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Predicting human-carnivore conflict at the urban-wildland interface

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ABSTRACT

A major threat to mammalian carnivores is death due to human conflict, including carnivore use of anthropogenic food sources, predation of livestock, or car accidents. To reduce conflicts, it is critical to target proactive mitigations using reliable evidence on where conflict is likely to occur. We tested hypotheses about the importance of anthropogenic and environmental predictors in explaining the timing and distribution of human conflict with black bears (*Ursus americanus*) and cougars (*Puma concolor*) in a North American hotspot of human-carnivore conflict. Using reported conflict locations and spatial data in use-availability models, we estimated and mapped the probability of conflict for both species, including seasonally for bears, between 2011 and 2017. We found conflict increased for both species along the urban-wildland interface. Conflict with black bears was present in all seasons and increased with intermediate human density (i.e. suburban neighbourhoods). However, in autumn, bear conflict was more common in agricultural areas. Conversely, cougar conflict was primarily in rural areas, as their main attractant was livestock. We recommend targeting areas and times of expected conflict with proactive mitigations, such as bear-resistant garbage bins in communities adjacent to forests, electric fences that deter both carnivore species, and elimination of rural food attractants in autumn.

1. Introduction

Mammalian carnivores are important for ecosystems and the people in them. For instance, carnivores serve as natural controls against herbivore over-population, which can degrade plant communities (Ripple et al., 2014) or cause car accidents (Gilbert et al., 2017). However, where people and carnivores co-occur, they may compete for resources and space, leading to conflict (Woodroffe et al., 2005; Teichman et al., 2013). Conflicts include many forms of interaction, from food conditioning, to property damage, to injury or death of livestock, pets, or people. There is potential for increased human-carnivore conflict due

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to the expanding urban-wildland interface, and such conflict can represent a key threat for increasingly isolated carnivore populations (Ripple et al., 2016). Where conflict can be avoided or effectively mitigated, many carnivore populations have shown resilience and recovery (e.g. Chapron et al., 2014). To enable human-carnivore coexistence, there is an urgent need to identify effective ways of reducing conflict in different contexts (Nyhus 2016).

While many studies have highlighted the importance of changing human behaviour to reduce conflict (e.g. Dickman 2010; Pooley et al., 2017), mitigation strategies frequently focus on the animals. To minimize harmful interactions, people often try to influence carnivore behaviour or kill animals deemed to be incompatible with human needs (Woodroffe et al., 2005). Reactive mitigation acts after a conflict has occurred, and thus does not prevent financial burdens on affected humans, and, when lethal, can negatively affect the viability of threatened or endangered carnivore populations (Ripple et al., 2016). Relocation of “problem” carnivores is often preferred to lethal mitigation by people directly impacted by conflict (Don Carlos et al., 2009). However, relocated carnivores often return and “re-offend”, or experience higher than expected rates of mortality due to competition or a lack of access to resources in their new territory (Linnell et al., 1997). To avoid prolonging conflict or animal suffering, people often resort to lethal mitigation after a conflict has occurred (Baruch-Mordo et al., 2014).

Conversely, proactive mitigation attempts to avoid conflict by reducing the probability of its occurrence. Proactive measures include carnivore deterrents (e.g. interaction with guard dogs, electric shock, sudden visual and auditory stimuli; Smith et al., 2000), public education, and policy (Nyhus 2016). These methods have been tested, but yield inconclusive results, either due to different effectiveness on multiple species (Smith et al., 2000), or opposing findings between studies. For example, simulation models have suggested that education programs focused on reducing attractants, such as garbage, can be effective at decreasing conflict with bears (Marley et al., 2017). However, an empirical study in Colorado found education programs did not change human behaviour towards attractant management (Baruch-Mordo et al., 2011). Local bylaws and policy may then be required to incentivize rapid change, such as securing garbage (Morehouse and Boyce 2017).

Regardless of which proactive method is deemed appropriate for a given target species and area, local landowners may consider methods to be prohibitively costly or labour intensive, requiring funding or capacity from government or non-government programs. Cost-sharing programs may be important for motivating proactive methods, such as for the electric fence cost-sharing program implemented for brown bear (*Ursus arctos*) conservation in western North America (Proctor et al., 2018). But even with help for start-up costs, mitigations like electric fences around attractants need regular maintenance to ensure they have not been shorted by growing vegetation, or damaged by animals attempting access (Breitenmoser et al., 2005). Landowners without access to ongoing support for proactive mitigations may consider conflict resolution to be the domain of government agencies that focus on reactive methods of removing problem animals. However, by avoiding conflict, proactive mitigation can not only protect carnivores but also reduce negative impacts on humans, including conflict-related costs (McManus et al., 2015). Therefore, areas more likely to experience conflict must be identified and targeted with mitigation measures.

Patterns in conflict occurrences can be characterized using predictors of conflict, allowing mitigation targeting conflict “hotspots”, to reduce management costs and increase effectiveness (Treves et al., 2011; Broekhuis et al., 2017). Predictors of conflict are anthropogenic and environmental variables that are associated with conflict to build predictive spatial models of relative conflict probability. Previous studies have found that spatial variation in conflict can be predicted by factors such as: human density (Merkle et al., 2011; Treves et al., 2011), trail density (Wynn-Grant et al., 2018), roads (Teichman et al., 2013; Wynn-Grant et al., 2018), farms (Treves et al., 2011), and forest cover (Broekhuis et al. 2017; Kertson et al., 2011; Merkle et al., 2011; Treves et al., 2011). In some cases conflicts were found to be higher in medium human density urban environments near wild areas (e.g. for black bears, *Ursus americanus*; Baruch-Mordo et al., 2008), suggesting that conflict may have a non-linear relationship with human density. Likewise, Teichman et al. (2013) found that human-cougar (*Puma concolor*) conflict was more common at intermediate elevations. Predictors of conflict may also change seasonally for species who den or follow seasonal food sources, such as black bears (Beckmann and Berger 2003b; Davis et al., 2006). Although some bears in urban areas do not den due to availability of food year-round and climate change driven warmer winter temperatures (Johnson et al., 2017).

Here, we used conflicts reported by residents of southern Vancouver Island − a carnivore conflict hotspot due to high carnivore densities meeting rapid suburban growth (Campbell and Lancaster 2010; Teichman et al., 2013) − to model the timing and distribution of conflicts with black bears and cougars. We defined conflict as any interaction between carnivores and humans that was negative for one or both parties (e.g. carnivores eating anthropogenic food attractants, damaging property, or car accidents). Food related conflicts with black bears were diverse, ranging from garbage and compost, to fruit trees and livestock, because black bears have an omnivorous diet (Merkle et al., 2013). Human-cougar conflict was primarily concerned with livestock and pets because cougars are obligate carnivores (Kertson et al., 2011). We tested associations between reported conflicts and hypothesized anthropogenic and environmental drivers of conflict (noted above). We hypothesized that conflict would be driven by the diversity of anthropogenic attractants accessible to bears or cougars, and thus that conflict reports would be highest in the urban-wildland interface because it provides the widest variety of attractants (both urban and agricultural food sources). Therefore, we predicted that conflict would increase in areas with high human-carnivore overlap and decrease away from overlap, peaking in areas of intermediate human density and elevation (Baruch-Mordo et al., 2008; Teichman et al., 2013). We hypothesized that if bears followed historical denning behaviour, conflict would be absent during the winter denning period (November to April; Davis 1996). We also expected bears to have a seasonal difference in conflict driven by changing food availability, with reduced conflict during peak availabilities of natural foods like salmon (in October) and berries (June to October, depending on the berry species; Davis et al., 2006).

2. Materials and methods

2.1. Study area

The Capital Regional District (CRD) is the government administrative area for the southern end of Vancouver Island, Canada (Fig. 1). It includes British Columbia's capital city, Victoria, and twelve other municipalities (the scope of this research excludes the Gulf Islands to the east, although they are a part of the CRD). Mainland CRD encompasses 2000 km^2 and has a growing human population, currently of 383,000 individuals. Agricultural landcover is 2% of the CRD. There are some larger produce farms, including berries, in the eastern part of the region, but much of the livestock are on smaller family and hobby farms (mainly chickens and sheep, some horses, pigs, and cattle). Urban land cover is 6% of the CRD. Vancouver Island is part of the Pacific Maritime ecozone, which is characterized by a warm and wet climate (Davis et al., 2006).

In the CRD, most reported human-carnivore conflict is with black bears (89.5%; British Columbia Conservation Officer Service, *unpublished data*), but Vancouver Island was previously reported to have the world's highest level of human-cougar conflict (Beier 1991). The British Columbia Conservation Officers Service (COS) rarely relocates animals, so in cases of repeated or dangerous conflict, the problem animal is destroyed. Between 2011 and 2017, 60 black bears and 34 cougars were killed due to conflict in the CRD.

2.2. Carnivore conflict data

We used reports of conflict with black bears and cougars from 2011 to 2017 in the CRD that were recorded in the COS's Human Wildlife Conflict Reporting Database (HWCRD). This database contains reports about interactions with wildlife that are phoned in by BC residents to the COS call centre (British Columbia Conservation Officer Service 2019). Reports include a description of the interaction with wildlife, the species involved, and the location, date, and time. Only reports with verified species identification were included (i.e. direct sightings, tracks, scat, and/or COS verification visits). The HWCRD is unlikely to represent a complete record of all conflicts occurring in the CRD, as some residents may not report interactions with black bears or cougars for a variety of reasons (e.g. different perceptions of conflict, awareness of the COS program). However, research in other jurisdictions found that demographic factors (such as age, gender, socioeconomic status) had little influence on the likelihood of a person reporting a conflict with black bears, and conflicts perceived as more severe (i.e. those relating to safety or property damage) had the greatest impact on reporting (Wilbur et al., 2018). Given that most cougar conflicts

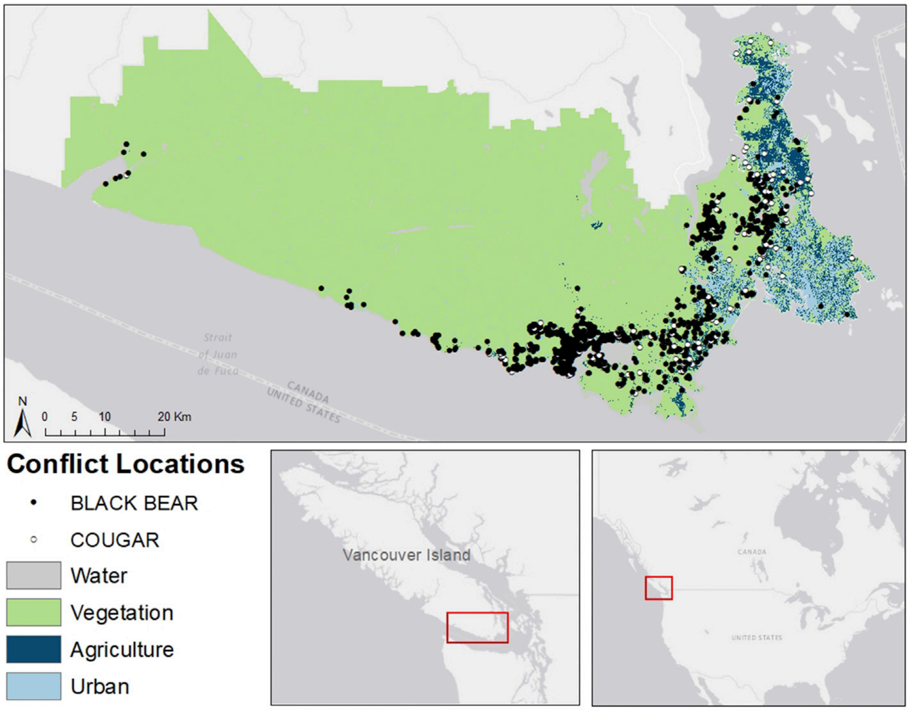

Fig. 1. Map of reported human-carnivore conflict in the Capital Regional District (CRD) on Vancouver Island, BC, Canada. Circles represent locations of reported conflicts with black bears and cougars from 2011 to 2017. Vegetation includes coniferous and deciduous forest, shrubs, herbs, and grass. Land cover adapted from CRD Regional Parks (Caslys Consulting Ltd 2017).

involved livestock or pet injury/death and cougars are perceived as more dangerous overall (Campbell and Lancaster 2010), we expected the same trend for cougar and bear conflicts. We therefore assumed that the HWCRD reports provide a robust sampling of conflicts occurring across the CRD and are not systematically biased, although we suggest that future research further examine the potential for reporting bias (see Discussion).

We re-categorized interactions from the HWCRD into instances of human-carnivore conflict or non-conflict. We defined conflict as any interaction between one or more carnivores and one or more humans (or their property/possessions/livelihoods) that was negative (causing financial or physical harm) for one or both parties. Non-conflict interactions were those that were positive or neutral (i.e. carnivore sightings). We converted street addresses for reported interactions to UTM coordinates using the DataBC's batch geocoder (British Columbia 2017, Fig. 1). We also classified black bear interactions by four seasons: spring, February–April; summer, May–July; autumn, August–October; and winter, November–January (Davis, 1996). Cougar interactions were not separated and modelled by season due to limited sample size.

The HWCRD included 1261 reported conflicts with black bears between 2011 and 2017 (Table S1). The number of conflicts reported was similar in each year (mean = 180.1, sd = 42.2). Most conflicts occurred in the summer (41%) and autumn (37%), followed by winter (16%) and spring (6%). The HWCRD also included 140 cougar conflicts between 2011 and 2017 (Table S2), with greater variability between years than for black bears (mean = 20.0, sd = 10.6). Common conflicts with bears included garbage and other anthropogenic food sources, property damage, and livestock predation. Cougar conflicts were primarily related to livestock injury or death and pet attacks. However, due to a greater number of conflicts overall, black bears were responsible for more livestock predation than cougars (105 events with 453 known deaths, compared to 66 events with 155 known deaths, Table S3). Due to small samples sizes when separated, all conflicts for each species were combined.

2.3. Predictor variables

We selected anthropogenic and environmental variables expected to influence the probability of carnivore conflict based on previous research (Table S4). We developed raster layers describing distances from a conflict location to the closest edge of the following land cover classes: agriculture, urban, intact forest and forest patches, using a 3 m resolution 2017 land cover raster from CRD Regional Parks resampled to 5 m to reduce mapping error (Caslys Consulting Ltd 2017). We separated intact forest and forest patches as black bears have been found to use core habitats differently than disturbed patches (Larkin et al., 2004). We distinguished small patches of forest from contiguous forest (hereafter “patch” and “intact” forest, respectively) based on a break point in size classes of forest areas at 300 m^2.

We extracted elevation from the ASTER Global Digital Elevation (NASA/METI/AIST/2009) and human density from the Gridded Population of the World (projected to 2015; CIESIN 2017). Road and trail densities were generated using the Line Density tool in ArcMAP 10.6.1 (ESRI 2018), based on GIS layers accessed from BC Provincial and CRD Parks. All GIS variables were extracted from a weighted buffer (which reduce the contribution of raster cells not fully within the circular buffer by the percent excluded) around the conflict points at two scales: 150 and 500 m. Given the potential for locational error when converting street addresses to points, we used a buffer with a radius equal to the length of an average suburban block (150 m) to represent the conflict location (Merkle et al., 2011). The larger buffer of 500 m represented the area surrounding a conflict point, allowing for different scale selection by carnivores (Fisher et al., 2011). Extracted variables were standardized by subtracting the mean and dividing by one standard deviation, to allow for direct comparison of estimated coefficients.

2.4. Analysis

We modelled the relative probability of conflict with black bears and cougars using generalized linear models in a resource selection function, use-availability framework (Johnson et al., 2006). Models were implemented in R statistical software, version 3.5.2, using the *glm* function in base R (R Core Team 2018). To compare locations where conflict was reported with a sample of “available” locations where conflict was possible, we created a polygon around all known locations of interactions with carnivores in the HWCRD (both conflict and non-conflict, n = 4543) by buffering point locations by the average home range of female black bears on the island (7.83 km^2; Davis et al., 2006) and merging those buffered areas into a single polygon. We chose the female black bear home range to be conservative as bears typically have smaller home ranges than cougars, and females have smaller ranges than males (Carter et al., 2010). We randomly selected 10,000 availability points within the polygon with a minimum distance of 1 m (mean = 126 m) between adjacent points to avoid complete overlap (Northrup et al., 2013). We chose to use 10,000 points based on recommendations in the literature suggesting that a larger proportion of available points led to more reliable regression models (Barbet-Massin et al., 2012) and provided an accurate representation of the range of variable values in the study area (Northrup et al., 2013; Merkle et al., 2011). Our response variable was a binomial random variable representing the presence of a reported conflict (1) or an available location with no conflict reported (0).

We first ran univariate models for each of the eight spatial variables at the 150 and 500 m scales against conflict with black bears or cougars and compared them to a null model (intercept only) using Akaike's Information Criterion (AIC; Burnham and Anderson 2002). For each variable, the scale within the univariate model with the lowest AIC was used in subsequent multivariate models. We assessed pairwise correlations across all predictor variables at their selected scales for each species to ensure no variables had a Pearson $r > 0.7$ (Hosmer and Lemeshow 2000).

We established a set of candidate models representing predictions about the variables that would best predict reported conflict for each species. The set included: a) a model with additive effects of all predictor variables, representing the prediction that all variables identified in the literature were important in explaining conflict in our study area; b) models with all variables and quadratic terms for either or both human density and elevation to test if conflict was more probable at intermediate human disturbance or elevation; c) models with all variables plus an interaction between human and trail density to test if areas with many people and high access by trails had more conflict; and d) a full model with all variables and both quadratic and interaction terms (Table S5). We again used AIC to identify the best-supported model (Burnham and Anderson 2002), and assessed statistical significance of individual regression coefficients based on 95% confidence intervals (i.e., whether or not they overlapped 1 odds ratio). We ran models for black bear and cougar conflict separately and also ran separate models for black bear conflict in spring (February to April), summer (May to July), autumn (August to October), and winter (November to January; Beckmann and Berger 2003b; Davis et al., 2006).

Given that the home range size of individual bears and cougars would encompass an area much larger than our 150–500 m buffers around conflict points, we tested for spatial autocorrelation in the residuals from best-supported models using Moran's I test (Plant 2012). We used K-fold cross validation to evaluate how well the best-supported models for species and seasons predicted conflict locations (Boyce et al., 2002; Merkle et al., 2011). We divided the dataset for each model into 5 folds, training the model on 80% of the data and testing it against the last 20% (Boyce et al., 2002). We separated predicted values into 10 equal ranked bins and used Spearman rank correlations (r_s) to compare the number of known correct conflict locations from the withheld 20% within each bin to the bin rank, where r_s can range from −1 to 1, with zero meaning no association (Boyce et al., 2002). Calculations were done using the R package "hab" (Basille 2015).

Using the coefficients from our best-supported models for species and seasons, we projected (mapped) the relative probability of conflict across the study area on standardized raster layers. We then converted likelihood of conflict on the logit scale to the relative probability of conflict using Raster Calculator (ESRI 2018) and the formula from Johnson et al. (2006):

$$Relative\ probability = \exp(X\widehat{\beta})$$

Where relative probability is the exponent of the model outputs of predictions, X, and estimated coefficients, $\widehat{\beta}$. We rescaled relative probability values from 0 to 100 using Rescale by Function in ArcMap 10.6.1 (ESRI 2018).

3. Results

3.1. Human-black bear conflict

The best-supported (lowest AIC) model explaining black bear conflict in all seasons was the full model (Table 1). The relative probability of conflict with bears increased with road density and proximity to urban land cover, intact forest, and forest patches (Fig. 2; beta coefficients and 95% CI for all best-supported models in Table S6). Conflict peaked at intermediate human density and decreased with increasing elevation, trail density, and the interaction between human and trail density. The linear effects of human density and distance to agriculture, and the quadratic form of elevation, were not statistically significant (Fig. 2). The K-fold cross validation Spearman rank correlation was close to 1, suggesting the model had good predictive power (r_s = 0.981, SE = 0.013, Table 1). The null hypothesis of no spatial autocorrelation in model residuals was rejected (Moran I = 0.008, p = 0.018). The projected map showed relative conflict probability was highest in the urban-wildland interface between urban and forested land cover (Fig. S1).

Table 1
Candidate models within 2 AIC for probability of conflict with black bears (seasonally and non-seasonally) and cougars (see Table S4for details on predictor variables and Table S5 for full candidate set). Top models indicate which predictor variables best explained locations of conflict for each species/season. Linear variables were: human (HD), road, and trail density (TD), distance to agriculture, urban, forest patch, and intact forest, and elevation (Ele). All variables extracted at 150 m except human density and distance to forest patch were 500 m in the cougar model. Df is the degrees of freedom of the model, AIC is the Akaike's Information Criterion score for each model, ΔAIC is the difference in AIC scores from the top model, and AICwt is the AIC weight attributed to that model. K-fold (r_s) is the Spearman rank correlation value for the association between the model's predicted and known conflict locations, SE is the standard error for the r_s.

Species/Season	Predictor Variables	df	AIC	ΔAIC	AICwt	K-fold (r_s)	SE
Black Bear	[Linear Variables] + HD^2 + Ele^2 + TD*HD	12	6262.8	0.0	0.998	0.981	0.013
Black Bear - Spring	[Linear Variables] + HD^2	10	777.6	0.0	0.60	0.767	0.196
	[Linear Variables] + HD^2 + Ele^2	11	779.3	1.7	0.25	0.812	0.145
Black Bear - Summer	[Linear Variables] + HD^2 + Ele^2 + TD*HD	12	3417.6	0.0	0.46	0.974	0.021
	[Linear Variables] + HD^2	10	3417.9	0.3	0.39	0.970	0.029
Black Bear - Autumn	[Linear Variables] + HD^2 + Ele^2 + TD*HD	12	3108.2	0.0	0.996	0.926	0.076
Black Bear - Winter	[Linear Variables] + HD^2 + Ele^2 + TD*HD	12	1664.6	0.0	0.862	0.895	0.042
Cougar	[Linear Variables] + Ele^2	10	1360.4	0.0	0.615	0.875	0.126
	[Linear Variables] + HD^2 + Ele^2	11	1362.4	2.0	0.229	0.881	0.130

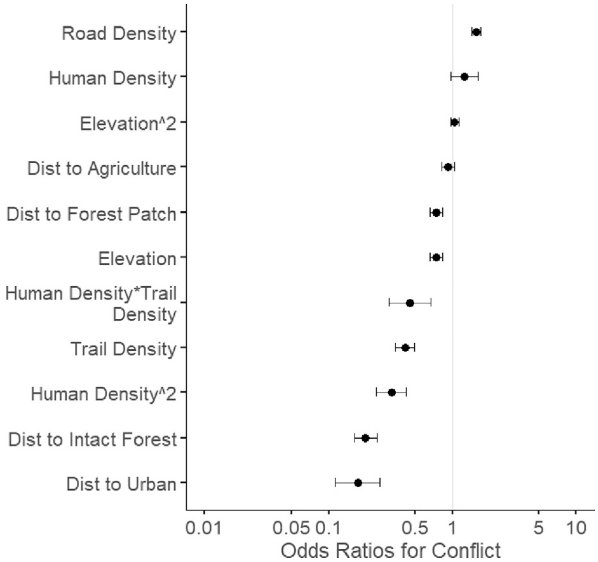

Fig. 2. Estimated effects of anthropogenic and environmental variables on human-black bear conflict in the Capital Regional District (CRD), BC, Canada. Coefficient estimates (mean and 95% confidence intervals) from best-supported resource selection function of conflict locations between 2011 and 2017, back transformed from the logit scale to odds ratios (OR). Predictor variables have been standardized to a mean of zero and standard deviation of one to allow for direct comparison. Distance-to coefficients <1 OR represent selection for that feature.

The top models for black bear conflict in summer, autumn, and winter were also the full model, while the top model for conflict in spring did not include the quadratic term for elevation or the interaction between human and trail density (Table 1).

The seasonal models followed a similar pattern of associations to anthropogenic and environmental variables as the non-seasonal model; however, fewer variables were significant (Table S7). In spring, conflict was only associated with medium human density, high road density, proximity to intact forest, and lower trail density. The top summer and winter models had those same significant variables in addition to distance to urban, linear human density, and the interaction between human and trail density, as well as linear elevation for summer only. However, all three maps were similar with relative conflict probability predominant in urban areas (Fig. 3a, b, d). In contrast, for conflict in autumn, the effect of the linear variable for human density was not significant and autumn was the only season where distance to forest patch was significant. In the projected maps, this appeared as a decrease in conflict probability in urban centres with a corresponding increase in rural areas (Fig. 3c).

The k-fold Spearman rank correlations showed weaker predictive power for the seasonal models than for the non-seasonal model, but r_s remained close to 1 and was higher for seasons with greater sample sizes of conflicts (spring, $r_s = 0.767$, SE = 0.196; summer, $r_s = 0.974$, SE = 0.021; autumn, $r_s = 0.926$, SE = 0.076; and winter, $r_s = 0.895$, SE = 0.042, Table 1). There was no evidence of spatial autocorrelation in the seasonal models (spring, Moran I = -2.98×10^{-4}, $p = 0.519$; summer, Moran I = -4.74×10^{-6}, $p = 0.491$; autumn, Moran I = -1.41×10^{-4}, $p = 0.504$; and winter. Moran I = 0.003, $p = 0.249$).

3.2. Human-cougar conflict

The best supported model for conflict with cougars included all additive variables and a quadratic term for elevation (Table 1).

Similar to black bears, cougar conflict increased with proximity to urban areas and forest (intact and patch), decreased with increasing trail density, and peaked at medium elevation (Fig. 4). However, cougar conflict decreased with increasing human density. Road density, linear elevation, and distance to agriculture did not have significant effects on cougar conflict (Fig. 4). The predictive power of the model was also close to 1 ($r_s = 0.875$, SE = 0.126, Table 1), and there was no evidence of spatial autocorrelation in the residuals (Moran I = 0.001, $p = 0.365$). The projected map showed high conflict in the urban-wildland interface, but less in urban centres than the black bear maps (Fig. 5).

4. Discussion

4.1. Key predictors of carnivore conflict

We combined reported black bear and cougar conflict locations in the CRD between 2011 and 2017 with spatial variables describing anthropogenic and environmental features to model and map variation in the probability of conflict across the

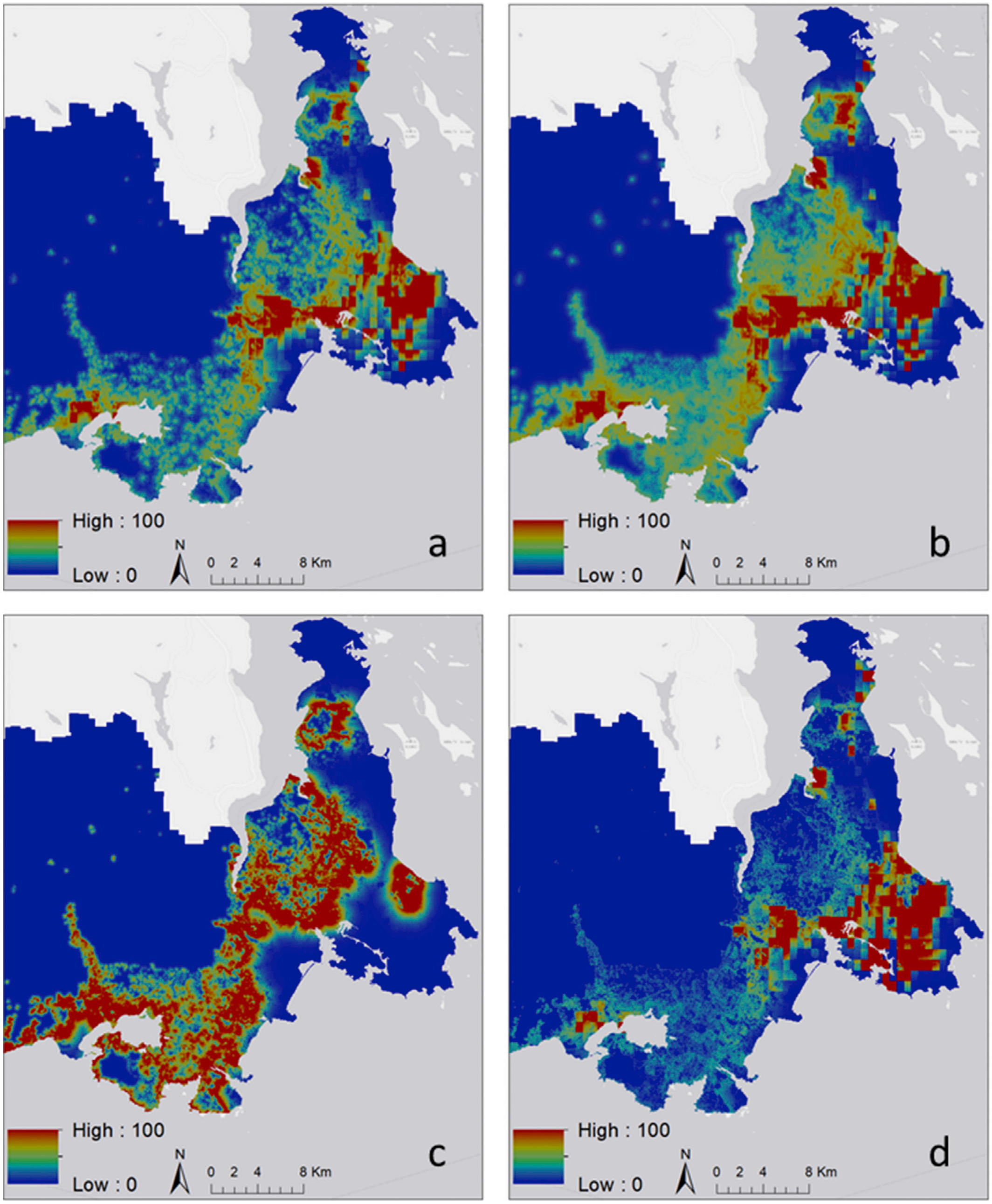

Fig. 3. Relative probability of human-black bear conflict in the eastern Capital Regional District (CRD), BC, Canada in four seasons: a) spring: February–April, b) summer: May–July, c) autumn: August–October, and d) winter: November–January. Probabilities estimated from resource selection function of reported conflict locations (2011–2017) relative to human, road, and trail density, distance to agriculture, urban, forest patch, and intact forest, and elevation as variables.

region. As hypothesized, we found that human-carnivore conflict occurred predominantly along the urban-wildland interface, where human disturbance adjoined natural habitat.

Conflict was more likely to occur close to forests, as the relative probability of conflict increased with proximity to intact and patch forests for both black bears and cougars. This may be because forest edges represent areas with greater human-carnivore overlap and anthropogenic food attractants (both urban food like garbage and agricultural attractants such as livestock or crops; Treves et al., 2011). The importance of both contiguous forest and patches suggests that carnivores in the CRD are using forested areas regardless of size, which differs from Merkle et al. (2011) who found that small forest patches were not a significant predictor of black bear conflict. While that study concluded that land planners may not need to consider

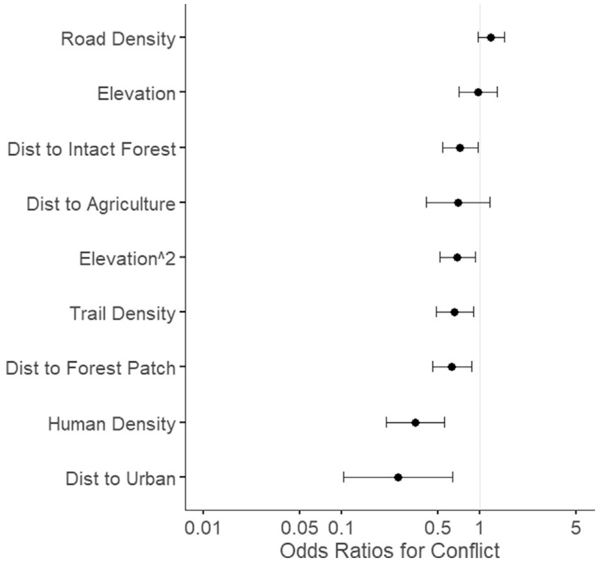

Fig. 4. Estimated effects of anthropogenic and environmental variables on human-cougar conflict in the Capital Regional District (CRD), BC, Canada. Coefficient estimates (mean and 95% confidence intervals) from best-supported resource selection function of conflict locations between 2011 and 2017 back transformed from the logit scale odds ratios (OR). Predictor variables have been standardized to a mean of zero and standard deviation of one to allow for direct comparison. Distance-to coefficients <1 OR represent selection for that feature.

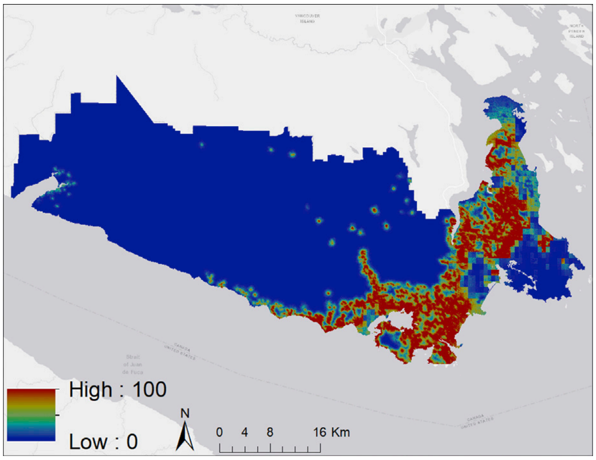

Fig. 5. Relative probability of human-cougar conflict in the Capital Regional District (CRD), BC, Canada. Probabilities estimated from resource selection function of reported conflict locations (2011–2017) relative to human, road, and trail density, distance to agriculture, urban, forest patch, and intact forest, and elevation as variables.

the impact of forested urban parks on conflict, our results suggest forest patches are used by carnivores and should be considered in conflict management planning.

For black bears, conflict was likely in both urban and rural areas, with higher probabilities of conflict at medium human densities (similar to results reported by Baruch-Mordo et al., 2008; and Merkle et al., 2011), near urban edges, lower elevation, and lower trail density. In the CRD, lower elevations typically have more human disturbance and density (correlation between elevation and human density, Pearson $r = -0.370$), so black bears may be attracted to urban anthropogenic food sources such as garbage (Merkle et al., 2013). Additionally, humans in suburban and rural areas often have more land for growing food and livestock. These areas may also represent intermediate risk to bears as they can access attractants while remaining close to secure cover (Lyons et al., 2003).

Surprisingly, there was a lower probability of black bear conflict in places with a convergence of trails and populated areas. It is possible that humans living near heavily-trailed systems are more aware of carnivores and thus more likely to reduce or remove attractants and minimize conflict. In India, livestock owners with a history of leopard and tiger attacks were more likely to have protection methods in place (Miller et al., 2016). Furthermore, people who frequently see carnivores may become desensitized and less likely to report conflicts they perceive as minor, compared to urban communities which may have a lower tolerance for conflicts or experience more severe interactions (i.e. those relating to safety or property damage), factors shown elsewhere to increase conflict reporting (Wilbur et al., 2018).

For cougars, conflict was more likely in rural areas. While the trends for trail density and distance to urban areas were similar to bears, cougar conflict occurred further from human density and at medium elevation. In the CRD, locations at medium elevations are an intermediate distance from high human development; that is, areas on the wildland interface that are more likely to contain multiple types of attractants for cougars, including livestock. Cougars are a more elusive species that avoids people and are also obligate carnivores (Kertson et al., 2011), thus urban areas without livestock may be less attractive. These findings match previous results for human-cougar conflict across BC (Teichman et al., 2013), providing finer resolution support for patterns observed at the coarser provincial scale. We found that conflict with black bears was positively associated with increasing road density. This is consistent with our prediction based on previous studies showing that mortality risk for black bears increased with road density due to car accident conflicts (Wynn-Grant et al., 2018). While road density was not significant in the cougar conflict model, a provincial study found that cougars experienced more conflict in BC close to roads (Teichman et al., 2013). Although higher mortality may decrease use of an area by a carnivore species, the attraction of roads as travel routes (Carter et al., 2010), food sources (particularly seeded ditches and banks and road killed carcasses), or the necessity of crossing them to find better habitat, may explain the continued use of roads by carnivores.

4.2. Seasonal variation

We predicted that black bear conflict would be highest in summer, when bears are most food-limited following the winter denning period and before natural foods such as salmon and berries hit their peaks (Davis et al., 2006; Davis 1996). Consistent with this prediction, we found that conflict with bears peaked in summer (Table S1); however, conflict was present in all seasons, rejecting our hypothesis of no winter conflict on the assumption that all bears were following historical denning patterns. Indeed, some bears on Vancouver Island do not fully den, potentially due to available food year round and warmer winter temperatures (Johnson et al., 2017). Therefore, conflict mitigation should be practiced in all seasons.

In urban areas, conflict probability was highest during winter, spring, and summer, which we suggest is due to high availability of garbage. Garbage is attractive to bears because it is available year-round, renewable, and has a clumped dispersion, making it a high energy reward at low effort (Beckmann and Berger 2003). In autumn, however, conflict probability increased in rural areas. This may relate to the greater presence of natural foods or agricultural harvest in these areas during the autumn season. In fact, the ratio of conflicts associated with non-garbage human foods (compost, animal feed, or fruit; as reported in the HWCRD) also increased in autumn. Merkle et al. (2013) found that bears foraged on human foods even when natural options were available, which may suggest they are changing their seasonal behaviour to adapt to anthropogenic environments. In the autumn, bears that are preparing to den through hyperphagia may instinctually choose the highest density of calories, which is often aggregated human attractants (Baruch-Mordo et al., 2014).

We found an indication of unexplained spatial autocorrelation in the overall model of black bear conflict, but not in the seasonal models. This may suggest that seasonal differences in black bear conflict meant that explanatory variables in the non-seasonal model were unable to account for all the spatial autocorrelation in conflict locations. However, given the similarity in the seasonal and non-seasonal models it is unlikely spatial autocorrelation had a large effect on the results.

4.3. Applications and future research

Overall, our results provide targets for efficient deployment of conflict mitigations. As the maps are spatial depictions of the modelled associations, some care is required in their interpretation. For example, areas predicted to have high conflict probability in Figs. 3 and 5 have values of the anthropogenic and environmental variables associated with observed conflicts; however, some may experience lower conflicts if they are not frequently used by carnivores. Therefore, the maps (and underlying models) can be used as general guides for considering mitigation measures, but should be combined with local knowledge of managers and residents. Due to small sample sizes, we combined all conflict types, so specific mitigations still require case-based solutions. However, for both black bears and cougars, the majority of conflicts were related to human food (Table S3) and thus if the goal is to reduce overall conflict in the CRD, food attractants should be targeted. Conservation officers, educators, and land managers should target communities along the borders of forests to contain their garbage in bear-resistant bins and deploy electric fences set to deter multiple species (i.e. fences that are multi-strand to deter bears, while also tall enough to deter jumping cougars). Other deterrents that protect livestock against multiple carnivore species, like guardian dogs, may also be appropriate (Breitenmoser et al., 2005). Temporally, rural attractants increase in importance for bears in the autumn, so focus should shift from urban garbage to also include rural compost containment and fruit removal. These results largely support the current recommendations of BC governmental programs such as Bear Smart and WildSafe BC (Davis et al. 2002). However, the explicit need to consider deterring multiple carnivore species from common attractants such as livestock is an important outcome of this research.

This project was designed to use readily available information to allow land managers to continue testing and updating these models with new conflict data, and to use the results to target proactive mitigation. However, to improve model performance, especially for cougars, further information would be beneficial. Cougar habitat selection is often driven by prey (particularly deer; Kertson et al., 2011), so knowledge of prey distribution may help in predicting the likelihood of cougar conflicts. For bears, data on berry crops, salmon timing and abundance, and the location of all salmon bearing rivers/streams could help tease apart the degree to which patterns of conflict are influenced by those natural food sources relative to agriculture harvest. It would also be interesting to include the sex and age of animals engaged in conflict in the models, potentially using carcasses from conflict-related deaths, as younger, male carnivores have been more frequently found to be in conflict with humans (Beier 1991; Teichman et al., 2013; Johnson et al., 2015).

Additionally, while we assumed that demographic factors were unlikely to have biased our conflict reports (Wilbur et al., 2018), other biases such as conflict type (Morehouse et al., 2020) or knowledge and perception of management plans (Howe et al., 2010) may have an impact on reporting that could affect our inferences. Therefore, switching to a standardized conflict data collection method where randomly selected households are surveyed about human-carnivore conflicts would remove the possibility of a reporting bias and thus a skewed detection probability. A new expanded dataset could also allow for the modelling of different types of conflict (e.g. anthropogenic food attractants vs. car accidents) to target mitigations to different issues. We attempted modelling of specific conflict types in the CRD dataset, but sample sizes were too small to draw meaningful conclusions.

The conflict modelling and mapping methods that we used here for black bears and cougars could be applied to any wildlife species that comes into conflict with people and for which conflict reports are recorded and spatial predictor data are available. For example, our methods could be applied to conflicts with wolves (*Canis lupus*) in the CRD if they increase their presence near human settlements (there were only 7 sightings reported from 2011 to 2017). More generally, there are many carnivore and other wildlife species increasingly in conflict with people, and insights based on empirical models of conflict can help to navigate challenging trade-offs (König et al., 2020). For instance, connectivity between urban and wild areas has provided brown bears access to human-dominated landscapes in North America where they face high conflict-related mortality, leading to a population sink (Lamb et al., 2020). Thus, mitigations are needed to reduce the attractiveness of human spaces, and since the study area was almost 400,000 km^2, targeting mitigation to potential hotspots is crucial to maintain feasibility.

As humans expand further into carnivore ranges around the world (Crooks et al., 2011), conflict with carnivores will increase and spread over a greater area, and even more so if anthropogenic attractants are not effectively managed (Beckmann and Berger 2003; Baruch-Mordo et al., 2008). Given the wide interface of human-carnivore overlap, proactive measures such as education, bylaw enforcement, or electric fencing need to be deployed efficiently. By using available data on conflict and its spatial predictors, the underlying drivers of conflict can be understood at local scales where it is critical that conflict management actions achieve more effective outcomes. Our results for the CRD supported current recommendations by land managers, however with new human developments bordering carnivore habitat, these methods could be employed to describe emerging patterns of conflict and inform the process of selecting appropriate mitigations for those areas. Only through better understanding carnivore behaviours in human-dominated environments, and adapting human behaviours to reduce negative interactions, will we achieve human-carnivore coexistence in the Anthropocene.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01322.

Data accessibility

Given the confidential nature of the locational data from a Provincial Government database we are unable to provide the full dataset online. Please contact the BC Conservation Officer Service for access: Conservation.Officer.Service@gov.bc.ca

Target audience

This paper aims to reach researchers and practitioners addressing human-carnivore conflict and illustrate an approach for modelling conflicts to inform management, as well as improve understanding of the ecology of black bears and cougars at the urban-wildland interface.

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