Northern goshawk diet in southwestern British Columbia

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# 1 Abstract

Effective wildlife conservation often requires understanding diet composition and its consequences for population demographics. We measured breeding season diet of an at-risk population of northern goshawks (*Accipiter gentilis*) in coastal British Columbia using a combination of egested pellets, prey remains, and nest camera photos. We compared diet composition across two ecological zones and assessed the impact of diet diversity and dietary specialization on goshawk productivity. Our results differed between source (pellets, remains, or cameras) and measurement (biomass or counts), highlighting the importance of clearly reporting methods in raptor diet studies. Goshawks consumed 29 different prey species but primarily consumed tree squirrels (*Tamiascuirus* spp.), with this single taxon making up 59% of the biomass delivered to nests. Diet composition differed slightly between ecological zones but dietary specialization on tree squirrels was equally high in both zones. Goshawk nests monitored with nest cameras fledged 1.4 0.79 chicks. However, we found no evidence to support an effect of diet diversity or dietary specialization on variation on goshawk productivity.

# 2 General Introduction

Once valued primarily for high timber yields, temperate rainforests of the Pacific Northwest are now managed with increased emphasis on the conservation of biodiversity (Thomas et al. 2006). Among the drivers of this shift are declining populations of species whose life histories depend on old-growth forests. Some of these species have been placed under federal, provincial, or state protection: among others, the marbled murrelet (*Brachyramphus marmoratus*) is protected under the Species at Risk Act in Canada (COSEWIC 2014) and the coastal population of the pacific marten (*Martes caurina*) is protected under the Endangered Species Act in the United States (Wildlife Service 2020). Management under these types of legislation is typically reactive and focuses on conserving each imperiled species on a case-by-case basis (Simberloff 1998). This approach has been widely criticized for failing to provide management for wider ecosystems, including the very ecosystems on which the imperiled species depend (Lambeck 1997). Alternatively, focusing on the broader scales of landscapes or ecosystems should preserve the ecosystem processes and services on which wild species and humans alike depend (Franklin 1993 ). Yet ecosystem-based management is itself beset by numerous practical, theoretical, and even philosophical challenges which have made it difficult to implement (Lambeck 1997, Simberloff 1998).

Managers have often turned to surrogate species as a solution for the dilemma posed by the single-species and ecosystem-based management debate. At the core of the surrogate species concept is the belief that the requirements or wellbeing of a single species, or a small suite of species, can stand in for the needs and health of numerous co-occurring species or entire ecosystems (Caro 2010). Numerous variations and conflicting definitions are present in the literature, but the original concept may be that of the *indicator species*. The presence and population size of an indicator species is believed to reflect ecosystem processes or the populations of other species (Landres et al. 1988). Perhaps more widespread than indicator species is the *umbrella species* concept. Protections which benefit umbrella species–typically wide-ranging habitat specialists–are assumed to confer protection to co-occurring species with smaller ranges and less restrictive habitat requirements (Roberge & Angelstam 2004, Seddon & Leech 2008). A related concept is the *flagship species*, a species whose protection, like an umbrella species, confers benefit on other species, but which is selected for its charisma and ability to serve as a rallying point for conservation (Andelman & Fagan 2000). These concepts all attempt to extend the relative simplicity of single-species methods to achieve the promise of ecosystem-based management (Lambeck 1997).

No species better embodies the challenges of managing forest species and ecosystems in the Pacific Northwest than the northern spotted owl (*Strix occidentalis caurina*). The spotted owl is strongly associated with old-growth temperate rainforests (Forsman et al. 2004) and has at various points been proposed as an indicator (Gutiérrez and Carey 1985), an umbrella (Tracy and Brussard 1994), and a flagship species for this ecosystem. In the late 1980s, public outcry and litigation in the United States led to the development of a spotted owl conservation strategy concurrent with the species’ listing as threatened under the Endangered Species Act (Thomas et al. 2006). This single-species plan rapidly expanded to include other species, particularly the marbled murrelet and several salmon stocks, and ultimately evolved into the Northwest Forest Plan. The Northwest Forest Plan remained rooted in spotted owl management, but also included protections for watersheds, monitoring of rare species, and a sustainable annual timber harvest (DellaSala and Williams 2006). Not all the Northwest Forest Plan’s goals have been achieved–notably, spotted owl and marbled murrelet populations have continued to decline, although at a slower rate–and some parts of the plan have been eroded under subsequent presidential administrations (DellaSala et al. 2015). Yet the Northwest Forest Plan remains a powerful example of an ecosystem-based management plan with a single species at its core.

The story of the northern goshawk (*Accipiter gentilis*) in North America parallels that of the spotted owl. Goshawks are found in boreal forests across the continent and range as far south as the high-elevation forests of the American Southwest. Two subspecies (*A. g. atricapillus* and *A. g. laingi*) are widely recognized and a third (*A. g. apache*) is acknowledged by some authors (Squires et al. 2020). Goshawks are not associated with old-growth forest to the same degree as the spotted owl, but do show a clear preference for extensive tracts of mature forest with large-diameter trees and closed canopies (Andersen et al. 2005, Squires and Kennedy 2006). Like the spotted owl, goshawks have been proposed as a flagship (Sergio et al. 2006), an indicator, and an umbrella species (Ozaki et al. 2006). In the American Southwest, alarms were sounded over the impact of timber harvest on northern goshawks at the same time the Northwest Forest Plan was developing in the Pacific Northwest (Crocker-Bedford 1990). Decades of litigation failed to result in listing the southwestern population (proposed subspecies *apache*) under the Endangered Species Act, but a new management plan was eventually developed (Peck 2000). This single-species management plan disallowed timber harvest near known goshawk nests and required a minimum amount of mature forest within the larger home range surrounding nests (Reynolds et al. 1992). Notably, the plan also specified the inclusion of younger forest, small clearings, snags, and woody debris to provide habitat for eight important goshawk prey species. This recommendation was based on the assumption that goshawks are habitat generalists limited by the abundance, not the availability, of prey–an assumption which has been the subject of heated debate (Greenwald et al. 2005, Reynolds et al. 2008). However, by incorporating multiple species, dynamic ecosystem processes, and human use, the goshawk management plan approaches the principles of ecosystem-based management and shows its potential to scale up to a more cohesive plan in the style of the Northwest Forest Plan (Graham et al. 1994, Peck 2000).

In the Pacific Northwest, naturalists described a small, dark subspecies of goshawk unique to the coastal temperate rainforests of Haida Gwaii and Vancouver Island (Taverner 1940). The size and plumage characteristics of *A. g. laingi* may be an adaptation the dark, dense forests the subspecies inhabits (Ethier 1999) and the agile avian prey believed to dominate its diet (Penteriani et al. 2013, McClaren et al. 2015). The precise range of *laingi* is unclear; based on morphometrics, genetics, and ecosystem mapping, it is believed to extend along the west coast and islands of British Columbia, from Southeast Alaska south to Washington’s Olympic Peninsula (Team 2008, Sonsthagen et al. 2012). In the portion of its range within the United States the *laingi* subspecies has no additional protections, but in Canada it is designated as Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). The *laingi* subspecies is further Red-listed by the British Columbia Conservation Data Centre and is an Identified Wildlife Species under the Forest Practices Code (COSEWIC 2013). Existing management plans call for the creation of buffers around known goshawk nests and the maintenance of a minimum amount of mature forest within the larger home range, similar to the plan from the American Southwest (McClaren et al. 2015, Agency 2018). However, plans do not include recommendations for providing habitat for goshawk prey species. To some extent this is due to the single-species nature of the plan, but it is also a result of several knowledge gaps. Goshawk managers have acknowledged that a landscape-scale plan would be superior to the current fine-scale plan, and ecosystem-based management has been implemented elsewhere in British Columbia, most notably the Great Bear Rainforest (Price et al. 2009 ). Together these suggest an ecosystem-based approach incorporating the goshawk as a focal species may be possible for coastal rainforests elsewhere in British Columbia. Yet while *laingi* nesting habitat is relatively well documented, foraging behavior and habitat remain poorly understood. The knowledge gaps surrounding goshawk foraging ecology hinder current single-species and potential ecosystem-based management alike.

My thesis attempts to fill one knowledge gap identified by the Northern Goshawk Recovery Team (NGRT) by providing basic ecological information regarding the breeding season diet of goshawks in coastal British Columbia (Team 2008). The following chapter describes my research quantifying goshawk diet in coastal British Columbia and investigating potential links between dietary variation and goshawk reproductive success. The final chapter summarizes my results, describes the outcome of a pilot study of goshawk space-use, and discusses the implications of both for management and future research efforts.

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# 1 Introduction

Effective wildlife conservation often requires understanding diet composition and its consequences for population demographics (Ferrer and Negro 2004, Stier et al. 2016). Specialist predators consume a narrow range of prey species, which increases foraging efficiency on preferred prey at the cost of decreased reproductive success for the specialist when that prey is scarce (Newton 1998). Generalist predators consume a greater diversity of prey and readily switch between prey species, so are less sensitive to changes in prey abundance (Steenhof and Kochert 1988, Terraube and Arroyo 2011). However, for a generalist predator a single key prey species may still be a major driver of reproductive success (Elmhagen et al. 2000, Resano‐Mayor et al. 2016). For at-risk predators, increasing the abundance of key prey species may consequentially be a useful conservation tool (Ferrer and Negro 2004, Forsman et al. 2004, Resano‐Mayor et al. 2016).

The northern goshawk (*Accipiter gentilis*) is a large forest-dwelling raptor with a Holarctic distribution. A generalist predator, the goshawk hunts a variety of small- and medium-sized mammals and birds, including squirrels, rabbits and hares, grouse, jays and crows, and pigeons (Squires et al. 2020). Despite this diverse diet, a single prey species or narrow suite of species has a strong effect on the demographics of many goshawk populations. In the Yukon, goshawks depend on snowshoe hare (*Lepus americanus*) and show strong variation in productivity, mortality, and space use in response to cyclical changes in hare abundance (Doyle and Smith 1994). Goshawks in Scandinavia likewise rely on a single prey taxon (subfamily Tetraoninae) and show changes in productivity and occupancy based on the annual abundance of four grouse species (Tornberg et al. 2005). In contrast, goshawks in the American Southwest have a wide prey base and regularly consume some fourteen different species (Boal and Mannan 1994). Fluctuations in goshawk productivity in this region are small and driven by total prey abundance, though the most influential single species is red squirrel (*Tamiasciurus hudsonicus*) (Salafsky et al. 2007). These examples suggest the identity and influence of key prey species in such an adaptable predator may be specific to each population.

In British Columbia, Canada, the coastal population of northern goshawks is the subject of federal and provincial management which focuses on the protection of breeding habitat to increase nest site availability (COSEWIC 2013). Like many raptors, goshawks are generally considered to be limited by both nest site availability and prey abundance (Reynolds et al. 2006, Rutz et al. 2006). However, current management plans contain minimal protections for foraging habitat and do not include actions to increase prey populations, in part due to a lack of knowledge regarding goshawk diet and foraging behavior in this region.

Goshawk diet in the coastal Pacific Northwest is variable, with hawks on Vancouver Island, British Columbia, consuming primarily red squirrels (Ethier 1999), whereas hawks in nearby southeast Alaska (Lewis et al. 2006) and western Washington (Bloxton 2002) consume mostly medium and large birds. The mainland coast of British Columbia is ecologically similar to Vancouver Island and hawks in this region might be predicted to consume a similar diet to hawks on Vancouver Island. However, a gradient of forest types across the coastal mainland may produce dietary variation at fine scales. Snowshoe hare, a key prey species in many portions of the goshawk’s range, is absent from Vancouver Island, scarce on the coastal mainland, and abundant in the British Columbia interior (Nagorsen 2002). Goshawk diet on the mainland coast may reflect this variation in available prey between Vancouver Island and the mainland, as well as the variation in prey abundance between the coast and the interior. Where coastal forest types transition to interior forest types, it is unclear how goshawk diet might respond to fine variation in prey availability and abundance. Detailed, local information on goshawk diet is therefore necessary if limiting factors beyond nest site availability are to be included in management plans.

Here we describe the breeding season diet of northern goshawks in coastal British Columbia over a two-year period using nest cameras, egested pellets, and prey remains. We assess whether goshawk diet differs within this region between the wetter *coastal* zone and the drier *transition* zone. We further evaluate whether diet composition and diet diversity influence goshawk reproductive success.

# 2 Methods

## 2.1 Study Area and Species

In North America the northern goshawk ranges from the boreal forests of the Yukon south to the high-elevation forests of Arizona and New Mexico. Two subspecies are recognized: the widespread *atricapillus* and the restricted *laingi* (Squires et al. 2020). The *laingi* subspecies was first described on the Haida Gwaii archipelago in British Columbia and is smaller and darker than the *atricapillus* subspecies found elsewhere on the continent (Taverner 1940). The range of this subspecies is limited to the west coast of North America, from southeast Alaska through mainland British Columbia and Vancouver Island, possibly as far south as Washington’s Olympic Peninsula (COSEWIC 2013). Within British Columbia the Coast Mountains form a major barrier to movement and mark the boundary between the *laingi* and *atricapillus* ranges. *A. g. laingi* is considered a species at risk in British Columbia by both the federal and provincial governments due to significant habitat loss from industrial timber harvest (Team 2008, COSEWIC 2013).

We conducted research in southwestern British Columbia, where goshawks are considered part of the *laingi* subspecies [Team (2008); COSEWIC (2013); but see Geraldes et al. (2018)). The region is characterized by rugged mountains interspersed with coastal fjords and low-lying valleys. The maritime climate supports temperate rainforest dominated by western redcedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), and Douglas-fir (*Pseudotsuga menziesii*) (Meidinger and Pojar 1991). Within this region, goshawk managers have delineated a *transition zone* comprised of low-elevation valleys in the Coast Mountain Range which connect the coast and the interior (Team 2008). The narrow transition zone contains temperate rainforest ecosystems which are slightly drier than the forests found further west, termed the *coastal zone*, and somewhat intermediate with the arid interior forests forests found further east (Figure 5.1). The transition zone may represent an area of overlap between the coastal *laingi* population and the interior *atricapillus* population (Team 2008).

## 2.2 Data Collection

We assessed goshawk diet during the 2019 and 2020 breeding seasons through a combination of egested pellets, prey remains, and nest camera photos. Active goshawk nests were located as part of long-term population monitoring conducted by the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD). For detailed survey methodology see McClaren (2005). Some study sites contained active nests in both years of the study.

Prey remains and egested pellets were collected from 33 nests (2019 *n* = 18, 2020 *n* = 15). Pellets and remains were gathered from beneath active nests, from within nests after juveniles fledged, and from plucking-posts located within the site. Logistic constraints prevented more than one collection of pellets and remains at most sites, but some sites were visited multiple times during the breeding season. All prey remains and all pellets from a collection location (one nest or one plucking post) were combined into a single sample for each visit to that location.

Nest cameras were installed at a subset of these nests (2019 *n* = 6, 2020 *n* = 7) to record prey delivered to goshawk chicks. Nest cameras are an effective and relatively unbiased method of measuring avian diet (García-Salgado et al. 2015 , Harrison et al. 2019). However, cameras may overestimate prey deliveries because goshawks cache prey items for redelivery to the nest at a later time, which creates a risk of double-counting items. Due to the discrete nature of our data we were unable to differentiate cached, re-delivered items from new items and did not attempt to account for caching in our analysis. We also did not attempt to differentiate between prey consumed by the female at the nest and prey consumed by the chicks.

Nest cameras were digital trail cameras (Reconyx brand, UltraFire and HyperFire models) mounted 2-5 meters distant from and slightly above the nest, usually in an adjacent tree. Cameras in 2019 were programmed to take three photos one second apart when triggered by motion, and an additional one photo every thirty minutes. Cameras in 2020 were programmed to take five photos one second apart when triggered by motion, and an additional one photo every twenty minutes. Installation took place during the early nestling phase (between 4 June and 18 July; mean installation date 21 June) and cameras were left in place until after juveniles dispersed in the fall. Camera site selection was not random but constrained by topography, site access, and timing of nest discovery. We observed no nest abandonment following camera installation.

Breeding chronology was not available for most sites. At 12 of the 13 nests with cameras (2019 *n* = 6, 2020 *n* = 6), chicks were aged from photos taken shortly after camera installation using a pictorial guide (Boal 1994). Productivity was defined as the number of chicks to reach 32 days of age (Boal 1994, McClaren et al. 2002).

## 2.3 Diet Quantification

We reconstructed prey from pellets and prey remains following a modification of the protocol used by Lewis et al. (2004). Within each sample, remains were identified to the lowest possible taxonomic category and the minimum number of individuals counted (i.e. 3 hare femurs = 2 *Lepus americanus*). Intact pellets and broken but reassembled pellets were analyzed individually within each sample, while fragmented pellets were combined within each sample. Pellets were dissected and feathers, fur, and hard parts (bones, teeth, claws) were identified to the lowest taxonomic level possible. We counted the minimum number of individuals represented within the pellet or pellet collection. Prey items from pellets and remains were additionally categorized by size (small = sparrow- or vole-sized, medium = jay- or squirrel-sized, and large = grouse- or hare-sized).

Prey items identified to species were assigned a mass using data from the literature. We assigned mass to mammals from Nagorsen (2002) and to birds from Billerman et al. (2020), using the geographically closest estimates available and averaging the mass of males and females. We treated some homogenous genera for which we could not differentiate species (such as *Eutamias* and *Myotis*) as a single taxonomic grouping. For these genera, we assigned mass by averaging the masses of all possible species, based on range maps. Red squirrels (*Tamiasciurus hudsonicus*) were present at a single site within our study area; when unable to distinguish between the two members of the genus *Tamiasciurus* we assigned the item to the more common *T. douglasii*. Unidentified grouse were common among remains; these were assigned the mean mass of the two grouse species present in our study area (*Bonasa umbellus* and *Dendragapus fulignosus*). Juveniles prey items (mainly grouse) were assigned 50% of adult mass. Unidentified items were assigned mass by averaging the masses of the identified species in that size category and taxonomic class.

Data from prey remains and egested pellets are known to be biased indices of diet. Some authors have found combining data from both sources to produce relatively unbiased results that can serve as a helpful supplement to nest camera data (Simmons et al. 1991, Lewis et al. 2004). After testing for differences between pooled pellets-and-remains data and camera data we found significant differences between these two sources. We therefore report results from pellets, pooled pellets-and-remains, and cameras separately. We do not report results from prey remains alone, as diet composition estimates from prey remains are highly biased and infrequently used in raptor diet studies.

Nest camera photos were reviewed and each new prey item delivered to the nest was recorded and identified to species when possible. When items could not be identified to species, they were identified to the lowest possible taxonomic level. Prey items identified from photos were assigned a size category and biomass by the same method used for remains and pellets. Partial items were assigned the average mass for that size category and taxonomic class.

We quantified goshawk diet across the entire study area in several ways using data from pellets, pooled pellets-and-remains, and nest cameras. For ease of comparison, we simplified prey items into eight broad categories: tree squirrels (genus *Tamiasciurus*), hares (genus *Lepus*), all other mammals, grouse (subfamily Tetraoninae), thrushes (family Turdidae), corvids (family Corvidae), all other birds, and unidentified items. We calculated the relative proportion of avian and mammalian biomass, as well as the relative proportion of biomass composed of tree squirrels (genus *Tamiasciurus*), which are known to be an important source of prey for goshawks in British Columbia (Ethier 1999). For nests with cameras, we additionally quantified diet at the level of the individual nest and further calculated diet diversity with Simpson’s Diversity Index (Simpson 1949) using counts of items identified to genus or better. We report all diet quantification as percent of biomass or mean percent biomass the standard deviation except where counts or percents of items are explicitly specified.

## 2.4 Statistical Analysis

Sites were classified as either coastal or transition based on whether the site was centered within the transition zone defined by Team (2008). We used counts of items assigned to the eight broad prey categories to assess differences in goshawk diet between the coastal and transition zones. We combined all data within each zone and tested each data source separately using a chi-squared test with simulated Monte Carlo *p*-values (2000 permutations) due to small sample sizes (Hope 1968). For nests with cameras, we also calculated the proportion of squirrel biomass and diet diversity at the individual nest level and compared these between the zones using a *t*-test. Finally, we tested for differences in goshawk productivity between the two zones using a *t*-test.

To determine the potential reproductive consequences of dietary variation, we examined how two aspects of diet, diet diversity and the proportion squirrel biomass in the diet, influenced productivity using linear regressions. We pooled data from both years of the study after testing for differences in prey group composition, diet diversity, proportion squirrel biomass, and productivity between years. We included all available nests in this analysis, including one site which contained an active nest in both years of the study. The presented results are not altered if variables for this site are averaged across years or a single year is randomly selected for inclusion. Because productivity data were available only from sites with nest cameras and nest-level diet data from pellets and prey remains were sparse, we performed this analysis using only diet data from nest cameras. All analyses were performed in R (Team 2020). We used a significance level of *P* = 0.05 for all tests.

# 3 Results

## 3.1 Goshawk Diet

We identified a total of 9 unique species from pellets collected at 25 nests. Of the 135 prey items obtained from pellets, 58% could be identified to genus or better and all items were identified at least to class. Of the 121 prey items obtained from remains, 51% were identified to genus or better and all items were identified at least to class. There were 18 species identified from remains collected at 30 nests, for a total of 21 unique prey species from the pooled pellets-and-remains sample (Table 5.1).

The majority of prey identified from pellets was mammalian (75% of biomass). Squirrels made up 61% of biomass, while other birds (neither grouse, corvids, nor thrushes) made up 21%, and other mammals (neither tree squirrels nor hares) made up another 15%. The remaining 4% of biomass was made up of corvids and thrushes.

In contrast, the majority of prey (63% of biomass) identified from the pooled pellets-and-remains sample was avian. The largest prey group was grouse (37%), followed by other birds (23%) and hare (18%). Squirrels made up only 14% of the pooled sample. The remaining 3% of biomass was made up of corvids and thrushes.

We identified a total of 22 unique species from 518 prey deliveries recorded on 13 nest cameras (Table 5.1. After excluding 68 deliveries that were completely obscured from the cameras, each nest contributed an average of 35 items (range 1 - 69). We were able to identify 60% to genus or better, and 78% at least to class. Small and medium birds were disproportionately represented among items identified only to class, frequently arriving at the nest already plucked and decapitated. Variability in the number of items recorded and the rate of identification was due to differences in camera placement and sensitivity settings.

The majority of prey identified on nest cameras was mammalian (73% of biomass, mean = 71 12, n = 13). Birds accounted for only 15% of biomass (mean = 16 10), and the remaining 11% could not be identified to class (mean = 20 27). The high proportion of mammalian biomass was driven by the dominance of tree squirrels (49% of biomass, mean = 50 14) and other mammals (16%, mean = 17 12). Unidentified items accounted for 11% of biomass (mean = 20 27). The remaining biomass was composed of hare (8%, mean = 31 2), other birds (7%, mean = 7 8), grouse (5%, mean = 9 5), thrushes (3% , mean = 4 3) and corvids (1%, mean = 3 3). Overall diet diversity for the study area, based on counts of items identified to genus or better, was moderate (0.56). Diet diversity of individual nests was highly variable, ranging from 0 to 0.72 (mean = 0.46 0.21.)

## 3.2 Difference between ecological regions

We observed a difference in the diet of goshawks in the coastal and transition zones, although these differences were more pronounced in the camera data (2 = 23.84, *P* = 0.001) and pooled pellets-and-remains data (2 = 41.75, *P* = 0.0005) than in data from pellets alone (2 = 7.53, *P* = 0.11) (Figure 5.2). A post-hoc comparison revealed that the difference between zones present in the camera data was due to a significantly higher number of unidentified prey items in the coastal zone than the transition zone. The difference between zones present in the pooled pellet-and-remains data was driven by the number of other birds, which was significantly higher, and the number of tree squirrels, which was significantly lower, in the coastal zone than the transition zone.

However, we observed no significant difference in diet diversity (mean = 0.46 0.21; coastal zone mean = 0.29 0.24, *n* = 5, transition zone mean = 0.54 0.14, *n* = 8; *t* = -1.9, df = 4.13, *P* = 0.13) or the proportion of squirrel biomass (mean = 50 14; coastal zone mean = 57 20, *n* = 5, transition zone mean = 47 10, *n* = 8; *t* = 1, df = 3.75, *P* = 0.38) between the zones when using individual nest-level data from nest cameras.

## 3.3 Productivity

We were able to measure productivity for 12 of 13 [**this will be updated to 14 when GRV data comes in**] nests monitored with nest cameras. Productivity data were not obtained from two nests because the camera memory cards filled prior to fledging.

Goshawks successfully fledged young from 11 of 12 nests, producing 0-3 chicks per active nest (mean = 1.36 0.81) and 1-3 chicks per successful nest (mean = 1.55 0.69). Siblicide was common, accounting for two of the three deaths in the failed nest and one death in each of four other nests. We observed no difference in productivity between years (mean = 1.42 0.79; 2019 mean = 1.67 1.03, *n* = 6, 2020 mean = 1.17 0.41, *n* = 7; *t* = 1.1, df = 6.53, *P* = 0.31). Nor did we observed any difference in the prey group composition (using counts of items) in either in data from nest cameras (2 = 8.34, *P* = 0.3), pooled pellets-and-remains (2 = 1.46, *P* = 0.84), or pellets alone (2 = 0.4, *P* = 0.99). We also observed no difference in diet diversity (mean = 0.46 0.21; 2019 mean = 0.56 0.16, 2020 mean = 0.36 0.22; *t* = 1.8, df = 9.35, *P* = 0.1) or proportion of squirrel biomass (mean = 50 14; 2019 mean = 44.44 9.91, 2020 mean = 47.95 25.58; *t* = -0.33, df = 7.99, *P* = 0.75) between years.

We found little evidence to suggest goshawk productivity was impacted by either the proportion of diet composed of squirrel biomass (*F*1 = 0.65, df = 9, *P* = 0.44) (Figure 5.3) or diet diversity (*F*1 = 1.31, df = 9, *P* = 0.28) (Figure 5.4). There was also no significant difference in goshawk productivity between the coastal and transition zones (*t* = 0.93, df = 4.71, *P* = 0.4).

# 4 Discussion

Northern goshawks are considered generalist predators and consume a wide variety of prey species. Despite this, a single key prey species often contributes disproportionately to goshawk diet, and the identity of this species may be specific to each goshawk population (Doyle and Smith 1994, Ethier 1999, Tornberg et al. 2005). In coastal British Columbia we found goshawks consumed 29 different species during the breeding season. These prey ranged in size from tiny bats (~ 6 grams) to grouse larger than the goshawks themselves (~ 1000 grams). However, the majority of their diet was composed of tree squirrels of the genus *Tamiasciurus*. Across the entire study area this single taxa made up approximately half of the total biomass recorded. Individual nests varied in the degree to to which they specialized on tree squirrels, with some nests consuming as little as 26% squirrel biomass and others as much as 86%. Despite the clear importance of tree squirrels in the diet, the proportion of squirrel biomass delivered to the nest did not influence northern goshawk fledging success.

Goshawk survival, migration, reproductive success, and other demographic parameters are often related to the abundance of a key prey species (Doyle and Smith 1994, Tornberg et al. 2005, Rutz and Bijlsma 2006). Although we lacked data on prey abundance within our study area, other authors have found goshawk diet does reflect site-level prey abundance (Lewis et al. 2006, Rogers et al. 2006). We observed significant variation in the proportion of tree squirrel biomass delivered to each nest, which may reflect differences in squirrel abundance between sites. However, we did not find evidence to support an effect of this variation on goshawk productivity. When key prey abundance is low, high diet diversity may indicate a reliance on alternate prey, with associated negative reproductive consequences (Resano‐Mayor et al. 2016). We found no evidence of an effect of diet diversity on goshawk productivity, but it is notable that the only nest in our study to experience a complete breeding failure received the smallest proportion of squirrel biomass we observed. Given the strength of evidence from other studies and the clear importance of tree squirrels in the diet of this population, it seems probable tree squirrel abundance has some affect on goshawk productivity. Tree squirrels experience large fluctuations in abundance following cyclical changes in conifer seed crop size (Smith 1970). Given the potential cascading consequences for goshawks, understanding the relationship between variation in tree squirrel abundance and goshawk demography remains a crucial knowledge gap.

Across much of North America the key goshawk prey species is usually mammalian, often from the family Leporidae or Sciuridae (Boal and Mannan 1994, Doyle and Smith 1994, DeStefano et al. 2006, Rogers et al. 2006, Miller et al. 2014). However, in the coastal temperate rainforests of the Pacific Northwest, goshawk diet generally contains more birds than mammals and the key prey is usually a species of grouse (subfamily Tetraoninae) (Watson et al. 1998, Thrailkill et al. 2000, Bloxton 2002, Lewis et al. 2006). Despite inhabiting coastal rainforests, goshawks on Vancouver Island, British Columbia, consume primarily red squirrels (*T. hudsonicus*) (Ethier 1999). Our results from the coastal mainland of British Columbia are consistent with findings from Vancouver Island and more broadly with results from the interior of North America, but stand in contrast to findings from elsewhere in the Pacific Northwest. Goshawk diet varies at large scales in response to available prey species and prey abundance (Drennan 2006), suggesting tree squirrel abundance is higher within Vancouver Island and the south coast than other temperate rainforest ecosystems.

Prey availability and abundance may vary at both broad and fine scales due to differences in habitat type (Kenward 1982, Penteriani et al. 2013). Within our study area, low-elevation mountain valleys bridge the wet forests of the coast and the dry forests of the interior, creating a narrow region of intermediate habitat types (Team 2008). Coastal rainforests are believed to contain a lower overall abundance of goshawk prey (McClaren et al. 2015) and a lower abundance of key mammalian prey, such as snowshoe hare (Nagorsen 2002), than interior forests. Available prey species and prey abundance in the transition zone may be intermediate between the coastal zone and the interior, with associated consequences for goshawk diet and demography. We found mixed evidence for a difference in goshawk diet between the two zones. Overall, our analyses show the diet of goshawks in the transition zone is very similar to that of goshawks in the coastal zone. However, data from pooled pellets-and-remains indicate goshawks in the coastal zone consume more small- and medium-sized birds than goshawks in the transition zone, consistent with the hypothesis that the coastal zone is relatively depauperate of mammalian prey. Identifying small and medium birds was more difficult using nest cameras than for other data sources, and the high number of unidentified prey items in the coastal zone may be further evidence goshawk diet there contains relatively more avian prey than in the transition zone. Given our small sample size and the large variation in diet between nests it is difficult to make any strong conclusions, but any dietary difference between the coastal and transition zone appears to be minor and the importance of tree squirrels appears to be universal.

Raptor diet is studied through a variety of indirect methods, such as the collection of pellets and prey remains, and direct methods, such as nest cameras and observation from blinds. Nest cameras are considered one of the least biased methods for measuring diet at the nest in raptors (Tornberg and Reif 2007, García-Salgado et al. 2015, Harrison et al. 2019). Cameras in this study provided significantly more data at a finer resolution than either pellets or prey remains, which could only be collected during the infrequent surveys each site received. However, the cost, effort, and logistical challenges of camera installation restricted the number of sites from which camera data could be collected. Additionally, technical issues relating to camera settings and placement resulted in a loss of data at some sites. Despite these limitations, we believe nest cameras provided the most accurate and complete picture of goshawk diet. Compared to cameras, pellets were relatively unbiased in measuring coarse diet composition, but severely underestimated prey species richness. The pooled pellets-and-remains sample captured a much greater prey richness, including several species not detected on nest cameras, but greatly overestimated the proportion of avian biomass relative to camera data. Measuring diet composition by counts or biomass adds further uncertainty, with measurements of counts overestimating avian prey relative to measurements of biomass. These complex results highlight the importance of clearly reporting the source and measurement of raptor diet data. Because these methods have all been used in past studies we believe there is value in reporting the results of each for ease of comparison. However, we advocate for future diet studies to prioritize the collection of data via cameras, either video or still images, rather than physical specimens.

Our study addresses a fundamental question regarding the basic ecology of an at-risk population of the northern goshawk. This population is currently considered part of *A. g. laingi*, a subspecies restricted to the coastal Pacific Northwest. In portions of *laingi*’s range the diet is dominated by mammalian prey, specifically tree squirrels (this study, Ethier 1999), and in other by avian prey (Bloxton 2002, Lewis et al. 2006). Tree squirrels clearly play a key role in the diet of some *laingi* populations, including the population of Haida Gwaii (Roberts 1997, cited in COSEWIC 2013), where red squirrel is an introduced species. Genetic evidence indicates goshawks on this isolated archipelago may be distinct from goshawks on the mainland coast and Vancouver Island (Sonsthagen et al. 2012, Geraldes et al. 2018). Regardless of their taxonomic relationship, dietary evidence suggests the goshawk populations of Haida Gwaii, Vancouver Island, and the mainland coast are more similar to each other in foraging habits and habitats than to other putative *laingi* populations. Ecological similarity, such as diet and habitat characteristics, may therefore prove a better guide than genetic similarity when when incorporating foraging habitat or prey populations into management plans.

# 5 Figures

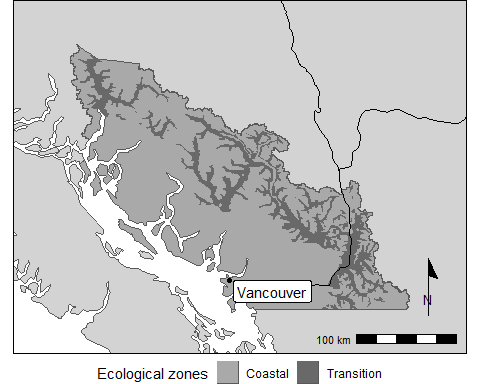


Figure 5.1: Map of study area (highlighted region) showing the coastal and transition zones.

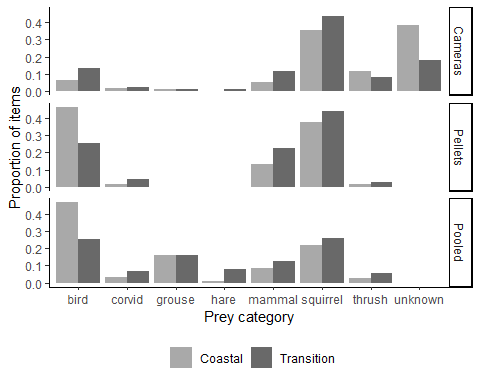


Figure 5.2: Comparison of the diet of goshawks from the coastal and transition zones. Prey items are divided by data source and grouped into eight broad categories and measured by the proportion of items in a given group out of all items from that data source.

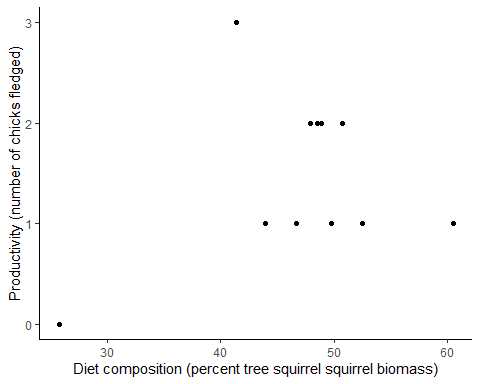


Figure 5.3: Relationship between diet composition and the productivity of northern goshawks at 12 sites in southwestern British Columbia from 2019-2020.

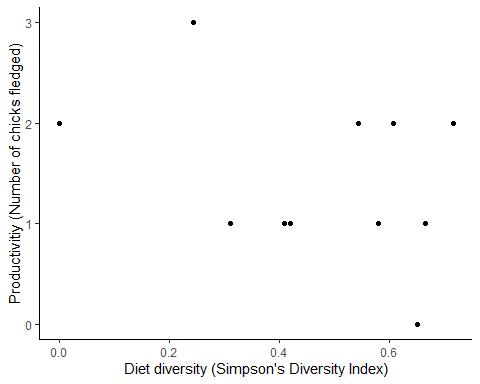


Figure 5.4: Relationship between diet diversity and the productivity of northern goshawks at 12 sites in southwestern British Columbia from 2019-2020. Diet diversity measured using counts of items identified to genus or better.

Table 5.1: Summary of prey items recorded at 33 active goshawk nests in the south coast of British Columbia in 2019-2020. Nest camera data from 13 sites, pellet data from 25 sites, and prey remains data from 30 sites

|  | | | | Camera | | Pellets | | Remains | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Class | Common name | binomial | N | % items | % biomass | % items | % biomass | % items | % biomass |
| Aves | Unknown |  | 157 | 14.22 | 4.76 | 25.19 | 11.10 | 48.76 | 54.86 |
| Aves | Northern goshawk | Accipiter gentilis | 2 | - | - | - | - | 1.65 | 1.81 |
| Aves | Mallard | Anas platyrhynchos | 1 | - | - | - | - | 0.83 | 1.60 |
| Aves | Ruffed grouse | Bonasa umbellus | 4 | 0.67 | 1.65 | - | - | 0.83 | 0.74 |
| Aves | Swainson's thrush | Catharus ustulatus | 7 | 1.33 | 0.23 | 0.74 | 0.16 | - | - |
| Aves | Northern flicker | Colaptes auratus | 14 | - | - | 6.67 | 7.75 | 4.13 | 1.11 |
| Aves | Northwestern crow | Corvus caurinus | 1 | - | - | - | - | 0.83 | 0.55 |
| Aves | Steller's jay | Cyanocitta stelleri | 18 | 1.33 | 0.81 | 2.96 | 2.80 | 6.61 | 1.35 |
| Aves | Sooty grouse | Dendragapus fulignosus | 8 | 0.67 | 3.33 | - | - | 4.13 | 6.69 |
| Aves | Downy woodpecker | Dryobates pubescens | 3 | 0.67 | 0.11 | - | - | - | - |
| Aves | Hairy woodpecker | Dryobates villosus | 4 | 0.44 | 0.20 | 1.48 | 0.88 | - | - |
| Aves | Pileated woodpecker | Dryocopus pileatus | 3 | 0.22 | 0.36 | - | - | 1.65 | 0.81 |
| Aves | Varied thrush | Ixoreus naevius | 19 | 2.00 | 0.90 | 1.48 | 0.87 | 6.61 | 0.84 |
| Aves | Mew gull | Larus canus | 1 | - | - | - | - | 0.83 | 0.55 |
| Aves | Band-tailed pigeon | Patagoienas fasciata | 4 | 0.67 | 1.44 | - | - | 0.83 | 0.53 |
| Aves | Gray jay | Perisoreus canadensis | 5 | 1.11 | 0.44 | - | - | - | - |
| Aves | Spotted towhee | Pipilo maculatus | 3 | - | - | 1.48 | 0.46 | 0.83 | 0.06 |
| Aves | Red-breasted sapsucker | Sphyrapicus ruber | 5 | - | - | 1.48 | 0.64 | 2.48 | 0.25 |
| Aves | Barred owl | Strix varia | 2 | 0.22 | 0.90 | - | - | 0.83 | 1.01 |
| Aves | American robin | Turdus migratorius | 4 | 0.89 | 0.35 | - | - | - | - |
| Aves | TOTAL |  | 265 | 24.44 | 15.50 | 41.48 | 24.65 | 81.82 | 72.75 |
| Mammalia | Unknown |  | 38 | 2.89 | 6.75 | 17.04 | 14.34 | 1.65 | 2.03 |
| Mammalia | Mountain beaver | Aplodontia rufa | 1 | 0.22 | 1.27 | - | - | - | - |
| Mammalia | Flying squirrel | Glaucomys sabrinus | 3 | 0.67 | 0.59 | - | - | - | - |
| Mammalia | Snowshoe hare | Lepus americanus | 17 | 1.11 | 8.46 | - | - | 9.92 | 22.65 |
| Mammalia | Bat | Myotis sp | 1 | 0.22 | 0.01 | - | - | - | - |
| Mammalia | Chipmunk | Neotamias sp | 8 | 1.56 | 0.59 | 0.74 | 0.36 | - | - |
| Mammalia | Bushy-tailed woodrat | Neotoma cinerea | 2 | 0.22 | 0.47 | - | - | 0.83 | 0.53 |
| Mammalia | Rat | Rattus sp | 19 | 4.22 | 6.47 | - | - | - | - |
| Mammalia | Shrew | Sorex sp | 1 | 0.22 | 0.01 | - | - | - | - |
| Mammalia | Douglas squirrel | Tamiasciurus douglasii | 240 | 39.78 | 46.00 | 40.74 | 60.65 | 4.96 | 1.72 |
| Mammalia | Red squirrel | Tamiasciurus hudsonicus | 10 | 2.00 | 2.55 | - | - | 0.83 | 0.32 |
| Mammalia | TOTAL |  | 340 | 53.11 | 73.17 | 58.52 | 75.35 | 18.18 | 27.25 |
| Unknown | Unknown |  | 101 | 22.44 | 11.34 | - | - | - | - |
|  | TOTAL |  | 706 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

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Northern goshawk diet in southwestern British Columbia

# 1 General Conclusion

## 1.1 Overview

Specialist and generalist predators differ in their degree of dependence on prey species with cascading consequences for many aspects of their life history (Korpimaki and Norrdahl 1991, Resano‐Mayor et al. 2016). Specialist predators are efficient hunters of their main prey at the cost of poor success when hunting other species, whereas generalist predators hunt many species with equal skill (Terraube et al. 2011). A specialist predator may struggle to compensate when its main prey becomes scarce, but generalist predators readily switch to alternate prey (Steenhof and Kochert 1988, Terraube and Arroyo 2011). As a result, specialist predators depend on a single species and their demographic parameters–such as migration, reproductive success, and survival–vary in synchrony with its abundance (Korpimaki and Norrdahl 1991, Terraube et al. 2011). In contrast, generalist predators make use of many species and their populations are relatively stable (Andersson and Erlinge 1977, Hanski et al. 1991).

The familiar dichotomy between specialist and generalist predators is, of course, an oversimplification. The abundance of a single prey species can be a major driver of demographic parameters, such as reproductive success, for a generalist and specialist predators alike (Elmhagen et al. 2000, Resano‐Mayor et al. 2016). Furthermore, within a single species some populations (Salamolard et al. 2000, Roth et al. 2007), or some individuals within a population (Woo et al. 2008), may be more or less specialized. A single individual may also become more specialized over its lifetime as a result of age and experience (Rutz 2006). Correctly identifying the degree of specialization and understanding its effect on demographic parameters is more than a matter of theory or curiosity: the consequences of specialization can scale up from individuals through populations to entire species, with profound implications for conservation (Ferrer and Negro 2004, Terraube et al. 2011, Resano‐Mayor et al. 2016).

The complex relationship between dietary specialization and conservation is exemplified by the northern spotted owl (*Strix occidentalis caurina*). Spotted owls depend on old-growth forests, but the cause of this association has been a source of speculation from the earliest years of spotted owl research (Gutiérrez and Carey 1985). The association appears to be driven, in part, by the spotted owl’s relatively specialized diet (Carey et al. 1992, Ward et al. 1998). More than half the biomass spotted owls consume comes from just two taxa, flying squirrels (*Glaucomys sabrinus*) and woodrats (bushy-tailed woodrat *Neotoma cinerea* and dusky-footed woodrat *N. fuscipes*; reviewed in Carey et al. (1992)). This holds true across the subspecies’ range, although the relative contribution of each taxa varies with geographic region and forest type in response to local abundance. In Washington’s Olympic Peninsula, where woodrats are absent, spotted owls consume primarily flying squirrels (Carey et al. 1992), whereas in northern California flying squirrels make up a smaller portion of the diet and woodrats, which are more abundant, dominate (Ward et al. 1998). Even within a single spotted owl population some individuals specialize on one taxa or the other (Zabel et al. 1995). Home range sizes in the flying squirrel-dependent Olympic Peninsula are among the largest ever recorded (Carey et al. 1992), and where both taxa are present owls which consume primarily flying squirrels have larger home ranges than those which consume mostly woodrats (Zabel et al. 1995). Evidently diet and prey abundance affect some demographic parameters, such as breeding density, which has led some authors to recommend increasing prey abundance as a route to increase owl abundance (Forsman et al. 2004). Yet prey abundance does not appear to affect spotted owl productivity (Rosenberg et al. 2003). Instead, productivity appears to be the result of complex interactions between climate and prey abundance (Glenn et al. 2011).

In contrast to the spotted owl’s dependence on a few prey species, the northern goshawk is considered a generalist predator and consumes an enormous diversity of prey across its wide geographic range (reviewed in Drennan 2006, Rutz et al. 2006). I identified 29 different prey species in the diet of goshawks in coastal British Columbia, which is consistent with a generalist foraging strategy. However, over 60% of goshawk diet in my study area was composed of tree squirrels (*Tamiasciurus* spp.), which indicates a level of specialization even greater than that of the spotted owl. Some goshawk populations appear to be strongly generalist (e.g. Arizona, Salafsky et al. 2007), whereas in others a key prey species is a major driver of productivity, survival, and other demographic parameters (e.g. Yukon, Doyle and Smith 1994, and Finland, Tornberg et al. 2005). I found no affect of the degree of dietary specialization on goshawk productivity. There are several explanations for this unexpected finding. First, specialists may not be more productive than generalists. Specialist individuals may preferentially consume tree squirrels but have similar levels of fitness as generalist individuals in this population (Woo et al. 2008). Alternately, specialization may not be the result of preference. Individuals may lack strong prey preferences and take tree squirrel in proportion to their abundance. Total prey abundance, rather than tree squirrel abundance, may drive productivity (Salafsky et al. 2007 ). Finally, as in the spotted owl, prey abundance and diet during the breeding season may be a lesser driver of productivity than other factors, such as weather or winter prey abundance.

Goshawk diet varies across its range in response to the regional presence and abundance of prey species (Drennan 2006). I found the key prey of goshawks in the south coast region was tree squirrels. This contrasts with studies of goshawk diet elsewhere in the Pacific Northwest where the key prey is generally grouse (Watson et al. 1998, Thrailkill et al. 2000, Bloxton 2002, Lewis et al. 2006), but is similar to work on Vancouver Island where the key prey is also tree squirrels (Ethier 1999). My results also contrast with studies from other regions of western North America where the key prey may occasionally be a species of squirrel, but is most often a species of hare or rabbit. The unexpected difference between diet in my study area and the larger Pacific Northwest may in part be due to differences in methodology. When the results from studies across temperate rainforest ecosystems are standardized (data from pooled pellets-and-remains or remains only, measured by counts), the contrast between regions within the Pacific Northwest is much less pronounced. However, the proportion of mammalian prey, particularly tree squirrels, in the diet remains markedly higher within coastal British Columbia than outside it. Tree squirrel abundance is higher in the south coast region than in other temperate rainforest ecosystems (Carey 1995, Ransome and Sullivan 2003). No Pacific Northwest study has assessed goshawk diet and and absolute prey abundance simultaneously (but see Ethier (1999)). Nonetheless, regional data hint at a pattern of higher dietary specialization in regions or forest types with higher tree squirrel abundance (see Figure 2.1). Across the two ecological zones present in my study area I observed only minor variation in goshawk diet and no variation in the dominance of tree squirrels in the diet. If goshawks are more specialized on tree squirrels where tree squirrels are more abundant, this would indicate a slight difference in the prey community of these two zones but a similar abundance of tree squirrels. Overall, goshawks in my study area appear to be a generalist predator opportunistically exploiting a locally abundant prey species.

## 1.2 Directions for future research

Comparing the foraging ecology of the northern spotted owl and the northern goshawk highlights significant knowledge gaps regarding goshawk biology. The controversy surrounding spotted owl conservation, combined with its position at the heart of a major management plan, has made it one of the most-studied birds in the world (Gutiérrez et al. 2020). The northern goshawk, although likewise shrouded in controversy, has not received the same level of study. Where data are available, it is more difficult to generalize research on the widespread, generalist northern goshawk than for the more restricted, relatively specialized spotted owl. As a result, there is a pressing need for detailed, local information on goshawks in the Pacific Northwest, particularly in coastal British Columbia.

One knowledge gap related to the work I present here is how variation in prey abundance affects the degree of dietary specialization, productivity, and survival of individual goshawks. Dietary specialization such as goshawks in my study area exhibit may be the result of a preference for the main prey or simply an absence of other options. Data on prey abundance is necessary to understand the mechanism of goshawk specialization and whether it is the result of high selectivity for tree squirrels, high abundance of tree squirrels, or some combination of both. This information could in turn be used to evaluate how changes in key prey abundance and total prey abundance influence goshawk demographic parameters, particularly productivity. Without this knowledge it is impossible to fully understand the factors limiting goshawk populations in coastal British Columbia.

A second knowledge gap is how the amount and type of habitat goshawks use for foraging varies with diet and prey abundance. Goshawk home range size varies across their geographic range and goshawks have been observed foraging in diverse habitat types, leading to ongoing debate over how and why goshawks select habitat (Greenwald et al. 2005, Reynolds et al. 2008). Research on spotted owls indicates that home range size is inversely related to prey abundance and foraging habitat selection varies with the identity of the main prey (Zabel et al. 1995). Variation in goshawk home range size and habitat selection may likewise be explained by diet and prey abundance (Kenward 1982, Penteriani et al. 2013). If so, foraging habitat management could only be conducted with knowledge of goshawk diet and recommendations made for one population could be applied to others only with great caution. Filling this knowledge gap with information specific to coastal British Columbia is vital and has been identified as a priority by goshawk managers (Team 2008, Agency 2018).

To address this crucial knowledge gap, the British Columbia Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD) and I conducted a pilot study of foraging habitat use in coastal British Columbia. Between 2018-2020 we tagged and tracked 4 male and 9 female goshawks. Captures were conducted during the early breeding season using a dho-gaza trap with a live great-horned owl (*Bubo virginianus*) as a lure (Bloom et al. 2007). Goshawks were fitted with 14-gram solar-powered GPS-UHF tags (Ecotone Telmetry brand, Harrier model) with an additional VHF tag, attached via backpack-style harness. Tags were programmed to take a location point every 15 minutes and to download data to a base station when within range (approximately 100 m from the station). Base stations were placed beneath or above nests and tags checked for proximity to the station every 15 minutes.

We were able to retrieve data from 10 out of 13 birds, collecting location data from 3 to 73 (mean 37.89 26.69 standard deviation) days of the breeding season (20 April - 15 September; Table 2.1). Tracked birds provided 45 - 2964 location points (mean 837.78 923) with an average of 31.03 ( 62.28) locations per bird per day. Over the study period we observed only one probable mortality. I estimated breeding season home ranges and core-use areas using 95% minimum convex polygons (MCPs) and 50% MCPs, respectively. The mean breeding season home range was 2008.89 ha but male home ranges were far larger than female home ranges (male mean = 4409.16 1408.38, n = 4; female mean = 829.13 1816.72, n = 6; *t* = -3.5, df = 7.68, *P* = 0.01). Male core-use areas were also larger than female core-use areas, but not significantly so (male mean = 851.51 508.29; female mean = 151.87 368.85; *t* = -2.37, df = 5.1, *P* = 0.06). Female home ranges and core-use areas were smaller due to the significantly higher amount of time females spent near the nest (*t* = -3.32, df = 6.9, *P* = 0.01). Males also traveled further from the nest than females. The mean furthest distance from the nest a male traveled was 7.05 ( 1.76) km, while on average females only ventured 2.86 ( 2.02) km from the nest (*t* = -3.32, df = 6.9, *P* = 0.01). As the breeding season progressed, the length of time spent away from the nest increased noticeably for males but less so for females. Home ranges were rarely circular, but rather shaped by geographic constraints such as coastlines or mountains peaks (see Figures 2.2 and 2.3). Within home ranges, kernel density estimates show habitat use is not even across a male’s territory. Instead, there are clusters of activity around areas which are likely high-quality foraging habitat.

We encountered several challenges over the course of the three-year pilot. First, the location data we obtained were biased toward females. Females are more aggressive near the nest than males and so are more likely to be captured when using the dho-gaza trapping method. Data from female tags downloaded more frequently onto the base stations than data from male tags because of the large amount of time females spent near the nest, where the base stations were located. Consequently, we collected far more location data on females than males, which offered relatively little insight into foraging habitat use since males provide most of the food during the breeding season. Second, we were unable to retrieve data from some tagged birds. Several birds were detected via the VHF transmitter but could not be relocated with sufficient precision to download data from the UHF tag. As a result, we could not retrieve data from the winter or subsequent breeding season. Our inability to relocate birds is likely due to a combination of the limited range of the VHF tags and the difficult topography of our study area, compounded by the birds’ failure to return to known breeding areas. Finally, technical malfunctions resulted in no data downloads for two birds, too many location points for one birds, and too few location points for many others. Future work should consider more powerful VHF tags for easier relocation and an alternate-days duty cycle to reduce the number of missed locations.

Despite these setbacks, the pilot study provided insight into goshawk movement and habitat use, with relevance to goshawk management. The location data we were able to retrieve, although less than anticipated, was of much higher resolution than VHF data and much higher accuracy than satellite data and may therefore be uniquely well-suited to studies of foraging habitat selection. The high fidelity of females to the nest area confirms the importance of protected buffers around nests to prevent the disturbance of habitat critical for breeding females and fledglings. However, the large distances traveled by males and the irregular shape of their home ranges shows that circular buffers based on estimates of mean home range size are not good approximations of true space use. Areas used extensively by males usually fall outside the nest area and are not be captured by current nesting habitat protections. Preliminary inspection of movement data indicates goshawks readily crossed narrow barriers such as roads, rivers, and powerline cuts, and sometimes appeared to use these features for travel or foraging. On the other hand, goshawks seemed to generally route around larger barriers such as lakes or clearcuts. This suggests managed areas around nests should be tailored to the amount and configuration of suitable foraging habitat present in the surrounding landscape, and that any timber harvest within the foraging area should prioritize the preservation of connectivity between patches of high-quality foraging habitat. However, a great deal of additional research is needed to confirm and refine these suggestions, particularly regarding the characteristics of suitable and high-quality foraging habitat.

## 1.3 Management implications of goshawk diet

Climate change is one of the largest and most difficult to anticipate threats facing biodiversity (Bellard et al. 2012). The current understanding of how climate change will impact goshawks in coastal British Columbia is largely speculative (Agency 2018). Although I found no evidence of a link between the degree of dietary specialization and goshawk productivity, the level of specialization I observed and findings from other studies suggest goshawks in my study area are highly dependent on tree squirrels for successful reproduction. Notably, Ethier (1999) found goshawk productivity on Vancouver Island to be significantly correlated with red squirrel abundance. Tree squirrels are themselves highly dependent on conifer seeds and their abundance varies with the size of the annual cone crop (Smith 1970). Seed production is cyclical, but may be increased by higher temperatures and inhibited by drought (Boucher et al. 2020). As the climate warms and drought risk rises, climate-driven changes in seed production may cascade upward through prey abundance to impact goshawk populations in coastal British Columbia. Significantly more work is needed to understand the relationship between prey abundance, the buffering ability of alternate prey, and goshawk productivity, but my results provide an important starting point for incorporating climate change into goshawk management.

Wildlife management, whether founded on a single-species or ecosystem-based approach, generally centers around species, subspecies, or unique populations at risk of extinction. My thesis examines a single population of goshawks on the south coast of British Columbia which is currently classified as part of the subspecies *laingi*. The precise range of *laingi* has never been entirely clear, but recent genetic evidence indicates the Haida Gwaii population is highly unique and distinct from other putative *laingi* populations (Geraldes et al. (2018)). My results suggest a strong ecological similarity between goshawks within my study area, Vancouver Island, and Haida Gwaii, where goshawks are also highly dependent on tree squirrels (COSEWIC 2013). The diet of these populations stands in contrast to others in temperate rainforest ecosystems which are currently considered *laingi*, such as the Olympic Peninsula or Southeast Alaska, where goshawks consume mainly birds. Goshawks in coastal British Columbia may therefore be ecologically similar to each other, and ecologically distinct from other populations, regardless of their genetic relationship. The ecological similarity of these populations supports the strategy used by the Northern Goshawk Recovery Team to delineate the boundaries of the *laingi* range, which relies more on ecosystem mapping than genetics (Team 2008).

Rooting management in ecosystems, rather than individual species, has been a success–albeit a conditional one–for forest conservation in the United States. Ecosystem-based management has also been applied in the temperate rainforests of British Columbia. In the early 2000s an ecosystem-based management plan, which includes the northern goshawk as a focal species, was developed for the Great Bear Rainforest on the northern coast of British Columbia (Price et al. 2009). My work provides some of the habitat-specific ecological information needed to broaden existing single-species goshawk management, or even to incorporate goshawks as a focal species in future ecosystem-based management. While it will be years before the success of Great Bear Rainforest agreement can be assessed, the groundbreaking plan offers a glimpse of the future of forest management in British Columbia–and the role northern goshawks may play in it.

# 2 Figures

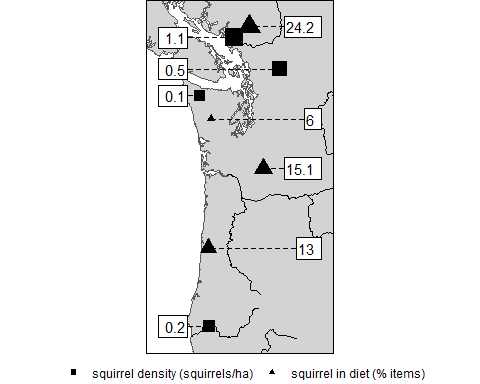


Figure 2.1: Comparison of goshawk dietary specialization and squirrel abundance in the Pacific Northwest. Size of symbol represents relative specialization or abundance. Goshawk diet estimated pellets-and-remains or remains only and measured using counts of items. Tree squirrel abundance estimated from number of individuals/ha. Adapted from Carey et al. (1992), Watson et al. (1998), Thrailkill et al. (2000), Bloxton (2002), Ransome and Sullivan (2003), and this study.

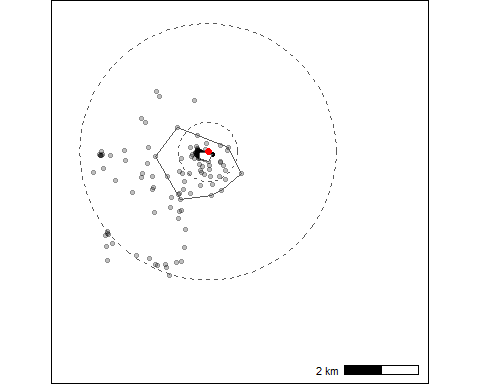


Figure 2.2: Breeding season home range and core-use area of one tagged female goshawk in 2020.

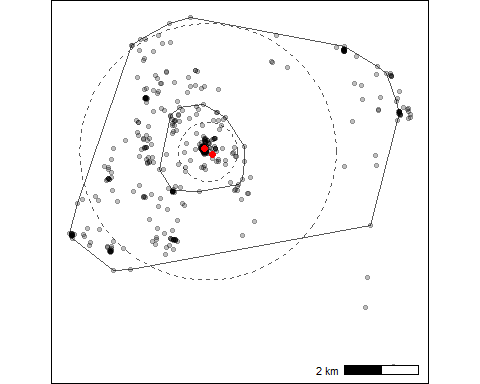


Figure 2.3: Breeding season home range and core-use area of one tagged male goshawk in 2019

Table 2.1: Summary of telemetry data from pilot study

|  | | | Days of data collected | | | Relation to nest | | | Home range (ha) | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sex | ID | Site | first | last | N. days | N. points | Max. distance from nest (m) | % points taken at nest | 50% MCP | 95% MCP | 50% KDE | 95% KDE |
| f | HAR12 | FMT | 2020-06-25 | 2020-06-28 | 3 | 104 | 2.3 | 3.9 | 0.7 | 103.7 | 13 | 152.1 |
| f | HAR03 | GRV | 2020-06-08 | 2020-06-28 | 20 | 2964 | 2.4 | 95.9 | 0 | 0 | 0 | 0 |
| f | HAR10 | MTC | 2019-05-02 | 2019-06-29 | 58 | 315 | 5.5 | 78.4 | 0.3 | 58.9 | 8.7 | 113.4 |
| f | HAR02 | RLK | 2020-06-13 | 2020-07-08 | 25 | 977 | 4 | 72.1 | 5.4 | 280.6 | 12.7 | 267.4 |
| f | HAR08 | TCR | 2019-06-10 | 2019-06-27 | 17 | 45 | 0.1 | 82.2 | 0 | 0.2 | 0 | 0.4 |
| f | AVERAGE | - | - | - | 25 | - | 2.9 | 66.5 | 1.3 | 88.7 | 6.9 | 106.7 |
| m | HAR09 | MTC | 2019-05-02 | 2019-07-02 | 61 | 409 | 4.4 | 2.4 | 530.1 | 2611.2 | 636.3 | 3032.8 |
| m | HAR04 | RLK | 2019-06-22 | 2019-07-08 | 16 | 532 | 7.8 | 9 | 423 | 4441.1 | 662.3 | 4407.6 |
| m | HAR05 | SKA | 2019-06-23 | 2019-09-04 | 73 | 1557 | 8 | 0 | 1548.2 | 6052.9 | 1642.2 | 6674.7 |
| m | HAR07 | TCR | 2018-07-08 | 2018-09-14 | 68 | 637 | 8 | 0 | 904.8 | 4531.4 | 850.6 | 5263.1 |
| m | AVERAGE | - | - | - | 54 | - | 7 | 2.9 | 851.5 | 4409.2 | 947.9 | 4844.5 |

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