

## Research Paper

# Habitat use by barn owls across a rural to urban gradient and an assessment of stressors including, habitat loss, rodenticide exposure and road mortality

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## ABSTRACT

Urbanization and agricultural intensification resulting in habitat loss is having a profound negative effect on grassland and farmland birds worldwide. Barn owls (*Tyto furcata*), as a species, have been affected by this intensification. To evaluate how urbanization and agricultural intensification affects barn owls we sought to address: 1) how human land use influences barn owl hunting behavior and diet, and 2) do habitat and prey choice influence the likelihood of barn owls consuming anticoagulant rodenticide (AR) exposed prey. We radio tagged 11 owls across the rural-urban landscape gradient in the Lower Mainland, British Columbia, and collected sufficient location data on 10 barn owls. We found that the 95% kernel home-ranges ranged from 1.0 to 28.5 km<sup>2</sup> ( $n = 10$ ) and were positively correlated with the proportion of urban land use within home-ranges. Barn owls across all landscapes selected roadside grass verges significantly more than other habitat types within home-ranges, which may reflect the loss of grassland associated agriculture in the region. The risk of consuming AR exposed prey was highest in roadside grass verges compared to other habitat types. However, the overall likelihood of consuming AR exposed prey significantly decreased when the proportion of grass patches within home-ranges increased, which suggests smaller linear grass sections are more likely to contain AR exposed small mammal prey. These results highlight the need to retain and enhance hunting habitat for barn owls during urban development and to mitigate the risk of barn owl road mortality along major highways.

## 1. Introduction

Urban development is responsible for some of the greatest local extinction rates and losses of native species worldwide (McKinney, 2002). The reasons urbanization is having such profound effect on species richness compared to other threats is first, due to the direct loss of habitat that occurs when land is covered with buildings and infrastructure, and becomes impermeable. Second, unprecedented human population growth over the last century has resulted in the total footprint of urban sprawl surpassing the geographical area of protected native landscapes in many jurisdictions (Benfield, Raimi, & Chen, 1999). Urbanization and sprawl fragment the remaining habitats into discrete patches, and populations into smaller units due to the barrier effects of roads and railways. Fragmentation can have a disproportionate impact on wildlife, restricting access to resources, or causing direct mortality from collisions with vehicles (Forman et al., 2003; Jaeger et al., 2005).

The agricultural landscape has also become a less viable habitat for native species due to new agricultural practices that have increased

crop yields, resulting in a farming system that is highly dependent on agro-chemicals (i.e. fertilizers, herbicides and pesticides) and heavy machinery (Krebs, Wilson, Bradbury, & Siriwardena, 1999; Elliott, Wilson, & Vernon, 2011). Consequently, the agricultural landscape is less diverse and more heavily utilized, with large monoculture fields, often with no hedgerows or grassy field margins (Norris, 2008; Poggio, Chaneton, & Ghera, 2010). Many species associated with agricultural lands, particularly birds, have experienced population declines and range contractions over the last three decades (Fuller et al., 1995; Peterjohn, 2003; Brennan & Kuvlesky, 2005; Donald, Sanderson, Burfield, & van Bommel, 2006; Doxa et al., 2010).

Certain species are more adept at coping with human landscape modifications than others and are even capable of persisting in landscapes as they become increasingly urban (Bird, Varland, & Negro, 1996; Boal & Mannan, 1998). However, species that inhabit more intensively human modified landscapes may be at a greater risk of being exposed to anthropogenic threats such as trauma from collisions with vehicles and buildings (Hager, 2009). Exposure to chemical contaminants like lead, persistent organic pollutants and polycyclic

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aromatic hydrocarbons can also be greater in urban environments (Newsome et al., 2010; Henny et al., 2011; Morrissey et al., 2014; Elliott, Brogan, Lee, Drouillard, & Elliott, 2015). Many chemical stressors are persistent and bioaccumulative and thus most evident in predators, which feed at higher trophic levels (Henny & Elliott, 2007).

The barn owl (genus *Tyto*) is an iconic farmland bird. The genus *Tyto* is typically divided into three groups (*Tyto alba*, *Tyto furcata*, *Tyto delicatula*), each of which have several daughter taxa giving barn owls (*sensu lato*) a worldwide distribution (König & Weick, 2008). Like many other cosmopolitan raptors, barn owls have shown some resilience to land use changes, and still persist in intensive agricultural landscapes and in areas that are becoming increasingly urban. However, barn owls are now experiencing population declines and contractions across their range in many parts of the world. This is due to agricultural intensification and urbanization which is causing habitat loss, habitat degradation and fragmentation, and road mortality (Taylor, 1994; Marti, Alan & Bevier, 2005; Hindmarch, Krebs, Elliott, & Green, 2012; Hindmarch & Elliott, 2015).

The core Canadian barn owl (*Tyto furcata*) population is found in southern British Columbia in the Lower Mainland and the Fraser Valley. Grassland associated agriculture has historically been a dominant feature in both regions, but there have been considerable changes in crop types and land use over the last 50 years (Elliott et al., 2011; Metro Vancouver, 2012). Based on land use conversion, blueberries and greenhouse-grown vegetables are the most rapidly expanding crops in the region, (Metro Vancouver, 2012). These changes, along with urbanization, have contributed to a 53% decline in grassland habitats surrounding barn owl nest/roost sites in the Lower Mainland over the last two decades (Hindmarch et al., 2012). The remaining grassland habitats are often quite fragmented and border urban lands, or are confined to field edges and grassy-roadside verges along major highways. As a result road mortality is also a concern, and likely has a strong negative effect on the local population (Preston & Powers, 2006). The threats from the loss of habitat and nest sites were the main reasons barn owls were recommended to be upgraded in 2014 to 'threatened' in Western Canada (COSEWIC, 2014).

High density human developments and farming also attract commensal pest species such as rats (*Rattus* sp.) and house mice (*Mus musculus*) (Feng & Himsworth, 2014). Consequently, the need for rodent control may be greater in human modified landscapes (Riley et al., 2007; McMillin, Hosea, Finlayson, Cypher, & Mekebre, 2008). The primary method for controlling commensal rodents worldwide is the use of anticoagulant rodenticides (hereafter ARs) (Corrigan, 2001). Second generation ARs (hereafter SGARs), introduced in the 1970s as a result of Norway rats' (*Rattus norvegicus*) resistance to the first generation ARs (hereafter FGARs), are now the most commonly used ARs worldwide in both rural and urban settings (Corrigan, 2001). However, SGARs are designed as highly toxic compounds to avoid the development of resistance in target species, and hence a single feed of SGARs is sufficient to kill the target species (Eason, Murphy, Wright, & Spurr, 2002; Fisher, O'Connor, Wright, & Eason, 2003). SGARs are also metabolized slowly, increasing the risk of toxic accumulation in the livers of predators that feed on poisoned prey (Erickson & Urban, 2004). The documentation of secondary AR contamination of raptors through the consumption of poisoned prey has been increasing over the last three decades (Newton, Wyllie & Freestone, 1990; Stone, Okoniewski & Stedelin, 1999; Lambert, Pouliquen, Larhantec, Thorin, & L'Hostis, 2007; Walker et al., 2008; Albert, Wilson, Mineau, Trudeau, & Elliott, 2010; Murray, 2011; Christensen, Lassen, & Elmeros, 2012).

AR residue testing in small mammals points to rats as the main exposure route for the uptake of ARs in non-target predators (Elliott et al., 2014; Geduhn, Esther, Schenke, Mattes, & Jacob, 2014). However, a wide array of non-target prey species documented in the diet of barn owls (Taylor, 1994; Hindmarch & Elliott, 2015) have been detected with AR residues, such as voles (*Microtus* sp.), shrews (*Sorex* sp.),

deer mice (*Peromyscus maniculatus*), wood mice (*Apodemus sylvaticus*), songbirds (*Passeridae*) and insects (Tosh et al., 2012; Elliott et al., 2014; Geduhn et al., 2014).

The propensity of barn owls to nest and roost in structures that are often permanently baited with SGAR bait stations, such as barns and industrial buildings, combined with an increasingly urban and fragmented landscape could increase their risk of consuming rodenticide-laden prey. Our goal was to increase our understanding of barn owls' hunting behavior and diet across a rural to urban landscape continuum in the Lower Mainland, and assess the extent to which risks such as AR exposure and road mortality are indirectly driven by land use within their associated home-ranges. Our two main research questions were (1) How does human land use influence barn owl hunting behavior and diet?, and (2) Do habitat and prey choice influence the risk of barn owls consuming AR exposed prey?

## 2. Methods

### 2.1. Study area and trapping locations

The study was conducted in the Lower Mainland, British Columbia, Canada in the following municipalities: Richmond, Surrey, Delta, Burnaby and New Westminster, from May 2010 to June 2014 (49°8'0" North, 122°18'0" West; Fig. 1). Prior to European settlement in the mid nineteenth century, the low lying floodplains were dominated by grassland and low shrub vegetation, while higher elevations were covered primarily by coniferous forest (North & Teversham, 1983). Today the landscape ranges from agricultural land to suburban to highly urban, with the remaining lower elevation grassland and forested habitats facing ongoing development pressure as the projected human population in the region is expected to increase by 50% by 2036 (Storen, 2011).

In the breeding seasons of 2011 and 2012, we focused on locating and radio tagging barn owls in urban landscapes, and in 2013 the focus was on barn owls in agricultural landscapes. Previous records of barn owls nesting in urban areas of the Lower Mainland were limited and outdated. Hence we surveyed for urban barn owl nest and roost sites in order to identify key areas for trapping (Hindmarch & Elliott, 2015). Our focus was on structures with permanent openings near the roof for nesting and roosting, such as old, tall industrial buildings and bridges or overpasses. If permission was obtained from the landowner, we would inspect the inside and perimeter of the structure for barn owls or indications of their presence such as pellets or feathers. If evidence of barn owls was present, we targeted the surrounding grass habitat for trapping. In the summer of 2013, we trapped barn owls in agricultural landscapes by using recent survey records of where barn owls had been observed hunting.

### 2.2. Trapping and monitoring

We trapped barn owls using bal-chatri traps placed along the perimeter of grass habitats such as grass fields and field margins. In urban landscapes, we placed bal-chatri traps in the middle of the grassy verges of highway access ramps, or in undeveloped patches of residual grassed areas. We monitored traps at all times from a vehicle, and when a barn owl was trapped, we immediately processed it.

We used Holohil RC-1C radio transmitters with mortality switch (6 g), and a battery life of up to 12 months. The transmitter was attached with a leg-loop harness made out of 3 mm thick natural rubber. The design and size of the harness was determined by the weight of the barn owl following estimates by Naef-Daenzer (2007). The natural rubber was adhered with generic superglue (cyanoacrylate) and was expected to disintegrate or break apart within a year, resulting in the transmitter falling off the barn owl. The transmitter and rubber harness weighed 7 g which is < 2% of the body mass of the barn owls we trapped (range: 413–561 g), and well within the 5% guidelines for

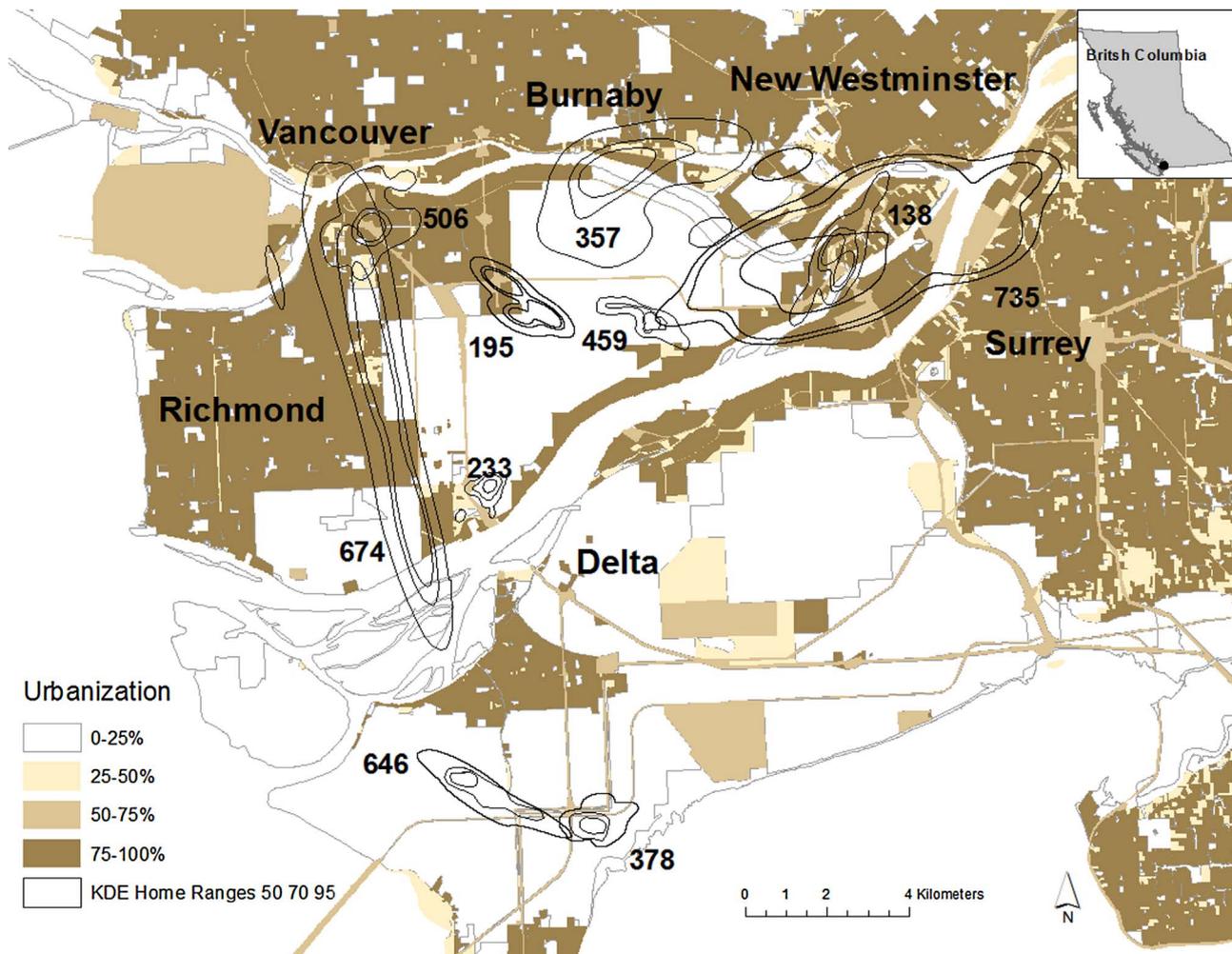


Fig. 1. Study area, the Lower Fraser Valley, British Columbia, Canada, used to assess the hunting behavior of barn owls. The map includes 50, 70, 95 kernel density estimate barn owl home-ranges ( $n = 10$ ), and the percentage of urbanization.

the use of radio transmitters on wild birds (Fair, Paul, & Jones, 2010). Standard morphometric measurements such as weight, wing and tail length were collected. Sexing was based on Pyle (2001).

In total, we trapped and radio-tagged 11 adult barn owls between 2010 and 2013, of which seven were females and four were males (Table 2). We monitored all owls until their transmitter fell off or the transmitter battery died (5–12 months). One female was reported dead two weeks after being radio-tagged, likely the victim of a vehicle collision.

We located and monitored tagged owls using a portable VHF receiver (ATS model R4000) and a hand-held three prong yagi antenna. We actively tracked each tagged barn owl a minimum of three times a week at different randomized shifts for a minimum of 30 min for each shift. The hours of each shift varied depending on the season, but were: early (2–4 h after dusk), mid (> 2–4 h after dusk), and late (2–4 h before dawn). We tracked tagged barn owls by vehicle at the start of each shift, and following this, the exact location and habitat used by the hunting barn owl was determined on foot. Visual location of the barn owl was attempted for each monitoring session.

The location where an individual owl hunted during the 30 min monitoring session was used as one independent location/fix for calculation of kernel density home-ranges. For each independent location we noted the time, weather and hunting behavior (perched/flying with dives to the ground). The habitat surrounding the hunting location was also noted for the majority of locations. Interactions with other barn owls were also recorded. Fixes were only included in the home and land use analysis when the owl was found hunting. This

research was carried out under all the appropriate wildlife and animal ethics permits: Provincial wildlife permit (SU13-85610), Animal care permit (979B-10), Industry Canada Radio License (5093896) and Canadian Bird Banding Office Permit (10759).

### 2.3. Home-range and landscape analyses

Telemetry fixes were mapped using Arcmap 10.1, and 95%, 70% and 50% Kernel density estimates (KDE) home-ranges were calculated using Geospatial Modelling Environment (GME, 2012). The KDE home-ranges were calculated using least squares cross validation (LSCV) bandwidth and Gaussian kernel function. We obtained a minimum of 30 fixes for each owl as this is the smallest number recommended by Seaman et al. (1999) when calculating KDE home-ranges.

To determine barn owl habitat selectivity, we first quantified the available hunting habitat, and then analyzed the telemetry data using a Compositional Analysis (Aebischer, Robertson, & Kenward, 1993). We identified and quantified 10 different land use covers within KDE home-ranges using 2009 provincial ortho photos in ArcMap 10.1 (Data BC, 2014). We ground-truthed home-ranges to verify the different types of crops grown, and surveyed for rodenticide bait stations placed along the perimeter of buildings, along fence lines and hedgerows. The following 10 land use covers were mapped within the barn owl home-ranges (1) hayfields, (2) vegetable and crop fields, (3) berry fields (blueberry and cranberry), (4) field margins, (5) roadside and railway track grass verges (including the medians and on-and-off ramps), (6) patches of unmown and rough grass in parks, gardens

**Table 1**

Definition of land use covers assessed, and where they are typically found, within the 95% kernel density home-ranges of barn owls in the Lower Mainland, British Columbia Canada.

Name	Code	Definition	
Hayfield	Hayfield	Hayfields and pastures	Agricultural
Vegetable field	Veg Field	Vegetable and crops fields such as potatoes, barley, wheat and corn	
Berry field	Berry Field	Blueberry and cranberry fields.	
Field margin	Field Margin	The grass margin between fields and along the edges of fields. Predominantly unmown rough grass and shrubs	
Old field and unmanaged grassland	Oldfield	Fields and patches of unmown grasslands, found in agricultural areas.	
Riparian	Riparian	Collection of deciduous trees, predominantly cottonwoods interspersed by patches of unmown rough grass and marsh. Found along the foreshore and other waterbodies	
Roadside grass verge	Road Verge	Grass in roadside verges along farm roads, residential streets and highways. For highways this also includes medians, and the on – and – off ramps. Consists of unmown rough grass mown 2–3 times a year.	
Old field grass in parks and gardens	Oldpg	Patches of unmown rough grass in parks and gardens and urban green corridors	Urban
Undeveloped parcels of grass	Grass Und	Parcels of unmanaged/unmown grass habitat that is in the process of being rezoned to residential or industrial development	
Impermeable surfaces	Imp	Impermeable surfaces constituted residential, commercial and industrial usage. In addition, intensively managed greenspaces such as soccer fields and tennis courts	

**Table 2**

Chronological list of radio-tracked barn owls in the Lower Mainland, British Columbia Canada, including roost/nest location, and proportion of grass habitat and impermeable surfaces within home-ranges.

Barn Owl #	Year	Land Use Category <sup>b</sup>	Roost/Nest Structure	Evidence of Breeding <sup>c</sup>	Paired Up	Sex	Weight g	KDE 95	Prop Imp <sup>d</sup>	Prop Grass <sup>e</sup>
195	2010	Semi-Urban	Silo/Roof of house	yes	Yes	M	413	2.5	0.54	0.17
138	2010	Urban	Hwy bridge/Hwy bridge	yes	Yes	F	453	3.1	0.74	0.18
674	2010	Urban	Tree	no	No	F	553	22.1	0.66	0.09
506	2010	Urban	Indust build/Indust build	yes	Yes	M	423	5.3	0.83	0.15
233	2010	Semi-Urban	Tree/Tree	yes	Yes	F	508	1.0	0.28	0.54
357	2011	Semi-Urban	Tree/Nest box build	yes	Yes	M	468	13.1	0.40	0.11
735	2011	Urban	Indust build/Hwy bridge	no	Yes	F	527	28.5	0.70	0.09
459	2013	Agricultural	Barn/Barn	yes	Yes	M	465	1.4	0.20	0.37
646	2013	Agricultural	Barn/Platform	yes	Yes	F	523	2.6	0.22	0.18
378	2013	Agricultural	Barn/Nest box	yes	Yes	F	561	1.6	0.14	0.35
418 <sup>a</sup>	2013	Agricultural				F	490			

<sup>a</sup> Reported dead after two weeks of radioing.

<sup>b</sup> Primary human land use within home-ranges.

<sup>c</sup> Any evidence of breeding during and after radio transmitter was attached.

<sup>d</sup> Impermeable surfaces constituted residential, commercial and industrial usage. In addition, intensively managed greenspaces such as soccer fields and tennis courts.

<sup>e</sup> Grass habitat includes: Hayfield, field margin, roadside grass verges, undeveloped parcel of grass, old field and unmanaged grassland and unmanaged grass in parks, green-corridors and gardens.

and golf courses, (7) riparian, (8) parcels of grass habitats under rezoning for urban development, (9) unmown old field habitat (10) impermeable surfaces which were strongly associated with urban areas, and constituted residential houses, industrial buildings and greenhouses, parking lots, roads, railway tracks, and tennis courts. For additional description of land use covers and abbreviations, see [Table 1](#). We included nine land use covers in the habitat selectivity analysis as this was the maximum number of habitats allowed for the analysis (number of animals – 1 = habitat types, Compositional Analysis; [Aebischer et al., 1993](#)). Hence, we excluded the impermeable surface land use cover from the selectivity analysis, as land uses such as buildings and paved parking lots are the least suitable hunting habitat for barn owls.

Prior to conducting a habitat selectivity analysis, we conducted an Eigenanalysis of habitat selection ratios to evaluate whether there was any variability in habitat selection among monitored barn owls that could be explained by the difference in the availability of the various habitat types within home-ranges ([Calenge & Dufour, 2006](#)). The Eigenanalysis is considered an extension of the Principal Component Analysis (PCA), and allows for the exploration of habitat selection in order to identify whether a group of animals select their habitat in a common way, or if there are groupings of animals that select habitats differently, i.e. different habitat selection strategies explained by differences in habitat availability, structure and home-range size ([Calenge & Dufour 2006](#)). For all habitat selectivity analysis we used the package ‘adehabitatHS’ in the statistical software R ([Calenge, 2015](#);

[R Development Core Team, 2013](#)). To test whether barn owls had specific habitat preferences within their home-ranges we carried out a Compositional Analysis ([Aebischer et al., 1993](#)). This analysis ranks habitats based on its relative use compared to the habitat’s actual proportion within home-ranges (third order habitat selection; [Johnson, 1980](#)).

#### 2.4. Distances to bait stations and relative risk model

Distances from barn owl hunting locations to visible bait stations placed along the perimeter of buildings, fence lines, hedgerows and in blueberry fields were measured in meters using Arcmap 10.1. We created a model that calculated the relative risk of barn owls consuming AR-laden prey within each habitat polygon in their respective home-ranges. The distance from each habitat polygon to the closest outside AR bait application was measured in Arcmap 10.1. We used spatial AR non-target small mammal data from [Geduhn et al. \(2014\)](#) and [Tosh et al. \(2012\)](#) to derive our own proportion AR positive small mammals distance index. This index takes into account the proportion of AR positive non-target small mammals trapped within various distances from AR application during baiting. The index ranged from 0 – 160 m, with the following increments and probabilities of AR positive rodents: 0–15 m (0.55), 15–30 m (0.15), 30–45 m (0.15), 45–60 m (0.10), 60–160 m (0.05), > 160 m (0). We used a 160 m cut-off, as this is the furthest away AR positive rodents have been documented from an AR source ([Tosh et al., 2012](#)). The proportion of AR laden rodents

within each habitat polygon, which was dependent on the polygon's distance to the closest bait station, was multiplied with the proportion use of the polygon's habitat type for each barn owl with their respective home-range. The likelihood of consuming rodenticide exposed prey = (Polygon distance converted to proportion positive small mammal index \* Individual barn owl use of habitat within the polygon).

### 2.5. Pellet collection and prey analyses

We collected pellets from the radio-tagged barn owls' nests or roost site every three to four months. Pellets were dissected and prey items were identified by following the same protocols as in Hindmarch & Elliott (2014). We identified prey items to species when possible, however we were unable to separate shrew species, and few rat remains were intact enough to separate to species, hence all shrew and rat samples were categorized as "shrew" or "rat". Weights of rats were estimated based on the length of their lower mandibles from the prey remains and using the allometric formula developed by Morris (1973). Songbird (*Passeriformes*) prey remains were allocated into two categories: a small songbird category (< 30 g) and a medium songbird category (30–60 g). All exoskeleton remains were considered to be in the order Coleoptera. We conducted a linear regression to evaluate whether there was any relationship between the proportion of commensal rodents in the diet and the proportion of impermeable surfaces within home-ranges. Statistical analyses were carried out using IBM SPSS 22, and we considered a p-value of  $\leq 0.05$  as significant. (IBM SPSS, IBM Inc.Armonk, New York).

## 3. Results

### 3.1. Tracking and home-ranges

In total, we trapped seven barn owls in semi-urban to urban landscapes and four in agricultural landscapes. The sizes of the 95% Kernel home-ranges were quite variable ranging from 1.0 to 28.5 km<sup>2</sup> (Fig. 1, Table 2). Home-range sizes were positively correlated with the proportion of  $\bar{X}$  impermeable surfaces (Range: 14–83%, 47%, Kendall's Tau 0.82,  $p < 0.001$ , Fig. 1). The radio-tagged barn owls nested and roosted in many kinds of human structures such as barns, silos, industrial buildings, underneath highway bridges, and in trees. Only one owl (# 674) did not appear to be paired with a mate, as she was never seen hunting with a mate, unlike all the other owls we monitored. Five of the owls attempted nesting during our study, and four successfully fledged young. Female # 138 had two clutches during the 2010 breeding season underneath a highway bridge (Fig. 2). Sometimes, barn owls other than the mates of the radio-tagged owls were seen within the home-ranges. Overlap of home-ranges is believed to be quite common (Cayford, 1992; Taylor, 1994), and up to two pairs of barn owls were seen on occasion hunting the same grass fields, making them less territorial than other non-migratory owls in the region such as the great-horned owl (*Bubo virginianus*) and the barred owl (*Strix varia*). On five occasions barn owls flew up to 8–10 km from their regular roost site for one night only, but these were isolated incidents that did not recur for the remainder of the study. These events happened during the fall and winter on clear and wind still evenings and none of the individuals were breeding at the time.

### 3.2. Land use and habitat selectivity within home-ranges

There was considerable variation in the amount of different land use types within the home-ranges we mapped. On average 17.4% of the 95 Kernel home-ranges were grass associated land uses such as hayfields, old fields, unmown grass in parks and gardens, and parcels of grass covered land currently under rezoning to high density residential or industrial. The proportion of impermeable surfaces ranged from 14 to 83% within home-ranges, with an average of 47%. Roadside grass was



Fig. 2. October 2010: the second clutch by barn owl # 138. She and her mate nested underneath a highway bridge on one of the main highway corridors going in to Vancouver. There were sound barriers installed along the highway which we noticed encouraged the barn owls to fly high enough over the highway to avoid collisions with vehicles. Photo credit: Ian Routley.

mainly associated with major highways and constituted the verges, medians and on-and-off ramps (67%), with the remaining roadside grass being found on the verges of urban streets and farm roads (33%) (Table 2).

Although the home-ranges were quite heterogeneous, ranging from primarily agricultural to highly urban landscapes, and varying in size and patch structure, those differences did not significantly influence habitat selectivity for barn owls. Eigenanalysis of habitat selection amongst barn owls showed that most of the habitat selection was explained on the first axis (69%, Fig. 3). There was no clear grouping of barn owls based on differences in habitat availability and use within home-ranges. Consequently, all 10 barn owls were evaluated together in the third order Compositional Analysis which tested overall habitat selectivity within the individual home-ranges. The Compositional Analysis indicated that habitat types were not chosen at random ( $\lambda = 0.07$ ,  $p < 0.001$ ). The habitat "roadside grass verges" was significantly preferred over all other habitat types (Table 3). The analysis suggests the following decreasing ranking of habitat preferences: Road Verge > Grass Und > Field Margin > Hayfield > Oldpg > Oldfield > Riparian > Veg Field > Berry Field. Barn owls were only observed hunting in blueberry fields on three occasions, although field margins and roadside grass verges bordering the blueberry fields were often utilized.

### 3.3. Distance to bait stations and relative risk model for AR exposed small mammals

Rodenticide bait stations were commonly observed along the outer perimeter of industrial, residential and commercial buildings, and often in hedgerows surrounding condominium buildings and townhouses. All bait stations were baited with the SGAR bromadiolone. A commonality for all these buildings, which were located in more urban environments, was that the closest suitable grass habitat for barn owls to hunt was unmown grass in parks and gardens, undeveloped parcels of grass habitat in the process of being rezoned, or roadside verges.

AR use in agricultural landscapes was also prevalent. Over the last decade, food and safety regulations have become more stringent, requiring vegetable farmers to have an audited rodent control program in place (Canada GAP, 2014). Hence, barns on non-organic farms storing vegetables, and greenhouses have permanent placements of bait stations with the SGAR bromadiolone along the outside perimeter. In addition, blueberry farmers will often control for field voles (*Microtus townsendii*) which may damage their blueberry bushes, by using FGAR bait in PVC tubes placed in blueberry fields.

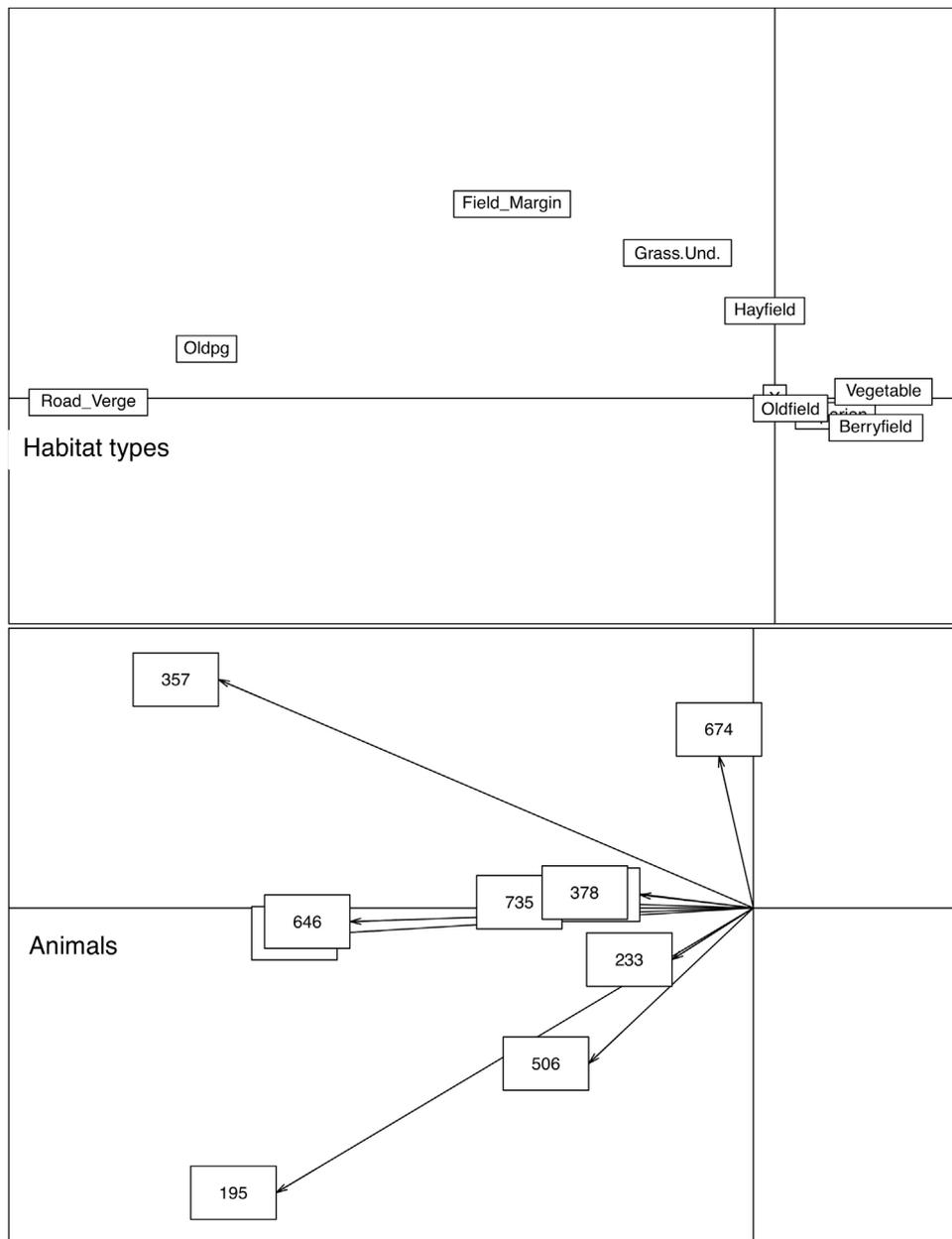


Fig. 3. Eigenanalysis of habitat selection ratios to evaluate whether there was any variability in habitat selection among monitored barn owls ( $n = 10$ ) that could be explained by the difference in the availability of different habitat types within home-ranges. The Eigenanalysis is considered an extension of the Principal Component Analysis (PCA) and allows for the exploration of habitat selection in order to identify whether a group of animals select their habitat in a common way, or if there are groupings of animals that select habitats differently, i.e. different habitat selection strategies explained by differences in habitat availability, structure and home-range size. The Eigenanalysis showed that habitat selection amongst barn owls was similar as most of the habitat selection was explained on the first axis (69%).

Table 3

Ranking matrix of selected habitat types for barn owls ( $n = 10$ ) based on comparing proportional habitat use within the 95 kde home-ranges with proportion of available habitat for each type within the kde home-ranges. Signs indicate pairwise habitat preferences (+) and avoidances (-) when reading each column. Three symbols show a significant difference ( $P < 0.05$ ) and one symbol indicates a trend.

Habitat Type	Grass Und	Riparian	Road Verge	Oldpg	Hayfield	Field Margin	Veg Field	Oldfield	Berry Field
Grass Und	0	+++	---	+	+	+	+++	+++	+++
Riparian	---	0	---	-	-	---	+	-	+
Road Verge	+++	+++	0	+++	+++	+++	+++	+++	+++
Oldpg	-	+	---	0	+	-	+++	+	+++
Hayfield	-	+	---	-	0	-	+++	+	+++
Field Margin	-	+++	---	+	+	0	+++	+	+++
Vegetable Field	---	-	---	---	---	---	0	-	+
Oldfield	---	+	---	-	-	-	+	0	+
Berry Field	---	-	---	---	---	---	-	-	0

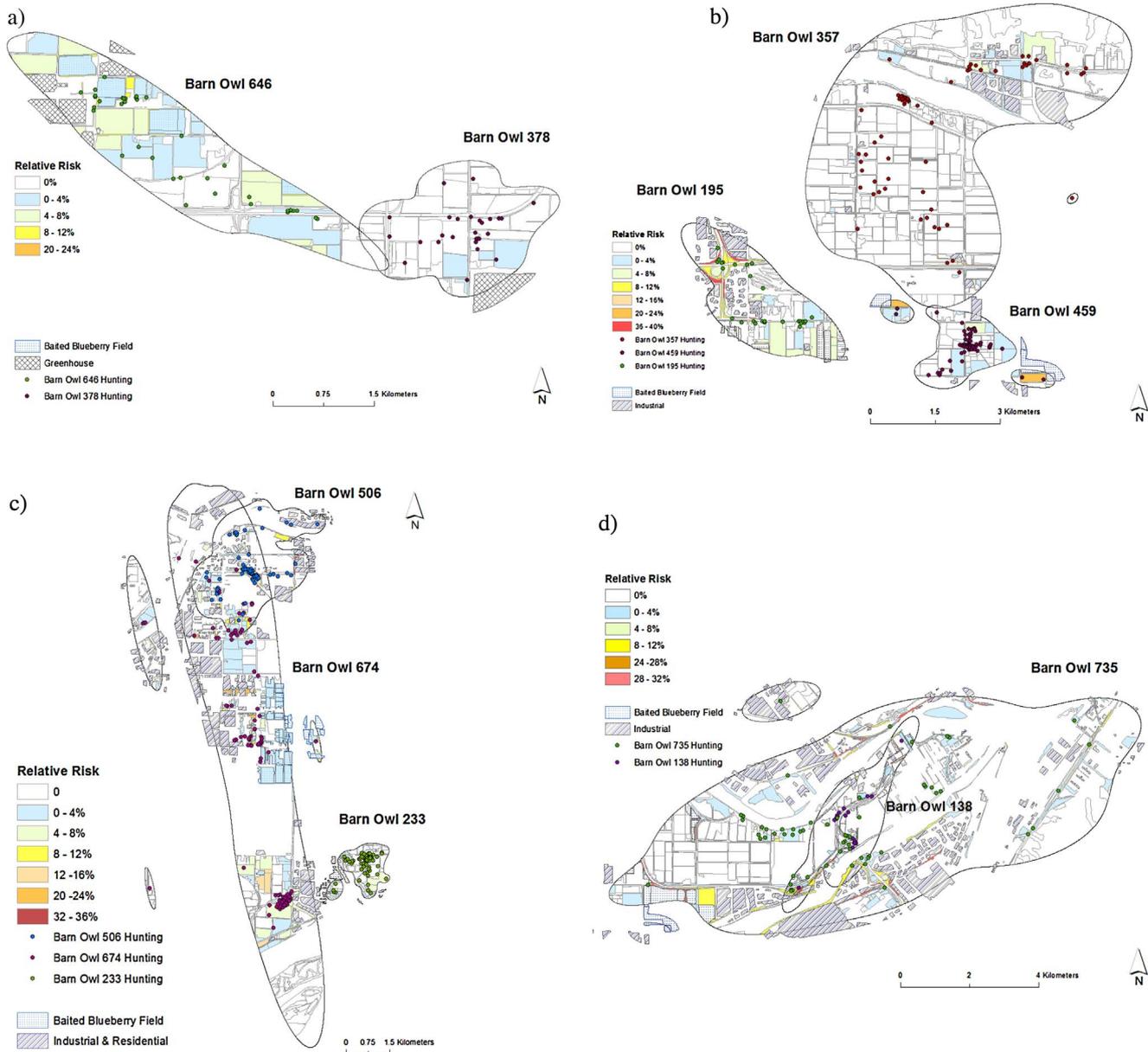


Fig. 4. a-d Relative risk habitat map showing the likelihood of consuming rodenticide exposed prey within different habitat polygons. The likelihood is a product of the proportion of AR exposed small mammals and the proportion use of the polygon's habitat type for each barn owl. The proportion of AR exposed small mammals depends on the habitat polygons distance from outside AR application. The index ranges from 0 to 160 m, with the following increments and probabilities of AR positive rodents: 0–15 m (0.55), 15–30 m (0.15), 30–45 m (0.15), 45–60 m (0.10), 60–160 m (0.05), > 160 m (0). The mapped industrial, residential and greenhouse buildings had outside placement of the SGAR bromadiolone. Baited blueberry fields had pvc tubes in which AR bait is placed.

Overall barn owl hunting distances to the nearest bait station within their home-ranges varied depending on the location. In some instances the barn owls hunted from atop bromadiolone baited buildings, while others were hunting over a kilometer away from any source of outside placement of ARs. The average distance from AR placements to the area where individual barn owls hunted ranged from 107 m (SD ± 71 m) to 654 m (SD ± 573 m, Table 2).

The likelihood of consuming rodenticide exposed prey, which was a product of the habitat polygons' distance to AR bait, and the individuals owl's proportional use of different habitat polygons, ranged from 0 to 40% (Fig. 4a–d). Roadside verges had the highest likelihood of containing AR exposed small mammal prey (Fig. 5). In addition, the likelihood of consuming AR exposed prey significantly decreased when home-ranges had a higher proportion of patches of grass habitat (hayfield, oldpg, grass und. oldfield) relative to other land use types (Log likelihood exp. prey = -2.60(0.29) - Prop Grass \* -3.20(1.32),

$$r^2 = 0.42, n = 10; p < 0.05, \text{ Fig. 5}).$$

### 3.4. Diet

We were able to obtain pellets and prey remains from eight of the monitored barn owls. Overall, we identified 15 prey types in the 1535 prey remains we examined (Table 4). Voles (all field voles with the exception of one *Microtus oregoni*) were the main prey item for barn owls, regardless of land use within home-ranges (range: 64.3–90.0%,  $\bar{X} = 76.7 \pm 7.1\%$ ). Shrews were the second most consumed prey ( $\bar{X} = 12.1 \pm 6.0\%$ ), and rats were the third ( $\bar{X} = 4.3 \pm 4.3\%$ ). There was considerable variation in the consumption of rats between sites (range 0–11.8%), but the consumption increased significantly with increased impermeable surfaces within home-ranges (Prop. Rats = -0.02(0.02) + Impermeable Surfaces \* 0.13(0.04),  $r = 0.79$ ,  $r^2 = 0.63, n = 8; p < 0.05; \text{ Fig. 6}$ ). The average mass of rats consumed

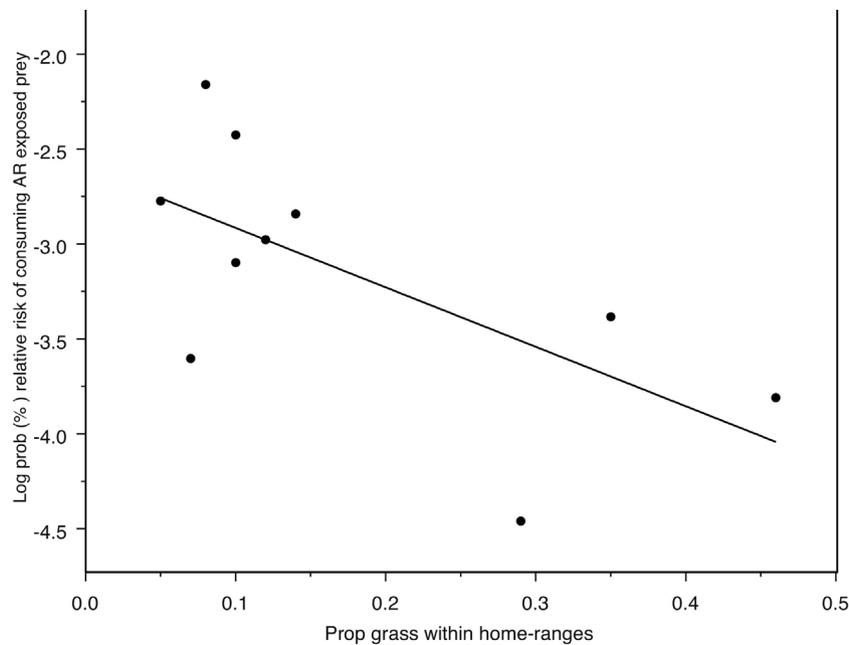


Fig. 5. Log-transformed relative risk of consuming AR exposed small mammal prey decreases when the proportion of patches of grass habitat (hayfields, patches of old field grass in parks and gardens, unmanaged grass and old field on agricultural lands and parcels of grass in the process of being rezoned) within home-ranges increases (Log likelihood exp. prey =  $-2.60(0.29) - \text{Prop Grass} * -3.20(1.32)$ ,  $r^2 = 0.42$ ,  $n = 10$ ;  $p < 0.05$ ).

Table 4

Prey species and/or taxon (%) found in pellets collected from radio-tracked barn owls in agricultural and urban landscapes from July 2010 to June 2014 in the Lower Mainland, British Columbia Canada.

	Barn Owl #							
	138	506	233	357	735	459	646	378
# Prey	357	491	81	79	144	70	230	83
% Impermeable surfaces	74.4	82.9	27.7	40.0	69.6	20.2	22.0	14.3
Prey								
Order Rodentia								
<i>Microtus townsendi</i>	79.3	77.2	71.6	72.2	79.9	64.3	90	78.3
<i>Microtus oregoni</i>								1.2
<i>Peromyscus maniculatus</i>	3.9		1.2	6.3	2.1	7.1	1.3	2.4
<i>Mus musculus</i>		0.8						
<i>Rattus</i> sp.	8.7	11.2			3.5	5.7		
<i>Rattus norvegicus</i>	0.8	0.2	1.2	1.3	0.7			
<i>Rattus rattus</i>	0.6							
Order Lagomorpha								
<i>Sylvilagus floridanus</i>								1.2
Order Soricomorpha								
<i>Scapanus orarius</i>	0.6	0.2		8.9	1.4			
<i>Neurotrichus gibbsii</i>								0.4
<i>Sorex</i> sp.	5.9	10.4	23.5	10.1	12.5	20	6.1	8.4
Order Passeriformes								
<i>Passeriformes (30–80)*</i>						1.4	0.4	
<i>Passeriformes (&lt; 30 g)*</i>	0.3		1.2	1.3		1.4	1.3	8.4
Order								
Small Fish								0.4
Order Coleoptera			1.2					

\* Unidentified songbirds were allocated into two categories based on mass (g).

was  $77.3 \pm 40.2$  g (Range: 20–180 g,  $n = 60$ ). Only two house mice were found in the prey remains, in addition to a more unusual finding, a 10 cm long fish.

#### 4. Discussion

Our study showed that barn owls still persist in urban areas of the Lower Mainland that were predominantly agricultural 20–30 years ago, however in much lower numbers than before. These urban barn owls nest in industrial structures and under highway bridges, and hunt the

remaining grass habitats in the urban landscape, such as roadside grass verges, major highway on-and-off ramps and medians, patches of unmown grass in parks, backyards, and parcels of grass in the process of being rezoned for industrial or residential development. The need to travel longer distances to locate suitable hunting habitat is evident from the large home-ranges of urban barn owls. Barn owls in both urban and agricultural landscapes selected roadside grass verges significantly more than other habitat types based on availability within home-ranges. This habitat selection may reflect the loss of grassland associated agriculture experienced in the region. The relative risk of consuming rodenticide exposed small mammal prey was also highest in roadside grass verges. Conversely, blueberry fields were not a preferred hunting habitat for barn owls. However, barn owls were often observed hunting near blueberry fields, along their margins or the roadside verges bordering them. Overall, the risk of consuming small prey exposed to ARs decreased when home-ranges had a higher proportion of patches of grass habitats, which included hayfields, oldfield, and undeveloped parcels of grass habitat in urban environments. This suggests that smaller, linear grass sections are more likely to contain rodenticide exposed small mammal prey. Similar to Hindmarch & Elliott (2015), field voles were the main prey item for all barn owls, irrespective of land use. Nevertheless, even with our limited sample size, and similar to other barn owl diet studies, the consumption of rats increased with the proportion of impermeable lands within home-ranges (Buckley & Goldsmith, 1975; Campbell, Manuwal, & Harestad, 1987; Salvati, Ranazzi, & Manganaro, 2002; Hindmarch & Elliott, 2015).

Previous barn owl radio telemetry studies have focused on rural and agricultural landscapes when evaluating land use and habitat selectivity within home-ranges (Colvin, 1984; Hegdal & Blaskiewicz, 1984; Rosenburg, 1986; Gubanyi, Case, & Wingfield, 1992; Taylor, 1994; Arlettaz, Krähenbühl, Almasi, Roulin, & Schaub, 2010). Our study is the first to look at barn owl habitat selectivity within home-ranges across the agricultural-to-urban landscape continuum. The average amount of urban land (47%) within home-ranges, was similar to what was reported when estimating land use within a theorized 1 km radius home-range for a larger subset of barn owls monitored in the same study area (Hindmarch & Elliott, 2015; 45% urban,  $n = 33$ ), but considerably higher than other reported estimates of urban lands within

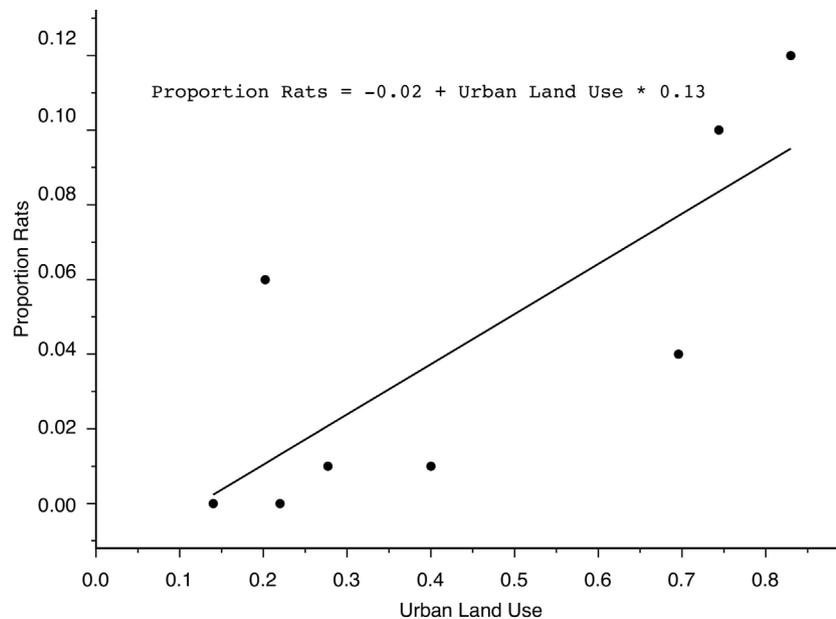


Fig. 6. The relationship between the proportion of impermeable surfaces within each barn owls' home-range and the corresponding proportion of rats in their diet. (Prop. Rats =  $-0.02(0.02) + \text{Impermeable surfaces} * 0.13(0.04)$ ,  $r = 0.79$ ,  $r^2 = 0.63$ ,  $n = 8$ ;  $p < 0.05$ ).

theorized barn owl home-ranges, all of which reported  $< 10\%$  urban (Meek et al., 2009; Frey, Sonnay, Dreiss, & Roulin, 2011; Hindmarch et al., 2012). Interestingly, barn owls selected habitats in a similar fashion irrespective of the dominant land use within their home-ranges. Linear roadside grass verges, including highway medians and on-and-off ramps, were the most selected habitats relative to availability in both agricultural and urban landscapes.

Barn owls nesting and roosting in semi-urban to urban landscapes hunted predominantly within the urban landscape. They selected grass lots ( $\geq 1$  acre) in the process of being rezoned for urban development as the second most important habitat relative to availability. These land parcels, which had historically been single family rural homes, were often left unmanaged during the rezoning and development application process, which can span several years. During this time the lots revert back to being semi-wild, and predominantly consist of unmown grass which has an abundance of voles, giving it a high value as barn owl hunting habitat (pers. observ.). We identified a total of  $1.48 \text{ km}^2$  of grass lots across all home-ranges that were in the process of being rezoned to high density residential or industrial. During our study we witnessed several of these properties being developed, and subsequently they were abandoned by barn owls as roost/nest sites and hunting grounds. These properties, along with patches of old field grass in parks, green corridors, and roadside grass verges, were often fragmented and interspersed between high density urban developments. This may explain the significant variation in home-range size, as well as the three unusually large home-ranges documented in this study of  $13.14$ ,  $22.12$  and  $28.54 \text{ km}^2$  respectively (Colvin, 1984; Hegdal & Blaskiewicz, 1984; Rosenburg, 1986; Gubanyi, 1989; Taylor, 1994; Arlettaz et al., 2010).

Most of the industrial and commercial buildings had permanent placement of the SGAR bromadiolone around their perimeters, as did most non-organic barns and greenhouses in agricultural landscapes. Hence, the average distance to AR bait was generally lower when barn owls hunted in grass lots in the process of being rezoned, roadside verges, or patches of old field grass in parks and green corridors. In agricultural settings, non-target small mammals with AR residues have been trapped as far as  $160 \text{ m}$  from the bait source (Tosh et al., 2012). However, non-target small mammals such as voles, wood mice and deer mice have much lower concentration levels of AR residues compared to Norway rats and house mice (median brodifacoum concentration

$0.24 \mu\text{g/g}$  versus  $6.46 \mu\text{g/g}$  and  $25.12 \mu\text{g/g}$ , respectively; Geduhn et al., 2014). There are no similar data for non-target small mammals in urban landscapes, but given the persistence of bromadiolone in rodents (i.e. half-life: 170–318 days in the liver of rats; Erickson & Urban, 2004), and urban barn owls' greater consumption of rats (Hindmarch & Elliott, 2015), long-term low level contamination is a concern. Given the potential for lethal and sub-lethal effects on barn owls and other raptors, low level AR contamination may be of greater consequence than is currently understood. We also documented solely the exterior placement of SGARs as we were unable to note indoor usage, leading to a likely underestimation of the number of AR sources in the landscape.

Similar to Grilo et al. (2012), our study found that barn owls did not avoid roadsides, but rather the opposite occurred, as roadside verges, including highway on-and-off ramps and medians were selected more than they were available as hunting habitat within all home-ranges. The dependency on roadside verges as hunting habitat may reflect the general loss of grassland habitat in the region due to urbanization and changes in agricultural production (Hindmarch et al., 2012). In addition, the ongoing loss of larger grass lots ( $\geq 1$  acre) to development might further increase urban barn owls' dependency on roadside verges as hunting habitat. The radio-tagged barn owls, in addition to other non-tagged barn owls were frequently observed hunting the road verges, medians, and most frequently, the highway on-and-off ramps. Voles and small mammals are known to inhabit roadside verges and medians, making this good hunting habitat for barn owls (Bellamy, Shore, Ardeshir, Treweek, & Sparks, 2000; McGregor, Bender, & Fahrig, 2008). We found several locations under bridges where there was evidence of roosting, and possibly nesting, based on the white wash on the bridge, pellets, and the occasional barn owl feather on the ground below.

Barn owls' hunting behavior usually involves flying within a meter of the ground, making them particularly vulnerable to collisions with vehicles, and road mortality is recognized as one of the main threats negatively affecting barn owl populations in both Europe and North-America (Massemin, Maho, & Handrich, 1998; Ramsden, 2003; Preston & Powers, 2006; Boves & Belthoff, 2012). Vehicle collisions are also known to kill or injure a large number of owls within our study area (Preston & Powers, 2006). Two of the radio-tagged female barn owls died from collisions with vehicles. One died during our study

period, and the second was found, dead, a year after our study was completed. Further, barn owl road mortality data collected between 1995 and 2014 on a 67-km section of the trans-Canada highway in the Fraser Valley showed that on average 0.39 owls get killed/year/km of highway (Krebs, unpublished data). Many of the barn owls that are killed on roads have tested positive for ARs, which raises concerns regarding potential cumulative impacts from AR toxicosis and habitat loss. In these cases we ask: Could AR residue burdens have been responsible for causing sub-lethal symptoms, leaving barn owls less reactive and more prone to getting hit by vehicles when hunting roadside verges and medians?

In British Columbia where voles occasionally chew and destroy the roots of blueberry bushes, the FGARs chlorophacinone and diphacinone are used as baits in blueberry fields to reduce field vole abundance. However, voles were by far the main prey item for barn owls in this study as well as in other studies from the region (see Campbell et al., 1987; Hindmarch & Elliott, 2015). They are also an important prey item for many raptors in British Columbia (Marks, Evans, & Holt, 1994; Wiggins, Holt, & Leasure, 2006; Hindmarch & Elliott, 2014). When voles are considered a non-target, studies have shown that in comparison to other non-targets such as field mice (*Apodemus* sp.) and shrews (*Sorex* sp.), voles are less likely to carry AR residues, however, reported residue levels in exposed individuals have been similar, and in some cases higher than other non-targets (Brakes & Smith, 2005; Elliott et al., 2014; Geduhn et al., 2014). Conversely, when voles are the target species, as is the case in central Europe where bromadiolone is applied in grasslands to combat voles, a high proportion carry bromadiolone residues after AR treatment, and residues have been found to persist in populations beyond 135 days post treatment (Sage et al., 2008). While barn owls avoided blueberry fields within their home-ranges, they would often hunt along the field margins or perch on signs and posts along the roadside verges bordering blueberry fields. On closer inspection, these un-mowed verges and field margins often had vole tunnels, confirming the presence of field voles (pers. observ.).

Another consideration is the scale of non-compliant use of ARs. Non-compliant uses include the outdoor use of products specified for indoor-use only (SGARs: brodifacoum and difethialone) (PMRA, 2009). In 2012, an AR user survey among farmers within a portion of our study area determined that 17% of the farmers surveyed used the two most toxic and persistent SGARs, brodifacoum or difethialone, outdoors (Hindmarch et al., unpublished data). This highlights the need for more outreach and education programs on rodenticide use, similar to what has been implemented in the UK (The Campaign for Responsible Rodenticide Use [CRRU], 2015).

Finally, there are two ways in which our model (relative risk of consuming exposed prey) can be improved. First, with the increasing amount of land devoted to blueberry production in the Lower Mainland and Fraser Valley (Metro Vancouver, 2012), and the corresponding use of ARs by blueberry farmers, we need to understand the role of field voles as vectors of ARs to barn owls and other raptors. It would be useful to incorporate into our model the proportion of AR-affected voles, how this value fluctuates seasonally, and given barn owls dependency on field margins as hunting habitat, their dispersal distances. Second, we are currently only modelling the likelihood of small mammal exposure. We need to assess exposure and concentrations in small mammals and rats during and after AR baiting, and incorporate this into the model. Although rats are in most instances only a minor component of the barn owls' diet, if they are disproportionately affected by ARs, as preliminary research suggests, it would be important to incorporate this into our model (Elliott et al., 2014; Geduhn et al., 2014).

#### 4.1. Management implications

Our study demonstrates that barn owls in the Lower Mainland are faced with multiple stressors, such as habitat and nest site loss, risk of

rodenticide exposure, and road mortality. Their dependency on roadside grass verges as hunting habitat, combined with a higher relative risk of consuming AR exposed small mammals in this habitat highlights the need to create, retain and enhance hunting habitat for barn owls during urban and infrastructure development. The retention of parcels and linear strips of old field habitat within and along the perimeters of proposed developments, along greenways, or in parks could be a management strategy for maintaining barn owls in increasingly urban landscapes. Barn owl road mortality on our major highways also needs to be addressed, focusing on high risk areas. Low-flight barriers such as screens or closely placed shrubs and trees should be planted along the highway to prevent barn owls from flying < 3 m above the road (Ramsden, 2003).

The widespread and permanent outdoor placement of the SGAR bromadiolone, which we documented in our study area, calls for a careful re-examination of how to most effectively use AR compounds to suppress rodent populations while also minimizing the risk of poisoning of non-target species (Elliott, Rattner, Shore, & van den Brink, 2016). This process should also take into consideration that SGAR compounds are persistent, and that we know very little about the potential effects of ingesting multiple compounds over a short period of time (Rattner, Lazarus, Elliott, Shore, & van den Brink, 2014). Finally, we need to decipher whether the residue levels documented by Albert et al. (2010) and Huang et al. (2016) are causing sub-lethal impacts on a barn owl population that is already facing multiple threats.

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