Conservation Biology

Contributed Paper

Land Development in and around Protected Areas at the Wilderness Frontier

SHAWN J. LEROUX* AND JEREMY T. KERR

Canadian Facility for Ecoinformatics Research, Department of Biology, University of Ottawa, 30 Marie Curie, Ottawa, Ontario K1N 6N5, Canada

Abstract: *Protected areas' chief conservation objectives are to include species within their boundaries and protect them from negative external pressures. Many protected areas are not achieving these goals, perhaps in part due to land development inside and outside protected areas. We conducted spatial analyses to evaluate the ability of Canadian protected areas to mitigate the effects of nearby land development. We investigated correlations of national patterns of land development in and around protected areas and then examined national patterns of roads, urban area, and croplands in protected areas. We calculated the amount of developed land in protected areas and within 25–100 km of protected-area borders, the density of roads, and extent of urban and cropland area in protected areas. We constructed logistic-regression models to test whether development in a protected area was associated with landscape and protected-area characteristics. Land development was far less extensive inside than outside protected areas. However, several protected areas, particularly small southern areas near small urban centers had substantial development inside their boundaries, and nearly half of protected areas had roads. The cumulative extent of development within 50 km of protected areas was the best predictor of the probability of land development in protected areas. Canadian First Nations, industries, government, and nongovernmental organizations are currently planning an unprecedented number of new protected areas. Careful management of areas beyond protected-area boundaries may prove critical to meeting their long-term conservation objectives.*

Keywords: biodiversity, ecological benchmark, greater park ecosystem, intactness, land-use planning, matrix, park, reserve

Desarrollo de Tierras Dentro y Alrededor de Áreas Protegidas en la Frontera Silvestre

Resumen: *Los objetivos principales de las áreas protegidas son la inclusión de especies dentro de sus límites y protegerlas de presiones negativas externas. Muchas áreas protegidas no están cumpliendo estos objetivos, en parte quizás debido al desarrollo de tierras dentro y fuera de las áreas protegidas. Realizamos análisis espacial para evaluar la capacidad de áreas protegidas Canadienses para mitigar los efectos del desarrollo de tierras cercanas. Investigamos las correlaciones de los patrones nacionales de desarrollo de tierras dentro y alrededor de áreas protegidas y posteriormente examinamos los patrones nacionales de carreteras, área urbana y cultivos dentro de áreas protegidas. Calculamos la cantidad de tierra desarrollada dentro de áreas protegidas y a 25–100 km de los límites de áreas protegidas, la densidad de carreteras y la extensión de áreas urbanas y agrícolas dentro de áreas protegidas. Generamos modelos de regresión logística para probar si el desarrollo en área protegida se asociaba con características del paisaje y de áreas protegidas. El desarrollo de tierras fue mucho menos extensivo dentro de áreas protegidas que afuera. Sin embargo, varias áreas protegidas, particularmente áreas sureñas pequeñas cerca de centros urbanos pequeños tuvieron desarrollo sustancial dentro de sus límites, y casi la mitad de áreas protegidas tenía carreteras. La extensión acumulada de desarrollo a 50 km de áreas protegidas fue el mejor pronosticador de la probabilidad de desarrollo de tierras dentro de áreas protegidas. Canadian First Nations, industrias, gobierno y organizaciones no gubernamentales actualmente están planeando un número sin precedentes de áreas protegidas nuevas. El*

**Current address: Department of Biology, Memorial University of Newfoundland, St John's, NL A1B 3X9, Canada, email sleroux@mun.ca*
Paper submitted August 23, 2011; revised manuscript accepted July 5, 2012.

Conservation Biology, Volume 27, No. 1, 166–176

DOI: 10.1111/j.1523-1739.2012.01953.x

manejo cuidadoso de áreas más allá de los límites de áreas protegidas puede ser crítico para el cumplimiento de sus objetivos de conservación a largo plazo.

Palabras Clave: Biodiversidad, ecosistemas de parques mayores, integridad, matriz, parque, planificación del uso de suelo, punto de referencia ecológica, reserve

Introduction

Protected areas are cornerstones of global conservation strategies but cannot meet all conservation goals. In most areas, only small proportions of land receive formal protection; thus, there has been an increased focus on the conservation value of lands surrounding protected areas (e.g., Noss & Harris 1986; Hansen & DeFries 2007; Hansen et al. 2011). There has been a great deal of research conducted to better understand the influence of developed land on protected-area effectiveness. For example, deforestation near a protected-area boundary in China has spilled inside parks and threatens the survival of giant pandas (*Ailuropoda melanoleuca*) (Liu et al. 2001). Conversely, the presence of protected areas may influence the surrounding landscape. For example, McDonald et al. (2007) observed that in 2 out of 3 study areas, development rates were higher in regions with more protected area.

Two key roles of protected areas are to capture biodiversity and mitigate the negative effects of external pressures on this biodiversity (Gaston et al. 2008). Globally, many species are excluded from protected areas (Rodrigues et al. 2004) and filling these gaps in protection is a priority for signatories to the Convention on Biological Diversity (COP 10 2010). External pressures, such as forestry (e.g., Curran et al. 2004) and urbanization (e.g., Wade & Theobald 2010), erode effectiveness of protected areas. Unless these pressures can be anticipated and addressed, further species losses in protected areas seem inevitable. One approach to mitigating further loss of species would be to design conservation strategies at landscape scales (Noss & Harris 1986; Hansen & DeFries 2007; Hansen et al. 2011). The application of multiple-use modules (Noss & Harris 1986) and the identification of zones of interaction surrounding protected areas (DeFries et al. 2010) represent 2 approaches to landscape-level design and management of protected areas.

The effects of land development on biodiversity are well known. Habitat loss, due mainly to agriculture and urbanization, is the leading threat to endangered species in Canada (Kerr & Deguise 2004; Venter et al. 2006). Roads and other linear features are barriers to movement and a major source of mortality for animals (reviewed in Fahrig & Rytwinski 2009). Animals in parks are not immune to the negative effects of roads. For example, highway and railway mortalities accounted for 19% of the 131 known grizzly bear (*Ursus arctos horribilis*) mortalities from 1971 through 1998 in Banff and Yoho National Parks (Behn & Herrero 2002). Human activities also can alter the behavior of wildlife. Wolves (*Canis lupus*) tend to avoid areas that are heavily used by humans, which can have cascading effects on the structure and dynamics of ecosystems (Hebblewhite et al. 2005). Noise pollution associated with land use also can affect biodiversity. Passerine densities are significantly lower near energy-sector infrastructure (i.e., compressor stations) than in control sites (Bayne et al. 2008). Finally, human activities may alter ecosystem characteristics and processes, such as the risk of large natural disturbances. For example, in the western boreal forest of Canada road density and lightning-fire frequency are positively correlated likely due to greater availability of flammable fine fuels near roads (Arienti et al. 2009).

Canada is a unique area to undertake analyses of the patterns of land development inside and surrounding protected areas because Canada has a strong gradient of development from areas with a very large human footprint in the south to wilderness areas in the north. Results of recent research bring into question whether protected areas in Canada can capture and maintain biodiversity over time as climate changes (Kharouba & Kerr 2010). In addition, few reserves in eastern North America are large enough to avoid extirpations of mammal species given their insularization (Gurd et al. 2001), and significant gaps remain in Canadian protected areas' inclusion of mammal species (Wiersma & Nudds 2009). Canada has perhaps the most extensive intact wilderness areas slated for protection in the world (roughly 600,000 km^2 of new parks are anticipated). This protection plan follows a process that involves multiple stakeholders, including resource industries, environmental organizations, First Nations, and provincial and federal governments. However, there is increasing pressure for the expansion of industrial development (e.g., mining, forestry) into relatively pristine northern areas of the country (e.g., Quebec's Plan Nord [Government of Quebec 2009]). An improved understanding of the interaction between protected areas and surrounding lands in Canada will inform current land management and emerging land-use planning in Canada with potential implications and lessons globally.

We investigated the ability of protected areas in Canada to mitigate the effects of nearby land development. Specifically, we asked whether the quantity of developed land inside protected areas is related to the quantity of developed land adjacent to protected areas. We define *land development* as human activities that leave lasting, visually detectable infrastructure (e.g., roads) or footprints (e.g., clearcuts) on land- or waterscapes.

Methods

In forest and prairie ecozones of Canada, we examined patterns of land development inside and outside protected areas and patterns of roads, urban areas, and croplands inside protected areas (Agriculture and Agri-Food Canada 1999).

Protected Areas

We used the Global Forest Watch Canada's (GFWC) terrestrial protected-areas database, the most complete such source for Canada (Lee & Cheng 2010). It includes all legally designated terrestrial protected areas in the Conservation Areas Reporting and Tracking system of the Canadian Council on Ecological Areas (Vanderkam 2010) and the Commission on Environmental Cooperation (Department of Forestry and Natural Resources 2010) and lands under interim provincial protection. Interim protection is temporary legal or regulatory protection while negotiations and legal issues are resolved (Lee & Cheng 2010). The database contained 4507 protected areas. Legal protected areas cover 8.5% of Canadian lands and freshwaters and interim protected areas cover an additional 3.7% of Canadian lands and freshwater area.

Cumulative Land Development

We used GFWC's cumulative access (hereafter land-use data) (Lee et al. 2010*a*) and anthropogenic change (hereafter land-use change data) (Lee et al. 2010*b*) data sets to measure common human infrastructure in Canada, such as roads, reservoirs, populated places, well sites, seismic lines, airports, mines, pipelines, powerlines, and clearcuts. Both data sets are derived from spatial infrastructure data and Landsat satellite imagery (Landsat 5 Thematic Mapper [TM] and Landsat 7 Enhanced Thematic Mapper [ETM+]) at 28.5-m resolution. The land-use data cover 6.8 million km^2 and the constituent Landsat scenes within the coast-to-coast mosaic were collected from 1988 through 2006 (Fig. 1). The land-use change data cover 2.9 million km^2 (Fig. 1) and were collected from Landsat scenes from 1985 and 2006. These data are binary (i.e., developed or not developed) and therefore differ from other commonly used global data sets that represent continuous patterns of human activity (e.g., human footprint [Sanderson et al. 2002]). The GFWC data represent the finest resolution data available for capturing land-use patterns across Canada.

To develop the land-use data, GFWC first mapped all the anthropogenic disturbances that were already identified in readily available and reliable existing spatial data sets. These data were available for roads and other linear features such as seismic lines, pipelines (DMTI 2000; Geomatics Canada 2000), reservoirs (Lehner & Doll 2004), railroads, and power lines (Cihlar et al. 1999). Additional, independent image interpretation (from short-wave infrared, near infrared, and red bands [5, 4, 3]) identified other anthropogenic features in landscapes at 1:40,000 to 1:50,000 scales. GFWC used ancillary (e.g., Landsat 7 GeoCover 2000 ETM+ panchromatic 14.25 m and ASTER 1999–2000 15 m) data to validate land-use observations. Most images were orthorectified by NASA and had <10% cloud cover. Landsat images are of moderate resolution, so the finest scale human activities (e.g., some seismic lines, trapping lines) are not detected. Global Forest Watch Canada distinguished clearcuts from fires only if there was evidence of additional human activities nearby (e.g., roads).

Area that could not be resolved between 2 initial image analysts were flagged and often corrected by a third analyst or visited during field checks. Field checks were completed in 2003–2005 in 9 provinces. Interpreters flew low over the Gaspé Peninsula, Quebec (1 flight), and northern Ontario (2 flights) in fixed-wing aircraft for additional validation. Overall 538 in situ field checks and 155 aerial photos were used for validation purposes (see Fig. 15 in Lee et al. [2006]). The data were also subjected to a national peer review process.

GFWC defines *zone of influence* as "the distance from an anthropogenic activity or disturbance within which there are ecological effects resulting from the anthropogenic activity or disturbance" (Lee et al. 2006). A 500-m zone of influence was applied to local roads (i.e., subdivision roads in a city or gravel roads in rural areas), airports, mines, pipelines, power lines, reservoirs, and clearcuts and a 1000-m zone of influence to expressways, the Trans-Canada highway, 4-lane divided highways (hereafter series highways; e.g., highway 401), principal highways (e.g., highway 7 and 11), major roads, and county roads. Zones of influence were used to account for ecological zones of influence and to accommodate geometric correction problems with the imagery. The land development and zones of influence were combined to create the cumulative land-use data (Lee et al. 2010*a*). The final product represents a conservative estimate of the cumulative human footprint in Canada over the last 30–70 years. See Lee et al. (2006; 2010*a*) for more details on the geospatial data-processing techniques and accuracy assessments of land-use measures used.

The land-use data identified the footprint of all human activity present in the images, whereas the land-use change data measured only the change in human activity occurring from approximately 1990 through 2001. We obtained qualitatively similar patterns of land use inside and outside protected areas from the 2 GFWC data sets; therefore, we present only the key results for the analyses of land-use change data. Details on processing and

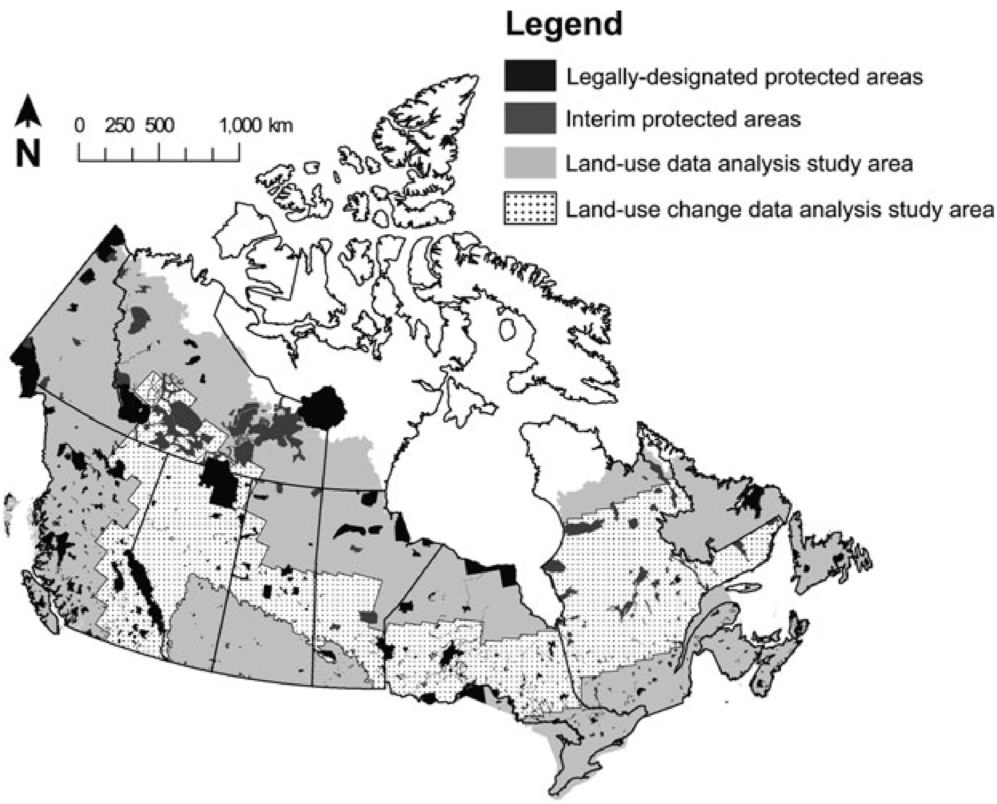

*Figure 1. Legally designated and interim (i.e., protected areas have temporary legal or regulatory protection while negotiations and legal issues are resolved [Lee & Cheng 2010]) protected areas in Canada (*n *= 829) and the extent of spatial analyses of land use and land-use change data.*

analyses of the land-use change data are in Supporting Information.

Road Density and Urban and Cropland Area

The cumulative land-development data sets do not distinguish among the different human activities (i.e., data are binary development or not), but the effects of human activities on biodiversity differ by activity and species. In Canada roads, urban areas, and croplands are key threats to endangered species (Kerr & Deguise 2004; Venter et al. 2006). Consequently, we used national data sets on roads, urban areas, and croplands to investigate patterns of these human activities in protected areas.

We downloaded the provincial and territorial road networks (version 2) from GeoBase (Natural Resources Canada 2007) and merged these data into a national road network database. The national road network data captures >1,000,000 km of roads across Canada at an approximate resolution of 1:10,000. Data on urban and cropland area were extracted from the 250-m resolution Land Cover Map of Canada 2005 (CCRS 2008). We considered urban areas as cells corresponding to land-cover classes of urban or built-up areas and croplands as cells corresponding to land-cover classes of cropland or woodland and high-, medium-, and low-biomass croplands.

Spatial Analyses

For our analyses, we retained 829 protected areas that had their centroids in forest and prairie ecozones of Canada (Agriculture and Agri-Food Canada 1999) (Fig. 1). We excluded protected areas <50 km^2 in the Boreal ecozones and <10 km^2 in the Temperate ecozones because contiguous patches of these sizes may contain human activity (Lee et al. 2010*a*). We delineated areas of 25, 50, 75, and 100 km around each protected area (hereafter buffers) and retained the area of buffers within the extent of forest and prairie ecozones. We used these buffer sizes because there are long-distance effects of disturbance outside protected areas on biodiversity inside protected areas (Hansen & DeFries 2007; DeFries et al. 2010). For example, the damming of the Athabasca River 1180 km upstream of Wood Buffalo National Park, Canada, has had substantial negative effects on the Athabasca delta and its flora and fauna in the park (Timoney 2002). In addition, Lee and Cheng (2010) undertook a complementary analysis with smaller (10 km) buffers. We used Geospatial Modelling Environment (GME) (Beyer 2010) to create the buffers and ArcGIS (version 10) Clip Tool (ESRI 2010) to clip the buffers to the study area extent. We removed 1000 m of the inside edge of each protected area and buffer because the land-use data are buffered by either

Table 1. Descriptive statistics for explanatory variables included in logistic regression models of land development in protected areas (PAs).

Variable	Description	PAs with development[a] median	PAs with development[a] SD	PAs without development[a] median	PAs without development[a] SD
BF	proportion of land development in 50-km buffers	0.49	0.23	0.17	0.23
AR	size of protected area (km^2 —1 km of edge)	76.87	4112.31	32.70	3827.64
DA	PA distance to major urban center (km)	166.79	271.70	303.58	341.56
DI	PA distance to minor urban center (km)	24.75	48.60	56.15	89.57
YR	PA year of establishment	1999	22	2001	13
NR	PA northing (standardized UTM)	−0.35	0.94	0.21	1.05
ES	PA easting (standardized UTM)	−0.31	1.01	−0.62	0.96
		number		number	
IU	IUCN PA category (2 levels)[b] Ia, Ib, II, III, IV, other	511		275	
	V, VI	31		12	
ST	PA status				
	legal	476		244	
	interim[c]	66		43	

[a] *Medians and standard deviations are given for protected areas that contained developed land (n = 542) and protected areas that did not (n = 287).*
[b] *International Union for Conservation of Nature (IUCN) categories are defined in IUCN (1994).*
[c] *Interim protected areas have temporary legal or regulatory protection while negotiations and legal issues are resolved (Lee & Cheng 2010).*

500 or 1000 m. We overlaid the protected areas and buffers on the land-use data and used GME to calculate the percentage of each protected area and surrounding buffer with land development (see Supporting Information for a conceptual diagram of spatial analysis methods).

We used GME to calculate the length of roads per full (i.e., inside edge not removed) protected area ($n = 829$). We used these data to calculate the density of roads per protected area. We used ArcGIS (version 10) Zonal Statistics as Table tool to calculate the urban and cropland area per protected area.

Statistical Analyses

We used Mann-Whitney U nonparametric tests to quantify the statistical difference in cumulative land development between protected areas and buffers. We used logistic regression to predict the likelihood of development in a protected area (i.e., development >0) given a suite of covariates, including percent land development in buffers, size of protected areas (without 1000-m edge), distance to minor and major urban centers, northing (standardized UTM with mean 0), easting (standardized UTM with mean 0), International Union for Conservation of Nature (IUCN) categories Ia–IV or V–VI (IUCN 1994), year of establishment, and status (legal or interim) (Table 1). We used easting and northing to account for the potentially large north-south and east-west variation in land development patterns across Canada. Urban centers were identified from the Land Cover Map of Canada 2005 data set's urban and built-up category (CCRS 2008). We categorized urban areas as major urban centers (i.e., 25 most populated areas in Canada on the basis of 2006 census data) or minor urban centers (all other urban areas) (Statistics Canada 2006). Fifty-eight percent of Canada's population lives in the 25 most populated places in the country (cities with >120,000 people).

We used Akaike's information criterion (AIC) to determine the model with the highest weight of evidence from a suite of candidate models. Then, we computed the predicted probabilities of land development in protected areas for each covariate in the top model while keeping the other covariates at their mean values. We determined the goodness-of-fit of the candidate models with Nagelkerke's R^2 and the Hosmer and Lemeshow test. For each of our final models, Spearman rank correlation coefficients between explanatory variables were $0.4 > \rho > -0.4$. To minimize the influence of spatial autocorrelation, we included spatial covariates in our model and used an information theoretic approach, which did not focus on the specific values of model coefficients.

We used Kruskal-Wallis nonparametric tests to determine whether there was a difference in the density of roads and urban and cropland areas in protected areas and in the 50-km buffers among IUCN categories.

Results

Land-Use Data

The size of protected areas spanned 4 orders of magnitude (range 10–63,431 km^2). Protected areas in the southern ecozones tended to be smaller than those in northern ecozones (Fig. 2c). All protected areas were within 500 km of a minor urban center (median distance 30.45 km) (Fig. 2d). The median distance of protected

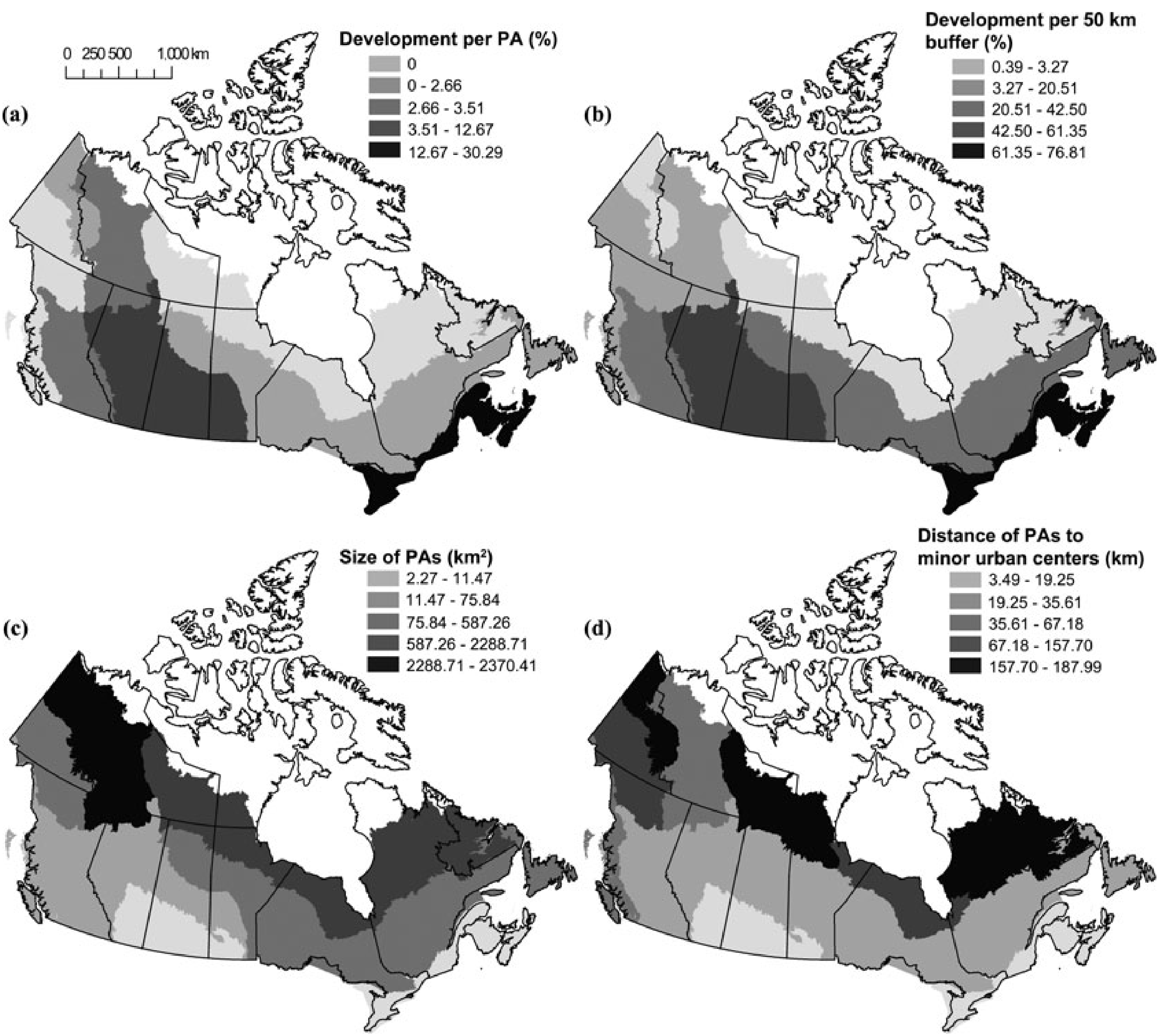

Figure 2. Median percent developed land in (a) protected areas (PAs) and (b) a 50-km buffer around protected areas; (c) median size of protected areas; and (d) median distance of protected areas to minor urban centers in terrestrial ecozones of Canada (Agriculture and Agri-Food Canada 1999). The data are classified into quintiles.

areas to major urban centers was 197.47 km, and there were 34 parks >1000 km from any major urban center (Table 1). Protected areas and buffers with the highest land development were in the south (Figs. 2a–b) and near minor urban centers (Fig. 2d). The median year of establishment of protected areas was 2000, and most protected areas were in category I-IV ($n = 770$) and had legal status ($n = 720$) (Table 1).

Cumulative land development per protected area ($\chi^2 = 32.10$, df $= 7$, $p < 0.001$) and 50-km buffers ($\chi^2 = 52.69$, df $= 7$, $p < 0.001$) varied among IUCN categories (Supporting Information). Cumulative development per protected area (median = 1.98%) was significantly lower than the cumulative development in 50-km buffers (median = 38.56% paired, Mann-Whitney U, $p < 0.001$) (Fig. 3a). All 4 buffer sizes (25, 50, 75, and 100 km) had similar levels of development; therefore, we report results only for the 50-km buffers.

Two hundred and eighty-seven protected areas had no development and 542 had development. Thirteen buffers had no development. Most predictors explained <12% of the deviance in the likelihood of development in protected areas. The percent development in 50-km buffers received the most support (11.6%), followed by distance to minor urban centers (6.89%), distance to major urban centers (4.07%), northing (3.06%), year of establishment

Table 2. Top 5 logistic-regression models used to examine the likelihood of land development in protected areas for a suite of protected-area and neighborhood explanatory variables.

Model[a]	*Description*[b]	k^c	LL^c	ΔAIC^c	ωAIC^c	R^{2c}	p^c
1	BF + AR + DI	3	−388.56	0.0	0.47	0.41	0.97
2	BF + AR + DI + YR + NR	5	−386.62	0.1	0.44	0.42	0.77
3	BF + AR + DI + IU + YR + NR + ST	9	−386.20	3.3	0.09	0.42	0.84
4	BF + AR	2	−396.27	13.4	0.00	0.39	0.62
5	BF + AR + IU + NR	5	395.65	16.2	0.00	0.39	0.69

[a]*Models ranked with Akaike information criterion (AIC).*
[b]*Explanatory variable abbreviations defined in Table 1.*
[c]*Key: k, number of parameters; LL, maximum log-likelihood; ΔAIC, differences in AIC for each model from the model with the greatest strength of evidence; ωAIC, model weights;* R^2*, Nagelkerke's* R^2*; p, Hosmer and Lemeshow goodness-of-fit p value.*

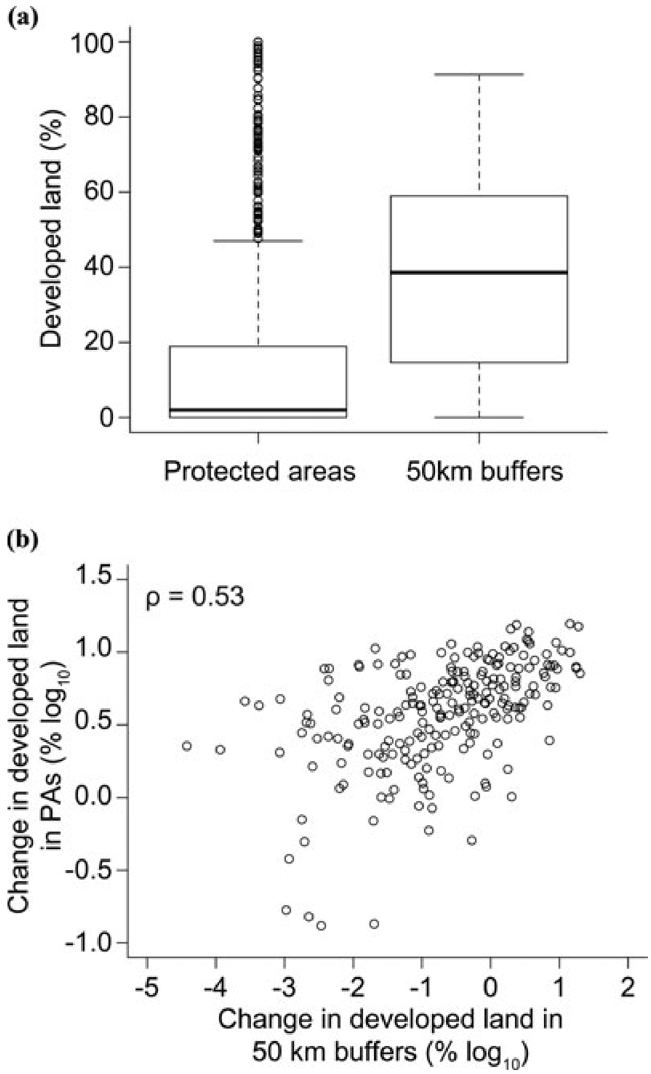

Figure 3. (a) Percentage (horizontal lines are 25th and 75th percentiles) of protected areas (PAs) and 50-km buffers around PAs that contain developed land (paired Mann-Whitney U, $p < 0.001$*) and (b) relation between percent change in developed land in PAs and percent change in developed land within 50 km of PAs (1990–2001) (Spearman rank correlation coefficient* $\rho = 0.53$*).*

(2.34%), and protected area size (2.15%). Nagelkerke's R^2 of the 5 most parsimonious models was 0.39–0.42 and the Hosmer and Lemeshow goodness-of-fit p values were 0.62–0.97. The 5 most parsimonious models all contained covariates for percent development in 50-km buffers and size of protected area (Table 2). The best supported model included covariates for percent development in 50-km buffers, size of protected area, and distance to minor urban center, had a ωAIC = 0.47, $R^2 = 0.41$, and a Hosmer and Lemeshow $p = 0.97$. These results indicate this model fit the data well.

The probability of land development in protected areas increased as the percentage of development in 50-km buffers (Fig. 4a) and protected-area size increased (Fig. 4b) and decreased as distance to minor urban centers increased (Fig. 4c). The probability that a protected area would contain land development once percent development in 50-km buffers reached 50% was >95% (Fig. 4a).

Land-Use Change Data

Similar to the land-use data, we observed that the rate of change in development from approximately 1990 through 2001 was much lower in protected areas (median = 0.05%) than in the buffers (median = 3.56%, paired Mann-Whitney *U*, $p < 0.001$) (Supporting Information). Protected areas established before 1990 had a very low rate of land-use change (<1.4%) inside their boundaries from 1990 through 2001, whereas the corresponding buffers had a rate of land-use change of 0.01–11.41% from 1990 through 2001 (Supporting Information). Protected areas established after 1990 also had lower human activity than the corresponding buffers from 1990 through 2001 (Supporting Information). Many protected areas established after 2001 had relatively high levels of human activity within their boundaries before their establishment (i.e., from 1990 through 2001) (Supporting Information). There was a positive relation between percent change in developed land in protected areas and percent change in developed land in 50-km buffers ($\rho = 0.53$) (Fig. 3b).

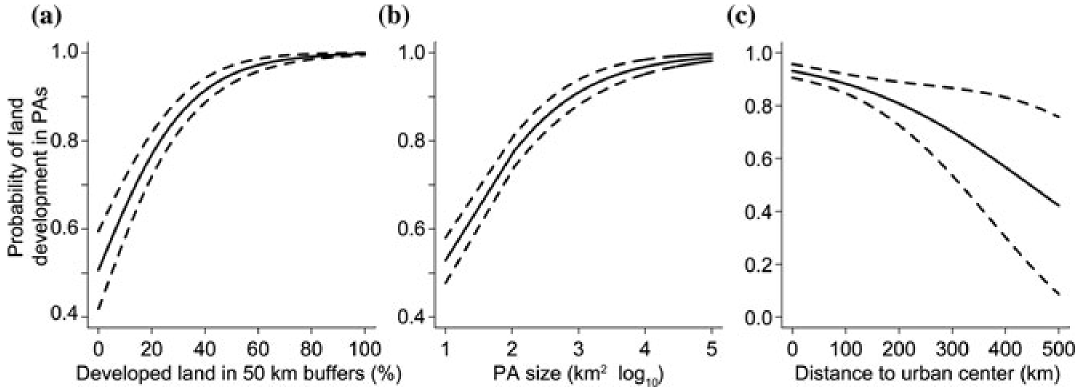

Figure 4. For the highest ranked logistic regression model (Table 2), probability of land development in protected areas (PAs) relative to (a) percent developed land within 50 km of PA, (b) size of protected area, and (c) distance of PA to a minor urban center (dashed lines, 95% CI; scales differ on y*-axes). Predicted probabilities are for when other explanatory variables are at their mean value.*

Road Density and Urban and Cropland Area

Roads were more abundant than cropland and urban area inside protected areas (Supporting Information). Four hundred and four protected areas had roads, 178 had croplands, and 18 had urban areas within their boundaries. The mean density of roads in protected areas, however, was generally low (0.71 km/km^2) (Supporting Information) but variable among IUCN protected-area categories ($\chi^2 = 45.39$, df = 7, $p < 0.001$). Categories IV and V had the highest mean density of roads (Supporting Information). The area of cropland per protected area varied among IUCN categories ($\chi^2 = 39.26$, df = 7, $p < 0.001$). There was no difference in urban area per protected area among IUCN categories ($\chi^2 = 10.94$, df = 7, $p = 0.141$).

Discussion

Ideally, protected areas protect species within their borders from external pressures such as industrial development and urbanization (Naughton-Treves et al. 2005; Gaston et al. 2008). They have an uneven record of success, partly due to site-specific physical, political, and economic factors (Maiorano et al. 2008). Our results show that Canadian protected areas have effectively prevented within-boundary development, except in the south, where smaller reserve sizes and proximity to urban areas interact. In these protected areas, roads were the most pervasive form of development.

We found that most Canadian protected areas limited human activity inside their borders (Fig. 3a & Supporting Information). These results were robust across a range of buffer sizes (25–100 km our results and 10 km Lee and Cheng's [2010] results) and suggest that patterns of development inside and outside protected areas in Canada are scale invariant. Our examination of over 800 protected areas in Canada contributes to the growing body of evidence that protected areas can effectively mitigate the effects of anthropogenic activity within protected areas (reviewed in Naughton-Treves et al. 2005). For example, in a recent global analysis, Seiferling et al. (2011) report that protected areas in high protection categories (i.e., IUCN categories I-III) effectively maintain the pattern of vegetation-cover heterogeneity in their boundaries, whereas vegetation cover of land surrounding protected areas is fragmented by human activity.

We offer 2 reasons Canadian protected areas have low levels of land development inside their boundaries. First, most protected areas in Canada are managed to maintain biodiversity and ecological integrity (Parks Canada Agency 2005), and a stable political and economic environment allow park managers to maintain that conservation focus. Second, many of these protected areas are in wilderness areas (Sanderson et al. 2002), beyond current frontiers of industrial development, and have not yet been subject to the level of development that pervades most other parts of the world. The largest protected areas are in remote northern locations. This remoteness may necessitate some development within park boundaries; however, we found that the core areas of the 25 largest protected areas in our sample had low levels of development (i.e., mean 55.13% [SD 33.67] of development inside these protected areas was within 5 km of protected-area boundaries). As in the Peruvian Amazon (Oliveira et al. 2007), isolation and size of protected areas are key defenses against development spillover into protected areas in Canada.

Our results indicate that development around protected areas may increase pressure for development within parks (Fig. 3b). Although protected areas in Canada generally had low levels of development within their borders relative to their surroundings, 24%

($n = 200$) of protected areas in our sample had >20% developed land within their boundaries, a level of development best predicted by amount of development surrounding the protected areas (Table 2 & Fig. 4a). These results are consistent with Rivard et al.'s (2000) results in their spatial analysis of 34 Canadian national parks. They found that development outside protected areas (i.e., roads and human land use) is positively correlated with development inside protected areas and indicates that development begets development in managed landscapes.

Our highest ranked logistic regression model predicts that after land development reaches a 50% threshold in the surrounding area, development within the protected area is extremely likely (Table 2 and Fig. 4a). Results of studies in other biomes show similar relations between land development inside and adjacent to protected areas. For example, in the tropics, a 25–55% decline in forest cover surrounding protected areas led to a decline in forest cover inside protected areas as a result of deforestation (DeFries et al. 2005). As development expands into wilderness areas of Canada (e.g., Quebec's Plan Nord [Government of Quebec 2009]), land use around established protected areas will increase and prospects for new protected areas will fade (Wade & Theobald 2010). Given the highly contagious nature of land development (Boakes et al. 2010), proactive protected-areas planning and effective landscape management in currently isolated regions may reduce otherwise inexorable development within protected areas that follows development in adjacent lands.

Degradation of protected areas due to the legacy of past human land uses within their boundaries can persist over long periods (Josefsson et al. 2009), a conservation challenge for some protected areas in our study (Supporting Information). Past human land uses also reduce the effectiveness of protected areas as reference sites for understanding and predicting effects of global change on biodiversity (Josefsson et al. 2009), effects that will likely be more pronounced if development activities are intense and include permanent infrastructure (Hansen et al. 2011). An improved understanding of current and past land development inside and surrounding protected areas will help in the management and future expansion of conservation networks in these complex landscapes.

Our results provide insight into the overall patterns of land-use in protected areas in Canada. The type of development, however, can affect biodiversity differently. We found that roads were the most pervasive type of development in Canadian protected areas (roads occur in 404 protected areas). The effects of roads and other linear features on biodiversity are well known, and some parks are mitigating the negative effects of roads on wildlife innovatively (e.g., Clevenger & Waltho 2000). Park-based tourism is a major industry in Canada (Jones & Scott 2006), so human infrastructure is inevitable and perhaps even desirable to improve public appreciation and support for park-based conservation. Its extent and effects must be monitored closely so that conservation challenges can be identified and addressed before they undermine legislated conservation goals in protected areas. This knowledge will be particularly critical to the success of plans for massive expansion of protected areas in Canada.

Acknowledgments

S.J.L. was supported by a PDF from the Natural Sciences and Engineering Research Council of Canada (NSERC). J.T.K. was supported by a Discovery Grant from NSERC and infrastructure from the Canadian Foundation for Innovation and Ontario Ministry of Research and Innovation. J.T.K. also gratefully acknowledges a Visiting Senior Research Fellowship from Mansfield College at the University of Oxford and research space provided by R. H. Whittaker at the Oxford University Centre for the Environment. We thank GFWC for making data accessible and A. Hurford, BEACONs, members of the Kerr and Currie labs, and anonymous reviewers for comments on this work.

Supporting Information

Methods and results of analyses of land-use change data (Appendix S1), conceptual diagram of our spatial analyses (Appendix S2), percent developed land per protected area and in surrounding 50-km buffers by IUCN protected-area category (Appendix S3), and mean and SD of road density, urban area, and cropland area in protected areas by IUCN protected-area category (Appendix S4) are available online. The authors are solely responsible for the content and functionality of these materials. Queries should be directed to the corresponding author.

Literature Cited

Agriculture and Agri-Food Canada. 1999. A national ecological framework for Canada. Agriculture and Agri-Food Canada, Ottawa. Available from http://sis.agr.gc.ca/cansis/nsdb/ecostrat/intro.html (accessed October 2011).

Arienti, M. C., S. G. Cumming, M. A. Krawchuk, and S. Boutin. 2009. Road network density correlated with increased lightning fire incidence in the Canadian western boreal forest. International Journal of Wildland Fire **18**:970–982.

Bayne, E. M., L. Habib, and S. Boutin. 2008. Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. Conservation Biology **22**:1186–1193.

Behn, B., and S. Herrero. 2002. Grizzly bear mortality and human access in Banff and Yoho National Parks, 1971–98. Ursus **13**:213–221.

Beyer, H. L. 2010. Geospatial modelling environment. Version 0.5.2. Beta, Edmonton, Alberta.

Boakes, E. H., G. M. Mace, P. J. K. McGowan, and R. A. Fuller. 2010. Extreme contagion in global habitat clearance. Proceedings of the Royal Society of London B **277:**1081–1085.

Canada Centre for Remote Sensing (CCRS). 2008. Land cover map of Canada 2005. Natural Resources Canada, Ottawa.

Cihlar, J., J. Beaubien, R. Latifovic, and G. Simard. 1999. Land cover of Canada. Version 1.1. Special publication. NBIOME Project, Ottawa.

Clevenger, A. P., and N. Waltho. 2000. Factors influencing the effectiveness of wildlife underpasses in Banff National Park, Alberta, Canada. Conservation Biology **14:**47–56.

Conference of the Parties 10 (COP 10). 2010. Decision X/31. Protected areas. Convention on Biological Diversity, Nagayo, Japan.

Curran, L., S. Trigg, A. McDonald, D. Astiani, Y. Hardiono, P. Siregar, I. Caniago, and E. Kasischke. 2004. Lowland forest loss in protected areas of Indonesian Borneo. Science **303:**1000–1003.

DeFries, R., A. Hansen, A. Newton, and M. Hansen. 2005. Increasing isolation of protected areas in tropical forests over the past twenty years. Ecological Applications **15:**19–26.

DeFries, R., F. Rovero, P. Wright, J. Ahumada, S. Andelman, K. Brandon, J. Dempewolf, A. Hansen, J. Hewson, and J. Liu. 2010. From plot to landscape scale: linking tropical biodiversity measurements across spatial scales. Frontiers in Ecology & Evolution **8:**153–160.

Department of Forestry and Natural Resources, Clemson University. 2010. Terrestrial protected areas of North America, 2010. Commission for Environmental Cooperation, Montreal.

Desktop Mapping Technologies Inc. (DMTI). 2000. Roads data for Canada. DMTI, Markham, Ontario.

Environmental Systems Resource Institute (ESRI). 2010. ArcMap 10.0. ESRI, Redlands, California.

Fahrig, L., and T. Rytwinski. 2009. Effects of roads on animal abundance: am empirical review and synthesis. Ecology and Society **14**(1):21. Available from http://www.ecologyandsociety.org/vol14/iss1/art21/ (accessed October 2011).

Gaston, K. J., S. F. Jackson, L. Cantu-Salazar, and G. Cruz-Pinon. 2008. The ecological performance of protected areas. Annual Review of Ecology, Evolution, and Systematics **39:**99–113.

Geomatics Canada. 2000. Updated road network for Canada. Geomatics Canada, Ottawa.

Government of Quebec Minister of Natural Resources and Wildlife. 2009. Plan nord. Minister of Natural Resources and Wildlife, Quebec. Available from http://www.plannord.gouv.qc.ca/english/documentation.asp (accessed September 2010).

Gurd, D. B., T. D. Nudds, and D. H. Rivard. 2001. Conservation of mammals in eastern North American wildlife reserves: How small is too small? Conservation Biology **15:**1355–1363.

Hansen, A., and R. DeFries. 2007. Ecological mechanisms linking protected areas to surrounding lands. Ecological Applications **17:**974–988.

Hansen, A. J., C. Davis, N. Piekielek, J. Gross, D. Theobald, S. Goetz, F. Melton, and R. DeFries. 2011. Delineating the ecosystems containing protected areas for monitoring and management. BioScience **61:**363–373.

Hebblewhite, M., C. A. White, C. G. Nietvelt, J. A. McKenzie, T. E. Hurd, J. M. Fryxell, S. E. Bayley, and P. C. Paquet. 2005. Human activity mediates a trophic cascade caused by wolves. Ecology **86:**2135–2144.

IUCN (International Union for Conservation of Nature). 1994. Guidelines for protected area management categories. CNPPA with the assistance of WCMC, Cambridge, United Kingdom.

Jones, B., and D. Scott. 2006. Climate change, seasonality and visitation to Canada's National Parks. Journal of Parks and Recreation Administration **24:**42–62.

Josefsson, T., G. Hörnberg, and L. Östlund. 2009. Long-term human impact and vegetation changes in a boreal forest reserve: implications for the use of protected areas as ecological references. Ecosystems **12:**1017–1036.

Kerr, J. T., and I. Deguise. 2004. Habitat loss and limits to recovery of endangered wildlife. Ecology Letters **7:**1163–1169.

Kharouba, H. M., and J. T. Kerr. 2010. Just passing through: global change and the conservation of biodiversity in protected areas. Biological Conservation **143:**1094–1101.

Lee, P. G., and R. Cheng. 2010. Canada's terrestrial protected areas status report 2010: number, area, naturalness. Global Forest Watch Canada, Edmonton, Alberta.

Lee, P. G., J. D. Gysbers, and Z. Stanojevic. 2006. Canada's forest landscape fragments: a first approximation. Global Forest Watch Canada, Edmonton, Alberta.

Lee, P. G., M. Hanneman, J. D. Gysbers, and R. Cheng. 2010*a*. Cumulative access in Canada's forest ecozones. 10th anniversary publication 2. Global Forest Watch Canada, Edmonton, Alberta.

Lee, P. G., M. Hanneman, and J. D. Gysbers. 2010*b*. Industrial-caused changes to Canada's forest frontier: 1990–2001. 10th anniversary publication 10. Global Forest Watch Canada, Edmonton, Alberta.

Lehner, B., and P. Doll. 2004. Development and validation of a global database of lakes, reservoirs, and wetlands. Journal of Hydrology **296:**1–22.

Liu, J., M. Linderman, Z. Ouyang, L. An, J. Yang, and H. Zhang. 2001. Ecological degradation in protected areas: the case of Wolong Nature Reserve for giant pandas. Science **292:**98–101.

Maiorano, L., A. Falcucci, and L. Boitani. 2008. Size-dependent resistance of protected areas to land-use change. Proceedings of the Royal Society B-Biological Sciences **275:**1297–1304.

McDonald, R., C. Yuan-Farrell, C. Fievet, M. Moeller, P. Kareiva, D. Foster, T. Gragson, A. Kinzig, L. Kuby, and C. Redman. 2007. Estimating the effect of protected lands on the development and conservation of their surroundings. Conservation Biology **21:**1526–1536.

Natural Resources Canada. 2007. National road network. Sherbrooke, Quebec. Available from http://www.geobase.ca (accessed October 2011).

Naughton-Treves, L., M. Buck, and K. Brandon. 2005. The role of protected areas in conserving biodiversity and sustaining local livelihoods. Annual Review of Environment and Resources **30:**219–252.

Noss, R. F., and L. D. Harris. 1986. Nodes, networks, and MUMs: preserving diversity at all scales. Environmental Management **10:**299–309.

Oliveira, P., G. Asner, D. Knapp, A. Almeyda, R. Galvan-Gildemeister, S. Keene, R. Raybin, and R. Smith. 2007. Land-use allocation protects the Peruvian Amazon. Science **317:**1233–1236.

Parks Canada Agency. 2005. Monitoring and reporting ecological integrity of Canada's National Parks. Volume I: guiding principles. Parks Canada Agency, Ottawa.

Rivard, D., J. Poitevin, D. Plasse, M. Carleton, and D. Currie. 2000. Changing species richness and composition in Canadian national parks. Conservation Biology **14:**1099–1109.

Rodrigues, A. S. L., et al. 2004. Effectiveness of the global protected area network in representing species diversity. Nature **428:**640–643.

Sanderson, E. W., M. Jaiteh, M. A. Levy, K. H. Redford, A. V. Wannebo, and G. Woolmer. 2002. The human footprint and the last of the wild. BioScience **52:**891–904.

Seiferling, I. S., R. Proulx, P. R. Peres-Neto, L. Fahrig, and C. Messier. 2011. Measuring protected-area isolation and correlations of isolation with land-use intensity and protection status. Conservation Biology **26:**610–618.

Statistics Canada. 2006. Population and dwelling counts, for uban areas, 2006 and 2001 censuses—100% data. Statistics Canada, Ottawa.

Timoney, K. 2002. A dying delta? A case study of a wetland paradigm. Wetlands **22:**282–300.

Vanderkam, R. 2010. Conservation areas reporting and tracking system procedures manual and database schema. Canadian Council on Ecological Areas, Gatineau, Quebec.

Venter, O., N. N. Brodeur, L. Nemiroff, B. Belland, I. J. Dolinsek, and J. W. A. Grant. 2006. Threats to endangered species in Canada. BioScience **56:**903–910.

Wade, A., and D. Theobald. 2010. Residential development encroachment on U.S. Protected Areas. Conservation Biology **24:**151–161.

Wiersma, Y. F., and T. D. Nudds. 2009. Efficiency and effectiveness in representative reserve design in Canada: the contribution of existing protected areas. Biological Conservation **142:**1639–1646.