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Research article

Mammal responses to the human footprint vary across species and stressors

Mary Toews [a, *], Francis Juanes [a], A. Cole Burton [a, b]

[a] Department of Biology, University of Victoria, PO Box 1700, Station CSC, Victoria, BC, V8W 2Y2, Canada
[b] Department of Forest Resources Management, University of British Columbia, 2045 - 2424 Main Mall, Vancouver, BC, V6T 1Z4, Canada

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A B S T R A C T

A rapidly expanding human footprint – comprised of anthropogenic land-use change and infrastructure - is profoundly affecting wildlife distributions worldwide. Cumulative effects management (CEM) is a regional approach that seeks to manage combined effects of the human footprint on biodiversity across large spatial scales. Challenges to implementing this approach include a lack of ecological data at large spatial scales, the high cost of monitoring multiple indicators, and the need to manage multiple footprints across industries. To inform development of effective CEM, we used large mammals as indicators to address the following questions: a) do species respond more strongly to individual footprint features or to cumulative effects (combined area of all footprint types, measured as total footprint), b) which features elicit the strongest responses across species, and c) are the direction of responses to footprint consistent? We used data from 12 years of snowtrack surveys (2001–2013) in the boreal forest of Alberta, coupled with regional footprint and landcover data, to develop generalized linear mixed-effects models relating the relative abundance of five boreal mammals [gray wolf (*Canis lupus*), Canada lynx (*Lynx canadensis*), coyote (*Canis latrans*), white-tailed deer (*Odocoileus virginianus*) and moose (*Alces alces*)] to individual and cumulative effects of the human footprint. We found that across species the strongest responses were to agriculture, roads, and young cutblocks (<10 years), suggesting these as potential priority stressors to address within CEM. Most species also responded to total footprint, indicating that in the absence of detailed information on individual features, this coarse measure can serve as an index of cumulative effects. There was high variability in direction and magnitude of responses across species, indicating that community-level responses are likely and should be considered within CEM planning.

1. Introduction

Landscape change can profoundly affect the abundance and distribution of species through several mechanisms, including habitat loss, fragmentation and conversion (Fahrig, 2003, 2001; Newbold et al., 2015). When distribution of species is altered, a suite of ecological and economic consequences may follow (Kareiva and Marvier, 2012). For example, altered abundances and distributions can lead to shifts in community composition (Hagen et al., 2012; Rayfield et al., 2009; Venier et al., 2014) – which in turn can result in reduced ecosystem functionality (Cardinale et al., 2006; Folke et al., 2004), with associated socioeconomic repercussions such as the loss of essential ecosystem services (Gonzalez et al., 2011).

The physical impact of anthropogenic landscape change is often described by the human footprint, a measure of the land area disturbed by human activities and development, such as transportation and energy infrastructure, buildings and developments, and landscape change from forestry, mining and agriculture (Sanderson et al., 2002). The human footprint collectively measures habitat loss, fragmentation and conversion, which are the leading causes of environmental degradation and biodiversity loss worldwide (Fahrig, 2003, 2001; Hannah et al., 1995; Newbold et al., 2015; Venter et al., 2016). Beyond measuring the direct effect of human disturbance, the human footprint can be a proxy for many related human influences, such as human activity levels and sources of pollution (Foley et al., 2005; Sanderson et al., 2002; Venter et al., 2016). Managing the human footprint may help to mitigate

* Corresponding author. Nanoose Bay, BC, Canada.
E-mail addresses: toews.mary@gmail.com, toewsm@uvic.ca (M. Toews).

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human-caused impacts on a suite of environmental values and effects on multiple species (Foley et al., 2005; Newbold et al., 2015; Watson et al., 2016).

Cumulative Effects Management (CEM; Weber et al., 2012) is a management approach that considers the impacts of all forms of human land use and activity on the environment, recognizing that these will accumulate over time and across space (Hegmann et al., 1999). CEM requires the consideration of habitat change on larger spatial scales than traditional environmental management, accounting for a wide range of human footprint components and multiple species (Boutin et al., 2009; Schultz, 2010). In this study, we refer to cumulative effects in relation to the human footprint, defining it as the combined additive or antagonistic effect of multiple footprint features (e.g. roads, agriculture, forestry, etc.) on the environment, either measured as the sum of effects from individual features or the overall effect of the total footprint.

Although CEM is a promising framework for managing an increasing human footprint, implementing CEM in an evidence-based manner remains an ongoing challenge (Ma et al., 2012; Schultz, 2010; Shackelford et al., 2017). CEM implementation may entail establishing ecological indicators to monitor impacts, establishing links between ecological impacts and footprint features, determining 'acceptable levels' of cumulative effects to avoid severe impacts (e.g. thresholds; Sorensen et al., 2008), and finally setting up frameworks (e.g. policies and guidelines) for managing these footprint features (Burton et al., 2014).

In CEM, it is ideal to monitor ecological indicators from a range of environmental values and over a range of spatial scales; however, a comprehensive approach is rarely feasible due to the costs of ecological monitoring (Wintle et al., 2010). Furthermore, CEM generally focuses on regional scales (Schultz, 2010; Sutherland et al., 2016), and as such indicators that respond at large spatial scales may be preferable. Using large mammals as ecological indicators and subsequently managing the human footprint to limit detrimental impacts on large mammals may meet social, economic, and ecological goals concurrently (e.g. Clark et al., 1996; Morrison et al., 2007). Large mammals are both socioeconomically and ecologically important, being a target for sport hunting, cultural use, meat consumption and non-consumptive viewing (Ripple et al., 2015b, 2014). Due to their ecological importance, declines in large mammals may result in other ecological impacts, such as an increase in invasive species (Estes et al., 2011), changes to fire regime (Estes et al., 2011; Ripple et al., 2015b), and loss of biodiversity (Estes et al., 2011; Ripple et al., 2015a, 2015b). Due to their size, large mammals often require extensive home ranges and dispersal movements to meet their biological needs (Bowman et al., 2002; Ripple et al., 2015b). Preserving habitat for these species thus requires preserving broad areas and maintaining landscape-level connectivity, which may provide protection for other species (Morrison et al., 2007; Woodroffe and Ginsberg, 1998; but see Roberge and Angelstam, 2004). Given the sensitivity of large mammals to the human footprint (Bowman et al., 2010; Northrup and Wittemyer, 2013; Venier et al., 2014), managing footprint may be an expedient way to mitigate changes in large mammal distributions.

Emerging CEM programs in Canada indicate that this may already be a developing strategy. For example, the draft Biodiversity Management Framework under Alberta's Land Use Framework for the South Athabasca Region includes boreal caribou (*Rangifer tarandus caribou*) as a primary indicator, and other large mammals, such as lynx (*Lynx canadensis*) and moose (*Alces alces*), as secondary indicators (Government of Alberta, 2014). Similarly, the ongoing cumulative effects monitoring program in the Northwest Territories considers caribou as a priority value (Northwest Territories Cumulative Impact Monitoring Program, 2015), and early visions for British Columbia's cumulative effects monitoring program highlight grizzly bear populations and caribou habitat as potential indicators (Government of British Columbia, 2014).

Canada has the second largest area of boreal forest globally, covering over 3,000,000 km^2 (Hansen et al., 2010). Although about 40% of this area is actively managed for forestry purposes, a multitude of other uses take place within the boreal forest, including mining, pipeline, rail and road corridors, agriculture and grazing as well as oil and gas development (Venier et al., 2014). These uses overlap extensively in Alberta, making it an important system in which to examine the cumulative effects of landscape change (Alberta Biodiversity Monitoring Institute, 2014).

In this study, we tested key elements needed to guide the implementation of CEM, focusing on a region and community of species where CEM is emerging, but with broader application to a range of regions and ecosystems globally. Using data from over a decade of snowtrack transect surveys and spatial landscape data, we investigated how large mammals in boreal Alberta respond to the human footprint, focusing on five widely distributed and relatively abundant species: gray wolf (*Canis lupus*), Canada lynx (*Lynx canadensis*), coyote (*Canis latrans*), moose (*Alces alces*) and white-tailed deer (*Odocoileus virginianus*). Specifically, we asked the following: a) do these species respond more strongly to the cumulative effects of total footprint (i.e. total disturbance) than to specific footprint features; b) do certain footprint features consistently elicit stronger responses across species, and c) are the direction of species-specific responses to footprint consistent? Addressing these questions will provide key insights for guiding implementation of CEM in order to manage the impacts of landscape change on large mammals.

2. Methods

2.1. Study area

The data were collected across the Boreal Forest and Lower Foothills natural regions of Alberta, Canada, spanning an area of approximately 400,000 km^2 (Fig. 1). The terrain varies from rolling foothills to mosaics of forested uplands and low-lying wetlands, bogs and fens, with elevations ranging from 150 m to 1500 m (Natural Regions Committee, 2006). Common tree species include trembling aspen (*Populous tremuloides*), balsam poplar (*Populous balsamifera*), willow (*Salix* sp.), white and black spruce (*Picea glauca* and *P. mariana*), tamarack (*Larix laricina*), jack pine (*Pinus banksiana)* and lodgepole pine (*Pinus contorta*) (Natural Regions Committee, 2006).

The province of Alberta is host to a wide range of economically important industries. Forest harvest is common in the Lower Foothills and Boreal Forest regions, while agriculture is concentrated at the southern extent of the Boreal Forest and throughout the Peace River area. Oil and gas activities are also widespread, with concentrations in the Oil Sands Region; an area of 140,000 km^2 or approximately 1/3 of the study area (Alberta Biodiversity Monitoring Institute, 2014). Within the oil sands region, 7.4% is converted due to agricultural use, 2.9% has been harvested for forestry, while energy features (mines, wells, seismic lines), roads, urban, rural, and industrial features only cover about 2.2% (Alberta Biodiversity Monitoring Institute, 2014). Although industrial features and roads cover a small total area, when these features are buffered by 2 km, they cover 97% of the oil sands region (Alberta Biodiversity Monitoring Institute, 2014). Hunting, fishing and trapping are popular throughout the region (Natural Regions Committee, 2006). The study area encompasses multiple municipalities such as Fort McMurray and Whitecourt, as well as numerous smaller population centers.