected within a given region. The basic idea is that if all species, as a sub-set of natural features, are represented within PPAs, this would mean that they should be protected from future risk of extinction or extirpation of ecological values. How-

Table 1. Major types of protected areas (PAs) in the Canadian boreal zone.

Protected area type	Main IUCN classes	No. of PPAs	% PA system (by reserve)	Area (km²)	% PA system (by area)	% boreal zone
Ecological reserves	Ia	85	5.48	5 284	1.17	0.10
Wilderness areas	Ib	48	3.09	76 808	16.95	1.39
National parks	II	16	1.03	117 525	25.94	2.13
Provincial parks	Ib, II	562	36.21	156 718	34.59	2.84
Wildlife reserves	Ib, IV	251	16.17	42 000	9.27	0.76
Waterbird reserves	Ib, IV	117	7.54	5 613	1.24	0.10
Salmon rivers	VI	134	8.63	5 182	1.14	0.09
Aquatic reserves	Unk	3	0.19	4 365	0.96	0.08
Protected waterways	II	32	2.06	10 691	2.36	0.19
Protected watersheds	VI	1	0.06	8	0.00	0.00
Marine protected areas	VI	5	0.32	7 645	1.69	0.14
Freshwater fish special management area	VI	1	0.06	31	0.01	0.00
Aboriginal reserves	Unk	19	1.22	7 157	1.58	0.13
Heritage reserves	Unk	4	0.26	5 735	1.27	0.10
Recreation reserves	II, V	232	14.95	1153	0.25	0.02
Sustainable use areas	VI	42	2.71	7 110	1.57	0.13

Note: The International Union for Conservation of Nature management categories: Ia, strict nature reserves; Ib, wilderness areas; II, national parks; IV, habitat and (or) species management areas; V, protected cultural landscapes; VI, protected sustainable use areas; Unk, designation unknown or unassigned. PPAs, parks and protected areas.

ever, this is a simple assumption and, as discussed later, the degree of effectiveness of PPAs, especially in the face of landscape dynamics and a changing climate, will ultimately determine if PPAs successfully maintain biodiversity. In addition, because natural features are distributed unevenly, the overall extent of PPAs in a broader region is not likely to be a reliable indicator of the degree of representativeness of natural features. For example, there are strong environmental gradients in the boreal zone, indicating that large parks spanning these environmental gradients may be required, depending on the protection objectives (see Wiersma and Nudds 2006a). The principle of representation implies that primarily establishing large protected areas in the relatively unimpacted northern regions of the boreal zone, where such conservation actions may still be relatively feasible, will not contribute to the conservation status of natural features associated with the more productive, more anthropogenically disturbed southern boreal zone. Representation is the simplest evaluation metric of PPA systems and is a common goal for PPA systems in Canada (Parks Canada 1997; Environment Canada 2006) and worldwide (UNEP 2010).

3.1. Representation targets and current PPA extent

At present, 9.9% of Canada's total land area is protected.[2] Further, 8.1% (449 178 km²) of Canada's boreal zone is protected (Fig. 1b). This constitutes 45.2% of the entire PPA system of Canada (55.3% of Canada's terrestrial area falls within the boreal zone). As such, Canada's boreal zone has proportionally less protected area than Canada's overall and less than the global protected land area (12.7%; IUCN and UNEP 2010), but note that standards for inclusion in a given protection category vary internationally (Chape 2004). For the most part, PPAs provide strict protection in boreal Canada: the majority of boreal PPAs by area (>90%; Table 1, IUCN categories I–IV) can be considered strictly protected, with 77% having management goals corresponding to those of wilderness areas (IUCN category Ib) or national and (or) provincial parks (IUCN category II). Canada's PPA system has expanded rapidly in recent years (Dearden and Dempsey 2004; Environment Canada 2009), and growth is ongoing (e.g., 12 000 km² of the boreal zone is under interim protection for future designation following land claim

settlements, and planning is ongoing to consider further additions to the National Park System (Parks Canada 1997)).

With respect to the total area protected, the current level of protection is currently found to be below many quantitative percentage-based protection targets that have been suggested for Canada, either nationally or specific to the boreal zone. Relevant targets include suggestions of protecting 12% of Canada's land area (Hummel 1995; Environment Canada 2006), following the recommendation of the Brundtland Commission that the protected area system of the time be tripled in extent (World Commission on Environment and Development 1987); an international goal to protect 17% of the global terrestrial area (UNEP 2010); and boreal-specific targets of protected areas ranging from 20% (Parliament of Canada 1999; Canadian Boreal Initiative 2003) to 50% (Canadian Boreal Initiative 2005) areal coverage, with sustainable development, including certified forestry practices, consistent with biodiversity protection in much of the remaining land base.

As is evident, there is a divergence in percentage-based areal protection targets. The proposed protection targets are often based on areal percentages of a region or a natural feature and encompass a wide range of percentage values. Svancara et al. (2005) reported that percentage-based goals are often based upon political considerations. From the percentage values for boreal Canada listed earlier in the paper, it is evident that government agencies typically have lower percentage targets than those generated outside of government. Government agencies have land ownership, stewardship, and (or) other management responsibilities and, as a result of the complex tradeoffs associated with protection (e.g., costs, land-use change, exclusion of future development), are therefore likely to set lower areal targets than those with academic interests or conservation advocacy missions. Science-based conservation targets for Canada are heterogeneous (section 5.1), with some studies identifying vast areas required to meet ecological objectives. Although it is not necessary that broad percentage targets established for a given region (e.g., 12% of land area) be maintained at lower levels of the organizational hierarchy (e.g., 12% of each natural feature within the region), for simplicity, targets are generally held constant across features. Where additional data or expert judgment exists to support the careful tailoring of conservation goals, protection targets may be

Table 2. A sample of protected area research in Canada.

Study	Type	Extent	Surrogate	Evaluation criteria and (or) target	PPA set	Algorithm	Design criteria	Special consideration	Conclusions	Relevance to boreal zone
Hummel 1995	R	Canada	Natural regions	Coverage of enduring features	PPAs that exclude extractive use	–	–	–	Only 4% of natural regions considered represented; 56% had little or no representation. Many types of PPAs permit industrial development and were excluded.	General pattern likely to hold true for boreal zone.
Cumming et al. 1996	P	Portion of northern Alberta	Forest type and age	Proportion under protection is similar to proportion in landscape, at least 5% of stands protected	–	Greedy iterative maximization algorithm, randomization algorithm	–	Stable mosaics	There is no representative area of boreal forests suggesting that these landscapes are not in shifting steady state equilibrium. Disjoint projected areas will be required to represent the landscape mosaic but will likely lose representation over time. Floating protected areas may be required to add temporal stability to representation levels.	This study was conducted in a portion of the boreal zone and highlights special considerations that may need addressing for effective conservation in the boreal zone. The dynamic nature of boreal systems may challenge traditional conservation design.
Rivard et al. 2000	E	Canada	Species distributions	Species retention	National parks	–	–	–	Most species losses occur in southern parks, in small parks, and are related not only to park characteristics but to the characteristics of the park surroundings.	Supports conservation matrix model for protection in the boreal zone.
Sarakinos et al. 2001	P	Quebec	Species point records	No. of occurrences (1–50)	–	Iterative algorithm based on rarity and complementarity	Adjacency	–	Biodiversity is not well represented in the current network of PPAs in Quebec. Expanding PPAs just in lands surrounding existing reserves will not meet conservation goals. Based on species observation data, 6.3% of Quebec will need to be protected to cover all species at risk records.	Identifies sites that may be conservation priorities in a portion of the boreal zone. Most priorities identified are in southern Quebec.
Scott et al. 2002	R	Canada	Biomes	% PPAs changing biome type, % change in biome representation	National parks	–	–	Projected biome distribution changes under climate change.	More than half of national parks change biome type under climate change.	Representation of taiga declines; paper recommends new parks be established in this biome to support conservation goals under climate change.
Warman et al. 2004	R, P	Canada	Species distributions	1 occurrence	>1000 ha	C-plan	–	–	Most protected areas do not overlap with identified priorities. 16% of species not represented.	Reports that several gaps remain in boreal zone, but most priorities in southern Canada.

Table 2 (*continued*).

Study	Type	Extent	Surrogate	Evaluation criteria and (or) target	PPA set	Algorithm	Design criteria	Special consideration	Conclusions	Relevance to boreal zone
Wiersma et al. 2004	E	Canada (south of 60 N)	Species distributions	Species retention	National parks	–	–	Habitat loss surrounding parks	Mammal extinctions in Canadian parks best explained by amount of habitat in and around park. Parks with as little as 3140 km² of effective habitat will maintain mammal populations if surrounded by 18000 km² of effective habitat.	Supports conservation matrix model for protection in the boreal zone.
Beazley et al. 2005	P	Nova Scotia	Landscape types, species distributions, special elements, focal species	12% by area of landscape types, occurrence of special elements	–	Expert	Size, roadless, forest age, connectivity	–	Core areas cover 24% of Nova Scotia, additional lands to meet targets and provide connectivity increase conservation needs to ~60%.	Similar considerations may drive conservation needs, planning in boreal zone. Protected area needs are much higher than currently protected area and typical, policy-based representation targets.
Lemieux and Scott 2005	R	Canada	Biomes	% PPAs changing biome type, % change in biome representation	All	–	–	Projected biome distribution changes under climate change	Between 37% and 48% of protected areas may experience biome change under double CO$_2$. The level of biome change varied by jurisdiction and protected area type.	Representation of northern biomes, including boreal forest, will decrease under climate change. Designing PPAs under current conditions will not ensure continued levels of representation.
Deguise and Kerr 2006	R	Canada	Species distributions	Relative to random sets, correlation	IUCN I–III	–	–	–	PPAs do not seem to be targeted to species at risk. Protected area size negatively related to number of species at risk.	General pattern holds true in boreal ecozones, but few species at risk are confined to the boreal zone.
Environment Canada 2006	R	Canada	Ecoregions	12% by area	All	–	–	–	Only 29% of ecoregions meet representation target; 17% have no protection at all.	General pattern likely holds for boreal zone, few boreal ecozones receive >12% protection.
Freemark et al. 2006	P	British Columbia	Species distributions	1 occurrence	–	Maximal location covering optimization	–	–	Conservation priorities remain in BC; most occur in the south. Species of concern required the greatest number of sites for representation performed the best as surrogates of other taxa.	Some sites within northern, boreal portions of BC are required to fully represent biodiversity of amphibians, birds, mammals, and species of concern.
Leroux et al. 2007b	E, P	Portion of northern boreal	Vegetation types, special elements, focal species	Areal representation of vegetation types and caribou habitat	–	MARXAN	Connectivity	Dynamic vegetation distributions due to disturbance	Most forest types receive some level of protection over time, but proportional targets are not generally maintained. Higher representation targets generally perform better at maintaining representation over time.	This study was conducted in a portion of the boreal zone and highlights special considerations that may need addressing for effective conservation in the boreal zone. The dynamic nature of boreal systems may challenge traditional conservation design.

Table 2 (*continued*).

Study	Type	Extent	Surrogate	Evaluation criteria and (or) target	PPA set	Algorithm	Design criteria	Special consideration	Conclusions	Relevance to boreal zone
Leroux et al. 2007*c*	P	Portion of northern boreal	Forest communities	1 occurrence	–	Iterative moving window	Min. size based on disturbance size and size distribution of communities	Dynamic vegetation distributions due to disturbance	Minimum dynamic reserves are an appropriate framework for conservation in relatively intact landscapes influenced by large disturbances.	This study was conducted in a portion of the boreal zone and highlights special considerations that may need addressing for effective conservation in the boreal zone. The dynamic nature of boreal systems may challenge traditional conservation design.
Leroux et al. 2007*a*	P	Portion of northern boreal	Land cover, special elements, focal species	Overlap between biodiversity conservation priorities and indigenous heritage priorities	–	MARXAN	Aggregation	Indigenous priorities	There is some overlap between heritage priorities and biodiversity conservation priorities, but this is only significant under some design criteria. Heritage sites have an aggregated distribution and tend to be associated with water features.	Aboriginal perspectives have increasing prominence in land use planning of northern regions. Protected areas designed for biodiversity and traditional heritage, respectively, will meet some shared criteria but comprehensive protection will require specific planning for both sets of objectives.
Mathey et al. 2008	P	Forest in Ontario	Old growth	12%–70% by area	–	Forest planning economic model	Intensive vs. extensive harvest, clustering of forest uses	Include economic objectives	Intensification of forestry can support greater conservation targets by concentrating industrial activities on the landscape. Clustering of reserves and forest harvest can reduce operating costs.	Integrated land use planning addressing competing activities in addition to conservation will be the most effective way to design protected areas and sustainable use matrices in the boreal zone.
Rayfield et al. 2008	P	Forest management unit in Quebec	Species distribution	10%–12% of study area	–	MARXAN	2 PPAs which can move every 50 years	Maintaining representation over time under fire, forest harvest, and succession dynamics	Different design strategies performed similarly. Dynamic PPAs provided most consistent levels of representation and maintained connectivity better but could be constrained at future time periods by ongoing forest fragmentation.	This study was conducted in a portion of the boreal zone and highlights special considerations that may need addressing for effective conservation in the boreal zone. The dynamic nature of boreal systems may challenge traditional conservation design.
Rayfield et al. 2009	P	Forest management unit in Quebec	Species distributions	12% of landscape	–	Zonation	Connectivity	Species interactions	Incorporating biological understanding such as home range requirements, connectivity for foraging movements, and explicitly defining species interactions improves reserve design over configurations developed from simply overlaying species distributions.	Provides an example of advanced conservation prioritization approaches. However, such an approach will be most valuable for a relatively low number of well understood species of special concern and is unlikely to be supported by data for all species and all areas in the boreal zone.

Table 2 (continued).

Study	Type	Extent	Surrogate	Evaluation criteria and (or) target	PPA set	Algorithm	Design criteria	Special consideration	Conclusions	Relevance to boreal zone
Rose and Burton 2009	R	British Columbia	Biogeoclimatic zone, forest type, rare species	–	–	% of PPAs in which targets maintain distribution	–	Constant habitat through time under climate change	Many existing PPAs do not have temporal connectivity.	Climate change will be a major driver of change in the boreal zone and will alter species distributions and representation levels in boreal protected areas. Individual protected areas are not effective at mitigating against climate change impacts.
Wiersma and Nudds 2006b, 2009	R, P	Temperate and boreal mammal provinces	Species distributions	1 occurrence per mammal province	>2700 km^2	Rarity based heuristic	>2700 km^2	–	By mammal province, 68%–99% of mammal diversity is represented. Existing PPAs are inefficient at representing mammals. Areal needs vary by mammal province.	Indicates that ~18 new PPAs needed in boreal mammal provinces to meet targets. Generic representation targets indicated as inappropriate.
Drever et al. 2010	R	Ontario subregion	Rare forest types	12% by area	All that exclude logging	–	–	–	All rare forest types protected, but not all meet targets. The northern, boreal forest portion of study area had greater protection overall.	Evaluates conservation status of a subset of the boreal zone.
Kharouba and Kerr 2010	R, E	Canada (9 ecozones)	Modeled species distributions	Similarity between historic and present community composition	>43.7 km^2	–	–	Distribution changes due to climate change and land use change	Protected area network generally no better than random areas at retaining species and maintaining community composition. Modeled species richness increased in protected areas over time.	Climate change will be a major driver of change in the boreal zone and will alter species distributions and representation levels in boreal protected areas. Individual protected areas are not effective at mitigating against climate change impacts.
Andrew et al. 2011a	R	Canada (south of 75 N)	Productivity	Bias estimate	All	–	–	Threats	Canada's PPA network is slightly biased to low productivities. PPAs at higher productivities are under greater threats.	These relationships are also generally observed in boreal ecozones.
Lee and Cheng 2011	R	Canada	Ecozones, watersheds	Various % targets	All	–	–	Access	20% of ecozones have >20% of their area protected; 23% of fundamental watersheds meet a 12.5% target.	1 boreal ecozone has >20% protection.

Table 2 (*concluded*).

Study	Type	Extent	Surrogate	Evaluation criteria and (or) target	PPA set	Algorithm	Design criteria	Special consideration	Conclusions	Relevance to boreal zone
Schneider et al. 2011	P	Forested portion of Alberta	Natural regions, vegetation types	15%–40% by area	–	MARXAN	Intactness, contiguity, connectivity along rivers	Opportunity costs of industrial activities	Including opportunity costs in conservation planning can identify reserve networks with similar ecological values but much lower costs than when networks are based on representation alone. Relative little trade-offs between conservation and development are necessary for moderate representation targets. Design features tend to increase costs. Costs are minimized when planning over large extents rather than combining prioritizations from subregions.	Proposes that integrated land use planning addressing competing activities in addition to conservation will be the most effective way to design protected areas and sustainable use matrices in the boreal zone.

Note: R, representation; P, prioritization; E, effectiveness; and PPA, parks and protected areas. The International Union for Conservation of Nature management categories: Ia, strict nature reserves; Ib, wilderness areas; II, national parks; III, natural monuments.

variable, reflecting the different conservation needs of different biodiversity features (Pressey et al. 2003). Generic protection targets have been criticized as inappropriate for ensuring the persistence of mammal species in Canadian PPAs (Wiersma and Nudds 2006b). Ultimately, protection goals reflect both species- and system-specific conservation assessments (Tear et al. 2005) and societal values (Wilhere 2008). As such, the answer to the question "how much protection is enough?", is not simple and remains dependent upon the protection aims, the accompanying characteristics that are sought to be protected (as related in this review), and the ecological requirements that must be met to promote persistence of the natural features of interest.

3.2. Previous PPA assessments with relevance to boreal Canada

To date, there has been no conservation gap analysis of PPA coverage in Canada's boreal zone. A collection of existing national and regional evaluations provides some indication of the status of protection of Canada's boreal species and ecosystems (Table 2). However, these studies are difficult to compare because they have been conducted at different points in time along the development of Canada's PPA system and employ a diversity of targets for representation (as discussed earlier in the paper), definitions of protection (i.e., which set of PPAs are included), and natural features used to evaluate representation (Table 2). In the studies, representation has been variously assessed along taxonomic or environmental surrogates, which are assumed to covary with the spatial distribution of biodiversity (Margules et al. 2002). Taxonomic surrogates are the ranges or occurrence records of well-studied taxa; environmental surrogates are higher order components of biodiversity or environmental variability, such as biome, land cover, biogeoclimatic, or land form classifications.

Despite the inconsistencies among the evaluations of Canada's PPA system (Table 2), studies agree that protection is unevenly distributed in Canada and not all natural features are well represented. Protection is highly variable among Canada's ecozones and ecoregions (Hummel 1995; Environment Canada 2006; Lee and Cheng 2011). As would be expected by the number and spatial distribution of PPAs, few ecoregions are found to meet a 12% protection target (Hummel 1995; Environment Canada 2006). Although reported for Canada as a whole (Hummel 1995; Environment Canada 2006), these findings are also found when restricted to boreal ecozones. For example, within boreal ecozones, protection is unevenly distributed both geographically and along environmental gradients of vegetation productivity (Andrew et al. 2011a).

Similarly, analyses of species level representation suggest that the Canadian PPA system is incomplete (Warman et al. 2004; Deguise and Kerr 2006; Wiersma and Nudds 2009). Species at risk are poorly represented by the existing formal protected areas network across ecozones, including the boreal ecozones (Deguise and Kerr 2006). However, species at risk may have limited relevance as a biodiversity surrogate in boreal Canada, where less than 20% of Canadian species at risk occur (Canadian Boreal Initiative 2005), as opposed to in the temperate, southern portions of Canada, where anthropogenic pressures and species endangerment are greater. Warman et al. (2004) found that 16% of Canadian vertebrate species were not represented in existing protected areas and most outstanding areas of protection priority are in the southern temperate region (fig. 2 in Warman et al. 2004). (Findings such as these highlight the potential disconnect between area- and values-based protection targets. Expansion of PPAs in northern environments may satisfy meeting an area-based target but be of lesser conservation priority relative to smaller, more at risk, locations.) However, these findings are contingent on the coarse spatial analysis units used and the very modest requirements for a species to be considered protected (only 1% of a 10 000 km² cell occupied by a species needed to be protected for the target to be

Fig. 1. Overview of the datasets used in this assessment of parks and protected areas (PPAs) in boreal Canada. (*a*) The gradient of vegetation productivity across Canada, mapped as a false color composite with the seasonality of productivity in red, integrated annual productivity in green, and elevation in blue. The fraction of absorbed photosynthetically active radiation (fPAR) is used as a proxy of productivity. The extent of the boreal zone and locations of characteristic landscapes are also shown. (*b*) Map of boreal PPAs and ecozones. Strictly protected PPAs correspond to IUCN categories I–IV; anthropogenic PPAs are categories V, VI, and parks to which a category has not been assigned. Ecozones are distinguished by shades of grey and are numbered as 1. Atlantic Maritime, 2. Boreal Cordillera, 3. Boreal Plain, 4. Boreal Shield East, 5. Boreal Shield West, 6. Hudson Plain, 7. Montane Cordillera, 8. Taiga Cordillera, 9. Taiga Plain, 10. Taiga Shield East, and 11. Taiga Shield West. (*c*) The extent of de facto protected areas, following Andrew et al. (2012). (*d*) The Earth Observation for Sustainable Development of forests (EOSD) land-cover classification (Wulder et al. 2008*a*). (*e*) Distribution of the distinct types of boreal forest landscapes, and (*f*) land-cover maps of the most characteristic landscapes corresponding to each landscape class (Cardille et al. 2012). The locations of the landscapes in (*f*) are plotted in (*a*). (*g*) Legend for the land-cover maps in (*d*) and (*f*).
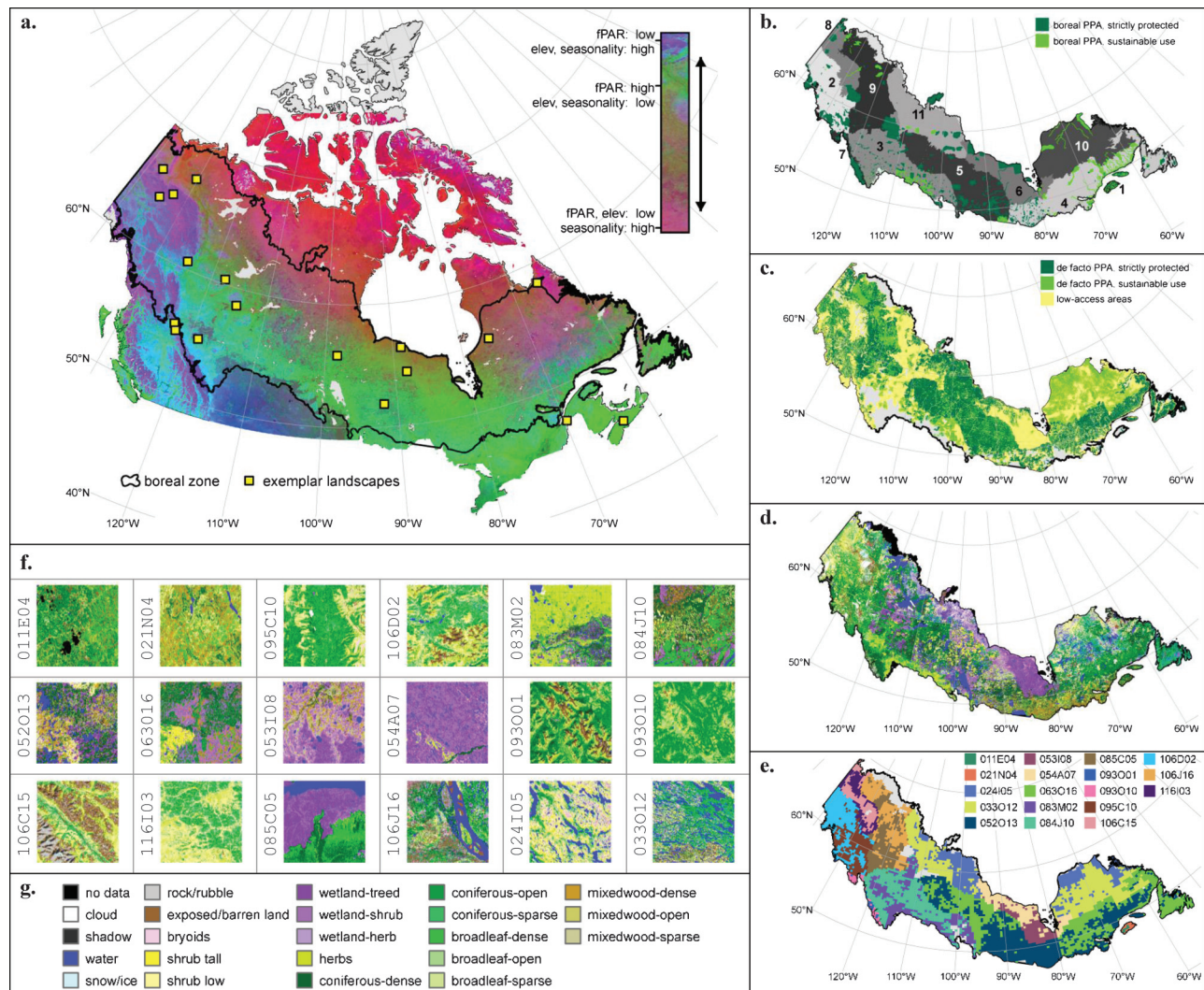

met). In contrast, Wiersma and Nudds (2009) reported that up to 30% of mammal species, by mammal province, were not represented in the current PPA system, and several new protected areas, expanding PPA coverage area by roughly 70%, were needed to meet their targets. The discrepancies between the conclusions of these two studies occurred because Wiersma and Nudds (2009) set greater representation targets (replicating occurrences across an ecological stratification) and required a larger minimum reserve size for a site to qualify as protected (2700 km²). At a regional extent, Drever et al. (2010) showed that all rare forest types are present in protected areas in their study area in boreal Ontario, although some individual rare forest types did not meet a 12% target. The representation of forest types was found to be more variable in the boreal portion of their study area than in the

neighbouring Great Lakes-St. Lawrence forest region to the south (Drever et al. 2010).

3.3. Gap analysis of the boreal PPA system

A protected area system evaluation that is comprehensive of, and specific to, Canada's boreal zone would provide valuable information to guide conservation and land-use planning over this vast region. To fill this knowledge gap, we have analyzed the distribution of boreal protected areas relative to several environmental surrogates, including ecozones, land cover, vegetation productivity, landscape diversity, and a classification of unique landscape types occurring in the boreal zone. This extends our previous work evaluating PPAs Canada-wide (Andrew et al. 2011*a*) and wilderness in the boreal zone (Andrew et al. 2012) and features

Fig. 2. Levels of protection (proportion by area) in parks and protected areas of boreal Canada for boreal ecozones. Shading and cross-hatching indicate the contribution by different protected area categories, as indicated by the IUCN classification framework. The thick, dashed vertical line corresponds to the overall level of protection throughout Canada's boreal zone. In the text, ecozones with greater protection than the boreal zone as a whole are referred to as "over-represented"; conversely, ecozones with less protection are "under-represented".
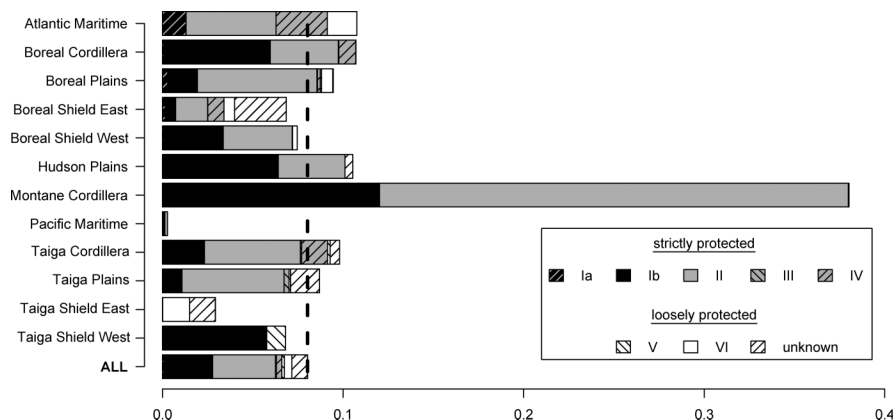
the addition of several new environmental surrogates. Andrew et al. (2011b) confirmed that many of these surrogates represent patterns of butterfly community composition in Canada and are thus likely to be effective tools for conservation gap analyses. However, due to the coarseness of the biodiversity surrogates, meeting their individual representation targets does not guarantee effective representation of biodiversity (Reyers et al. 2002). Ecozones are not internally homogenous in their composition of species and ecosystems. Land-cover classes likely exhibit considerable variation in species composition and ecosystem service provisioning either regionally (Scott et al. 2001; Hamann et al. 2005) or along productivity and elevation gradients. The converse is also true. Productivity ranges are likely to have strikingly different meanings for different land-cover classes or geographic regions. For example, in our dataset the 95th productivity percentile for the wetland land-cover classes corresponds to only the 80th percentile of the dense forest class. Although both exhibit the same absolute productivity, exceptionally productive wetlands and moderately productive forests will certainly host very different species and ecological processes. Conservation assessments along the productivity gradient alone will necessarily equate these two conditions and may obscure important gaps in protection. The simultaneous consideration of multiple biodiversity surrogates in conservation assessments may thus provide a more meaningful appraisal of protected area coverage than independent evaluations along single axes. For this reason, we also considered our environmental surrogates in two-way combinations. Our study extent was the boundary of the Canadian boreal zone (Fig. 1a), including naturally treeless areas and mountaintops. The PPA datasets, environmental surrogates, analyses, and detailed results are described fully in Appendix A.

As suggested by the previous studies of the Canadian PPA system (section 3.2), our results confirm that the protected area system in Canada's boreal zone does not provide uniform, consistent, high levels of protection across all biodiversity features. Few of the biodiversity surrogates meet the 12% representation goal established by Environment Canada (2006), the more recent 17% global protected area target (UNEP 2010), or the more ambitious percentage goals endorsed by some advocacy groups (section 3.1). Among the ecozones, it is in the boreal portions of the Montane Cordillera (38% protected) that the 12% target been achieved (Fig. 2), while only non-vegetated and wetland land-cover classes (Fig. 3) and productivity and elevation extremes (Figs. 4l and 5l) may be considered sufficiently protected by this criterion. The distribution of protection overall was statistically biased to land-

scapes with reduced land-cover diversity relative to the boreal zone as a whole, but was unbiased with respect to elevation or vegetation productivity (Table 3). When partitioning the PPA system into IUCN management categories, the observed landscape diversity bias was most negative for strict PPA designations and productivity biases became evident for some PPA management categories (especially those with limited occurrence in the boreal zone; Table 3). About one-third of the landscape types meet the 12% representation goal (Fig. 6), notably the mixed forest landscapes of the Atlantic Maritime, both landscape types in the Montane Cordillera, the more forested landscape type of the Boreal Cordillera, and the less forested landscapes of the Boreal Plains, Hudson Plains, and Taiga Cordillera (landscape types are illustrated in Fig. 1f; refer to Cardille et al. (2012) for more detailed descriptions). When considering each surrogate individually, the most pressing conservation needs in Canada's boreal zone appear to be (1) for the ecozone surrogate: the eastern Taiga Shield and those ecozones that are only peripherally boreal (e.g., boreal portions of the Pacific Maritime); (2) of the land-cover classes: low shrubs and sparse forests; (3) moderate productivities and elevations; and (4) in terms of landscape structure: diverse landscapes throughout the boreal zone and forest dominated landscapes in the Taiga Shield.

Protection was also quite variable within each of these environmental surrogates. For example, while wetlands had the greatest representation relative to all vegetated land-cover classes, protection was found most frequently over low productivity wetlands (Table 4). Similarly, though the boreal Montane Cordillera has relatively high protection, this is especially concentrated in non-forested land-cover classes (Table 5) occurring at high elevations with low productivities and landscape diversity (Table 6). Even in this ecozone, five land-cover classes, all of them forest classes, have <12% protected area, and no sparse broadleaf forests are protected (Table 5). Of the 209 possible ecozone – land cover combinations, 70% do not meet the 12% target and 13% currently have no protected area (Table 5). An ecozone's overall level of protection is related to the number of land-cover classes that are represented below 12% ($R^2 = 0.735$, $p < 0.001$), but is not predictive of the number of classes not represented ($R^2 = 0.150$, $p = 0.21$), or of the productivity ($R^2 = 0.056$, $p = 0.46$), elevation ($R^2 = 0.001$, $p = 0.94$), or landscape diversity ($R^2 = 0.033$, $p = 0.57$) biases of the PPA system. These findings indicate that there is an opportunity for increased protection in all boreal ecozones, if there is a desire to replicate the ecosystem-wide physical and ecological conditions in protected areas. This analysis also indicates that there is more infor-

Fig. 3. Levels of protection (proportion by area) in parks and protected areas of boreal Canada for boreal land-cover classes. Land-cover class names in plain text are the original categories from the EOSD classification; those in bold (underlined) are hierarchical aggregations of groups (subgroups) by life form. Shading and cross-hatching indicate the contribution by different protected area categories, as indicated by the IUCN classification framework. The thick, dashed vertical line corresponds to the overall level of protection throughout Canada's boreal zone. In the text, land-cover classes with greater protection than the boreal zone as a whole are referred to as "over-represented"; conversely, those with less protection are "under-represented".
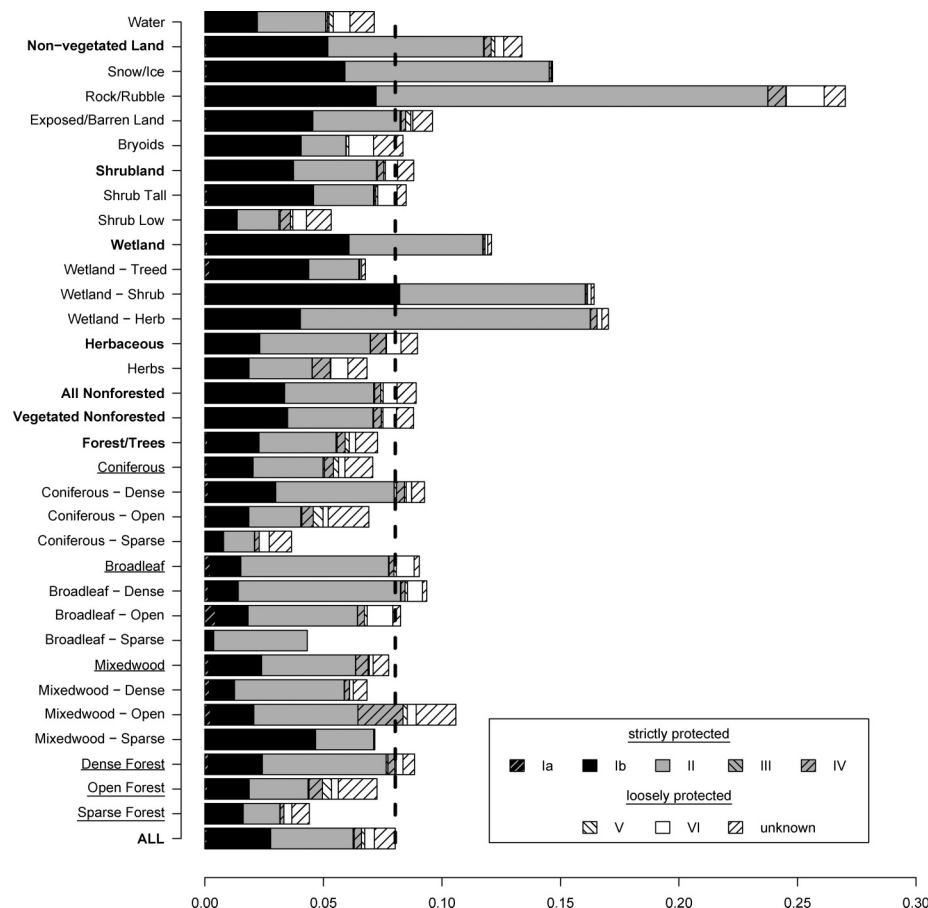
mation that is readily available (e.g., the spatial data sets utilized) that have the potential to support increasingly detailed investigations of representation, overcoming some limitations of coarse scale surrogates as indicators of the completeness of a PPA system. Further, our assessments along both site-level land-cover and broader landscape structure reveal that achieving protection targets set for coarse surrogates does not ensure that a protected area system will be representative of the regional context. For example, a forest-dominated landscape type with many PPAs designed to capture unique, anomalous environments may be considered well protected despite under-protected of forested sites themselves. This has also been shown by Venier and Pearce (2007), who found that a park in north-central Ontario protected bird communities and forest structures that were not characteristic of the surrounding boreal forest landscapes. The detailed results of analyses such as ours can provide quantitative, spatially explicit, data-driven recommendations of conservation requirements and guide the continued development of the boreal PPA system. Such findings should not diminish the perceived quality of the current protected area network, but are intended to present a context of what is protected, what could be protected, and what remains outside of protection. It is not expected that all landscape types will be protected evenly, but the detailed outcomes we present support increasingly sophisticated decision making and consideration of trade-offs.

4. Effectiveness of boreal PPAs

The effectiveness of a PPA system is much more difficult to determine than representation and has received less study (Table 2). Effectiveness refers to a PPA system's ability to retain species over time and allay the impacts of threatening processes (Gaston et al. 2008). Effectiveness is influenced by whether species' habitat area requirements are larger than the size of the reserve and temporal variation in the distribution of natural features in response to natural disturbance and succession dynamics or climate change. These are discussed further in the following subsections. In practice, effectiveness is most often evaluated by the spatial characteristics of a reserve or reserve network, especially park size and connectivity. The properties of the surrounding landscape will also influence effectiveness, i.e., whether unprotected area surrounding PPAs is able to support species with large area requirements or provide connectivity and maintained propagule sources for seral stages that may temporarily be absent from a reserve (termed "spatial resilience"; Bengtsson et al. 2003).

4.1. Conservation needs for large, wide-ranging mammals

Home ranges of charismatic boreal mammal species, such as woodland caribou (Stuart-Smith et al. 1997) and grizzly bears (Ciarniello et al. 2007) are hundreds to thousands of square kilometres, respectively. These range values represent the areal requirements for individual animals; for PPAs to effectively contain

Fig. 4. Levels of protection (proportion by area) in parks and protected areas of boreal Canada for ranges of vegetation productivity, using the integrated annual fraction of absorbed photosynthetically active radiation (fPAR) metric, stratified by land-cover classes aggregated to life form. As a guide, dashed horizontal lines represent national and international conservation targets of 12% and 50%, respectively.
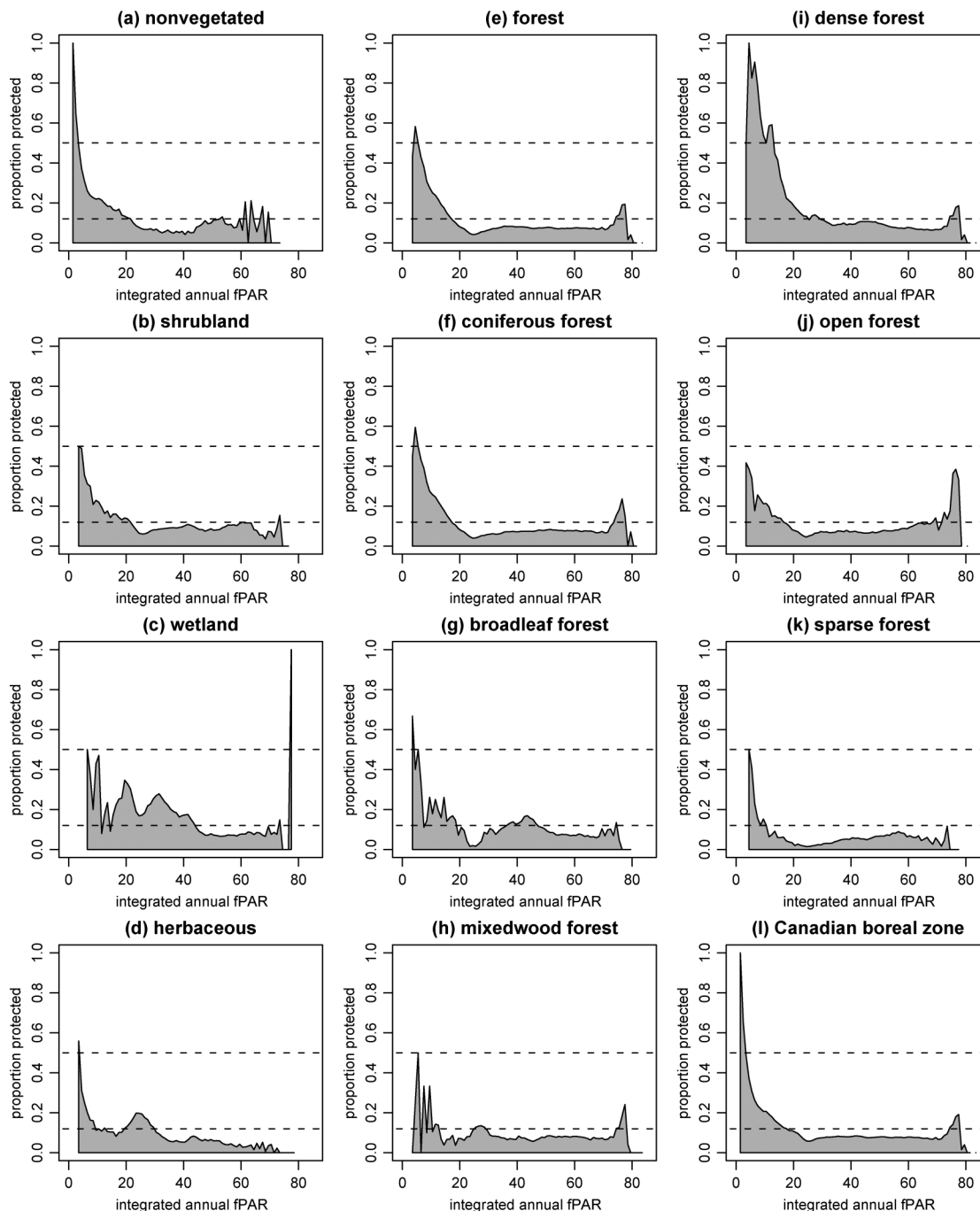
these species, minimum viable populations (MVPs) will need to be protected, requiring much larger areas. Wielgus (2002) estimated that maintaining a MVP of grizzly bears will require protecting 8556–17 843 km². In temperate North America, the spatial extents required to protect mammal species were estimated to be 7490–12 233 km², depending on the species present, using an MVP approach for western national parks (Newmark 1985) and 5037 km² from species–area relationships in eastern reserves (Gurd et al. 2001). Of the PPAs considered in the former study, only the complex of four national parks in the Canadian Rocky Mountains was found to meet these areal requirements; the remaining seven western parks assessed were each smaller than required for

up to four species (Newmark 1985). Nine protected areas in eastern North America exceeded the 5037 km² size threshold of the latter study (Gurd et al. 2001). However, Wiersma et al. (2004) suggested that PPAs as small as 3140 km² may maintain mammal assemblages, provided that they are situated within an additional 18 000 km² of suitable habitat. Although the largest PPA in the boreal zone is more than 50 000 km² (Wood Buffalo National Park and adjacent protected lands), few others currently meet the size requirements of large mammals established by these studies. The number of qualifying PPAs range from only five, for the 12 000 km² requirement, to 21 and 34 that are larger than 5037 km² and 3140 km², respectively.

Fig. 5. Levels of protection (proportion by area) in parks and protected areas of boreal Canada for ranges of elevation, stratified by land-cover classes aggregated to life form. As a guide, dashed horizontal lines represent national and international conservation targets of 12% and 50%, respectively.
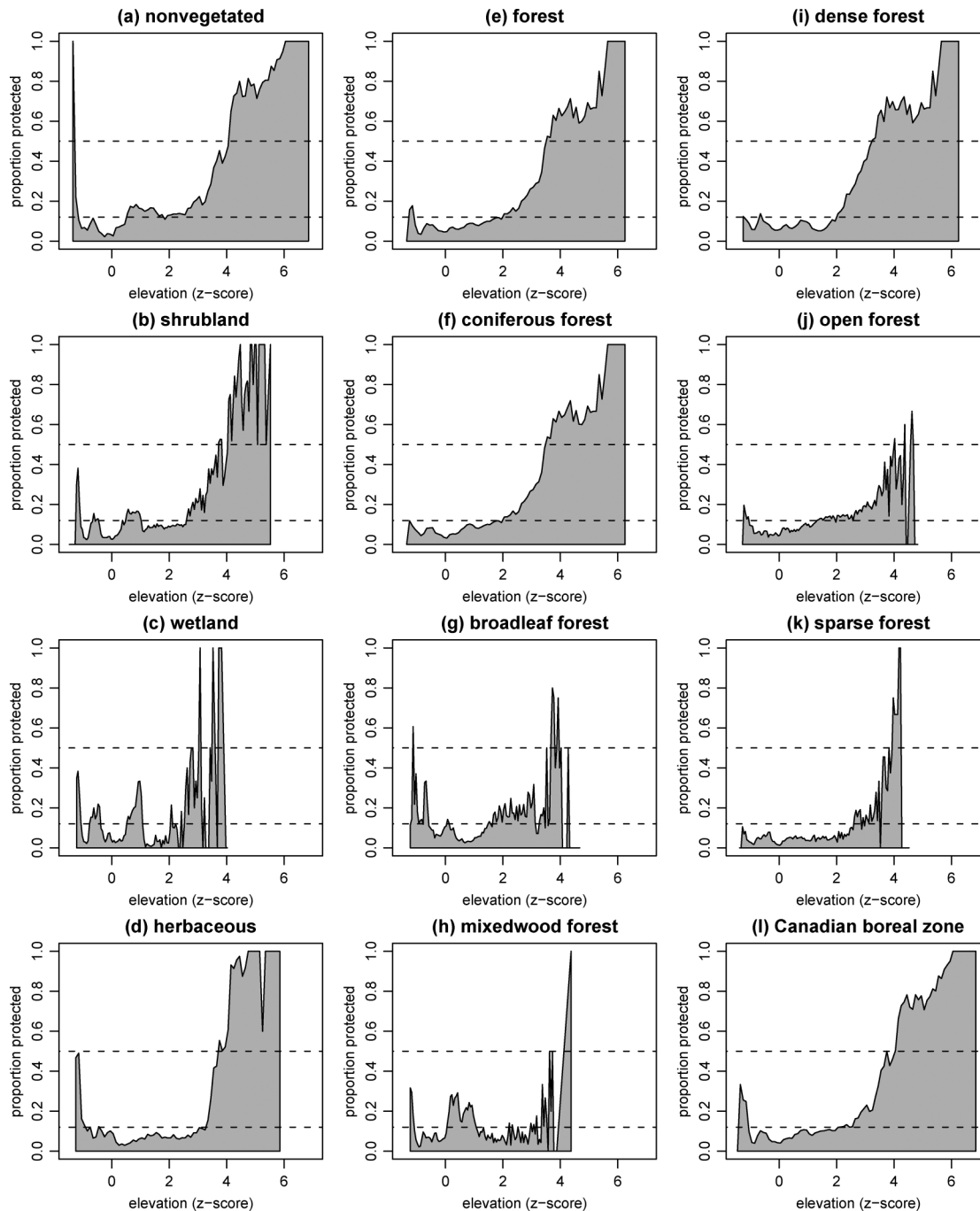
4.2. Protection of landscape dynamics and natural disturbance regimes

A defining characteristic of boreal landscapes is their dynamism, with spatiotemporal patterns created by large- and small-scale disturbance processes (e.g., fires, blowdowns, insect infestations; Lavigne et al., Manuscript in preparation). A major shortcoming of many conservation assessment and planning targets is that they are based on static representation (of areas or features) without consideration of landscape dynamics. Even an optimal PPA system under present landscape configurations is unlikely to meet representation targets in perpetuity (Leroux et al. 2007b). Our inclusion of landscape structure as a biodiversity surrogate implic-

itly recognizes the role of disturbances in patterning landscapes and the importance of the resulting patterns, but fails to address the temporal nature of these dynamics. Northern boreal forest ecosystems are among the few ecosystems on Earth where large areas are still governed by natural disturbances and landscape dynamics. It follows that the relatively few studies that do incorporate landscape dynamics into evaluating conservation effectiveness and planning have been conducted in Canada's boreal zone (e.g., Leroux et al. 2007b, 2007c; Rayfield et al. 2008).

In theory, landscape dynamics can be accommodated simply by establishing large protected areas. Indeed, the maintenance of ecological processes (such as disturbance) in addition to species is

Table 3. Productivity and landscape diversity biases by the International Union for Conservation of Nature classes.

	% boreal	% PA system (by area)	Bias					
			Minimum fPAR	Integrated fPAR	fPAR seasonality	Elevation	LC richness	LC diversity
Strict	6.61	82.25	0.000	0.007	−0.015	−0.008	−0.105	0.000
Ia. Strict nature reserves	0.08	1.04	0.058	0.194	−0.165	0.023	−0.053	0.000
Ib. Wilderness areas	2.70	33.56	0.000	−0.041	0.050	−0.013	−0.105	0.000
II. National parks	3.48	43.32	0.003	0.044	−0.046	−0.005	−0.105	0.000
III. Natural monuments	0.04	0.55	−0.003	−0.127	0.111	0.008	0.158	0.091
IV. Habitat/species management areas	0.30	3.78	0.006	0.096	−0.049	−0.008	0.053	0.091
Permissive	1.43	17.75	−0.003	−0.080	0.078	0.003	0.053	0.091
V. Protected cultural landscapes	0.14	1.73	0.000	−0.095	0.073	0.012	−0.053	0.000
VI. Protected sustainable use areas	0.41	5.13	−0.003	−0.053	0.021	0.000	0.053	0.091
Unknown	0.87	10.89	−0.003	−0.081	0.087	−0.001	0.053	0.091
All	8.03	100.00	0.000	−0.008	−0.001	−0.006	−0.053	0.000

Note: fPAR, fraction of absorbed photosynthetically active radiation; LC, land cover.

Fig. 6. Levels of protection (proportion by area) in parks and protected areas of boreal Canada for boreal landscape classes. Landscape classes are associated with their primary ecozone and labeled by the mapsheet ID of the most characteristic landscape of that class (Fig. 1f). For more information on the landscape classes, see Cardille et al. (2012). Shading and cross-hatching indicate the contribution by different protected area categories, as indicated by the IUCN classification framework. The thick, dashed vertical line corresponds to the overall level of protection throughout Canada's boreal zone. In the text, the landscape classes with greater protection within each ecozone are referred to as "over-represented"; conversely, those with lower protection are "under-represented".
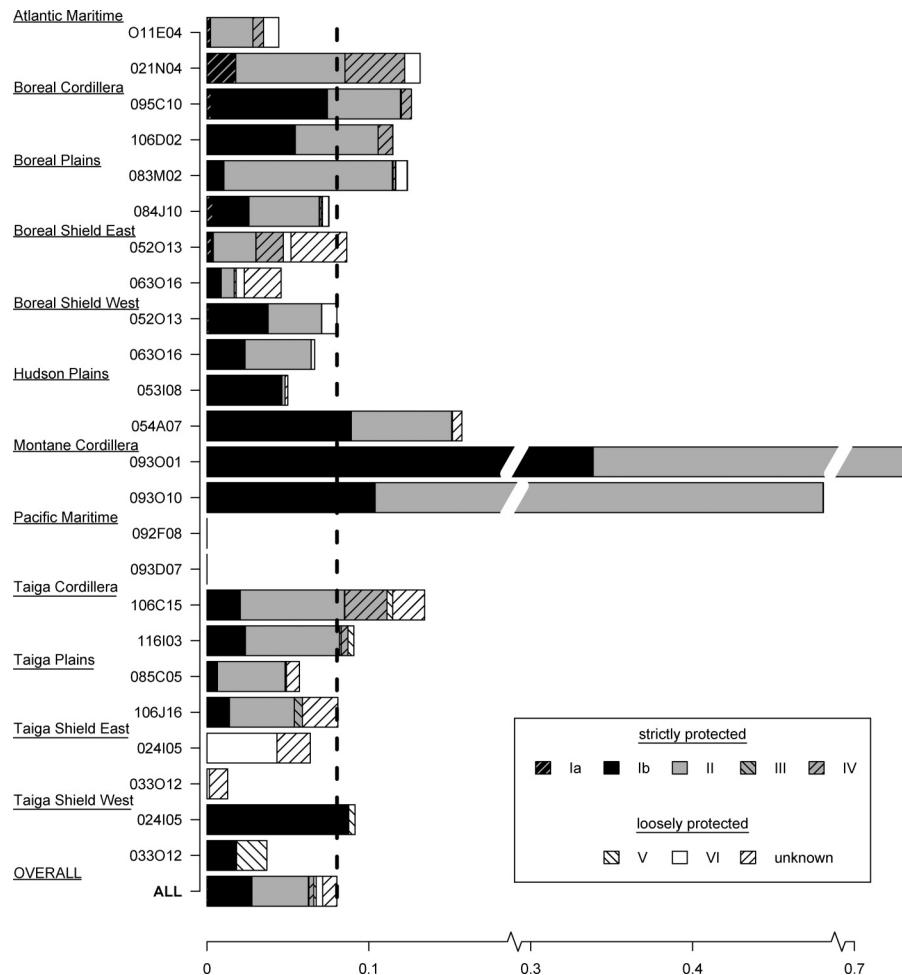
one of the justifications for large parks (Dudley 2008). But transforming the qualitative heuristic that bigger parks are better into quantitative recommendations of park size has proven difficult for conservation biologists. The most basic guideline is that protected areas be as large as the largest disturbance event (Leroux et al. 2007c), or at least ten times the size of an average disturbance event (Wiersma et al. 2005). Canada's boreal zone has 34 parks or aggregations of adjacent parks >3000 km², the minimum reserve size tentatively suggested by Wiersma et al. (2005) for northern Canada (these PPAs account for 70% of the total area protected and 5.7% of the boreal zone, but only 2% of the 1552 boreal parks). A report to the Ontario Ministry of Natural

Table 4. Productivity biases by land cover.

	% protected	% PA system (by area)	Bias Minimum fPAR	Integrated fPAR	fPAR seasonality	Elevation
Water	7.15	10.15	0.005	0.054	−0.061	−0.020
Nonvegetated land	13.37	8.64	0.000	−0.112	0.000	0.277
Snow/ice	14.67	0.86	0.000	−0.072	−0.031	0.076
Rock/rubble	27.02	3.32	0.000	−0.115	−0.025	0.246
Exposed/barren land	9.60	4.46	0.000	−0.065	0.030	0.275
Bryoids	8.36	2.30	0.000	0.030	−0.032	−0.086
Shrubland	8.81	23.34	0.000	0.010	−0.007	−0.014
Shrub tall	8.50	4.03	0.000	−0.073	0.067	0.001
Shrub low	5.33	7.87	0.000	−0.016	0.023	0.086
Wetland	12.09	18.69	0.000	−0.092	0.063	0.000
Wetland-treed	6.77	4.76	−0.005	−0.110	0.108	−0.081
Wetland-shrub	16.42	11.44	0.006	−0.054	0.012	0.007
Wetland-herb	17.02	2.49	−0.009	−0.107	0.135	−0.063
Herbaceous	8.97	6.29	−0.005	−0.080	0.209	−0.047
Herbs	6.84	3.79	−0.036	−0.089	0.251	−0.018
Nonforested, all	8.91	50.72	0.000	−0.010	0.016	−0.011
Nonforested, vegetated	8.81	31.93	0.000	−0.008	0.027	−0.019
Forested	7.29	49.28	0.010	0.003	−0.019	−0.002
Coniferous	7.09	33.18	0.018	0.023	−0.038	0.005
Coniferous-dense	9.27	14.41	0.000	−0.023	0.007	−0.005
Coniferous-open	6.92	15.55	0.000	0.000	−0.022	0.042
Coniferous-sparse	3.66	3.22	0.000	0.079	−0.073	−0.018
Broadleaf	9.05	4.76	−0.013	−0.022	0.020	−0.029
Broadleaf-dense	9.36	3.58	−0.017	−0.023	0.023	−0.084
Broadleaf-open	8.26	1.17	−0.009	−0.016	0.009	0.029
Broadleaf-sparse	4.32	0.01	0.258	0.515	−0.597	−0.056
Mixedwood	7.75	6.58	0.006	0.001	−0.018	0.009
Mixedwood-dense	6.84	2.90	−0.003	−0.008	−0.006	0.003
Mixedwood-open	10.59	1.97	0.021	0.050	−0.055	0.038
Mixedwood-sparse	7.17	1.72	0.022	0.005	−0.060	0.039
Dense forest	8.85	20.89	−0.003	−0.024	0.009	−0.007
Open forest	7.26	18.69	0.007	0.010	−0.026	0.039
Sparse forest	4.41	4.94	0.006	0.108	−0.116	−0.004
All	8.03	100.00	0.000	−0.008	−0.001	−0.006

Note: fPAR, fraction of absorbed photosynthetically active radiation.

Resources has suggested that the minimum reserve size to preserve ecological processes and landscape dynamics in the north should be 20 000 km² (The Far North Science Advisory Panel 2010). Only three reserves in the boreal zone currently exceed this size: Wood Buffalo National Park and adjacent provincial PPAs, Nahanni National Park Reserve, and Polar Bear Provincial Park in Ontario.

4.3. Park and protected area networks in the context of climate change

Natural landscape dynamics are not the only factor that may limit the effectiveness of representative protected area networks. Climate change, too, will alter the distribution of species and ecosystems (Price et al. 2013), potentially causing them to have reduced protection over time (that is, to no longer occur within the existing network of PPAs). As a conservation strategy, protected areas essentially address direct human impacts, habitat degradation, and overexploitation, but are less effective against indirect anthropogenic effects such as climate change (Kharouba and Kerr 2010; Kujala et al. 2011). At present, species endangerment in North America has been caused largely by habitat conversion and overuse of natural resources (Wilcove et al. 1998; Venter et al. 2006). Climate change will likely become an increasingly important threat in the future, changing the geographic pattern of risks to biodiversity and possibly serving to reduce the effectiveness of the conservation measures in place (Lee and Jetz 2008), especially at northern latitudes (i.e., the boreal zone) where changes are expected to be most dramatic (Price et al. 2013).

Canada's boreal zone is projected to experience warming winter and springtime temperatures of 2–5 °C by the mid-21st century (Plummer et al. 2006). These projections place Canada's boreal zone among the regions expected to experience the greatest climate change (Plummer et al. 2006). Several authors have suggested that Canada's protected area system may be sensitive to climate change impacts (Scott et al. 2002; Suffling and Scott 2002; Lemieux and Scott 2005; Lemieux et al. 2011a, 2011b). Notably, the representation of boreal forests, in particular, is expected to decline as biomes shift north, given the current distribution of PPAs (Scott et al. 2002; Lemieux and Scott 2005). Although protected areas cannot forestall climate change or its impacts, well designed PPA networks offer some capacity to limit species endangerment due to climate change. Comprehensive protected area networks that are complete with respect to the current patterns of biodiversity surrogates may lose surprisingly few species in the PPA network overall, although species turnover within individual reserves may be substantial (Erasmus et al. 2002; Hole et al. 2009). Current reserve systems may be inadequate to the task (Scott et al. 2002; Burns et al. 2003), in part because of an incomplete distribution of protection that is biased to regions more prone to climate change (Halpin 1997; Gaston et al. 2008). However, the maintenance of biodiversity within a reserve system, if not individual reserves, assumes that species are able to migrate between protected areas and distributions of species can track climate synchronously (which will not necessarily occur across species). In reality, habitat conversion and fragmentation outside of protected areas may limit

Table 5. Land cover representation by ecozone.

	Atlantic Maritime	Boreal Cordillera	Boreal Plains	Boreal Shield East	Boreal Shield West	Hudson Plains	Montane Cordillera	Pacific Maritime	Southern Arctic	Subhumid Prairies	Taiga Cordillera	Taiga Plains	Taiga Shield East	Taiga Shield West
All	10.76	10.71	9.45	6.85	7.46	10.54	38.02	0.27	8.48	1.00	9.81	8.70	2.93	6.81
Water	9.09	12.43	12.78	7.17	9.95	16.79	27.61	0.00	5.26	0.00	24.53	6.69	3.50	4.73
Nonvegetated land	8.54	26.95	6.75	6.43	30.09	12.46	61.66	1.31	32.14	–	7.57	9.46	4.41	6.56
Snow/ice	–	53.78	100.00	0.00	–	–	50.37	0.00	–	–	6.42	0.63	0.00	0.00
Rock/rubble	97.50	38.14	0.00	18.63	12.82	0.00	77.68	0.00	66.67	–	5.22	58.40	17.07	0.61
Exposed/barren land	2.28	22.36	6.48	5.95	42.79	12.59	14.08	1.80	28.00	–	8.71	5.22	1.45	10.04
Bryoids	–	20.51	–	6.78	–	40.98	–	–	0.00	–	2.44	4.28	5.67	5.26
Shrubland	2.87	7.90	20.16	4.22	7.60	10.21	46.96	0.00	12.50	20.00	11.38	12.18	3.46	10.02
Shrub tall	4.92	11.89	11.57	2.19	3.79	8.96	77.14	–	0.00	0.00	15.94	12.55	16.32	11.76
Shrub low	2.56	7.55	8.26	3.00	6.67	0.65	11.45	0.00	5.88	–	11.22	8.01	2.79	1.58
Wetland	–	5.40	12.67	11.95	10.55	11.11	33.05	–	23.81	12.50	30.20	12.12	2.47	16.73
Wetland-treed	–	7.95	5.92	9.91	6.08	8.39	5.88	–	0.00	0.00	0.00	4.96	5.00	1.05
Wetland-shrub	–	3.72	25.11	13.50	13.07	11.06	23.29	–	62.50	33.33	18.00	20.97	0.78	20.54
Wetland-herb	–	12.10	10.04	11.35	11.77	36.00	75.00	–	0.00	0.00	55.16	7.08	3.20	19.93
Herbaceous	–	8.61	3.23	3.14	8.23	30.02	57.28	0.00	0.00	0.00	15.26	12.06	3.20	18.50
Herbs	–	8.59	2.14	2.07	7.68	13.19	57.01	0.00	0.00	0.00	14.96	24.72	–	0.00
Nonforested, all	5.15	12.47	9.88	5.49	8.77	14.93	59.07	0.63	12.18	0.41	10.91	10.36	3.74	7.34
Nonforested, vegetated	2.87	8.04	9.29	4.18	7.73	14.75	52.15	0.00	8.89	0.44	12.62	11.81	3.77	9.18
Forested	11.41	9.18	9.93	7.29	6.65	4.42	28.54	0.00	0.00	3.85	5.99	7.86	1.67	5.94
Coniferous	12.57	8.88	8.64	7.61	6.08	5.01	29.15	0.00	0.00	0.00	5.91	8.08	1.67	6.12
Coniferous-dense	11.95	7.73	8.03	7.90	7.33	3.29	49.50	0.00	–	0.00	2.07	17.93	0.56	8.31
Coniferous-open	24.55	10.32	10.05	7.73	3.34	5.58	13.01	0.00	0.00	–	7.51	6.30	2.00	6.94
Coniferous-sparse	–	2.71	34.99	6.82	4.37	8.24	15.46	0.00	0.00	–	4.59	4.28	1.59	0.49
Broadleaf	2.50	20.79	9.66	11.27	7.97	12.43	12.26	–	0.00	4.08	12.16	5.33	1.41	4.46
Broadleaf-dense	0.00	18.89	9.05	11.40	8.71	12.43	13.97	–	0.00	5.26	0.00	10.37	2.00	6.21
Broadleaf-open	4.35	21.58	12.79	10.90	2.71	–	11.68	–	0.00	3.33	14.26	2.20	0.00	2.42
Broadleaf-sparse	–	9.09	0.00	0.00	31.03	–	0.00	–	–	–	0.00	0.34	0.00	0.00
Mixedwood	8.00	8.99	19.95	5.86	7.65	2.72	13.91	0.00	0.00	–	4.12	11.01	5.19	2.56
Mixedwood-dense	7.63	51.52	24.53	4.90	7.34	7.18	8.16	–	–	–	–	15.25	11.54	12.52
Mixedwood-open	8.59	8.84	18.01	11.57	3.69	4.55	18.18	0.00	0.00	–	4.12	9.34	3.91	1.63
Mixedwood-sparse	–	0.00	83.64	5.26	8.71	1.78	–	–	–	–	–	100.00	–	0.00
Dense forest	11.18	8.56	8.95	6.80	7.39	3.93	48.67	0.00	0.00	4.55	2.00	16.07	0.58	8.21
Open forest	12.91	10.53	12.67	8.07	3.38	5.58	12.96	0.00	0.00	3.33	7.65	5.97	2.01	6.63
Sparse forest	–	2.72	36.91	6.67	8.24	3.89	15.41	0.00	0.00	–	4.59	4.26	1.59	0.47

Note: Underlined numbers, underprotected; italicized numbers, overprotected relative to current levels of protection in ecozone; and –, absence of land cover from ecozone.

Table 6. Productivity and landscape diversity biases by ecozone.

	% protected	% PA system (by area)	Bias Minimum fPAR	Integrated fPAR	fPAR seasonality	Elevation	LC richness	LC diversity
Atlantic Maritime	10.76	0.39	−0.032	−0.009	0.013	0.033	0.000	0.000
Boreal Cordillera	10.71	10.49	0.000	−0.078	0.061	0.052	−0.056	0.000
Boreal Plains	9.45	15.41	−0.015	−0.036	0.028	−0.108	0.000	0.000
Boreal Shield East	6.85	12.94	0.003	0.013	−0.006	−0.014	−0.053	0.000
Boreal Shield West	7.46	13.71	0.014	0.032	−0.057	0.005	−0.083	0.000
Hudson Plains	10.54	9.29	0.000	−0.165	0.115	−0.173	−0.063	0.000
Montane Cordillera	38.02	5.44	−0.091	−0.146	0.126	0.117	−0.059	0.000
Pacific Maritime	0.27	0.00	0.000	−0.205	−0.010	0.364	0.045	0.000
Southern Arctic	8.48	0.00	0.000	−0.207	0.144	−0.018	0.000	0.000
Subhumid Prairies	1.00	0.00	0.000	0.351	0.053	−0.267	0.000	0.250
Taiga Cordillera	9.81	5.42	0.000	0.038	0.022	−0.118	−0.053	0.000
Taiga Plains	8.70	12.77	0.008	0.031	−0.080	0.088	−0.105	−0.091
Taiga Shield East	2.93	4.91	0.000	−0.044	0.041	−0.054	0.000	0.111
Taiga Shield West	6.81	9.21	0.000	0.023	0.001	−0.100	−0.158	−0.091
All	8.03	100.00	0.000	−0.008	−0.001	−0.006	−0.053	0.000

Note: fPAR, fraction of absorbed photosynthetically active radiation; LC, land cover.

species' abilities to migrate between protected areas in response to climate change (Hill et al. 1999; Opdam and Wascher 2004), presenting one of the greatest risks of climate change to biodiversity (Lovejoy and Hannah 2005).

In a study by Holmes et al. (2013), climate data were used to make projections of future vegetation productivity, which can be used as a biodiversity surrogate (see Coops et al. 2008). The modeling implemented allowed for pixel-based projections of expected productivity conditions in year 2065 as related to climate projections. The authors found that, given the modeling implemented, the specific characteristics under protection change with climate given the modeling implemented, with implications especially of note for sensitive or specialist species, and over-all conditions are predicted to be more productive and less seasonal. As modeled projections, the maps such as those developed by Holmes et al. (2013) are not to be taken as reality (i.e., as an absolute value), but to provide spatial and categorical insight of potential trends to aid in scenario development and planning exercises.

5. Conservation planning to expand the boreal PPA system

The development of systematic conservation plans for regional to national study extents is the last major theme of PPA system research in the boreal zone (Table 2). Conservation prioritization exercises draw on the principles of representation and effectiveness, discussed in the previous sections, to identify sets of sites where new PPAs could be established to meet conservation goals.

5.1. Prioritization frameworks and their application to the boreal zone

The designation of new protected areas is a complicated exercise that generally involves balancing trade-offs between competing land uses. A number of conservation prioritization tools have been developed to plan protected area networks (for examples see Cabeza and Moilanen 2001; Margules et al. 2002; Brooks et al. 2006; Sarkar et al. 2006). These planning tools identify a set of sites that collectively achieve the specified representation goals, while minimizing the cost of the identified network. In the absence of spatially explicit cost data, the land area needed for protection is often used as a proxy. However, many spatial planning frameworks have been adapted to introduce additional complexity and realism, for example spatial design criteria (Williams et al. 2005a) such as reserve compactness (Ball et al. 2009) or connectivity (Moilanen et al. 2005), land acquisition costs (Ando et al. 1998; Moilanen and Arponen 2011), species relationships (Rayfield et al.

2009), competing land uses (Mathey et al. 2008; Moilanen et al. 2011; Schneider et al. 2011), vulnerability (Lawler et al. 2003), ecosystem services (Chan et al. 2006), metapopulation dynamics (Nicholson et al. 2006), and so on. Such frameworks can be useful tools for assessing how best to expand the protected area system in boreal Canada.

Several researchers have implemented prioritization approaches to identify potential protected area networks in Canada (Table 2), and boreal-specific prioritization research is ongoing (e.g., http://www.beaconsproject.ca; Powers et al. 2012). As with the representation analyses, these studies are quite variable in terms of the biodiversity surrogates, representation targets, design criteria, and optimization algorithms applied (Table 2) and no conservation prioritization has yet been published specific to the boreal zone. These studies confirm that conservation needs remain, but prescriptions of how much land needs to be protected vary. Estimates range from less than 1% of the study extent (e.g., some scenarios of Sarakinos et al. 2001 in Quebec; Freemark et al. 2006 in British Columbia) to up to 72% of the landscape (Leroux et al. 2007a). The prioritization exercises that generated the lowest areal conservation needs generally based site selection on representation alone, requiring only a single occurrence of each species in the identified network. Incorporating additional design requirements that may improve reserve network effectiveness (such as connectivity, minimum reserve sizes, or replication requirements) tended to increase the area identified to meet conservation objectives (Beazley et al. 2005; Leroux et al. 2007a). Prioritized reserve systems tended to predominantly select sites in southern Canada, where both biodiversity and anthropogenic pressures are greater (Sarakinos et al. 2001; Warman et al. 2004; Freemark et al. 2006), but the boreal zone does require expansion of the current PPA network to represent all natural features and jurisdictional protection goals (Freemark et al. 2006).

5.2. Incorporating dynamics into prioritization exercises

5.2.1. Natural disturbance regimes

To protect landscape dynamics and successional mosaics, Pickett and Thompson (1978) suggested identifying and targeting protection to a "minimum dynamic area". This recommendation follows from shifting mosaic steady state theory, which predicts that, above a certain area, a single subregion can be identified that accommodates shifting patch mosaics and maintains all habitats as the region as a whole (Pickett and Thompson 1978). However, boreal landscapes appear to be non-equilibrial and may possess no

single minimum dynamic area that is smaller than the planning region as a whole (Cumming et al. 1996). Nevertheless, Leroux et al. (2007c) demonstrated how simulation models of disturbance and succession can be implemented within a prioritization framework to identify a site (or set of sites) with minimum dynamic characteristics.

However, it may not always be possible to identify or protect minimum dynamic reserves (which are likely to be large), especially in the southern, more intensively managed portion of the boreal zone. In such cases, maintaining connectivity within a comprehensive reserve network may assist the migration of organisms between ephemeral habitat patches in a dynamic landscape. Small protected areas can also provide important conservation functions, including contributions to connectivity (Bodin et al. 2006) and the protection of rare habitats or species. Alternatively, "floating reserves" may enable the continued protection of desirable habitat elements, albeit in different locations through time (Cumming et al. 1996; Rayfield et al. 2008). Although such dynamic reserves are an interesting possibility in areas where large protected areas are not feasible, they may pose management difficulties or be effectively locked in to particular locations by ongoing anthropogenic activities in the landscape.

5.2.2. *Climate change*

Those involved with conservation planning in Canada's boreal zone could proactively consider the anticipated effects of climate change. Climate impacts can be addressed in conservation planning in several ways. As with guidelines for the protection of landscape dynamics, the creation of large, connected protected areas is often recommended to protect shifting patterns of biodiversity, especially with reference to climate change (Halpin 1997; Heller and Zavaleta 2009; Lemieux et al. 2011a). Large and diverse reserves may contain sufficient environmental heterogeneity to accommodate shifting habitats within their boundaries, at least in the short term (Ackerly et al. 2010). The present bias of boreal protected areas to low landscape diversities may limit their spatial resilience to a changing climate (Tables 3, 6). Species' capacity to track their shifting habitat may also be facilitated by designing connectivity into a PPA network and engaging in sustainable forest management outside of reserves. An example of large-scale protection through the boreal zone is the Yellowstone to Yukon Conservation Initiative (http://www.y2y.net), which seeks to maintain ecological connectivity and integrated management of the protected areas throughout the northern Rockies and other associated mountain ranges.

Some researchers and managers argue that conservation planning should focus on environmental surrogates that represent drivers of habitat variability (e.g., land facets delineated along topography and geology; Wessels et al. 1999) and will thus continue to characterize enduring habitat, resulting in a PPA system more robust to changing conditions than one delineated from taxonomic surrogates (Branquart et al. 2008; Lemieux et al. 2011a). By protecting the full range of environmental surrogates, the habitat requirements for a region's species are expected to also be protected, though the exact location of suitable habitat, the identities of species at a site, and species assemblages themselves may change (Lemieux et al. 2011a). However, these expectations are most valid for environmental surrogates based on stable physical features (e.g., landforms) rather than on changeable patterns of climate and vegetation, such as the surrogates used in the present assessment (results herein, see Appendix A for details). Reserve network design can also plan explicitly for climate change by setting representation targets not only for current biodiversity patterns, but also for modelled species distributions under future climates (Hannah et al. 2007). However, habitat suitability models often ignore considerations of ecological complexity that may determine whether a species realizes its projected future distribu-

tion (Halpin 1997). Finally, connectivity among reserves can be implemented by requiring "climate corridors", physical connections of suitable habitat at intermediary time points between the current and modelled future distributions of surrogates (Williams et al. 2005b) or regions that provide continuous habitat despite a changing climate (Rose and Burton 2009). Few PPAs in British Columbia provide such climatic continuity (Rose and Burton 2009). In practice, conservation in the face of climate change will probably require protecting more area than if conditions were static to represent species distributions, both now and in the future, and the climate and habitat corridors that connect them (Hannah et al. 2007).

5.3. Conservation planning for freshwater resources

Aquatic systems in the boreal (see Kreutzweiser et al. 2013; Webster et al., Manuscript in preparation) could also be explicitly considered in PPA network design. The incidental representation of freshwater biodiversity in reserves designed along terrestrial criteria is often poor, except for wetland habitats, which are typical conservation targets (Herbert et al. 2010). The protection of aquatic ecosystems is also greatly challenged by their hydrological connectivity with each other and, especially, surrounding terrestrial ecosystems. Thus, protected aquatic systems may be compromised by activities outside of protected areas (Pringle 2001). Spatial planning tools that take into account these lateral, longitudinal, and vertical linkages have been identified as a focus for additional development (Cote et al. 2008; Amis et al. 2009; Linke et al. 2011). In the boreal zone, where conservation of large areas may still be possible, catchments have been suggested as the most relevant spatial units for conservation planning to maintain functioning ecosystems in both terrestrial and freshwater settings (Schindler and Lee 2010; Strittholt and Leroux 2012).

5.4. Conservation beyond PPAs—the need for integrated land-use planning

The large areas required to maintain viable populations of large, mobile organisms and the complexities of protecting the temporally dynamic distributions of biodiversity elements under natural disturbance regimes and climate change illustrate that conservation objectives are unlikely to be met by strict protected areas alone. This need for off-reserve conservation has been formalized in the conservation matrix model developed by the BEACONs project (http://www.beaconsproject.ca/), which guides much of the current thinking regarding conservation in the boreal zone (e.g., Wiersma et al. 2005; The Far North Science Advisory Panel 2010; Strittholt and Leroux 2012). The Canadian Boreal Forest Agreement (2010) is an example of an interdisciplinary, multi-stakeholder, science and planning exercise, with an aim of designating lands for protection and conservation.

The conservation matrix model designates the majority of the planning region as sustainable use areas (The Far North Science Advisory Panel 2010; Strittholt and Leroux 2012), emphasizing that not all human land use is necessarily incompatible with conservation objectives. For example, although some species require strict protection to persist, many do not and will tolerate some degree of anthropogenic activity (Pereira and Daily 2006; Polasky et al. 2008). Sites that retain these species on a landscape, maintain ecological connectivity, and serve as a regional species pool for a range of seral stages thus make a contribution to the retention of regional biodiversity, despite not being formally protected (Faith and Walker 1996; Moilanen and Cabeza 2007). Within this sustainable use matrix are dispersed core protected areas that are large enough to maintain natural ecological processes (termed benchmark areas), additional reserves as needed to protect specific features, and limited areas of intensive human land use (The Far North Science Advisory Panel 2010; Strittholt and Leroux 2012). The spatial distribution of these tiers of land use should be

carefully planned. Integrated land-use planning that seeks to maximize ecological and economic objectives both within PPAs and in the surrounding landscapes can minimize tradeoffs and achieve greater efficiency than when considering either alone (Polasky et al. 2008). Research considering both biodiversity and economic criteria within the boreal zone confirms that tradeoffs may be limited, and opportunities for win-win solutions can be realized when incorporating the spatial variation of natural features, opportunity costs, and anthropogenic infrastructure in land-use planning (Mathey et al. 2008; Schneider et al. 2011).

Although PPAs are traditionally perceived as excluding most anthropogenic activities, reserves that are more broadly defined and less restrictive may have a place in the continuum of land-use intensity described by the conservation matrix model. The IUCN identifies two classes of "anthropogenic" protected areas, which recognize humans as ecological agents that have shaped the systems with which they have had long association (Dudley 2008). These types of protected areas also allow sustainable natural resource use, provided it is not in conflict with the protection of biodiversity and is conducted in a limited fraction of the reserve. Some have questioned the appropriateness of considering sustainable use areas to be "protected" areas (Locke and Dearden 2005), but they may be particularly effective as buffer zones and linkages between strictly protected core areas. There is a potential for more widespread use of these anthropogenic protected area categories (e.g., IUCN class VI) in boreal Canada, especially in the context of managing the matrix. This potential is supported by the wide acceptance of sustainable forest management standards in Canada, with approximately 148 million ha certified nationally (http://www.certificationcanada.org, site visited on 22 May 2013). The area of certified forest in Canada represents over 14.5% of the country. It is noted that different certification standards are combined in this area statistic and the level of protection and ecosystem services provisioning will, therefore, vary accordingly, as will the potential for consideration of IUCN class VI designation.

The pursuit of integrated land-use planning and the conservation matrix model is feasible in much of the boreal zone, as it has not yet experienced extensive development (especially in the northern boreal zone). In contrast, the current patterns of habitat conversion and degradation throughout much of the world have precluded the attainment of win-win solutions maintaining both economic and ecological objectives on a landscape (Nalle et al. 2004; Polasky et al. 2008) and impede biodiversity protection outside of reserves (due to the present land-use intensity in these areas). In general, just over half of the forested ecosystems of Canada are tenured. The remaining areas outside of tenure are currently subject to fewer competing land-use practices and provide a range of ecosystem goods and services similar to protected areas. The de facto protected areas in Canada's boreal zone, as defined by Andrew et al. (2012; Fig. 1c) specifically from the perspective of protected area completion, suggest unique protection opportunities. Despite variable success of their mapping approach by ecozone, Andrew et al. found that the current extent of wilderness affords the ability to meet many representation targets (using ecozones and vegetation productivities, a subset of the surrogates used in the present study) with considerable flexibility. Most importantly, the wilderness state of large areas of the boreal forest can facilitate not only meeting representation targets, but also incorporating design features such as redundancies, large reserves, and management in the matrix that is compatible with providing connectivity and "spatial resilience" (Bengtsson et al. 2003) to landscape dynamics and climate change. To better convey the conservation roles of these lands, the assignment of IUCN class VI could be an option. For lands where harvesting may be considered, sustainable forest management, especially under certification, remains an option mitigating the possible perceived risk that future management opportunities are eliminated. Dis-

cussion and debate regarding the formalization of the protection status of these northern boreal forests remain to be undertaken.

6. Conclusions

Canada's PPAs have a noteworthy history. Canada established the world's 3rd national park (in 1885, with Banff) and created the world's 1st national park service in 1911 (McNamee 2009). A century later, protected areas are more explicitly tied to the preservation of biodiversity and the establishment of effective protected area systems is more complicated than perhaps was first anticipated. Beyond the declaration of a reserve, high-quality PPA systems demand consideration of spatial patterns of biodiversity and ecosystem service providers, accommodating the effects of landscape dynamics and climate change, and balancing the demands of competing land uses and residents. With these factors in mind, Canada retains capacity and flexibility to demonstrate leadership in the scientifically informed creation and management of parks and protected areas. Although today the Canadian boreal zone has a level of formal protection slightly below national and global averages, and important gaps and biases in the distribution of protection remain, the currently limited human activity in this region may enable the implementation of a globally unique, continent-scale, connected protected area network supplemented with integrated landscape management.

At present, like protected area systems in many other nations (Joppa and Pfaff 2009), alpine and non-vegetated areas are over-represented among protected areas in boreal Canada. Although the boreal zone is largely associated with forests, forested land cover is slightly under-represented in the current boreal PPA system. Depending upon the conservation targets put forward, notions for the expansion of the boreal PPA system can be supported by data and models, enabling insights on where to place conservation areas, what characteristics are protected, and what capacity for spatial resilience is present. Industrial development in boreal Canada need not be incompatible with regional scale conservation objectives (Mathey et al. 2008; Schneider et al. 2011). When conservation aims are included in comprehensive, spatially explicit land-use planning, the ecological needs of biodiversity and the economic needs of human societies can be met with limited tradeoffs (Mathey et al. 2008; Schneider et al. 2011). It is when planning is neglected and conservation only an afterthought that biodiversity tends to suffer, and it becomes difficult to achieve protected area representation goals (Pressey 1994). Unfortunately, due to a history of unchecked development, many parts of the world may no longer have the capacity to establish an optimal conservation network composed of large, connected reserves embedded in a sustainably managed matrix. In contrast, Canada retains the potential to consider further development of national conservation networks, especially over northern boreal forests — this is a remarkable and rare potential that can facilitate future policy and planning activities.

Acknowledgements

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Appendix A. Gap analysis of the current boreal PPA system

A1. Datasets and methods

A1.1. Environmental surrogates

A1.1.1. Ecozones

Regional-scale ecosystems, as delineated by ecoregion classifications, have been used for many protected area assessments, including several in Canada (reviewed in section 3.2). We used the Canadian ecozone framework (Ecological Stratification Working Group 1995) as an environmental surrogate, with the Boreal and Taiga Shields split into separate eastern and western units (Fig. 1*b*). Ecozones are large units exhibiting relatively homogenous climate, geology, topography, soils, hydrology, vegetation, wildlife, and land use. As such, they are assumed to contain unique elements of biodiversity and thus provide useful frameworks for conservation planning (Olson and Dinerstein 1998).

A1.1.2. Land cover

Land-cover and vegetation classifications are also widely used as biodiversity surrogates for conservation planning and assessment, in Canada (Table 2) and elsewhere (e.g., Scott et al. 1993; Groves et al. 2000). Vegetation classes are expected to represent distinct habitats hosting unique complements of species (Kerr and Ostrovsky 2003; Venier et al. 2004). Land-cover information was derived from the Earth Observation for Sustainable Development of forests (EOSD) dataset (Fig. 1*d*). This classification was generated for the forested area of Canada from classified Landsat imagery, re-sampled to 25 m spatial resolution, using a hierarchical legend with 23 classes (Wulder et al. 2008*a*). We aggregated the EOSD to 1 km resolution using a majority rule. Twenty of the EOSD land-cover classes occur in boreal Canada at 1 km resolution. We also collapsed land-cover classes along the legend (Wulder and Nelson 2003) to evaluate the PPA system by successively broad vegetation types. When aggregating land-cover classes, the wetland types were included with the appropriate physiognomic classes (e.g., "Herbaceous" cover includes "Herbs" and "Wetland–Herb"). The proportion of surface water within each 1 km pixel (Fernandes et al. 2001) was also used to assess the distribution of PPAs relative to aquatic features.

A1.1.3. Vegetation productivity

Vegetation productivity is the amount of solar energy captured by plants through photosynthesis, given the climate and resource limitations of an ecosystem, and represents the amount of energy that is available for ecological processes. Productivity is the strongest correlate of species richness at broad scales (e.g., Hawkins et al. 2003; Field et al. 2009). Productivity has rarely been used as an environmental surrogate of biodiversity in gap analyses of protected area systems, although relationships of productivity with species richness (Hawkins et al. 2003; Field et al. 2009) and species turnover (e.g., Buckley and Jetz 2008) suggest that it holds potential for conservation assessments. Here, we extend our earlier work evaluating productivity biases of Canada's PPA system (Andrew et al. 2011*a*) to the boreal zone, using the Canadian dynamic habitat index (DHI; Fig. 1*a*) of Coops et al. (2008). The DHI uses vegetation productivity (MODerate-resolution Imaging Spectrometer (MODIS) fraction of absorbed photosynthetically active radiation (fPAR) values) to represent spatiotemporal variability in habitat conditions along three axes: minimum annual productivity, integrated annual productivity, and the seasonality (coefficient of variation) of annual productivity. These three components were taken as averages over 2000–2005. The DHI has a spatial resolution of 1 km. Elevation (Rabus et al. 2003), an important variable linked to productivity, is often coupled with the DHI and is used here.

A1.1.4. Landscape structure

The spatial arrangement of habitats influences the flows of organisms, materials, and energy through a landscape, with effects on individual species distributions, emergent properties such as spatial patterns in species richness or community composition, and ecological processes (e.g., Titeux et al. 2004). Although concepts from landscape ecology inform many spatial design criteria in conservation planning (e.g., reserve size and connectivity; reviewed by Williams et al. 2005*a*), the varying spatial configuration of habitats has not been generally adopted as an element to target in representation goals. However, landscape structure is an important axis of natural environmental variability (Turner et al. 2001) and could be captured within a representative reserve network. We evaluated representation along landscape structure with two sets of surrogates. The first was landscape diversity metrics calculated when aggregating the EOSD land-cover information from 25 m to 1 km. Two metrics were used: the number of unique land-cover types within a 1 km grid cell (richness) and Simpson's diversity index, which weights the land covers by their abundance.

Our second environmental surrogate derived from landscape structure was a classification of boreal landscapes using their pat-

terns of forest cover (Figs. 1*e*, 1*f*; Cardille et al. 2012). This approach groups all landscapes within the study extent into a set of unique landscape types. Each landscape within a type has a common spatial configuration of forested land cover, which is defined by an exemplar landscape — the individual landscape most characteristic of the landscape type as a whole (Cardille and Lambois 2010). Cardille et al. (2012) identified two exemplar landscape types for each boreal ecozone using independent axes computed from nine forest fragmentation metrics calculated in 1:50 000 NTS map landscapes (800 km²) from the 25 m EOSD land-cover product (Wulder et al. 2008*b*). The exemplar landscapes are described in more detail in Cardille et al. (2012).

A1.2. Protected area data

The boundaries of protected areas in boreal Canada (Fig. 1*b*) were taken from two sources. The Conservation Areas Reporting and Tracking System (CARTS 2011) provided information on PPAs throughout most of the boreal zone but coverage of protected areas in Quebec was not readily available. Quebec PPAs were derived from the World Database on Protected Areas (IUCN and UNEP 2010). Evaluations were performed for the PPA system as a whole, for individual IUCN management designations (Dudley 2008), and for reserves grouped by their IUCN categories into strict (Ia–IV) and anthropogenic (V, VI, and unknown) protected areas. These databases were also used to summarize PPAs by management agency and type.

A2. Representation analyses

We assessed representation in two ways. First, we calculated proportional representation, by area, for categorical biodiversity surrogates (ecozones, land-cover classes, and landscape-structure classes). Second, for continuous surrogates (productivity, elevation, land-cover diversity, and water fraction), we calculated a measure of bias. Bias was calculated as the proportion by which the median of an environmental variable in protected areas differs from its median throughout the calculation extent; it is sensitive to systematic patterns in representation along environmental gradients. The spatial extent for each calculation was either the complete boreal zone, or individual boreal ecozones, or the set of areas containing individual land-cover classes, as appropriate.

To estimate representation and bias of ecozones, land cover classes and diversities, and vegetation productivities, the protected area and ecozone coverages were rasterized to the 1 km resolution of the land-cover and productivity datasets. As a result, each 1 km² pixel was attributed with a value for each of the biodiversity surrogates, protection status, and protected area category. Because of the much coarser resolution of the landscape classification (800 km²), representation of this surrogate was estimated from the areal extent of each landscape type overall and in overlap with the PPA polygons. Furthermore, although the identification and classification of landscape types was constrained to individual forested ecozones, some leakage occurred at ecozone boundaries due to the coarse resolution of the calculation landscapes. For simplicity, we associated each landscape type with its primary ecozone, rather than specifically accounting for vagrants within neighbouring ecozones. Because of these differences in processing between the landscape classification analyses and all others, specific numerical results did not match exactly. Inconsistencies were generally minor and only became extreme for ecozones with little area in the boreal zone (e.g., Montane Cordillera).

A3. Results

The distribution of protected areas is variable across ecozones, land-cover classes, vegetation productivities, and landscape structures, although all components of all biodiversity surrogates do occur within the boreal PPA system. For the most part, PPAs provide strict protection in boreal Canada. Most boreal PPAs (77%) have management goals corresponding to those of wilderness

areas (IUCN category Ib) or national parks (IUCN category II). Because we have not adopted a specific numerical target for evaluation, our presentation of the current representation levels of the boreal PPA system uses the proportional protection of Canada's boreal zone as a whole (8%) as a reference value. This can be thought of as the average protection status of the region. Thus, unless noted, biodiversity elements with greater than 8% of their area in PPAs are referred to below as "over-represented", and vice versa. Note that this is not meant to imply that conservation needs are met for such elements, rather that they receive a disproportionately high level of protection under the current PPA system.

A3.1. Ecozones

Protection is unevenly distributed across ecozones (Fig. 2), which agrees with previous assessments (Hummel 1995; Environment Canada 2006; Andrew et al. 2011*a*; Lee and Cheng 2011). The greatest extremes in protection occur for ecozones that are largely peripheral to the boreal zone. Note that all analyses were performed only for the boreal portions of ecozones and may not reflect the PPA coverage of peripheral ecozones in their entirety. Boreal portions of the Montane Cordillera have the greatest protection (38%), while less than 1% of the boreal portion of the Pacific Maritime is protected. All mountain ecozones (Boreal Cordillera, Montane Cordillera, and Taiga Cordillera) have above average protection. Canadian shield ecozones (Boreal Shield and Taiga Shield East and West) have lower proportional protection than the boreal zone overall.

A3.2. Land cover

The Canadian boreal zone has slightly greater forested (54% of total area) than non-forested (45%) cover. This estimate corresponds very closely to Brandt's (2009) finding that 58% of the boreal zone is covered by forest and other wooded land. Minor differences are due to the use of different forest cover datasets: EOSD versus CanFI. In contrast, forests account for 49% of the PPA system, indicating that forests are slightly under-represented in boreal protected areas. Nearly all non-forested land-cover categories were over-represented in the PPA system, especially non-vegetated and wetland classes (Fig. 3). Within the forested land-cover classes, levels of protection vary. Some forest types are proportionately better protected than the boreal zone overall. In general, broadleaf forests had the greatest representation, although they are the least common forest type in the boreal zone. Sparse forests (≤25% crown cover) had notably low protection, especially in the coniferous-sparse class (Fig. 3).

PPAs were generally unbiased along the fraction of open water in a 1 km pixel (bias = −0.016, results not shown). There was no strong over-representation of any water fractions; areas with moderate water fraction (~10%–20%) were under the least protection, but the difference was modest (~2%–3%, not shown). Note that the study extent excluded very large bodies of water such as the Great Bear Lake, Great Slave Lake, and Lake Winnipeg.

A3.2.1. Land cover by ecozone

Protection by land-cover category also varied among the ecozones (Table 5). For example, non-vegetated and non-forested land is under-represented (relative to the proportion of the ecozone protected overall) in the Boreal Plains and boreal portions of the Atlantic Maritime, respectively. Mountain ecozones (Boreal Cordillera and Montane Cordillera) had especially high representation of non-vegetated land covers, as did the Boreal Shield West. Mosses were most represented in the Hudson Plains. Forested classes, taken together, were not over-represented in any ecozone; but individual forest types have regionally variable protection.

A3.3. Vegetation productivity

There was little bias in protection of vegetation productivities or elevations across the entire boreal zone (Table 3), notwithstand-

ing high over-representation of the lowest productivities (Fig. 4l) and highest elevations (Fig. 5l), which are relatively rare in the boreal zone. The two dominant types of PPAs in Canada's boreal zone revealed contrasting productivity biases: Wilderness areas (IUCN Ib) were biased toward low integrated annual productivities while national parks (IUCN II) were slightly biased toward high productivities. IUCN categories V, VI, and parks with unknown designations were consistently biased to low productivities (Table 3). Biases in the seasonality of productivity mirrored these patterns in integrated annual productivity. No IUCN category was biased with respect to elevation (Table 3). There is very little variation in minimum annual productivity throughout the boreal zone and so biases were unlikely along this axis.

A3.3.1. Vegetation productivity by ecozone

Productivity and elevation biases were more extreme for individual ecozones (Table 6) and land-cover classes (Table 4). Ecozonal PPA systems were either unbiased or negatively biased with respect to integrated annual productivity. Both positive and negative biases occurred in relation to elevation. Interestingly, the Taiga Cordillera is largely protected in low elevations; this is notable since protection in mountain regions tended to be biased to high elevations.

A3.3.2. Vegetation productivity by land cover

As with the ecozone results, individual land-cover classes tended to be biased toward an over-representation of low productivities (high seasonalities) (Fig. 4; Table 4). Exceptions were the sparse forest classes, especially sparse coniferous and broadleaf forests. The mixedwood forests (especially open and sparse densities) in PPAs were also less seasonal than is this forest type overall. High elevations were strongly over-represented for nearly all land-cover classes (Fig. 5), but this translated into positive elevation bias only for the non-vegetated and low shrubland classes (Table 4). Protection of certain wetland and broadleaf forest classes was biased to low elevations (Table 4).

A3.4. Landscape structure

A3.4.1. Land-cover diversity

We found that protected landscapes were simpler than boreal landscapes in general. The richness of land-cover classes per km² was 5% lower in PPAs than throughout the boreal zone (Table 3). This bias to low-richness landscapes was especially true for strict categories of PPAs: Wilderness areas and national parks both had 10% lower land-cover richness than boreal landscapes as a whole. In contrast, less restrictive PPA types were found in landscapes with greater land-cover richness (Table 3). Simpson's diversity index was less variable than land-cover richness across the boreal zone and was generally less biased for boreal PPAs (Table 3). Only PPA types with positive biases in land-cover richness were biased in land-cover diversity. Greater biases for land-cover richness than diversity indicated that the reduced density of land covers within protected areas is primarily driven by types that are rare at the level of 1 km² pixels. The tendency for reduced land-cover richness within PPAs was also generally observed for individual boreal ecozones (Table 6), but the diversity of land-cover classes per km² was greater within PPAs than without for the Taiga Shield East ecozone (Table 6).

A3.4.2. Landscape types

The two landscape classes within each ecozone generally received unequal protection (Fig. 6). Patterns of protection within each landscape-level class were generally consistent with those by land-cover class (see section A3.2) and elevation (section A3.3). For example, just as forested land-cover classes were generally under-protected, so too were forest-dominated landscapes for most ecozones. Similarly, high-elevation sites and, as a consequence, forest landscapes that are fragmented by mountainous terrain were over-represented. In contrast to these general patterns, for the two

landscape types identified apiece in the Boreal Cordillera and the Boreal Shield ecozones, the more forest-dominated landscape of each pair (exemplified by landscapes 095C10 and 052013 in Fig. 1f) was more protected. Interestingly, for the exceptions, representation of landscape classes did not necessarily correspond to representation of land-cover classes. For example, for the Boreal Cordillera and Boreal Shield West ecozones, forested land cover was slightly under-represented (Table 5), despite the over-representation of forest-dominated landscapes in those ecozones. Similarly, while the more wetland-dominated landscape class (exemplified by landscape 054A07) was over-represented in the Hudson Plains, the wetland land-cover type was not. This can occur because the analysis units for the landscape classification were quite large (800 km²) and may thus be protected over only a fraction of their extent. There is no guarantee that the PPAs within those landscapes contain the dominant land-cover class. In other words, although these landscape types may be represented within the PPA system, the parks they contain may not represent the greater landscape context.

Four landscape exemplars (all exemplars in the Atlantic Maritime and Boreal Plains ecozones) reflect a role of anthropogenic activity in shaping landscape structure (Cardille et al. 2012). There does not appear to be a consistent relationship between representation and the presence or type of human use. Forestry and agriculture are detectable in both Atlantic Maritime landscape classes. In the Boreal Plains, the landscape exemplar with noticeable agriculture (landscape 083M02 in Fig. 1f) had substantially greater protected area than the landscape revealing a spatial signal of forest management (084J10).

A4. Caveats

It must be noted that some of our specific findings are subject to the quality of the biodiversity surrogate datasets that were used, although our general conclusions of uneven protection would remain unchanged. For example, while the EOSD land-cover classification has a stated overall accuracy target of 80% (Wulder et al. 2008a), each class was not mapped with equal success. In particular, the finest level of classification detail, such as forest density and shrub height classes, were the most uncertain because the distinctions between these successional classes are based upon subtle distinctions and poorly resolved both in the satellite imagery and to a human observer (Wulder et al. 2007).

Another consideration is that, with the exception of the ecozones, our surrogates reflect the state of the boreal zone circa 2000. This raises related concerns for setting representation targets (e.g., protect features relative to their current or historic extent? Vellend et al. 2008) and regarding the degree to which each natural feature is contaminated by anthropogenic activity. To some extent, these concerns are reduced in the boreal zone relative to other, more developed regions of the world. We evaluated the potential contamination of our environmental surrogates by human activity by determining the associations between each surrogate and anthropogenic infrastructure (using the distance to nearest road and settlement surfaces developed by Wulder et al. 2011). Areas of anthropogenic access were strongly biased to high productivities and herbaceous and densely forested land cover, but unrelated to patterns of landscape diversity (results not shown). Associations with landscape types were similar to the visible patterns of human development in the exemplar landscapes: Landscapes in the Boreal Plains were most associated with human infrastructure (results not shown). In general, we do not believe that these associations imply that particular natural features are a sign of anthropogenic disturbance (with the possible exception of the strong associations with herbaceous vegetation). Rather, they indicate the clear geographic bias of human settlement in Canada to southern regions of dense, highly productive forests. Such patterns have been discussed previously for Canada (Andrew et al. 2011a) and elsewhere (Luck 2007).