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Research Article

Understanding the role of traditional and user-created recreation data in the cumulative footprint of recreation

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ABSTRACT

Outdoor recreation is becoming more popular globally. However, recreation can contribute to biodiversity loss by modifying habitats and disturbing species. Understanding what activities are happening and where is crucial for mitigating negative impacts but is hampered by information gaps on patterns of human use, including the spatial footprint of recreation. Data on recreation trails and linear features traditionally have been managed in centralized government databases. Social media and user-created content, however, largely has been unexplored for tracking recreation patterns across large spatial extents, which is needed for landscape-level conservation (i.e., beyond a single protected area), planning, and management that meets the needs of people and wildlife. We compiled recreation data from government (documented) and non-government (undocumented) databases for motorized and non-motorized recreation in western Canada. Of all the trails mapped, 73% were classified as documented whereas 27% were undocumented. For undocumented trails, the primary data source was Open Street Maps, which is the basis for many recreation smartphone applications. Most undocumented trails had unknown activity types, indicating a lack of information in government databases about where recreation occurs, and which type(s) of activity occur there. Modeling revealed an increased probability of a trail being undocumented as elevation increased and the distance to nearest road decreased. Our results indicate that including data from user-created sources can improve estimates of the recreation human footprint.

Management implications:

- Over 51% of trails and linear features were primarily used for motorized activities. This calls for better land-use planning to ensure high quality recreation experiences.
- 27% of our trail data originated from non-government data sources, primarily Open Street Maps. Undocumented trails were similarly likely to occur in protected areas (PA), as compared to unprotected areas. Better monitoring of the recreation footprint is required, inside and outside PAs, and data quality control methods implemented.
- Likely, the situation will require a large-scale effort to centralize trail data, such as we have done here, strategically plan when and where recreation should occur, and educate user groups to mitigate ecological and wildlife effects.

1. Introduction

Outdoor recreation is booming, with more people going outside and doing more varied activities than ever before (Outdoor Industry Association, 2021). Globally, visitation to protected areas (PA) is estimated at eight billion people per year, and visitation rates are increasing (Balmford et al., 2009). Beyond PAs, international travel and tourism spending was US$1.8 trillion in 2019, and accounted for the creation of one in four new jobs globally (World Travel & Tourism Council, 2021). In addition to economic indicators signalling the importance of

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nature-based outdoor recreation and tourism, spending time outdoors in natural environments can directly and positively affect human physical, psychological, social, and emotional well-being (Bowler et al., 2010; Lemieux et al., 2015). Recently, the COVID pandemic has highlighted both our need to connect with nature (Chaudhury & Banerjee, 2020; Roll et al., 2021) and the need to redress the ecological impacts that result from burgeoning recreation (Smith et al., 2022).

Despite its positive contributions to economies and human well-being, recreation contributes to biodiversity loss via disturbance (Doherty et al., 2021) and land-use change (Newbold et al., 2015; Turner et al., 2007). From a global review of nearly 2000 protected areas in 149 countries, disturbance from recreation activities was the second most reported threat for protected areas (Schulze et al., 2018). Over the past 20-plus years, research has shown widespread and increasing human influence on landscapes through human footprint analyses (Gallardo et al., 2015; Leu et al., 2008; Sanderson et al., 2002, 2002van der Marel et al., 2020). For example, Venter et al. (2016) found that 71% of the world's ecoregions experienced a more than 20% increase in human footprint from 1993 to 2009. Crucially, however, these global human footprint analyses that are influential for conservation benchmarks do not include the recreation footprint, which can be substantial given how widespread motorized and non-motorized activities are on trails and linear features. In some areas, rough resource roads and seismic lines that are often used by off-highway vehicles (OHV) can result in high local linear densities (e.g., up to 6 km/km^2; Farr et al., 2018). This level of linear densities can have dramatic ecological effects. For example, recreation can impede vegetation and habitat recovery following disturbance. In Alberta, Canada, approximately one-third of legacy seismic lines failed to regenerate within fifty years (van Rensen et al., 2015), in part due to recreation use (Pigeon et al., 2016).

Recreation is also a threat to many species at risk (Doherty et al., 2021; McCune et al., 2013) and can have direct and indirect impacts on wildlife such as habitat loss, displacement, and reduced survival and fecundity (Gruas et al., 2020; Marion et al., 2020; Procko et al., 2022). Wolverines (*Gulo gulo*), a species of Special Concern in Canada (Committee on the Status of Endangered Wildlife in Canada, 2014), avoided motorized and non-motorized winter recreation areas in western United States (Heinemeyer et al., 2019). Grizzly bears (*Ursus arctos*), also a species of Special Concern (Committee on the Status of Endangered Wildlife in Canada, 2014), may experience population declines when road densities, many of which are remote low-traffic gravel roads built for resource extraction and used for recreation, exceed 0.6 km/km^2 (Boulanger et al., 2014; Mace et al., 1996). Wildlife species thatrequire secure habitat and that range widely, such as wolverines and grizzly bears, might be more susceptible to human disturbance such as recreation, and require careful planning for population and habitat maintenance. As well, real or perceived conflict can occur among different recreation user groups that recreate in the same area, including interpersonal or goal interference conflict, and social values conflict (Dertien et al., 2021; Jacob & Schreyer, 1980; Williams et al., 1992).

Data on recreation trails and linear features traditionally have been managed in centralized government databases, with agencies using site-specific surveys, interviews, and/or the number of entrance pass issued to determine usage and the type of activities occurring (Lawson, 2021). However, these data rarely occur at spatial or temporal scales finer than the park or forest area boundaries and often are recorded only within PAs. Further, the recreation footprint is widely assumed to be vastly underestimated. From the Trails Strategy for British Columbia (BC), Canada: "*BC has an estimated 30,*000 km *of formally recognized and managed trails. However, many recreation trails are not formally managed and currently there is no consistent record available to track these trails. The total amount of kilometres of trails in BC is estimated at hundreds of thousands of kilometres*" (Government of British Columbia, 2013).

A new type of data is available that occurs at fine spatial and temporal scales, across jurisdictional boundaries, and are user-created. There are now 4.6 billion social media users world-wide (Hootsuite, 2022) and the onset of geo-referenced and user-created content (i.e., volunteered geographic information; Goodchild & Glennon, 2010; Horst et al., 2023; Norman & Pickering, 2017) from social media (e.g., Twitter) and fitness apps (e.g., Strava) have emerged as new and flexible data sources to complement traditional data sources (Fisher et al., 2018; Wilkins et al., 2021; Wood et al., 2020). While these datasets represent a huge resource, they largely have been unexplored to track large-scale recreation patterns, and are rarely evaluated at spatial scales meaningful for large landscape conservation, management, and planning (i.e., beyond a small trail network; Marion et al., 2020). As well, it is unclear if similar processes give rise to user-created trails (e.g., close to roads or towns) as they do for trails already included in government-databases (e.g., well-established and documented). For example, user-created trails may occur in more remote terrain relative to government-documented trails. As a result of the ecological effects of an increasing human footprint and an increased popularity in outdoor-based recreation, land-use planning and recreation access and management have become priority issues for many managers. However, there is a significant knowledge gap in knowing where, at what intensity, and what type of recreation occurs, and at what spatial scale this knowledge gap exists.

As part of a larger research project developing functional models of wildlife disturbance from recreation,[1] in this study we assess where people recreate, and which activities occur. We use government and user-created data sources to evaluate the recreation footprint for a large multi-jurisdictional area in western Canada, a major hub of motorized and non-motorized outdoor recreation in winter and summer. Trails were classified into documented trails, which are government-sourced data, and undocumented trails, which generally originate from user-created databases like Open Street Maps (OSM) and recreation applications such as Trail Forks. We classify broad recreation activities along these trails. Our research questions are: 1) How do linear trail densities vary across a large multi-jurisdictional area (i.e., beyond PAs), and activity type, specifically motorized and non-motorized recreation; 2) What ecological variables are correlated with documented and undocumented recreation footprints; and 3) Do undocumented trails encroach more into high quality wolverine and grizzly bear habitats relative to documented trails? While 1) and 2) are not complex exercises, they are rarely done for large spatial extents, and are necessary to effectively plan for and manage recreation.

2. Study area

The study area encompasses 63,000 km^2 of mountainous terrain in western Alberta and eastern BC, Canada (Fig. 1). This area contains the North Central Rockies forest, Alberta mountain forests, and the Alberta-British Columbia foothills forests ecoregions. As well, 32% (20,260 km^2) of the area has federal or provincial protection such as provincial parks, wilderness areas, heritage rangelands, and national parks (hereafter, protected areas or PAs). It is renowned as an adventure tourism and recreation destination, with over four million visitors to Banff National Park (Parks Canada, 2020). Our study area also includes motorized designated areas, open public land, grazing leases, private lands and the communities of Canmore, Banff, Golden, Revelstoke, Nakusp and Invermere. Many towns within the study area have transitioned or are transitioning from resource-based to tourism-based economies (Williams & Bull, 2019). The study area is found within the territories of numerous Indigenous Nations[2] including the Okanagan/Syilx, Sinixt, Ktunaxa, Secwépemc, Īyāħé Nakoda (including the Chiniki, Goodstoney, and Bearspaw Nations), Tsuut'ina, Niitsítapi (including the Kainai, Siksika, and Piikani Nations), and within Region 3 of the Métis Nation of Alberta.

In addition to outdoor tourism, forestry and mining are important

[1] https://y2y.net/work/hot-projects/recreation-ecology.

[2] https://native-land.ca/.

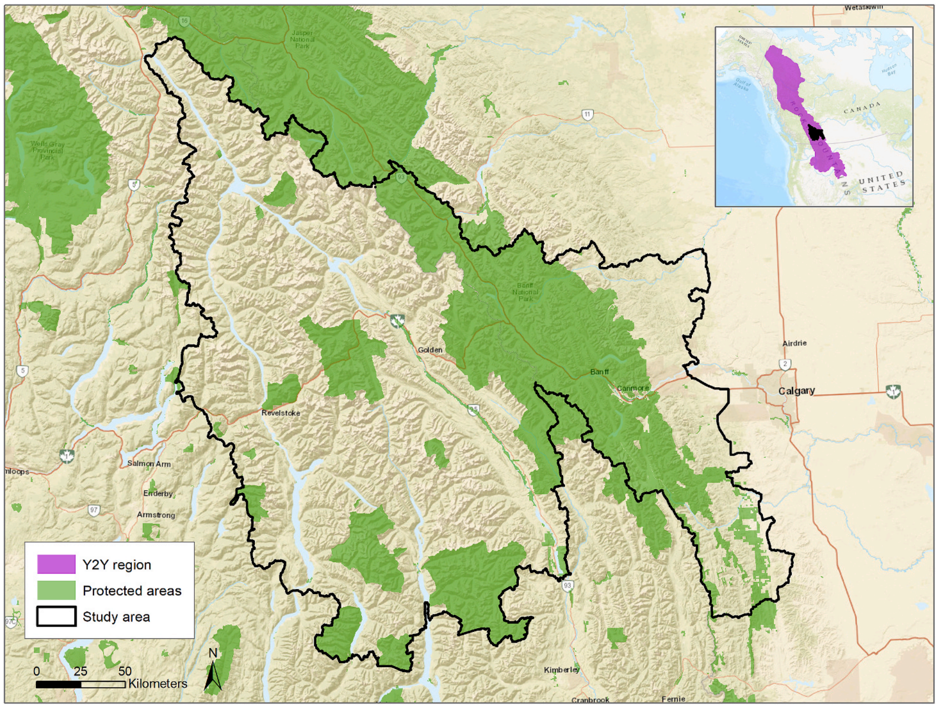

Fig. 1. The study area in western Alberta and eastern British Columbia, Canada. [COLOR].

sectors in Alberta and BC's economy, while oil and gas development is prominent in Alberta (Forest Practices Board, 2021). Industrial activities contributed to the high density of gravel and resource roads (0.18 km/km^2), which also provide access for motorized and non-motorized recreation (Forest Practices Board, 2021). Paved road densities are lower (0.06 km/km^2), with the Trans-Canada Highway bisecting the study area.

Our study area is part of the greater Yellowstone to Yukon (Y2Y) region, which is the most intact large mountain system in the world (Theobald et al., in prep). The Yellowstone to Yukon Conservation Initiative is an international non-profit organization with the mission to protect and connect habitat from Yellowstone to Yukon so that people and nature can thrive. In our study area, key threats to sensitive species such as grizzly bears and wolverines, which are both listed under Canada's Species At Risk Act as species of Special Concern (Committee on the Status of Endangered Wildlife in Canada, 2012), include habitat loss and fragmentation, harvest pressure (wolverines), and habitat shifts as a result of climate change (Barsugli et al., 2020; Fisher et al., 2022; Peacock, 2011; Roberts et al., 2014). Recreation is a documented threat to both grizzly bears and wolverines, especially during sensitive periods (e.g., denning female wolverines), as well as other species occurring in the study area.

3. Materials and methods

3.1. Trail data acquisition and processing

We acquired trails and linear feature data from provincial and federal government sources (Vilalta Capdevila et al., 2022) and searched for user-contributed datasets (e.g., OSM), regional recreation user groups (e.g., Revelstoke Snowmobile Club) and trail mapping and management sites (e.g., Southern Alberta Trail Mapping Project) that contained spatial recreation data (Fig. 2). We did this by exhaustively searching for online trail and linear feature data for our study years (2017–2019) based on local knowledge and knowledge sharing with recreation experts, users, user groups, and managers. We defined documented trails as originating from government databases, recreation

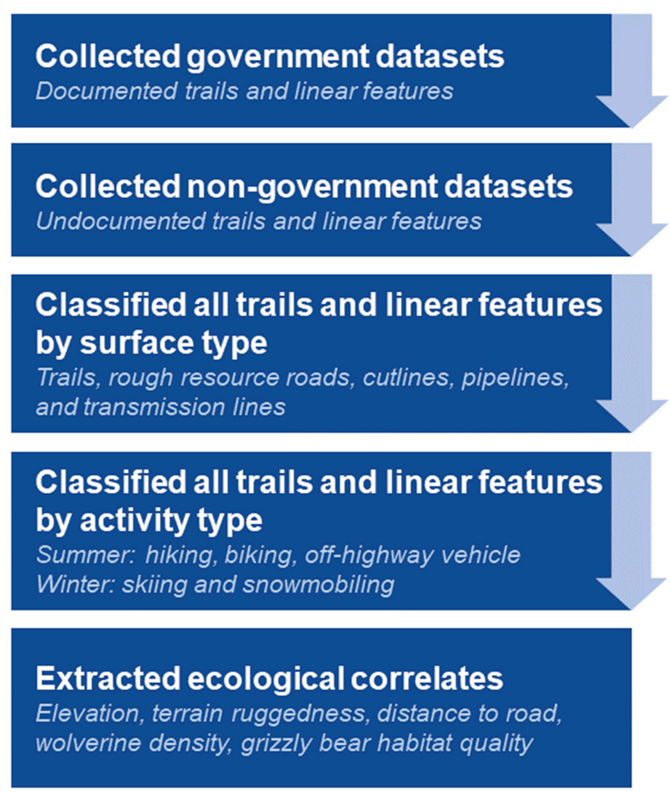

Fig. 2. Workflow chart for collecting government (i.e., documented) and non-government (i.e., undocumented) datasets, classifying trails, activity types, and extracting ecological correlates. [COLOR].

clubs, BC digital road atlas, and backcountry recreation access plans (Vilalta Capdevila et al., 2022). In certain cases, documented trails included unsanctioned, unofficial, informal, and/or undesignated trails, indicating that these trails were known to government agencies and thus 'managed' (e.g., maintained, closed, etc.). We defined undocumented trails as those not originating from the databases mentioned above, which primarily included user-created content such as OSM, Trail Forks, and the Southern Alberta Trail Mapping Project. For a full list of data sources including resolutions, data formats, and key quality attributes, please see the technical report (Vilalta Capdevila et al., 2022).

We defined each trail by the intended use. For example, we classified a linear feature had information on activity type, trail name, or trail type (i.e, a trail was a specific type of linear feature). However, trail-based recreation is often facilitated by cutlines, pipelines, transmission lines, and (unmaintained) resource roads. We term these 'linear features' (Vilalta Capdevila et al., 2022) and they represent an important, but often ignored, part of the recreation footprint (Government of British Columbia, 2013). Graveled and paved roads were excluded from this study unless they were used as a trail during winter (e.g., snowmobiling trails), because these roads often experience high vehicle traffic and are not used directly for off-road recreation. We did not have information on actual use (e.g., from trail counters) for this study so linear features represent the potential for recreation use.

Many datasets had overlapping spatial information. To reduce overlap, we filtered out spatial and attribute data. Generally, government datasets took precedence, and we joined additional attribute data to them (Vilalta Capdevila et al., 2022). If two datasets had similar spatial resolution and data origins (i.e., both government-based), we started with the dataset with the larger spatial extent as the priority layer. In most cases, the government-based datasets had the highest resolution and were therefore the base layer to which other information was added. From the final database, we calculated trail and linear feature lengths using the 'calculate geometry' function in ArcMap (Version 10.8.2; ESRI 2021).

Finally, we calculated linear densities for National Hydro Network 3rd-level watershed boundaries (Natural Resources Canada 2018). We also classified trails and linear features by motorized or non-motorized recreation (Table 1) based on the source datasets. Full details on the data collation and processing can be found in Vilalta Capdevila et al. (2022). For all described steps, data processing was completed in ArcMap.

3.2. Relating documented and undocumented trails to the landscape

To examine the ecological implications of recreation trails on the landscape, we intersected our spatial trails layer with terrain and wildlife covariates (Fig. 2). We used six covariates: i) elevation (digital elevation model; 30-m resolution; Government of Canada Natural Resources Canada, Canada Centre for Mapping and Earth observation. 2013. Canadian Digital Elevation Model Product Specifications. Edition 1.1. Sherbrooke, Quebec, Canada), ii) terrain ruggedness index (30-m resolution), iii) Euclidian distance to the nearest road (30-m resolution), iv) protected area status (binary; Canadian Protected and Conserved Areas Database[3]), v) predicted wolverine surface density (1500-m resolution; Mowat et al., 2020), and vi) grizzly bear habitat quality as indexed by a resource selection function (100-m resolution; Proctor et al., 2015). Wolverine densities were estimated using spatial capture-recapture models (Efford, 2004) with data from DNA hair snags that were visited from 2012 to 2016. Surface densities were predicted for nearly the full extent of our study area; methods are described in full in Mowat et al. (2020). For grizzly bears, Proctor et al. (2015) estimated a resource selection function (RSF) (Boyce & McDonald, 1999; Manly et al., 2002) from 27 GPS-telemetry collared grizzly bears (13 females, 14 males) for the western portion of our study area. Methods are described in full by Proctor et al. (2015).

The spatial resolution of our covariates did not match. Thus, we created a network of points placed every 1500 m along all trails (Supplemental Information Fig. 1), which is the maximum spatial resolution of the covariates. We extracted spaital covariates to this network of points. To evaluate differences in patterns related to documented and undocumented trails, we visualized patterns in the raw data, evaluated the data for correlation (values above $|0.6|$ were excluded from the same model), and fit the data to a binomial generalized linear model (GLM) with a logit fit. We used the trail status as the response variable (documented = 0, undocumented = 1). We fit a single model because we were interested in only specific variables, not the best model fit: $documented_i \sim \beta_0 + elevation_i + terrain\ ruggedness_i + distance\ to\ road_i + protection_i + \varepsilon_i$ for each ith observation where β_0 is the intercept and ε is the error term. For modelling, we withheld 60% of the data as test data and used the remaining 40% as training data. All continuous covariates were scaled (SD = 1) and centered (mean = 0) for model fitting. We evaluated model fit using the area under the curve, which is a measure of sensitivity, or the probability that the model will correctly predict a positive outcome for an observation, and specificity, the probability that the model correctly predicts a negative outcome (i.e., perfect predictive fit is a value of 1). We graphically report 95% confidence intervals and interpret the effect of each covariate on the response variable. We also checked for spatial autocorrelation in the residuals by visualizing the scaled residuals.

The spatial extent of the wolverine and grizzly bear studies were smaller than the spatial extent of our trail data. We subset the wolverine and trail data to match the smallest spatial extent (i.e., the grizzly bear dataset). We ran the modelling steps described above for this restricted dataset ('wildlife GLMs') and present results specific to the relationship between grizzly bear RSF, wolverine density, and trail status.

4. Results

4.1. Linear densities

We compiled trails and linear feature data, totalling 53,436 km across the study area and an overall density of 0.85 km/km^2. Densities were heterogenous within the study area, and ranged from 3.34 km/km^2 southwest of Calgary, a population center of 1.3 million people (Statistics Canada, 2022), to 0.12 km/km^2 in the Purcell Wilderness Conservancy, a 1981 km^2 area that prohibits bicycles and motorized use, including helicopter-accessed activities (Fig. 3A; Supplemental Information Fig. 2; Supplemental Information Table 1). Within protected areas, linear densities were roughly half (0.54 km/km^2) than those outside protected areas (1.00 km/km^2). Linear densities also differed by province, with linear densities slightly less than half in BC (0.63 km/km^2) than those in AB (1.42 km/km^2).

Table 1
Definitions of motorized and non-motorized recreation types on trails or linear features.

Recreation type	Description
Motorized	Any designated off-highway vehicles (OHV) or snowmobiling trail or linear feature that did not prohibit motorized activities (either snowmobiling or OHV use).
Non-motorized	Any trail or linear feature categorized as a hiking, biking, horse, skiing, snowshoeing and/or fat biking trail where motorized activities were either prohibited or not specified.
Motorized and non-motorized	Any trail or linear feature classified with at least one motorized and non-motorized activity.
Motorized prohibited	Any trail or linear feature categorized as a motorized trail occurring in a protected area, recreation, or motor vehicle closure area, grazing disposition or a non-motorized designated recreation management plan area. Non-motorized use was not specified.
Unknown	Any trail or linear feature without information on activity type.

[3] https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/protected-conserved-areas-database.html#toc0.

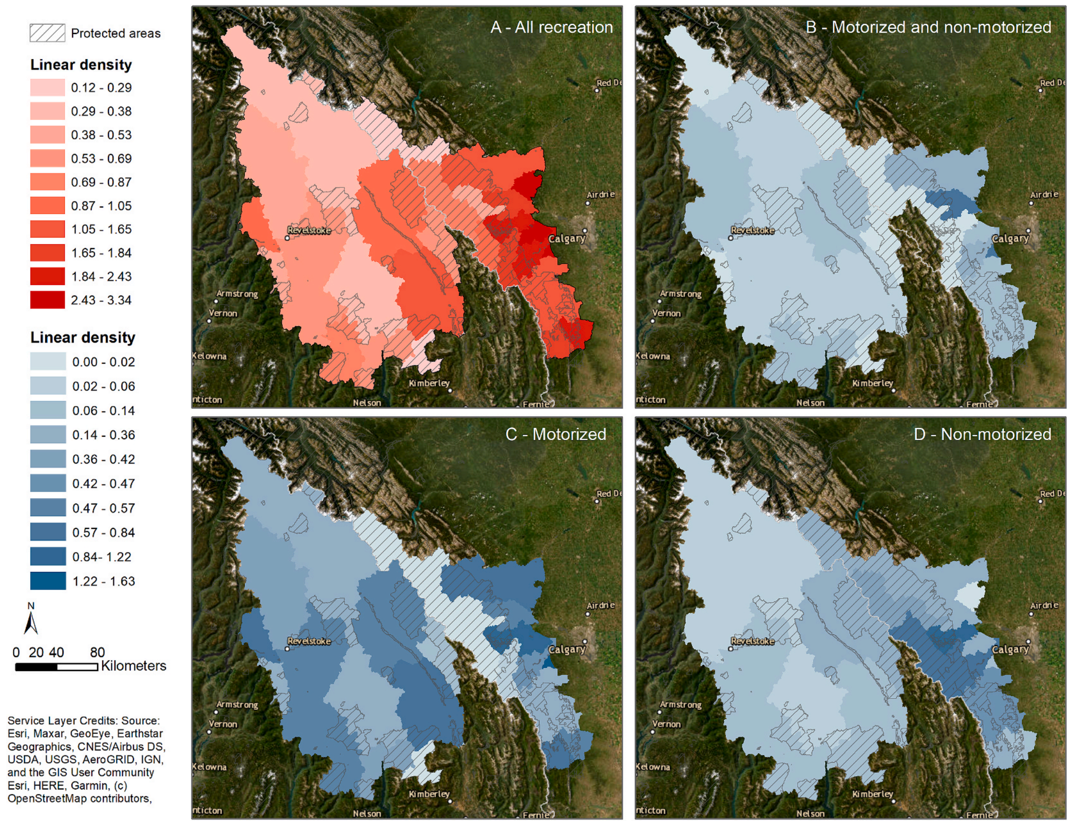

Fig. 3. Densities of recreation trails by recreation type and watershed basins in western Alberta and eastern British Columbia, between 2017 and 2019. Densities are reported in km/km^2. All recreation types are mapped in red (A), motorized and non-motorized recreation (B), motorized recreation (C), and non-motorized recreation (D). Protected areas are drawn with green hatching. [COLOR].

4.2. Trail types

Of all the trails, 73% (16,107 km) were classified as documented whereas 27% (5932 km) were classified as undocumented[4]. For undocumented trails, the primary data sources were OSM (4155 km), other online sources (856 km), Southern Alberta Trail Mapping Project (547 km), and Trail Forks (366 km; Fig. 4; Fig. 5). Other online sources include the Back Road Map Books Snowmobile Trails, Columbia Valley Greenways Trail Alliance, and the Summit Trail Makers Society. Of the documented trails, 3647 km were 'informal' trails (i.e., non-designated, unofficial; Supplemental Information Fig. 3). Hotspots of both documented and undocumented trails primarily occurred in the eastern portion of the study area (Fig. 6).

4.3. Activity types

We classified 51% (27,234 km) of trails and linear feature were motorized, 20% as non-motorized (10,897 km), and 15% as motorized prohibited (8070 km; Fig. 7A). For trails, most documented trails had a known activity type (only 275 km were unknown) whereas most undocumented trails had unknown activity types (2643 km; Fig. 7B). Motorized trails and linear features had the highest densities near the communities of Bragg Creek (Calgary), Canmore, Invermere, Golden, Revelstoke, and Nakusp (Fig. 3B). BC had lower motorized and non-motorized trail densities relative to Alberta (Fig. 3C). For non-motorized trails and linear features, the highest densities were near Canmore and Banff in Alberta (Fig. 3D).

4.4. Relating documented and undocumented trails to the landscape

Undocumented trails (n = 21,022 points on undocumented trails) were closer to the nearest road, in more rugged terrain, and spanned a larger elevational gradient than documented trails (n = 57,243 points on documented trails; Fig. 8). Generalized linear mixed modeling revealed an increased probability of a trail being undocumented as elevation and terrain ruggedness increased, and the distance to nearest road decreased (Fig. 9A–C). Slope and terrain ruggedness were highly correlated (0.95) so we excluded slope from the model. The probability of an undocumented trail was similar for protected as unprotected areas (Fig. 9D). Overall predicted probabilities of undocumented trails were much lower relative to documented trails (Fig. 9A–D). We initially fit GLMs but observed spatial autocorrelation (Supplemental Information Fig. 4). We re-fit models with a random effect structure with easting (x) and northing (y) as random intercepts to account for spatial dependencies. From the test data, the model correctly predicted the correct outcome 62% of the time (Supplemental Information Fig. 5).

For the wildlife GLM models (n = 8765 points on undocumented trails; 18,753 = points on documented trails), the probability of undocumented trail occurrence decreased with increasing wolverine density and grizzly bear habitat quality, but this relationship was weak (Supplemental Information Fig. 6). From the test data, the model predicted the correct outcome 64% of the time (Supplemental Information Fig. 7).

5. Discussion

This study evaluated the contribution of traditional and user-created content towards the cumulative footprint of recreation. Of the >22,000 km of trails mapped, 27% were derived from user-created sources,

[4] This differs from the 24% calculation in Vilalta Capdevila et al. 2022, which includes trails and linear features.

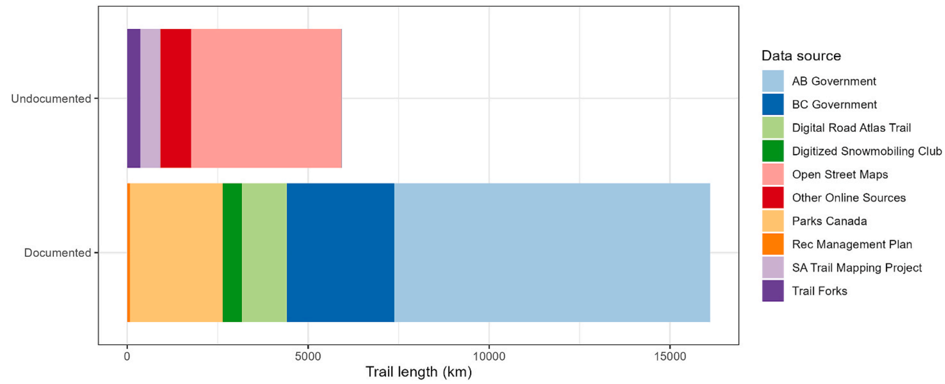

Fig. 4. Graph of data sources for documented and undocumented trails in western Alberta and eastern British Columbia. Data sources included the Government of Alberta (AB), the Government of British Columbia (BC), Digital Road Atlas, digitized data from snowmobiling clubs, Open Street Maps, other online sources, Parks Canada, Backcountry Recreation Management Plans, Southern Alberta (SA) Trail Mapping Project, and Trail Forks. [COLOR].

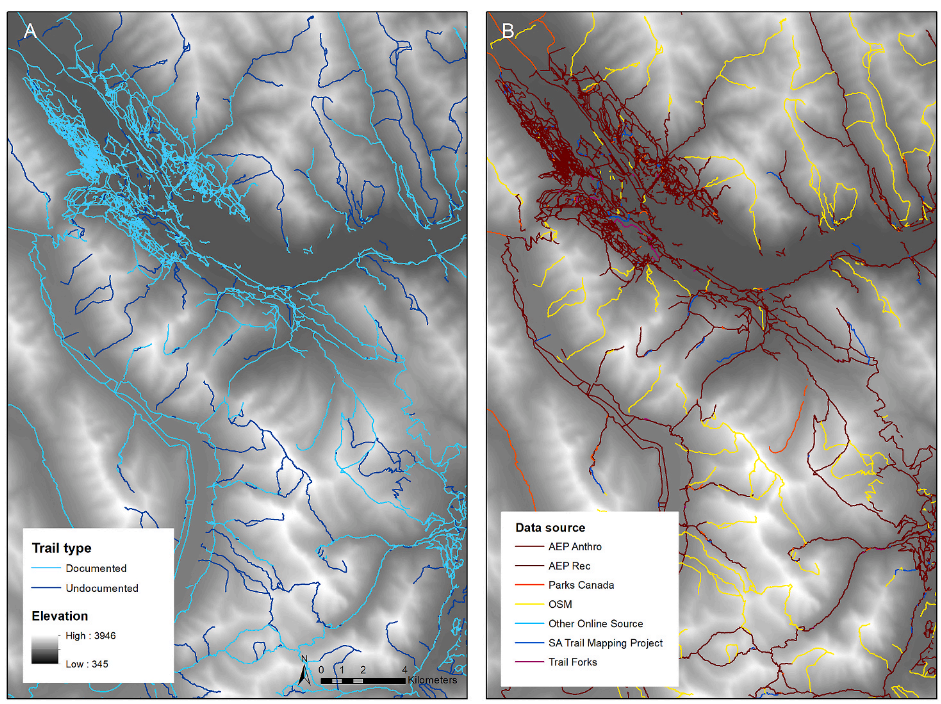

Fig. 5. Map representing a subset of the spatial distribution of documented and undocumented trails (A) and their respective data sources (B) in western Alberta and eastern British Columbia between 2017 and 2019. Elevation is shown in meters. [COLOR].

representing a substantial portion of trails that were otherwise "unknown" to management (e.g., not included in government databases for use in management and planning). In addition, activity types on most undocumented trails were unknown, representing a large knowledge gap in both where the trails occur and the type of activity. This could have large consequences when undocumented trails occur in sensitive habitats, in areas important to sensitive or at-risk wildlife, and for conflict among user groups. Our results showed that indeed undocumented trails have a higher probability of occurring in more rugged terrain and closer to roads.

At first glance, it appears that user-created and fitness application data have increased the cumulative footprint of recreation. OSM, which contributed the most to the user-created content in this study, is a fully open-sourced dataset that people can contribute to (the "Wikipedia" of trails). OSM is a commonly used dataset for recreation and is the base trail layer for many apps, including AllTrails, which has 40 million users worldwide. For OSM and other user-created datasets, standardized protocols and specifications for data quality are lacking, such as using a standard reference to avoid heterogeneity in spatial resolution (Girres & Touya, 2010; Goodchild & Li, 2012). Indeed, while the addition of user-created content has increased the cumulative footprint of recreation, there are additional caveats beyond the technical aspects of user-created data. For example, recreationists can add new routes and trails to online databases but many of these "new" trails may not be so new. For instance, such "new" trails may be animal trails or scrambling routes that are rarely used by people and are, instead, routes without much physical trace. While the physical footprint of OSM trails in high elevation and rugged terrain may be minimal, the spatial and attribute information posted on applications and websites allows other people to find and use these routes. Thus, the footprint of low-use trails could increase simply by advertising their existence - especially as high and moderate-use trails become crowded. Ground truthing trails would provide clarity on the physical impact of user-created trails, and we recommend this for future efforts to refine this study.

As well, "new" trails may follow old routes that land managers closed for specific reasons (e.g., sensitive habitat), representing a

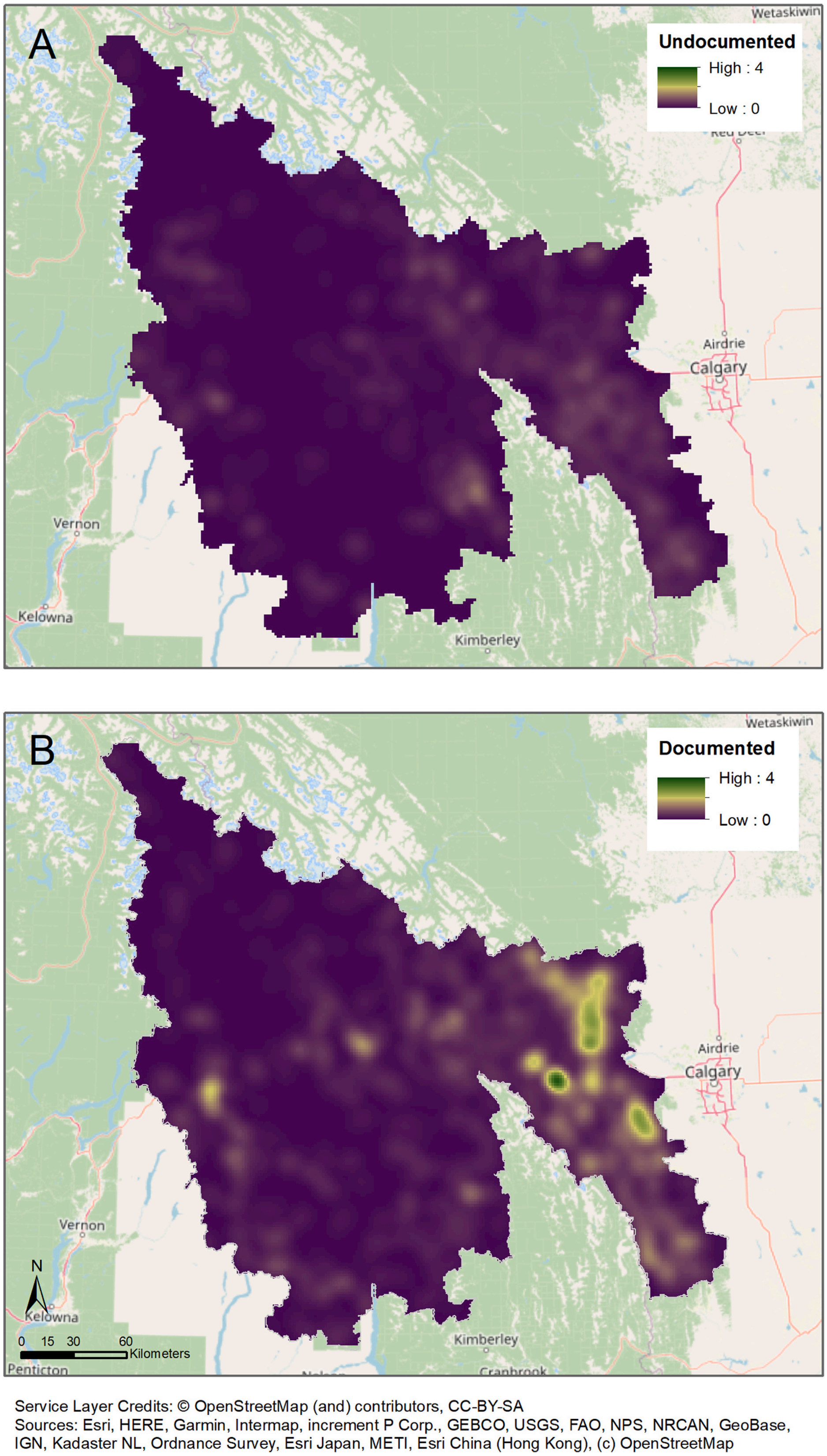

Fig. 6. Linear densities for undocumented (A) and documented (B) trails in western Alberta and eastern British Columbia between 2017 and 2019. Trail densities (km/km^2) for visualization were calculated using a kernel density estimator with a 10-km search radius.

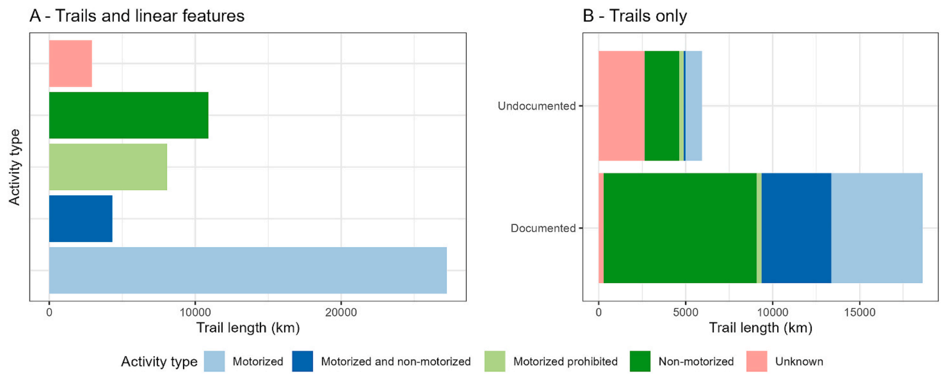

Fig. 7. Trail and linear feature length by activity type (A) in eastern British Columbia and western Alberta between 2017 and 2019. For trail data only (B), the length of documented and undocumented trails by activity type. [COLOR].

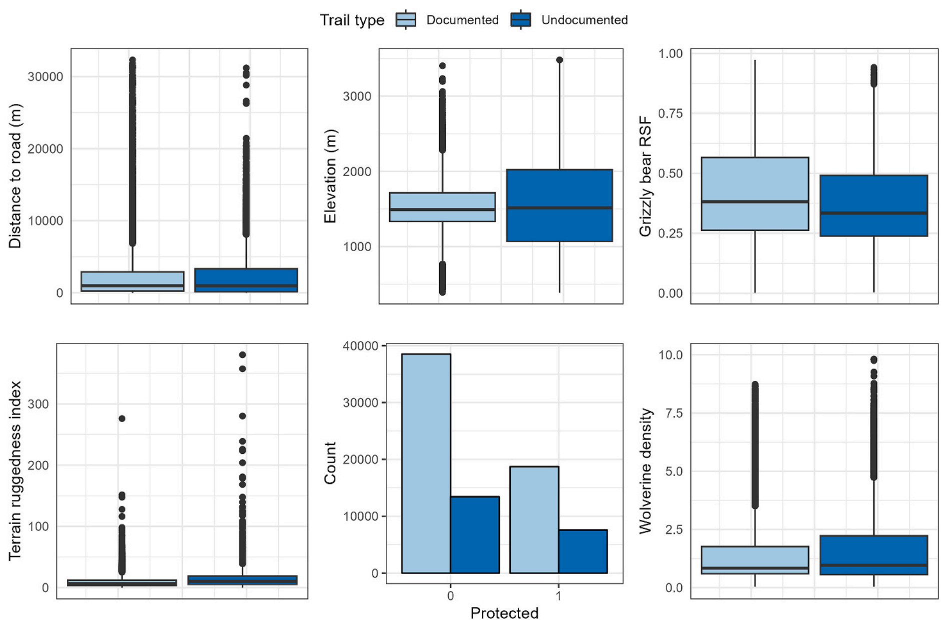

Fig. 8. Boxplots of predictor variables relative to documented and undocumented trails. Distance to road and elevation units are in meters. Grizzly bear resource selection function (RSF) units are a scaled relative value of 0 (low habitat quality) to 1 (high habitat quality). Wolverine density is the number of individuals per 1000 km2 [COLOR].

misinformation and potentially an enforcement issue to maintain a closure area. To address these issues, land managers would need to access multiple, often private databases (users can contribute data, but can rarely access full databases, e.g., TrailForks) to understand the full extent of recreation in their jurisdiction (Fig. 5). This is untenable for resource-strapped managers and agencies. Studies like this highlight that government monitoring systems do not match the pace at which recreation is expanding and require creative thinking to address a complex issue. An automated, standardized, and centralized method for monitoring the recreation footprint is needed. The onset of user-created and app-based datasets, however, provide a unique opportunity for agencies to partner with companies to study and better manage the recreation footprint. Companies such as AllTrails are partnering with land managers to allow back-end access to manage trails that are closed or are hazardous (e.g., recent flooding on trail). Interestingly, undocumented trails were equally likely to occur outside and inside protected areas. This provides insight from a social perspective, that lands governed under provincial, First Nations, or federal protection are equally 'at risk' of having unknown recreation within their boundaries. This highlights that recreation planning requires collaboration beyond jurisdiction boundaries.

Along with user-created content increasing the cumulative footprint of recreation, our study highlights that many undocumented trails have the additional challenge for managers of having unknown recreation activities occurring on them. In our study, over 2600 km of undocumented trails had unknown activity types. This represents a potential source for human-wildlife conflict between recreation users and wildlife (i.e., it is hard to mitigate conflict if the extent of recreation is unknown), but also between recreation user groups themselves. Different recreation user groups can posses different value and attitudes towards the environment, leading to interpersonal conflict (Carothers et al., 2001). Conflicts can also result from having different physical goals within overlapping terrain (e.g., mountain biking versus hiking on the same trails) (Knopp, 2018). These issues may result in unsatisfactory experiences, but also may pose a safety issue (e.g., travelling at vastly different speeds) especially with emerging technologies, such as electric bicycling (Elia et al., 2010; Happ & Schnitzer, 2022).

Within our full study area, we found strong heterogeneity in linear densities of trails and linear features, based on watershed boundaries. Maximum overall trail and linear feature densities were 28 times higher than the minimum densities, with motorized recreation trails and linear features having the highest overall density by recreation types (1.6 km/

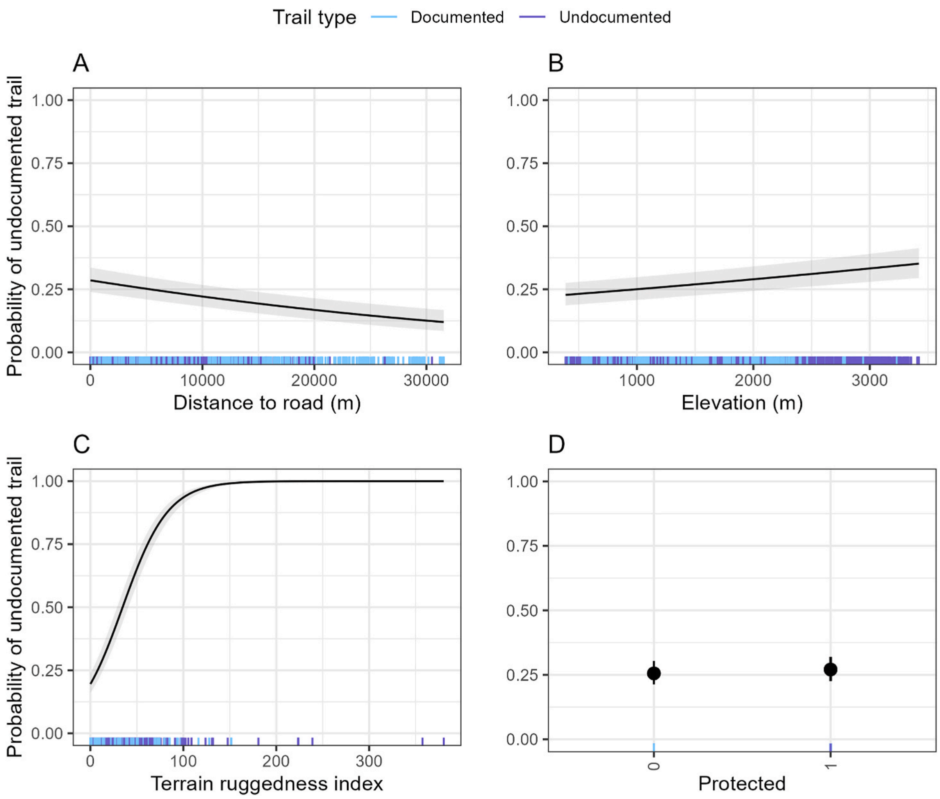

Fig. 9. Prediction plots from binomial models for documented (0) and undocumented trails (1) in eastern British Columbia and western Alberta for the distance to nearest road (A), elevation (B), terrain ruggedness (C), and protected area status (D). The grey ribbon represents 95% confidence intervals from back transformed beta coefficients. The rug (hatching) shows the distribution of raw data; light blue hatches are undocumented occurrences and dark blue hatches are documented occurrences. Distance to road and elevation units are in meters. [COLOR].

km^2; Supplemental Information Table 1). Linear densities have consequences to the flora and fauna, and density thresholds can provide a benchmark at which wildlife populations become negatively effected by recreation (Dertien et al., 2021, 2021van der Marel et al., 2020). For grizzly bears, road densities, which may elicit wildlife responses similar to motorized recreation trails, above 0.6 km/km^2 may result in population declines (Boulanger et al., 2014; Mace et al., 1996). If motorized linear features are equivalent to roads, linear densities for potential motorized features in our study area exceeded the grizzly bear threshold in eight of the 30 basins analyzed. Increasingly, human use along linear networks is shown to be influential on wildlife movement and behavior, above and beyond the linear footprint (Doherty et al., 2021; Heinemeyer et al., 2019; Naidoo & Burton, 2020). Note however, that ground truthing is required to confirm that all linear features are available for recreation as they may have become overgrown after disturbance (Hornseth et al., 2018; Pigeon et al., 2016). The timing of recreation and intensity of use requires further research, both inside and outside PAs.

Recreation is a booming industry and activity. Statistics available for PAs in BC show that visits between 2015 and 2019 total nearly 30 million and are increasing 5% annually (Forest Practices Board, 2021). This increased growth is reflected in updated management plans, such as Banff National Park[5] where recreation is explicitly addressed by, for example, decommissioning and relocating trails out of high-quality wildlife habitat to lower-quality habitat, and actively managing human disturbance in critical habitat to mitigate negative effects on sensitive species. As well, recreation is a key concern among many First Nations. For example, the Stoney Nakoda Grizzly Bear Cultural Assessment[6] cites recreation as a key concern and identify cultural monitoring and developing recommendations for grizzly bear conservation planning, including areas of restricted activity to reduce human-wildlife conflicts. However, as shown in this paper, the cumulative footprint of recreation is often underestimated. Additionally, data on recreation use outside PAs are rare and researchers and mangers often assume that the increasing recreation trend on public forest lands is similar to inside protected areas (Forest Practices Board, 2021). This study is a first step to collate recreation data across protected and non-protected lands and provide baseline information on the cumulative footprint of motorized and non-motorized recreation. Continued efforts need to be made to continually update the recreation footprint. Future research needs to understand intensity of use along this extensive network of motorized and non-motorized recreation trails.

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Data

This dataset contains restricted data. As such, the authors are unable to share the full dataset. See Vilalta Capdevila et al., 2022 for details.

5 https://parks.canada.ca/pn-np/ab/banff/info/gestion-management/involved/plan/plan-2022#section-2.

6 https://livingwtwildlife.ca/assets/pdf/Stoney-Nakoda-Nations-Cultural-Assessment-for-the-Enhancing-grizzly-bear-management-programs-through-the-inclusion-of-cultural-monitoring-and-traditional-ecological-knowledge-2016.pdf.

CRediT authorship contribution statement

Anne Loosen: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Talia Vilalta Capdevila:** Data curation, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Karine Pigeon:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing. **Pam Wright:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing. **Aerin L. Jacob:** Conceptualization, Supervision, Project administration, Funding acquisition, Writing – original draft, Writing – review & editing.

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Appendix A. Supplementary data

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