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Characterizing the forest fragmentation of Canada's national parks

Nicholas O. Soverel · Nicholas C. Coops · Joanne C. White · Michael A. Wulder

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Abstract Characterizing the amount and configuration of forests can provide insights into habitat quality, biodiversity, and land use. The establishment of protected areas can be a mechanism for maintaining large, contiguous areas of forests, and the loss and fragmentation of forest habitat is a potential threat to Canada's national park system. Using the Earth Observation for Sustainable Development of Forests (EOSD) land cover product (EOSD LC 2000), we characterize the circa 2000 forest patterns in 26 of Canada's national parks and compare these to forest patterns in the ecological units surrounding these parks, referred to as the greater park ecosystem (GPE). Five landscape pattern metrics were analyzed: number of forest patches, mean forest patch size (hectare), standard deviation of forest patch size (hectare), mean forest patch perimeter-to-area ratio (meters per hectare), and edge density of forest patches (meters per hectare). An assumption is often made that forests within park boundaries are less fragmented than the surrounding GPE, as indicated by fewer forest patches, a larger mean forest patch size, less variability in forest patch size, a lower perimeter-to-area ratio, and lower forest edge density. Of the 26 national parks we analyzed, 58% had significantly fewer patches, 46% had a significantly larger mean forest patch size (23% were not significantly different), and 46% had a significantly smaller standard deviation of forest patch size (31% were not significantly different), relative to their GPEs. For forest patch perimeter-to-area ratio and forest edge density, equal proportions of parks had values that were significantly larger or smaller than their respective GPEs and no clear trend emerged. In summary, all the national parks we analyzed, with the exception of the Georgian Bay Islands, were found to be significantly different from their corresponding GPE for at least one of the five metrics assessed, and 50% of the 26 parks were significantly different from their respective GPEs for all of the metrics assessed. The EOSD LC 2000 provides a heretofore unavailable dataset for characterizing broad trends in forest fragmentation in Canada's national parks and in their surrounding GPEs. The interpretation of forest fragmentation metrics must be guided by the underlying land cover context, as many forested ecosystems in Canada are

N. O. Soverel · N. C. Coops (✉)
Department of Forest Resource Management,
University of British Columbia, 2424 Main Mall,
Vancouver, V6T 1Z4, Canada
e-mail: nicholas.coops@ubc.ca

N. O. Soverel
e-mail: nsoverel@interchange.ubc.ca

J. C. White · M. A. Wulder
Canadian Forest Service (Pacific Forestry Center),
Natural Resources Canada, Victoria,
British Columbia, V8Z 1M5, Canada

naturally fragmented due to wetlands and topography. Furthermore, interpretation must also consider the management context, as some parks are designed to preserve fragmented habitats. An analysis of forest pattern such as that described herein provides a baseline, from which changes in fragmentation patterns over time could be monitored, enabled by earth observation data.

Keywords Forest · Fragmentation · Landsat · Canada · National parks · Ecosystem

Introduction

The overall aim of a network of protected areas is to represent regional biodiversity, including key species, landforms, and natural communities present within a local environment (Wiersma 2007). Specifically, Canada's national parks are designed to protect the habitats, wildlife, and ecosystem diversity representative of (and sometimes unique to) Canada's natural regions (Parks Canada 2009). Both the 1997 State of the National Parks Report (Parks Canada 1998) and the Report of the Panel on the Ecological Integrity of Canada's National Parks (Parks Canada 2000) concluded that Canada's national parks were under threat from a variety of internal and external pressures, including habitat loss and fragmentation, climate change, over use, and alien species. A number of these threats have been explored and their impact documented (Rivard et al. 2000; Scott et al. 2002; Dearden and Dempsey 2004; Young et al. 2006). In response to these reports, Canada's National Parks Act was revised in 2001 to reflect the increased emphasis on ecological integrity in Parks management. Under this revised legislation, each national park is required to have a management plan containing "a long-term ecological vision for the park, a set of ecological integrity objectives and indicators and provisions for resource protection and restoration, zoning, visitor use, public awareness and performance evaluation, which shall be tabled in each House of Parliament"; this management plan must be reviewed every 5 years.

The detection of ecological stresses inside Canada's national parks and in the areas surrounding national parks (hereafter referred to as the greater park ecosystem or GPE) not only provides an indication of changes to the ecological integrity of the national parks but also serves as a warning system for broader potential impacts outside of protected areas (Parks Canada 2008). The Panel on Ecological Integrity provided the following definition of ecological integrity (Parks Canada 2008): "An ecosystem has integrity when it is deemed characteristic for its natural region, including the composition and abundance of native species and biological communities, rates of change, and supporting processes." The concept of ecological integrity is particularly critical when the area protected within the park boundaries is less than the minimum reserve area suggested for conserving species diversity in parks in North America (which is approximately 10,000 km^2; Newmark 1995; Gurd et al. 2001; Wiersma 2001).

One of the potential threats to Canada's national parks is fragmentation (Parks Canada 2000), and in particular fragmentation of forests (CCFM 1997). Fragmentation is most commonly defined as the breaking apart of habitat (Fleishman and Mac Nally 2007), independent of habitat loss (Fahrig 2003), and is driven by a variety of factors, including both natural processes, such as fires and insect infestation, and anthropogenic activities, such as logging or road building (Linke et al. 2007).

Forest fragmentation has the capacity to impact habitat quality for more than 80% of all mammal, reptile, bird, and amphibian species (USDA Forest Service 1997), and while some species are naturally adapted to edge or interior forest habitats created by natural disturbance regimes, the competitive advantages among populations change significantly once fragmentation occurs (Bishop 1993; Kupfer 2006). This can result in irrevocable changes to biodiversity patterns and richness (Riitters et al. 2002) as the energy cost/benefit ratio of movement increases as patterns become more contorted (Gardner et al. 1991; Pearson et al. 1996). Extinction rates have been shown to peak immediately after habitat fragmentation and then slowly decrease (Terborgh 1974; Wilcox 1978).

Wulder et al. (2008a) discussed four types of landscape fragmentation likely to occur in

Canadian forested landscapes. First, forest fragmentation may be the natural state in wetland or alpine areas, which are dominated by non-forest cover types. Second, anthropogenic disturbance such as timber harvesting (Hudak et al. 2007) and road building (Trombulak and Frissell 2000) may result in the fragmentation of forested areas (Heilman et al. 2002). Third, natural disturbances such as fire (Hudak et al. 2007) windthrow, and insect infestations (Huges et al. 2006) will fragment forested landscapes. Finally, adjacent land cover, modified through urbanization or agricultural development, may also further fragment forest areas.

Understanding the extent, spatial character, and distribution of forest patches within parks and their GPEs draws on theories from island biogeography (MacArthur and Wilson 1967) and landscape ecology (McGarigal and Marks 1995). Forest pattern metrics provide a relative measure of forest fragmentation, facilitating comparisons between different geographic areas, as well as multi-temporal analysis within the same area. Capturing baseline information on forest pattern is important, as fragmentation is ephemeral and will vary as a result of changes to land cover, either through planned deforestation or reforestation activities, or as a result of natural succession processes (Wulder et al. 2008a).

While the task of monitoring parks and their GPEs is an important component of Parks Canada's mandate (Parks Canada 2007), many Canadian parks cover large areas and are often located in remote areas, resulting in financial and logistical barriers to the use of traditional field or airborne survey techniques. Fortunately, earth observation data are a cost-effective option for consistently capturing land cover information over large areas (Franklin and Wulder 2002). The recently completed, and publicly available, Earth Observation for Sustainable Development of Forests (EOSD) data represent land cover of the forested ecozones of Canada, as captured using circa 2000 Landsat imagery with a 25-m spatial resolution (EOSD LC 2000; Wulder et al. 2008b). The EOSD LC 2000 dataset provides an important opportunity to characterize national forest patterns for a range of applications.

In this paper, we focus on improving our understanding of forest fragmentation within Canada's national parks and their GPEs. Some parks have land cover types that result in inherent natural forest fragmentation (i.e., wetlands, alpine). Furthermore, forest patches resulting from natural disturbances often have different characteristics (i.e., size, shape) compared to patches generated through anthropogenic activities such as timber harvesting (Tinker et al. 1998). In this study, we focus on national parks that are predominantly forested (>40%, by area) and compare forest fragmentation patterns within these parks to patterns in their GPE. Based on these comparisons and the land cover context, we are able to make inferences concerning natural versus anthropogenic fragmentation (Parks Canada 2008).

The overall goal of this paper is to characterize forest patterns of Canada's national parks and their surrounding GPEs. Our primary objective is to use the EOSD LC 2000 to assess the relative fragmentation of forests within the boundaries of national parks and compare this to the level of fragmentation in the GPEs surrounding these parks. Our secondary objective is to compare and contrast the level of forest fragmentation between national parks located in different parts of Canada. Finally, we provide a discussion on the potential use of earth observation technology to monitor changes in forest fragmentation in national parks over time, recognizing that forest fragmentation is a dynamic process that requires ongoing monitoring for effective park management (Fortin and Dale 2005; Wagner and Fortin 2005).

Methods

Data

Earth observation for sustainable development of forests

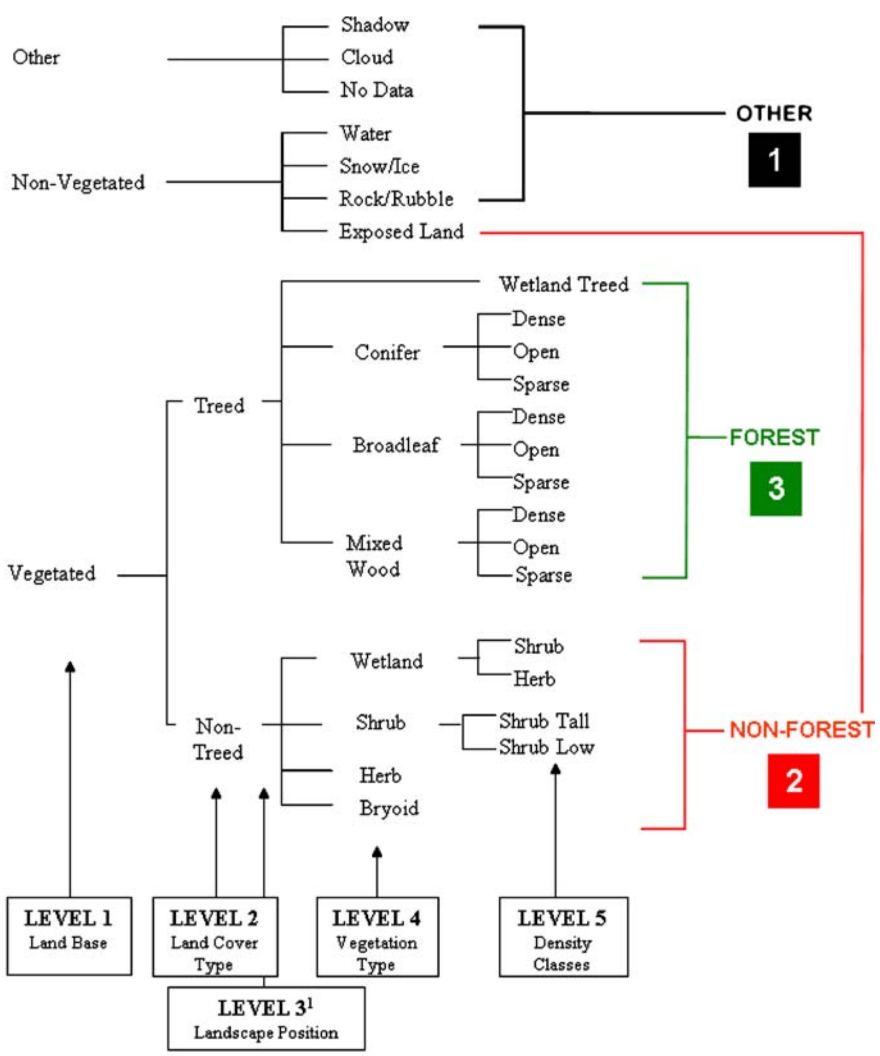
The EOSD LC 2000 product provides a 23 class land cover classification of the forested ecozones of Canada. The classification involved the pre-processing of over 450 Landsat Enhanced Thematic Mapper Plus (ETM+) and Thematic

Mapper (TM) images acquired between 1999 and 2001 to represent year 2000 conditions (Wulder et al. 2008b). A top of atmosphere correction was applied to account for the influence of sun illumination on pixel radiometric response (Markham and Barker 1986; Peddle et al. 2003), followed by an unsupervised classification (*k*-means) and clustering approach and interpreter-assisted cluster merging and labeling (Wulder et al. 2008b). Figure 1 shows the land cover legend used to construct the EOSD product. The accuracy of the EOSD LC 2000 is estimated to be approximately 80% over all classes, with greater accuracy found for the more dominant forest classes (Wulder et al. 2007a, b, 2008a). Further, class accuracy can also be expected to increase as class generalization or simplification is applied (Remmel et al. 2005).

Canada's national parks

The national park boundaries used in this analysis were acquired from The Atlas of Canada 1:1,000,000 National Scale Frameworks Data (Government of Canada 2006) and are current

Fig. 1 Landscape pattern metrics were generated from aggregated EOSD land cover classes: forest, non-forest, and other



[1]Level 3 is not illustrated here as this level does not exist in the same manner in the EOSD and NFI classification systems. In the NFI land cover classification scheme, this level refers to landscape position (e.g. alpine, upland, or wetland).

to 2006. The data contain spatial boundaries and attribute information for protected areas that are 1,000 ha or larger (43 national parks) and were created using polygon and attribute data supplied by the Canadian Wildlife Service at Environment Canada, on behalf of the Canadian Council on Ecological Areas.

Greater park ecosystems: ecoregions of Canada

The hierarchically structured system of ecozones, ecoprovinces, ecoregions, and ecodistricts forms Canada's National Ecological Framework (Ecological Stratification Working Group 1996). At the broadest level of generalization, the framework is comprised of 15 terrestrial ecozones, which represent the ecological mosaic of Canada at a subcontinental scale. Ecozones are divided into ecoprovinces, which area characterized by "major assemblages of structural or surface forms, faunal realms, and vegetation, hydrology, soil, and macro climate" (Ecological Stratification Working Group 1996). In turn, ecoprovinces are further subdivided into ecoregions, which are characterized by distinctive regional ecological factors, including climate, physiography, vegetation, soil, water, and fauna. There are 194 ecoregions in Canada, and in this study, ecoregions were used to define the GPE.

Forest fragmentation metrics

In order to characterize the fragmentation of Canada's forested land, it is necessary to select a set of landscape metrics that are appropriate for use over a large land area; depict fragmentation as a condition of the landscape; capture the different types of fragmentation caused by natural and anthropogenic disturbances, ecosystem characteristics, and land use activities; are not redundant; and are intuitive and meaningful to understand when reported regionally or nationally (Wulder et al. 2008a).

Based on a review of the recent literature regarding the use of landscape metrics for assessing forest fragmentation (Gergel 2007), five metrics were selected for use in this analysis: number of forest patches (f_patch), mean forest patch size (hectare; f_marea), standard deviation of forest patch size (hectare; f_sarea), mean forest patch perimeter–area ratio (meters per hectare; f_mratio), and edge density of forest patches (meters per hectare; f_dense; Table 1). Number of forest patches is an informative landscape metric, especially when used in relation to other metrics to compare landscapes of similar extent and data resolution (Leitao et al. 2006). When the number of patches is used in conjunction with mean patch size and standard deviation of patch size, a clearer picture of patch frequency, size of patch, and distribution of patch sizes over the whole landscape can be distinguished. According to McGarigal and Marks (1995), patch area is one of the most relevant and useful metrics for assessing landscapes.

Patch perimeter-to-area ratio is a measure of the geometric complexity of a patch and it deals with the variation in patch shape (i.e., simple shapes such as squares versus more complex forest shapes such as wildland fire perimeters). Edge density measures the standardization of edge on a per unit basis and enables the comparison of landscapes of varying sizes (McGarigal and Marks 1995). Unlike perimeter-to-area ratio which measures shape complexity, edge density is directly associated with the spatial heterogeneity in that landscape (McGarigal and Marks 1995). Although perimeter-to-area ratio and edge density are related at the patch level, edge density is considered to have strong adverse effects on organisms and appears to be directly or indirectly tied to many other class metrics (McGarigal and Marks 1995).

As noted by Gergel (2007), the image grain, minimum mapping unit, extent, and underlying classification, all influence the calculation of landscape pattern metrics. The grain size in this study is 25 m (the spatial resolution of the EOSD LC 2000), while the extent of the area within which landscape pattern metrics are calculated (i.e., the analysis unit) was 1 km by 1 km.

Fragmentation metrics were generated from the EOSD LC 2000 using APACK analysis software version 2.23, freely available from the University of Wisconsin Forest Ecology Laboratory (Mladenoff and Dezonia 2004). The partition of the EOSD classes for metric calculation represents level 2 of the National Forest Inven-

Table 1 Landscape pattern metrics used to compare parks and their respective GPEs

Metric	Name	Description and interpretation	Reference
Number of forest patches	f_patch	The number of forest patches within the analysis unit are enumerated. The more forest patches there are, the fragmented the forest is considered to be	Turner et al. (2001); McGarigal et al. (2002)
Mean forest patch size (ha)	f_marea	The average size of a forest patch within the analysis unit. A smaller average forest patch size is considered indicative of a more fragmented forest	McGarigal et al. (2002)
Standard deviation of forest patch size (ha)	f_sarea	A measure of the absolute variation in patch size for the analysis unit. The mean patch size can obscure the presence of very large or very small patches	McGarigal and Marks (1995); Cumming and Vervier (2002)
Mean forest patch perimeter–area ratio (m/ha)	f_mratio	Patches are expected to become less geometrically complex in a managed forest landscape. A low mean forest patch perimeter–area ratio may be associated with more fragmented forests (if the fragmentation is related to anthropogenic disturbance)	McGarigal and Marks (1995)
Forest edge density (m/ha)	f_dense	The amount of forest edge (m/ha) in the analysis unit. Larger values indicate more edge habitat and more forest fragmentation	McGarigal and Marks (1995); Li et al. (2005)

tory classification hierarchy, which distinguishes between vegetated treed (forest), vegetated non-treed (non-forest), and non-vegetated classes (Fig. 1). The class identified as "other" (Fig. 1), which included the non-vegetated classes of water, snow/ice, and rock/rubble, was regarded as background by APACK, and consequently was not included in metric calculation. APACK generates both landscape- and class-level metrics, with the landscape-level metrics incorporating both forest and non-forest classes. The non-forest class included the wetland, shrub, bryoid, herb, and exposed land classes, while the forested class included the wetland treed, coniferous, broadleaf, and mixedwood classes. For this analysis, we are primarily interested in class-level metrics for the forested group of classes. The number of neighboring cells used for metric calculation was eight, and the EOSD pixels found along the borders of the 1 km by 1 km analysis units were not included in the analysis (i.e., were not considered edges; Wulder et al. 2008b).

Analysis approach

Only those national parks that intersected the area mapped by the EOSD project and that had more than 40% of the park area as a forested class (Fig. 1) were included in our analysis ($N = 26$ parks; Table 2). In order to compare the level of forest fragmentation within national park boundaries to the GPEs, our approach followed that of Wulder et al. (2007a, b). Initially, two populations were defined: the primary population, which consisted of all the analysis units within the park boundary; and, the secondary population, which consisted of all the analysis units located within the GPE, but not within park boundaries. All of the analysis units within the primary population

Table 2 List of national parks examined in this study, their location, area, and the surrounding ecoregion(s) used to define the greater park ecosystem (GPE)

Name	Location	Area (km^2)	Greater park ecosystem (GPE)	Date est.
Banff National Park	Alberta	6,641	Eastern Continental Ranges	1885
Cape Breton Highlands National Park	Nova Scotia	949	Cape Breton Highlands, Nova Scotia Highlands	1936
Elk Island National Park	Alberta	194	Aspen Parkland	1913
Forillon National Park	Quebec	244	Appalachians	1970
Fundy National Park	New Brunswick	206	Fundy Coast, Southern New Brunswick Uplands	1948
Georgian Bay Islands National Park	Ontario	13	Algonquin—Lake Nipissing	1929
Glacier National Park	British Columbia	1,349	Columbia Mountains and Highlands	1886
Gros Morne National Park	Newfoundland	1,805	Long Range Mountains, Northern Peninsula, Southwestern Newfoundland	1973
Gulf Islands National Park Reserve	British Columbia	33	Georgia-Puget Basin	2003
Gwaii Haanas National Park Reserve and Haida Heritage Site	British Columbia	1,495	Queen Charlotte Ranges	1988
Jasper National Park	Alberta	10,878	Eastern Continental Ranges	1907
Kejimkujik National Park	Nova Scotia	404	Atlantic Coast, Southwest Nova Scotia Uplands	1968
Kootenay National Park	British Columbia	1,406	Western Continental Ranges	1920
Kouchibouguac National Park	New Brunswick	239	Maritime Lowlands	1969
La Mauricie National Park	Quebec	536	Southern Laurentians	1970
Mingan Archipelago National Park Reserve	Quebec	151	Mecatina Plateau	1984
Mount Revelstoke National Park	British Columbia	260	Columbia Mountains and Highlands	1914
Nahanni National Park Reserve	Northwest Territories	4,766	Nahanni Plateau, Selwynn Mountains, Sibbeston Lake Plain	1976
Pacific Rim National Park Reserve	British Columbia	511	Western Vancouver Island	1970
Prince Albert National Park	Saskatchewan	3,874	Boreal Transition, Mid-Boreal Uplands	1927
Pukaskwa National Park	Ontario	1,878	Abitibi Plains	1978
Riding Mountain National Park	Manitoba	2,973	Boreal Transition, Mid-Boreal Uplands	1929
Terra Nova National Park	Newfoundland	400	Central Newfoundland, Northeastern Newfoundland	1957
Waterton Lakes National Park	Alberta	505	Northern Continental Divide	1895
Wood Buffalo National Park	Alberta/Northwest Territories	44,807	Hay River Lowland, Mid-Boreal Uplands, Northern Alberta, Uplands Slave River Lowland, Peace Lowland, Tazin Lake Upland, Wabasca Lowland	1922
Yoho National Park	British Columbia	1,313	Western Continental Ranges	1886

were considered in the analysis, and a matching number of randomly selected analysis units were drawn from the secondary population in the GPE.

If a park was intersected by one or more ecoregions, which often occurred in large parks, the analysis units inside the park were allocated to the ecoregion in which they were found (inside the park). Then, outside the park, a random sample of analysis units equal in size to the number of analysis units found in that ecoregion inside the park, was selected from within that same ecoregion outside the park.

To fulfill our first objective, the mean values of the five forest fragmentation metrics were calculated for the samples within the park and within the park GPE. These mean values within each park were then compared to the forest fragmentation within each park's GPE using a two-tailed *t* test with a standard critical probability threshold of $p < 0.05$. To satisfy our second objective of comparing and contrasting the level of forest fragmentation among parks representing different ecological regions of Canada, we selected three national parks with contrasting land cover and management histories: Wood Buffalo, Kootenay, and La Mauricie National Parks.

Results

Figure 2 provides a summary of the EOSD land cover classes within each of the 26 national parks we investigated and demonstrates the range of environments that are represented by Canada's national parks. For example, of the parks included in our analysis, Gulf Islands National Park has the lowest proportion of forest (42%), while Fundy National Park has the greatest proportion of forests (95%). Wood Buffalo National Park has the greatest proportion of non-forest (41%) and Gulf Islands National Park has the greatest proportion of "other" or background class.

Forest fragmentation metrics: comparing parks to their GPEs

The distributions of the fragmentation metrics within all the national parks and the GPEs are

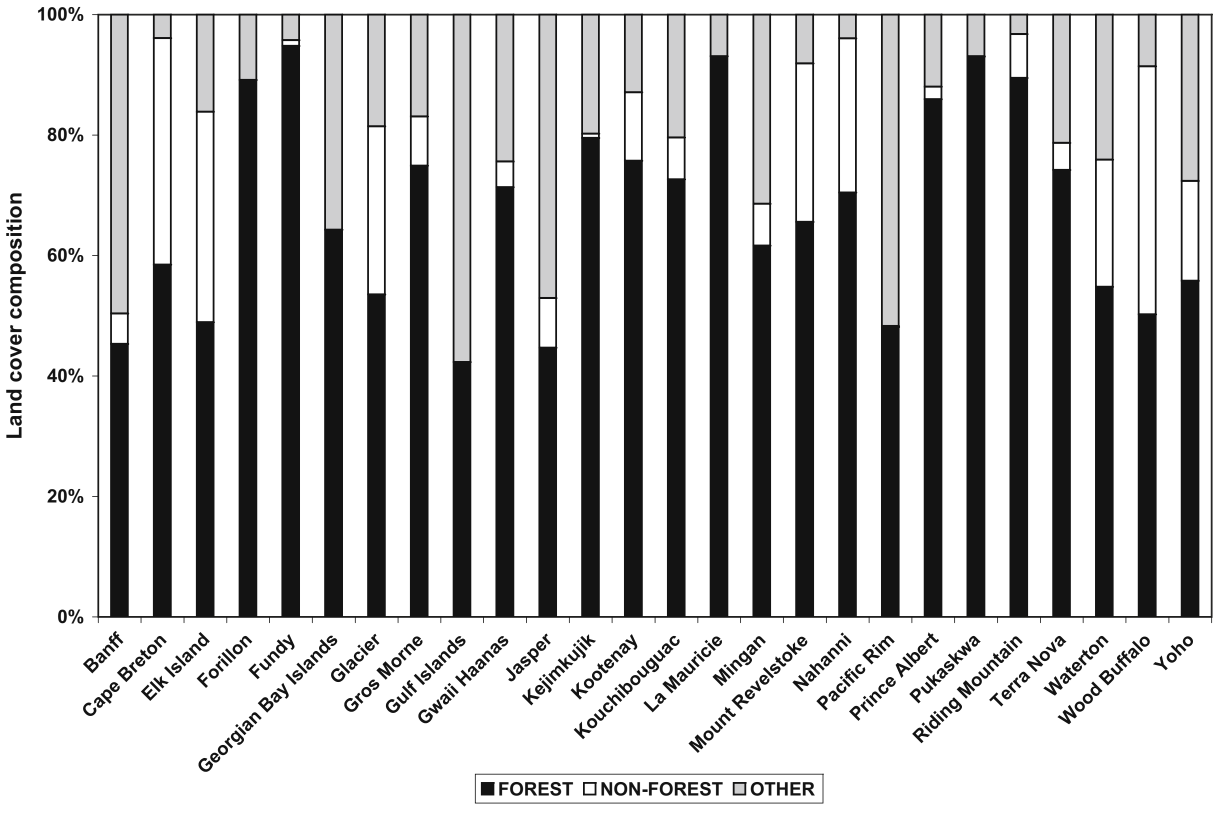


Fig. 2 Distribution of forest, non-forest, and other classes within each of the national parks included in the analysis

summarized in Fig. 3a–e and characterize overall trends in differences between parks and their surrounding areas. In general, GPEs appear to have more forest patches than their respective parks (Fig. 3a); however, a number of parks have more patches than their GPE, most notably Elk Island, Cape Breton, Gros Morne, and Wood Buffalo, which have an average of 9–11 patches

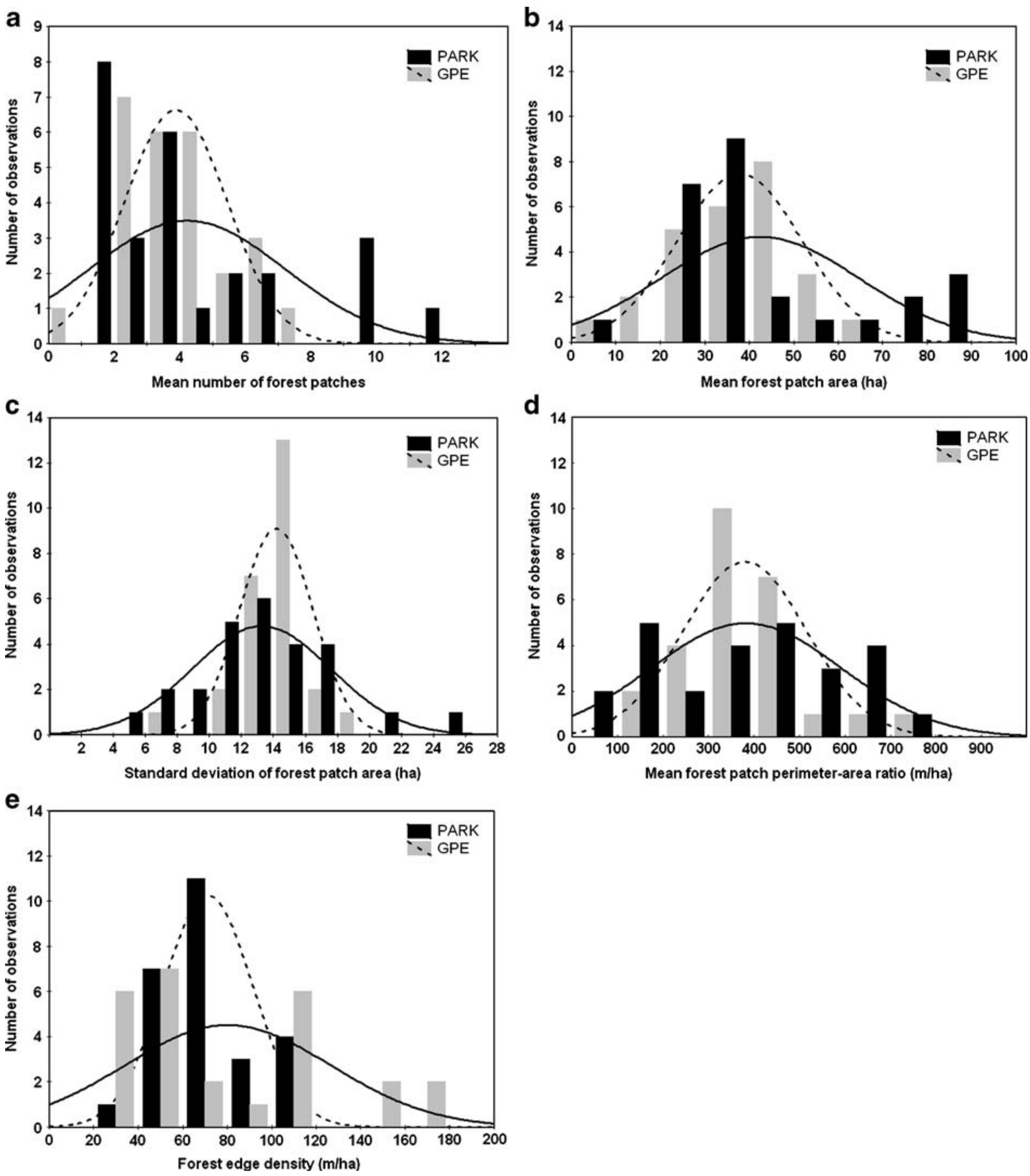


Fig. 3 **a**–**e** Distributions of values for the five landscape pattern metrics within national parks and within GPEs

per analysis unit inside the park, compared to and average of 5–6 patches per analysis unit in their GPEs. Mean forest patch size ranged from 2 to 60 ha in the GPEs and 8–83 ha in the parks (Fig. 3b). National parks with a mean f_marea > 80 ha included Fundy, Forillon, and Pukaskwa. Figure 3c indicates that there is more variability in patch size inside the parks compared to the GPE: mean values for f_sarea range from 7 to 19 ha in the GPE and 5 to 25 ha in the parks. The largest mean f_sarea values occur in Terra Nova, Kouchibouguac, and Nahanni National Parks.

The distribution of mean forest patch perimeter-to-area ratio values (f_mratio), measured in meters per hectare, is shown in Fig. 3d. The GPEs have a smaller range in mean f_mratio values (104–734 m/ha compared to 56–734 m/ha in parks), but there is no clear trend as 50% of parks have mean f_mratios larger than their surrounding GPEs, and 50% of parks have mean f_mratios smaller than their surrounding GPEs. Cape Breton, Kouchibouguac, and Gulf Islands are the parks with the greatest difference in f_mratio values (>200 m/ha larger than their GPEs). Conversely, Prince Albert and Forillon National Parks have mean f_mratio values that are more than 200 m/ha smaller than the mean f_mratio values in their GPEs. Elk Island, Gwaii Haanas, Mount Revelstoke, and Jasper are the parks with the smallest difference in mean f_mratio between the park and the GPE.

Figure 3e compares the distribution of forest edge density (f_dense), measured in meters per hectare. In parks, mean f_dense ranged from 23 to 80 m/ha, while in GPEs, mean f_dense ranged from 27 to 103 m/ha. Similar to the scenario for mean f_mratio, no clear trend emerged in mean f_dense values: 54% of parks had larger mean f_dense values than their surrounding GPEs, while the remaining 46% of parks had smaller f_dense values than their surrounding GPEs. Elk Island had a much greater mean f_dense than its GPE (169 m/ha in the park versus 43 m/ha in the GPE), while Fundy had a much lower f_dense than its GPE (30 m/ha in the park versus 71 m/ha in the GPE).

Figure 4 provides a summary of the two-sample t tests ($p = 0.05$) and indicates whether forest

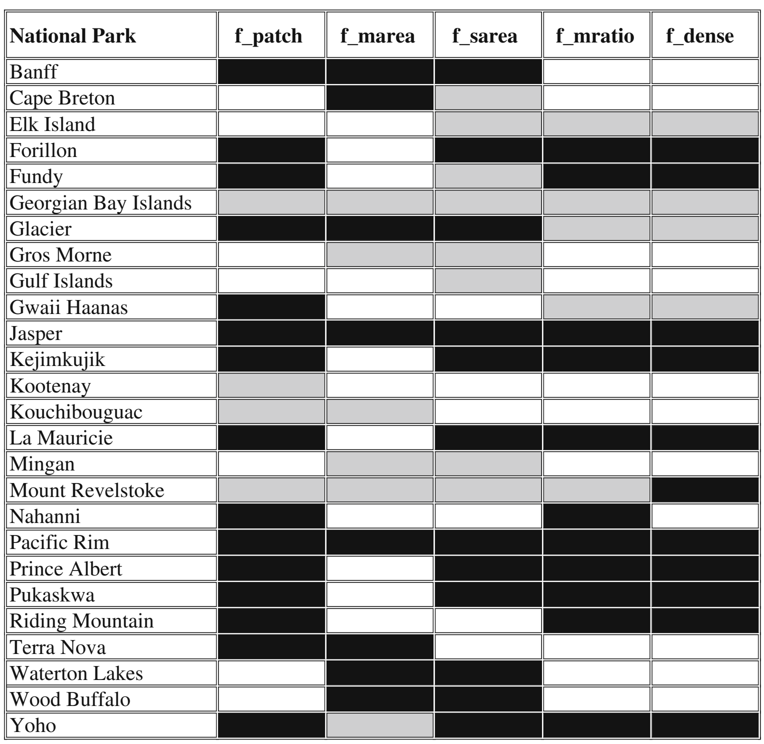


Fig. 4 Comparison of fragmentation metrics inside and outside the national parks (two-tailed t test; $p < 0.05$). The mean value of the fragmentation metric was either significantly less than (*black*), significantly greater than (*white*), or not significantly different than (*gray*) the mean value of the fragmentation metric in the surrounding GPE

fragmentation patterns, as measured by each of the five selected metrics, are significantly smaller (black), larger (white), or not significantly different (gray), from the forest fragmentation patterns in the park's GPE. In terms of the number of forest patches (f_patch), 58% of parks had significantly fewer patches than their corresponding GPE. Parks for which there was no significant

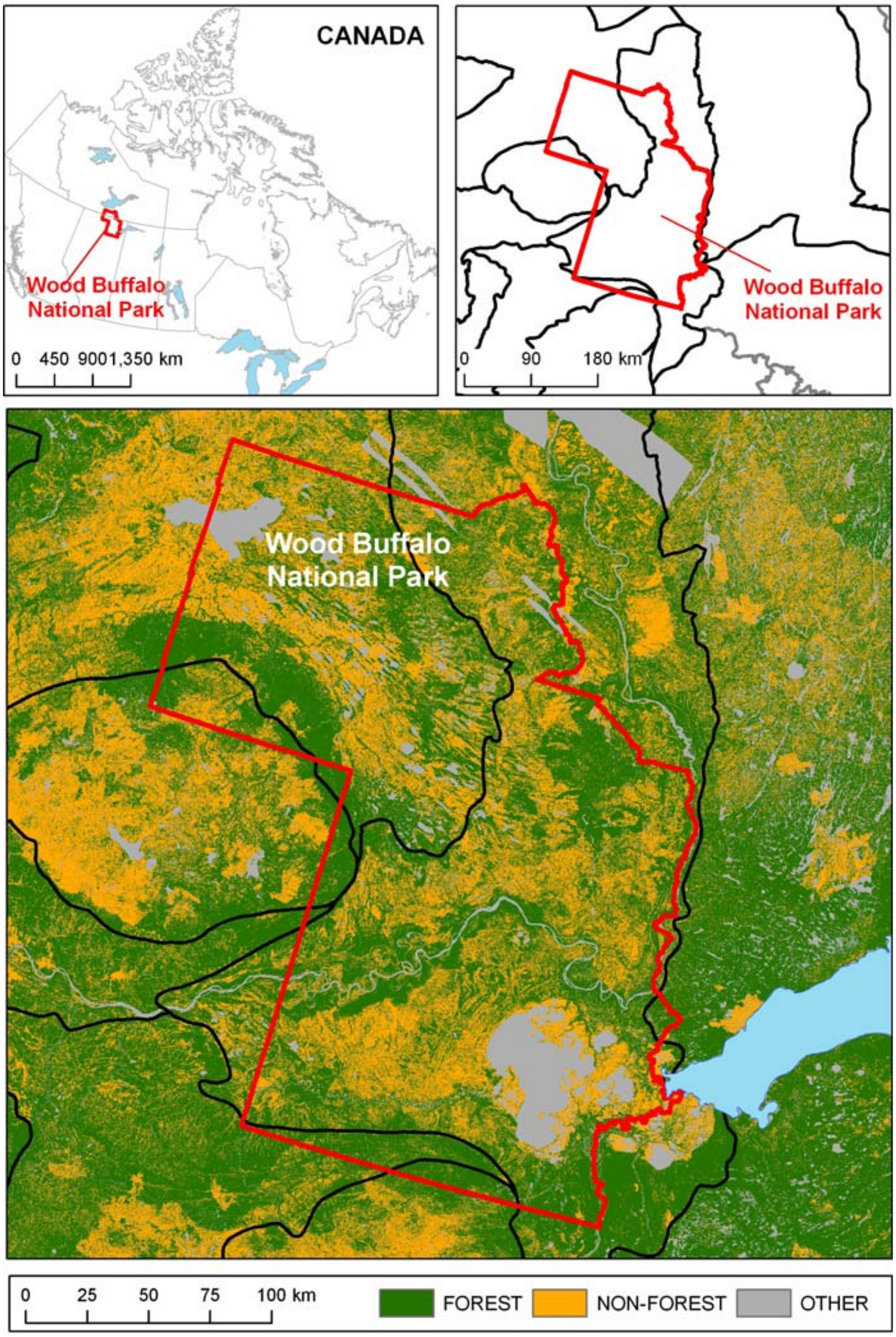


Fig. 5 Wood Buffalo National Park and surrounding GPE (composed of Hay River Lowland, Mid-Boreal Uplands, Northern Alberta, Uplands Slave River Lowland, Peace Lowland, Tazin Lake Upland, and Wabasca Lowland ecoregions)

difference in f_patch between the park and its GPE include Georgian Bay Islands, Kootenay, Kouchibouguac, and Mount Revelstoke National Parks.

Of the 26 parks analyzed, 31% had a mean forest patch size that was significantly less than the mean forest patch size in the GPE, while 46% of parks had a significantly larger mean forest patch size than their corresponding GPE. The remaining 23% of parks had a mean forest patch size that was not significantly different from their GPE. The standard deviation in forest patch size (hectare), was the metric for which there were the greatest number of parks (31%) where there was no significant difference between the park and the GPE (including Cape Breton, Elk Island, Fundy, Georgian Bay Islands, Gros Morne, Gulf Islands, Mingan Archipelago, and Mount Revelstoke National Parks). For the majority of parks (46%), however, mean f_sarea was significantly less than mean f_sarea in the GPE, indicating that in these cases, forest patch size was more variable in the GPEs than within the parks.

For f_mratio, an equal number of parks had significantly lower (38%) and significantly higher (38%) f_mratios than their corresponding GPEs. Typically, lower values for f_mratio are indicative of patches with less complex shapes. Anthropogenic disturbances, such as forest harvesting, often result in simpler patch shapes with lower perimeter-to-area ratios. Similarly, for density of forest edges, equal numbers of parks had significantly higher (42%) or significantly lower (42%) values for forest edge density than their GPEs. Larger values of forest edge density are typically indicative of greater levels of forest fragmentation. In summary, all but one national park (Georgian Bay Islands) were found to be significantly different from their corresponding GPE for at least one of the five metrics assessed, and 50% of the 26 parks were significantly different from their GPEs for all of the metrics assessed.

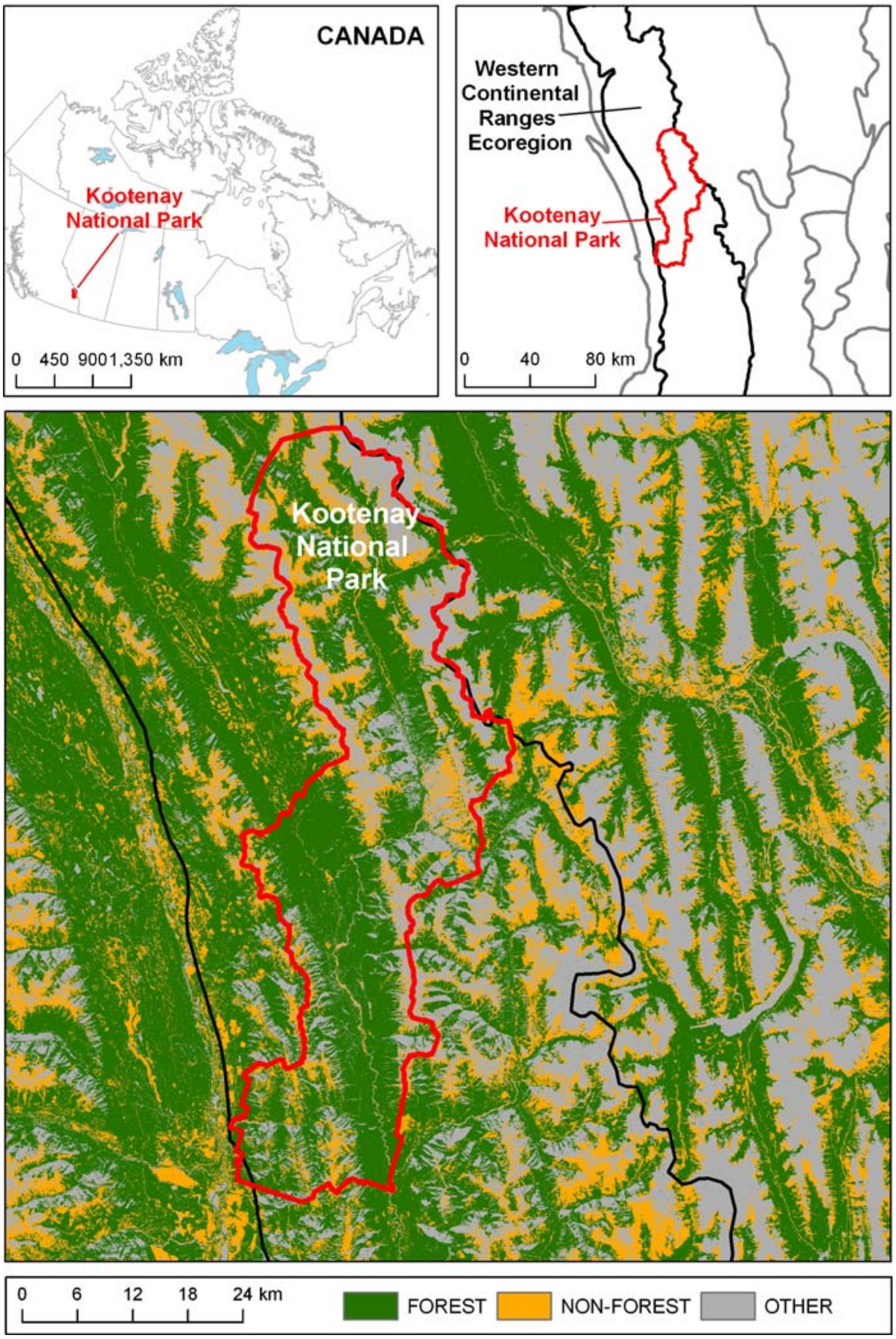
Wood Buffalo, Kootenay, and La Mauricie National Parks

Three Canadian parks that vary markedly in terms of their size, location, and land cover were selected for comparison: Wood Buffalo, Kootenay, and La Mauricie National Parks. Wood Buffalo National Park (Fig. 5), which borders Alberta and the Northwest Territories, is Canada's largest national park and is dominated by forest (50% of its area), followed by shrub and wetland classes (41%). Within the park, the number of forest patches per analysis unit is 9.66 which is significantly greater than the mean f_patch in the surrounding GPE (6.00), indicating that there is more forest fragmentation within the park boundaries. The mean f_marea within the park is 24.89 ha, significantly smaller than the mean f_marea in the GPE (35.07 ha), and the mean f_sarea is also significantly smaller within the park (13.71) compared to the GPE (15.77). The park mean f_mratio is 608.09 m/ha, which is significantly higher than the GPE mean f_mratio (486.25 m/ha). F_mratio has been shown to be an indicator of patch shape complexity especially in reference to fire disturbance (Hudak et al. 2007), indicating an increased presence of fire disturbance within the park itself. Similarly, f_dense for the park is also greater (106.35 m/ha) compared to 98.95 m/ha in the GPE. In terms of landscape processes, Wood Buffalo National Park appears to have a different disturbance regime across its landscape compared to its GPE; there are more forest patches in the park, the patches are smaller, and the patches within the park have a more complex shape.

Kootenay National Park (Fig. 6) is dominated by forest (76%). The mean f_patch within the park (3.86) does not differ significantly from the mean f_patch in the surrounding GPE (3.92), but the mean f_marea (36.15) and mean f_sarea (16.72) are significantly larger within the park compared to the GPE (f_marea = 32.53; f_sarea = 14.33). The mean f_mratio was also significantly greater within the park (430.09 m/ha) compared to the GPE (364.79 m/ha). Similarly, mean f_dense was significantly greater inside the park (79.99 m/ha) compared to the GPE (71.07 m/ha).

La Mauricie National Park (Fig. 7) is also dominated by forest (93%) and has significantly lower mean f_patch (1.49) compared to mean f_patch in the surrounding GPE (2.83). Mean patch size is larger within the park (76.81 versus 60.11 ha

Fig. 6 Kootenay National Park and surrounding GPE (Western Continental ranges ecoregion)



in the GPE) and mean patch size is less variable in the park (12.10 versus 15.21 ha in the GPE). The mean f_mratio is significantly lower in the park (112.52 m/ha) compared to the GPE (248.99 m/ha), as is mean f_dense (27.21 m/ha in the park; 57.73 m/ha in the GPE).

Discussion

Other studies have applied a similar approach to the one used in this study, whereby fragmentation patterns within a protected area are compared to fragmentation patterns in the area immedi-

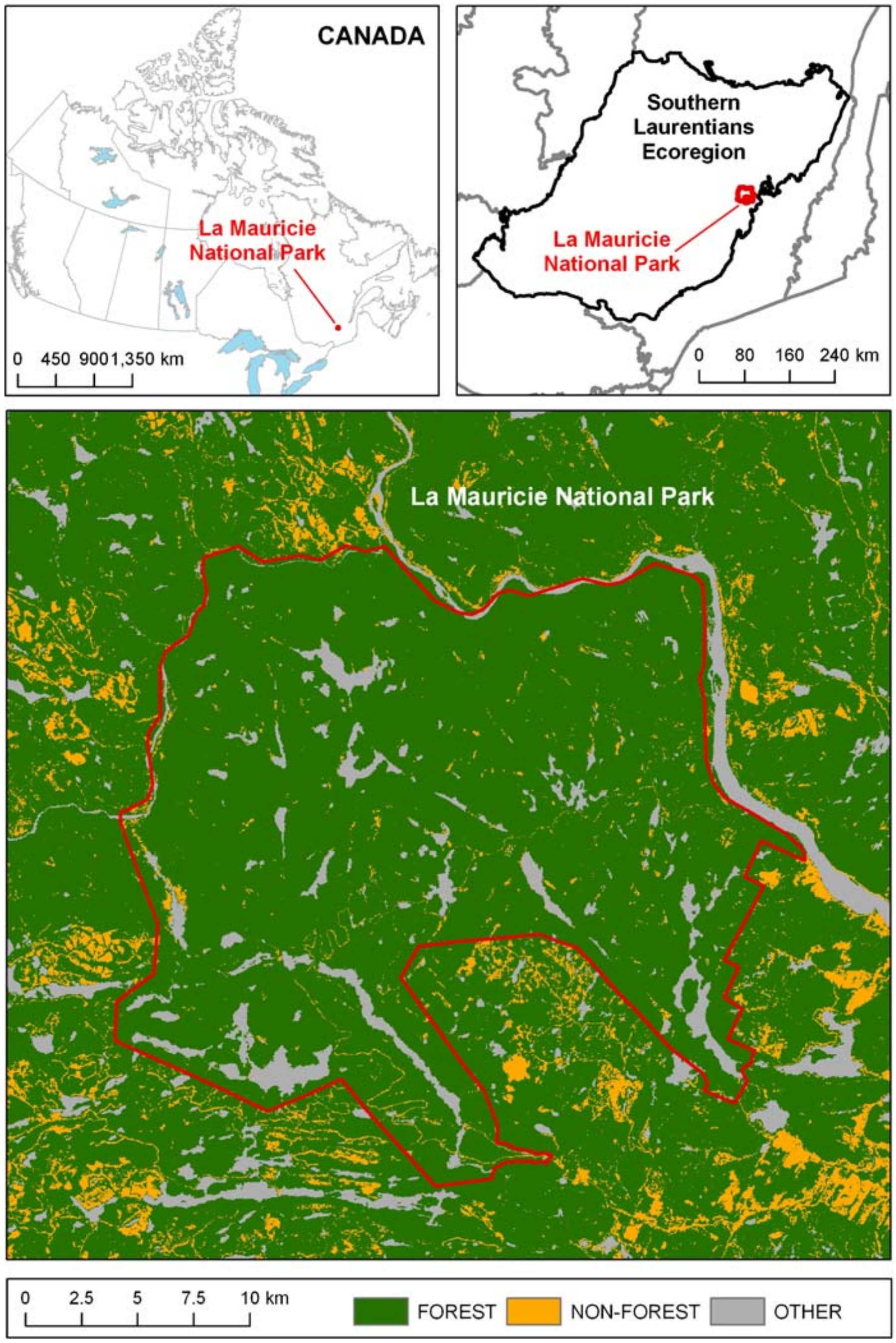


Fig. 7 La Mauricie National Park and surrounding GPE (Southern Laurentians ecoregion)

ately surrounding the protected area. For example, Narumalani et al. (2004) conducted a study at Effigy Mounds National Monument, Iowa, USA and compared fragmentation metrics for the protected area and the greater surrounding area using four landscape metrics: class area, number of patches, mean patch size, and area weighted mean patch fractal dimension. They concluded that land cover changes in the area surrounding the protected area reflected management decisions made in response to land use policy, while within the protected area, natural vegetation was "well maintained and devoid of any significant human activity."

Young et al. (2006) quantified forest and habitat fragmentation between the Beaver Hills region of central Alberta and the surrounding area. Fragmentation metrics used in this study included class area, number of patches, mean patch size, deviation in mean patch size, and mean shape index; all metrics indicated that fragmentation had increased in the Beaver Hills area from 1977 to 1998, relative to the surrounding area. Hierl et al. (2008) investigated the capability of using a similar comparative approach for prioritizing communities in the San Diego Multiple Species Conservation Plan, California, USA. In their study, currently protected areas were compared to unprotected areas targeted for conservation using number of patches, largest patch index, mean patch area, edge density, mean perimeter–area ratio, and mean Euclidian nearest neighbor distance.

While our results indicate some general trends in forest fragmentation for Canada's national parks, no single trend exists across all of the national parks included in our analysis. There was a strong correlation between perimeter–area ratio and edge density of forest patches as seen from Fig. 4. These metrics are likely interrelated due to the fact that they both measure edge of patches and they both are an indicator of spatial heterogeneity on the landscape. For instance, the metrics considered in this study indicate that forests in Canada's largest national park, Wood Buffalo, are significantly more fragmented than forests in the GPE surrounding the park. Wood Buffalo National Park, established in 1922 and located in the unpopulated, and largely unmanaged northern boreal forest, is one of the largest protected areas in the world (44,807 km^2). This remote wilderness park is located in the Boreal Plains and Taiga Plains ecozones and was declared a World Heritage Site in 1983. The park protects one of the largest free-roaming and self-regulating bison herds in the world, as well as one of the largest inland freshwater deltas in the world. Natural disturbances, predominantly fire, play a large role in creating a continually changing landscape in Wood Buffalo based on new and regenerating fire scars (Parisien et al. 2006). Fire suppression within the park is not a key management objective, and in most cases, fires started by lightning within the park are left to burn and extinguish naturally. In contrast, more aggressive fuel management programs are used in the areas surrounding the park, and attempts are made to either suppress or contain fires. As a result, there are significantly more forest patches inside Wood Buffalo National Park that are significantly smaller in size when compared to the GPE. Fires typically generate patches with complex shapes, creating more forest edges. The example of Wood Buffalo National Park highlights the importance of understanding the park's management context when interpreting fragmentation measures: this park was established to protect a population of wood bison (*Bison bison athabascae*), which require fragmented forest to provide high-quality habitat and forage opportunities (Strong and Gates 2009). Thus, in the case of Wood Buffalo National Park, a fragmented forest is a desirable management outcome.

Kootenay National Park (1,406 km^2), located in south-western region of the Canadian Rocky Mountains and established in 1920, receives significant public usage due to its proximity to the large metropolitan centers of Calgary and Vancouver. The forest in Kootenay National Park is less fragmented than the forest in its surrounding GPE, as indicated by a significantly larger forest patch size and more complex patch shapes. Until the recent time, Kootenay National Park had an actively managed fire program, with fire prevention and suppression key park management priorities. This is largely a result of the proximity of Kootenay National Park to surrounding communities, and the function of the park as a major tourist and recreation destination in western Canada. In addition, large parts of the surrounding GPE have been subject to developmental pressures from urbanization, agriculture, and tourism.

Finally, La Mauricie National Park (536 km^2) is located in the Boreal Shield ecozone and protects a representative sample of the Canadian Shield. Forest harvesting has had a major impact on this region, with an extensive 150-year history of logging. Consolidated Paper harvested over 50% of the forest land in the area of La Mauricie for pulp and paper production for 40 years prior to the park's creation in 1970. Controlled burns have been used in the park since 1991, primarily as a management tool in association with white pine stands. The forests of La Mauricie National Park are less fragmented than the forests in the surrounding GPE, with fewer forest patches with a larger average area and less variability in patch size. Also, the f_mratio and f_dense values are lower in the park than in the surrounding GPE.

Redundancy among landscape pattern metrics often exists (Riitters et al. 1995; Li et al. 2005; Cushman et al. 2008) and the selection of metrics must be made in the context of the information needed. For example, the use of several different fragmentation metrics is a practical approach to assessing fragmentation when the integrity of the ecosystem as a whole is being assessed as opposed to impacts on specific species (Davidson 1998; Bogaert et al. 2000). Figure 8 indicates the relative positions of Kootenay, La Mauricie, and Wood Buffalo National Parks and their GPEs in a feature space that includes f_patch, f_marea, and f_dense and illustrates the dissimilarity between La Mauricie Park and its GPE for all three metrics. In contrast, the difference between Wood Buffalo National Park and its GPE is primarily related to differences in the number of forest patches, while Kootenay National Park is very similar to its GPE, with a primary difference in the density of forest edges.

There is considerable interest in distinguishing between natural and anthropogenic causes of forest fragmentation, especially in the context of ecological integrity. In this paper, our objective was to provide a national assessment of forest fragmentation for parks that are predominantly forested. The lack of detailed, national-scale data on all forms of natural and anthropogenic disturbances limits our ability to identify specific causal processes for the observed patterns of forest fragmentation. Furthermore, the EOSD LC 2000 only captures land cover and not land use, precluding methods such as that used by Wade et al. (2003) to examine causal agents of fragmentation at a global scale.

Roads are considered a major driver of forest fragmentation because they contribute to decreased patch connectivity and increased edge density (Forman et al. 2002), a supplementary source of roads data was not included in our analysis. Roads, although not explicitly included in the EOSD LC 2000, are represented, where resolvable, as an “exposed land” class (Wulder

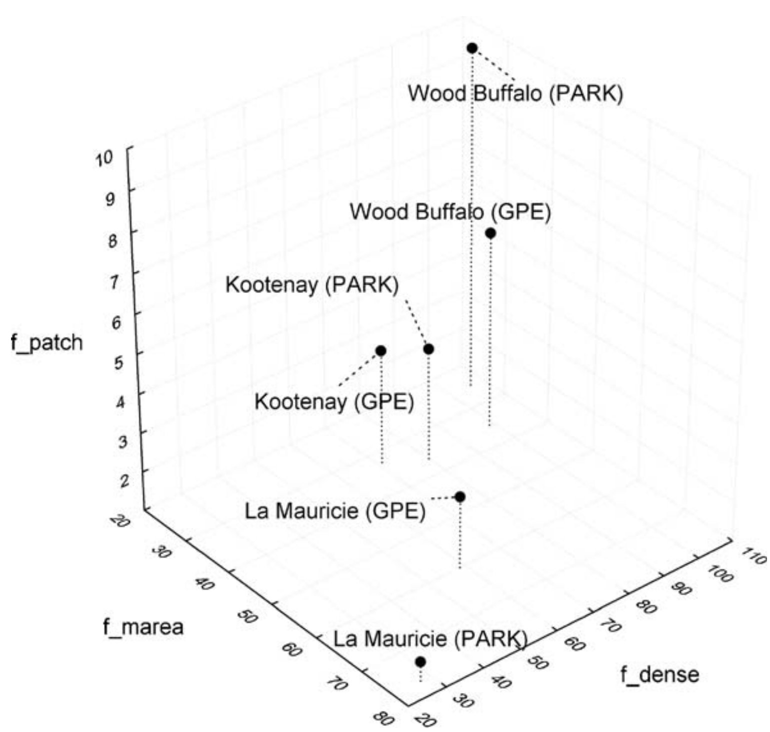


Fig. 8 Distribution of Wood Buffalo, Kootenay, and La Mauricie national parks and their respective GPEs by number of forest patches (f_patch), mean forest patch size in hectares (f_marea), and forest edge density in meters per hectare (f_dense)

et al. 2008b); however, roads are less likely to be detected in heavily forested areas traversed by small roads. Since roads are mapped with much more precision and occupy much less area relative to other classes, they have less impact on measures such as total forest area and patch size and more impact on edge metrics (Riitters and Wickham 2003).

Ecological monitoring is one of the primary goals of Parks Canada and the results presented herein provide a baseline assessment of forest patterns in Canada's national parks and GPEs. Forest fragmentation is a dynamic process and future monitoring efforts could build on this or a similar baseline assessment to evaluate changes in forest patterns over time and identify specific parks and GPEs which may warrant more detailed assessments. Studies conducted at a regional or local scale (c.f. Young et al. 2006) with higher spatial resolution data sources will reveal more detailed insights on land use, disturbance, and fragmentation patterns. Monitoring can also take advantage of a hierarchical and inherently cost-effective approach whereby the acquisition of expensive, high spatial resolution data is restricted to those areas flagged as undergoing rapid and/or spatially extensive changes by low or no cost image data such as Landsat. Finally, monitoring will not only provide an indication of changes in forest patterns, but will also enable the quantification of habitat loss, which is posited to have a greater negative effect on biodiversity than fragmentation (Fahrig 2003).

Conclusions

Of the 26 national parks we analyzed, a majority had significantly fewer patches than their GPEs, while 46% had a significantly larger mean forest patch size and a significantly smaller standard deviation of forest patch size. No clear trend emerged for edge metrics. With one exception, all of the national parks we assessed were found to be significantly different from their GPE for at least one of the five fragmentation metrics we considered. The EOSD LC 2000 provided a spatially extensive dataset for characterizing forest fragmentation in Canada's national parks and their surrounding ecological contexts. Forest fragmentation is one of the several indicators that could be used to assess the ecological integrity of Canada's national parks; however, the interpretation of fragmentation measures must account for the land cover types present and the management objectives of the park in question. The analysis presented herein provides a useful baseline that could support an ongoing monitoring program, enabled by earth observation data.

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