Climate Change Impacts in Alpine Meadows: Environmental Factors Correlated with the Decline of the Olympic Marmot (*Marmota olympus*) Population in Olympic National Park, Washington State

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ABSTRACT

Climate Change Impacts in Alpine Meadows:
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Maia Murphy-Williams

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Climate change is rapidly altering the environmental template globally, and detrimentally impacting the structure and function of both plant and animal communities locally. Endemic and high alpine species are especially vulnerable to these changes because of climate change impacts on the persistence of suitable habitat distribution and availability. The endemic Olympic marmot (*Marmota olympus*) population of Olympic National Park (ONP) has declined by ~50% in the past 30 years. Because the Olympic marmots are an ecologically important and charismatic species, it is important to determine what meadow conditions are correlated with their persistent occupancy and what conditions contribute to their decreasing population sizes and distribution range. If marmots are to be locally reintroduced into these alpine meadows, understanding what conditions cause marmots to abandon a specific meadow because it is unsuitable for their survival is also important.

A rich data set on Olympic marmot distribution and natural history exists; however, information is currently lacking on the impact of climate change on the meadow conditions that may cause marmot sub-populations to disappear from meadow habitats they have historically occupied. This research project builds on occupancy monitoring and distribution data collected by the ONP- led marmot monitoring citizen science project and focused primarily on understanding

which meadow characteristics were correlated to high marmot occupancy rates. The overarching research questions were: 1) Why are marmots disappearing from some meadows but not others? and 2) Specifically, are there certain habitat characteristics, or a range/threshold within each meadow that are correlated to a meadow's suitability for occupancy by marmots? To address these research questions, an analysis of habitat characteristics was conducted. The following were the primary areas of focus: identification of variables or combination of variables (e.g., elevation, aspect, availability of food in meadows, tree encroachment rates into meadows, and predation risk--visual obstruction) that constitute habitat conditions that are correlated with high marmot abundance; and determination of habitat and/or environmental thresholds that may trigger meadow abandonment by marmots. To assess habitat differences between the abandoned meadow habitat units and those that were still occupied, a semi-randomly selected subset of alpine meadows was examined on the eastside of the Olympic mountains. The regression tree approach was used in this study to search for potential thresholds in the measured variables that relate to marmot occupancy. Multi-variant spatial analyses were used to compare the characteristics of meadows that were occupied and not occupied by marmots.

Preferred habitat for marmots included meadows with a high proportion of herbs, grass and shrub as a dominant ground cover type, as well as a total meadow area of 3.5 hectares or larger in size. The highest marmot occupancy rates were found at elevation ranges between 1,676 and 1,829 meters and in meadows that had ~25% or less obstruction of the marmot's view of the meadow (and prospective predators' view of the marmots). This research identified environmental conditions and thresholds at which Olympic marmot subpopulations were more likely to persist and continue to occupy high alpine meadows. This research also established important baseline vegetation data and research ground plots to track habitat changes over time.

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INTRODUCTION

1.1 Changing climates and high alpine ecosystems

As the climate warms, the environmental template will shift, creating novel climatic conditions such as altering precipitation patterns, causing temporal and annual shifts in temperature, and changing resource availability (IPCC 2019, Jia et al. 2019). These shifts will cause both animal and plant community composition and distribution to change in response to the climate-induced variations in ecosystem structures and functions (IPPC 2019). Ongoing research and monitoring efforts must consider these impacts at both the fine scale of the habitat unit and the broader landscape scale, since organisms are influenced at multiple scales throughout their life span for essential resources such as food, nutrients and a safe space for refuge and reproduction. Endemic species are particularly vulnerable to climate mediated habitat shifts because of their limited geographic distribution and narrow environmental conditions in which they evolved (Dirnbock et al. 2011) (Harrison and Noss 2017). As the climate warms, certain habitat conditions may no longer exist for endemic species, like the Olympic marmot, whose range is restricted on the Olympic Peninsula and who depend upon a specific plant community composition to support survival (Thelin et al. 2018).

Climate change is disproportionately impacting high alpine ecosystems. Species inhabiting mountainous, high alpine ecosystems may not be able to shift distribution due to the limited space in higher elevations or northern latitudes as trees encroach upward in elevation (Dirnbock et al. 2011) (Jones et al. 2009). This prevents species from tracking with the climate-change-induced vegetation shifts, and species adapted to colder temperatures may be unable to adapt to the warmer temperatures that may exist at the southern edges of their range (Rumpf et al. 2018). Some vegetative communities are less able to adapt to the new environmental conditions due to some species out-competing them in the new environments. For example, trees are better adapted to multiple environmental conditions (Vogt et al. 2016) and encroach into alpine meadows resulting in the loss of meadows (Butler 1986). This effect is particularly strong in colder ecosystems that depend on seasonal processes, such as snowpack, to maintain a specific threshold of environmental conditions (Woodward et al. 1995). The decrease of annual snowpack in many high alpine areas will increase the dominance by forests and the loss of meadows as tree encroachment continues to occur in these landscapes (Jia et al. 2019). As the climate warms and ecosystems continue to experience novel environmental conditions, it is essential that baseline data is collected, and long-term monitoring programs are implemented (Schindler et al. 2015). This information gathering is particularly important for sensitive, high alpine ecosystems to ensure effective natural resource management practices in the future.

Many disciplines are dedicated to studying how an organism interacts with its surroundings and how it may react to landscape changes. However, the landscape-level approach considers not only how the organism interacts with its environment, but also how the composition and configuration of the landscape predicts organism interaction with it (Turner and Gardner 2015). This type of research is challenging to conduct because of the multiple factors that may determine why a species responds to a disturbance. Frequently, the causal factors are displaced in time and space, so identifying the factors that are important for managers to know in conservation planning is complicated. This research project builds on several decades of research

on the distribution and life history of the Olympic marmot to explore how the changing composition and topology of high alpine marmot meadow habitats may influence the distribution of the declining Olympic marmot sub-populations in Olympic National Park in Washington State.

1.2 Olympic marmot natural history

The Olympic marmot is a gregarious and highly social member of the rodent family. Although closely related to the Vancouver Island marmot (Steppan et al. 2011), the Olympic marmot are endemic to the Olympic Peninsula (Barash 1989), with ~90% of its range falling within Olympic National Park. Marmots dig burrow systems throughout their alpine habitat, using their burrows as shelter from harsh alpine weather, safety from predators, as latrines, nurseries and hibernacula. The Olympic marmot builds a burrow that is distinct from other marmot species—its burrow is large, with a distinctive porch. Habitats are characterized by lush forbs, grasses and roots important to marmot diet. Marmots eat primarily plants—roots, flowers, grasses, sedges and herbivorous plants; however, in rare cases when vegetation is scarce, marmots have been observed eating carrion (Barash 1973). Marmots hibernate through the winter period, which typically lasts for 8 months; they awaken during the spring to gorge themselves on the lush summer vegetation of the Olympic alpine meadows, typically almost doubling in weight by the end of the summer (McCaffery and Happe 2017). These charismatic, house-cat-sized rodents have an unusually slow reproductive rate, with females reaching reproductive maturity at 3-4 years of age, reproducing sometimes every year but primarily every two years, each time with a litter of 1-3 young (Barash 1973, Griffin et al. 2007a).

Alpine and subalpine meadows provide the Olympic marmot food, shelter and opportunity for reproduction; without alpine meadows' current configuration, the Olympic marmot would not survive. They inhabit meadows at elevations between 1,500 and 1,750 meters (Barash 1973). As of 1973, Olympic marmot populations were stable, estimated to be about 2,000 individuals (Barash, 1973). Starting in the 1990's anecdotal reports of habitat decline in the Olympic National Park (ONP) began to surface (Figure 1). Park employees and visitors reported vacant meadow habitat patches where marmots had previously been observed for generations (McCaffery and Happe 2017). This sparked a push within the park to investigate the status of Olympic marmots. Olympic marmots are a species of high conservation concern for the National Park Service (NPS). They have been monitored for decades, with historic occupancy data dating back to 1957 (Figure 1). More recent research found that approximately 50% of previously occupied colonies were abandoned (Griffin 2007). Current monitoring efforts include the ONP marmot monitoring citizen science program, which found that marmot subpopulations are abundant and persistent in the northeastern regions of the park, whereas many historically occupied southeastern meadow habitats no longer have marmots (Griffin et al. 2008) (Map 1). Consequently, we have a clear picture of where marmots have historically persisted, and, based on long-term monitoring, we know where they currently exist and where they have abandoned their meadows. However, why marmots abandon some meadows but persist in occupying others is not known. The research presented in this paper built on previous research conducted by Sue Griffin, Roger Hoffman and Julia Witczuk, who identified suitable marmot habitat and established long-term monitoring protocols (Witczuk et al. 2009, Witczuk et al. 2007, Griffin et al. 2008, Griffin et al. 2010). Also, the continued monitoring efforts by the marmot citizen

science project, led by Patti Happe, has contributed vital information on marmot occupancy trends and habitat utilization. The goal of this current research is to deepen the breadth of knowledge on the Olympic marmots' habitat use, preferences, and distribution in ONP.

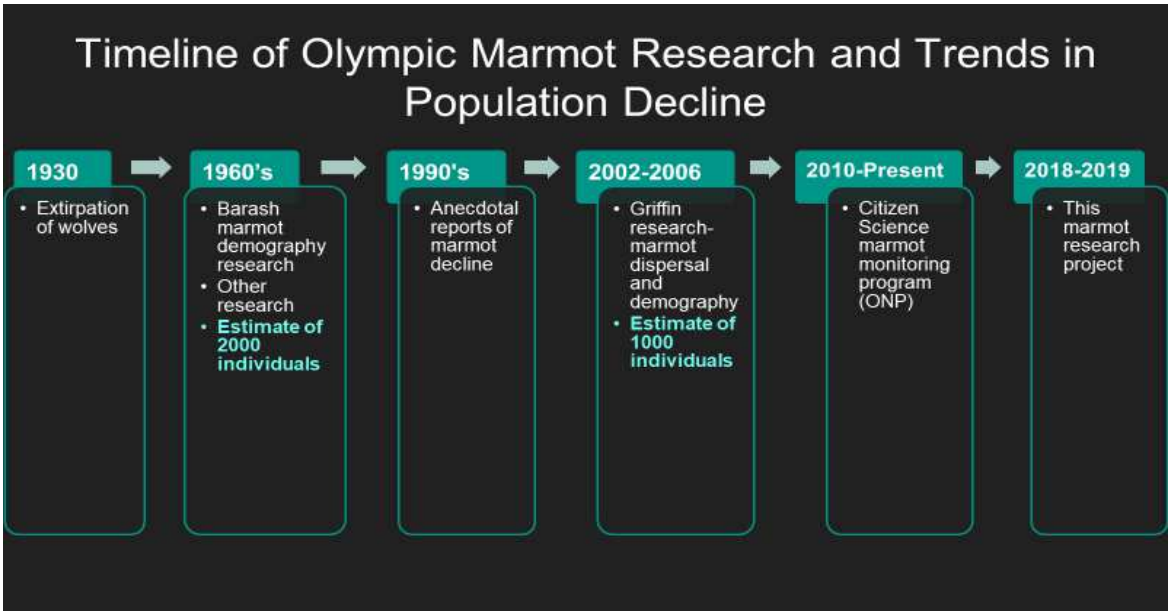
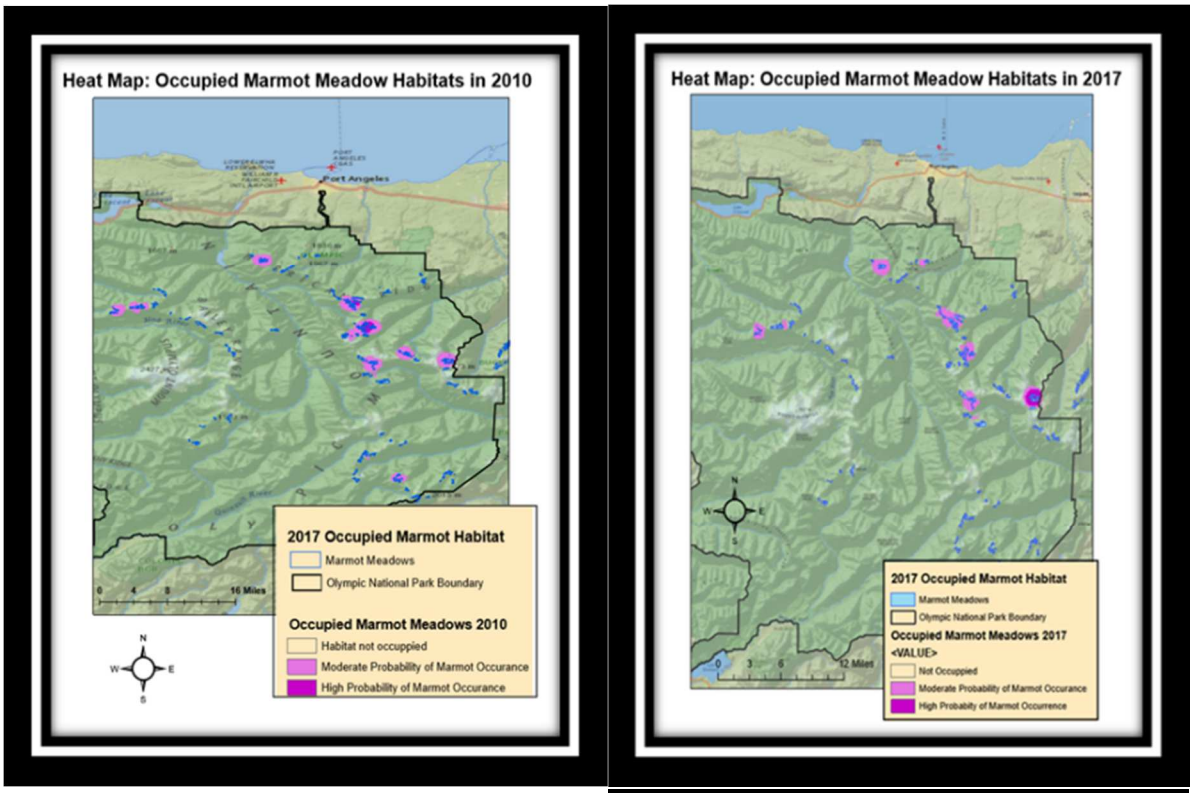


Figure 1. Timeline of Olympic marmot research (Barash 1989, McCaffery and Happe 2017, Griffin 2007, Witczuk 2007).



Map 1. Density map of marmot occupancy, 2010 vs. 2017. Citizen science collected data courtesy of Dr. Patti Happe. Map created by Maia Murphy-Williams.

1.3 Factors influencing marmot decline

Many factors have been implicated in the recent decline of the Olympic marmot population; the primary influences are predation, human influence, and climate change (Griffin 2007, Witczuk 2007) (Figure 2). Previous research focused on predation and human influence as explanations for these declines (Witczuk 2007); however, Griffin (2007) found that direct human influence had little effect on marmot population abundance, the results of which are discussed in further detail in the methods section. Witczuk (2007) found predation by invasive coyotes to be a significant source of marmot decline. However, previous research did not address habitat characteristics and climate impacts on marmot habitat as potential factors in the population decline. This paper focuses on examining the potential impacts of climate change on marmot habitat, the spatial distribution of meadows and which habitat characteristics are correlated with marmot abandonment of certain meadows (Figure 2).

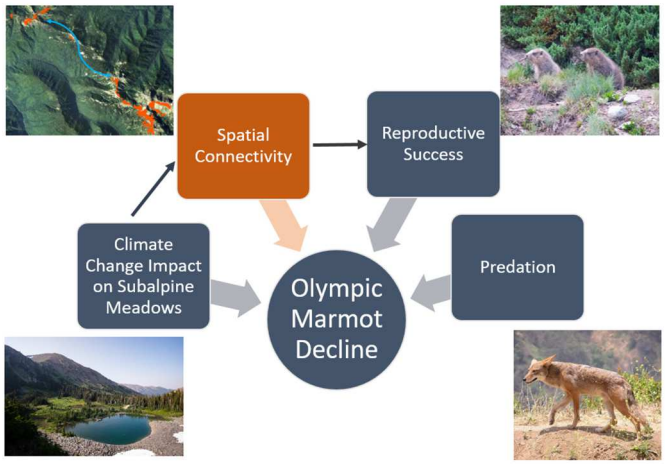


Figure 2. A conceptual diagram of factors influencing marmot decline. (Figure created by Sarah Burrington)

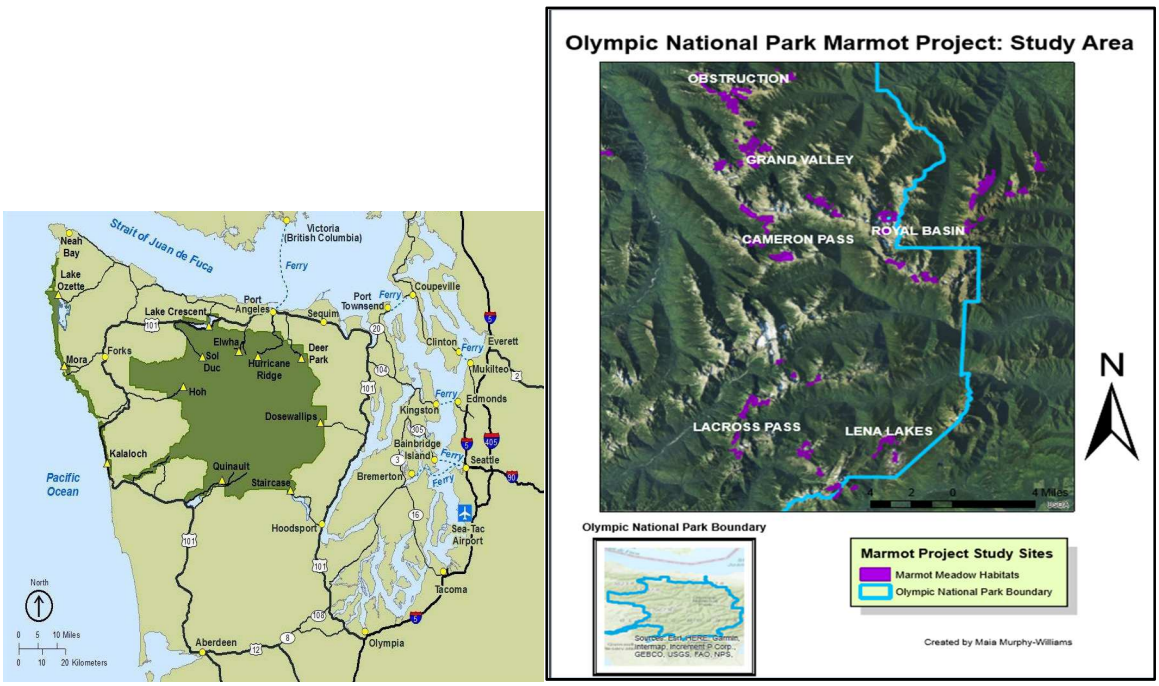
This research focus was designed to identify the within-meadow habitat characteristics and topographic features such as elevation and aspect, which are correlated to high marmot occupancy rates. The overarching research questions were: 1) Why are marmots disappearing from some meadows but not others? and 2) Specifically, are there certain habitat characteristics, or a range/threshold within each meadow that are correlated to a meadow's suitability for occupancy by marmots? Following are the primary areas of focus: identification of variables or combination of variables (e.g., elevation, aspect, availability of food in meadows, tree encroachment rates into meadows, and predation risk--visual obstruction) that constitute habitat conditions that are correlated with high marmot abundance; and determination of habitat and/or environmental thresholds that may trigger meadow abandonment by marmots. The ultimate goal of this research project is to deepen the breadth of knowledge on the Olympic marmot's habitat use/preferences and distribution in Olympic National Park to inform management decisions in the face of climate change.

METHODS

1.4 Site description

The Olympic marmot, found nowhere else in the world, inhabits the alpine meadows and subalpine montane slopes of the Olympic Peninsula, Washington (Barash 1973). Research was conducted in Olympic National Park, located in the northwest corner of Washington State, United States (Map 2). Olympic National Park (ONP) is a federally recognized protected wilderness area; it first received its designation as a protected area in 1897 and was officially established as the Olympic National Park in 1938 (NPS OLYM 2019). The park is currently protecting just under 1 million acres of land, which is home to over 1,000 plant species and a high diversity of animal species (NPS OLYM 2019). Before its designation, the ecologically rich and diverse landscape of the Olympic peninsula was home to many tribal communities, with the first evidence of human occupation dating back to 14,000 years ago. Currently, the Olympic peninsula and the land occupied by ONP are important cultural, medicinal and food gathering lands for the eight contemporary tribes on the Olympic peninsula (Turner et al. 2011).

Olympic National Park is rich in both ecological and topographical diversity. The three most distinct ecosystems are the high alpine (snow- and rock-dominated mountain ranges), the Pacific marine coastal region, and the old-growth temperate rainforests (NPS OLYM 2019). With the park's geographic isolation, diversity in ecosystem types and extreme gradient of environmental conditions, it has a high degree of endism in both plant and animal species. For example, species and subspecies such as the Olympic chipmunk (*Tamias amoenus caurinus)*, the Olympic purple bellflower *(Campanula piperi)* and the Olympic marmot are all found in the Olympics and nowhere else in the world. Conversely, certain species that are ubiquitous in the greater Pacific Northwest montane ecosystems, such as the pika (*Ochotona*), grizzly bear (*Ursus arctos*) and mountain goat (*Oreamnos americanus*), never made it to the Olympics. Although the Olympic marmot exists throughout ONP in alpine areas, previous research indicates that marmots are most abundant on the east side of the Olympics. Because of this, this research study focuses specifically on the high alpine mountain range on the dry, eastern side of the Olympics on a north to south continuum, starting in the north at the Hurricane Ridge visitors center and moving south through Cameron pass to Lena Lakes in the south (Map 3). It should also be noted that this research only focused on sites on the eastside of the Olympics, therefore the results are only applicable on the eastside and may not be valid on the Westside of the Olympics where the environment is much more wet.



Map 2ab. a) Olympic National Park, Washington State, United States (NPS OLYM 2019), and b) study area within Olympic National Park.

1.5 Olympic National Park visitation and its effects on marmots

In 2017, Olympic National Park was the eighth most visited National Park in the country and in 2019 ONP received over 3.4 million visitors (IRMA NPS, n.d.). Because marmots live in beautiful alpine meadows, many marmot colonies are in high visitation areas. Also, since marmots are diurnal and only active during the summer months, there is much overlap with human visitors. For some wildlife species, human presence has been shown to negatively impact and affect the success of a population over time (Johnson et al. 2005). However, previous research (Barash 1989, Griffin 2007) suggests that the presence of humans has not affected Olympic marmot populations or influenced the spatial pattern of marmots abandoning some meadows but not others. Griffin et al. (2008) found few differences in marmot survival rates between high-visitation and low-visitation areas. In fact, the presence of humans may benefit marmots because their presence may discourage predators, though this hypothesis has not been tested in the ONP. Observing marmot activity in the field, we found that they showed little fear of humans and sometimes even approached humans, though this may be a sign of food conditioning in high-use areas. As of now, the evidence suggests that human presence is not a significant factor in marmot decline.

1.6 Detailed description of marmot habitat: Alpine and subalpine ecoregion

The alpine and subalpine vegetation zone that the Olympic marmot inhabits is characterized by woody shrubs, herbaceous vegetation, rock, scree and persistent snow and ice.

The subalpine zone is described as "park-like" in nature. Moving upward in elevation from the mid-lower elevations in the Olympic mountains you will first find dense forests of mature western hemlock (*Tsuga heterophylla*) and Douglas fir (*Pseudotsuga menziesii*). Moving up in elevation the environment becomes harsher, more exposed and less forgiving; the trees get smaller and the composition shifts to higher-elevation tree species such as subalpine fir (*Abies lasiocarpa*), mountain hemlock (*Tsuga mertensiana*) and Alaska yellow cedar (*Cupressus nootkatensis*) (Woodward 1995, Turner et al. 2011). Moving up even further in elevation, tree establishment and growth is limited by harsh, high- elevation conditions such as low temperatures and lack of available precipitation (Frenzel 2003). It is at this point that you reach the subalpine parkland ecozone, with large open meadows characterized by grasses, sedges, flowering plants and woody, low-growing shrubs such as *Vaccinium* spp. and mountain heather *(Phyllodoce empetriformis)*, interspersed with clumps of trees. Continuing to move further up in elevation, beyond the tree line, you find true alpine vegetation, almost no trees, and rocky talus slopes (Turner et al. 2011).

Although mountain peaks are typically the domain of ice, rock and snow, plant communities do exist in these extreme environments. Pojar and MacKinnon (2016) describe the high-elevation habitats as "non-forested plant communities that occupy high elevations." Coastal mountain meadows are described as lush and dominated by herbs. Common species found in these meadows include Sitka valerian (*Valeriana sitchenis)*, subalpine daisy, arctic lupin (*Lupinus arcticus*), arrow leaved-groundsel (*Senecio triangularis*), Indian hellebore, Indian paintbrush, gentians grasses and sedges (Pojar and MacKinnon 2016). In the Olympic mountains specifically, there are some alpine plant species that are found nowhere else in the world such as the Olympic purple bell flower. In late summer, these alpine meadows launch into riotous bloom with a rich diversity of colorful wildflowers. This is the habitat in which the Olympic marmots make their home.

1.7 Site selection and experimental design

The experimental design and execution of this study were constrained by wilderness area restrictions, remote location limitations and heavy smoke conditions during the widespread 2018 wildfires. Research was conducted in a federally protected wilderness area that has strict rules and an extensive permitting process for what equipment and sampling techniques can be used and left in the study sites. Because of this, this research used non-invasive and non-destructive sampling techniques to help protect the alpine ecosystem and preserve wilderness character. No materials were left in the meadows post-sampling or no vegetation samples were collected. All recording was done using photos and GPS locations. In addition, most meadow sites were very remote, often requiring 2-5 days backpacking on foot to reach the survey locations, which also limited our capacity for data collection and experimentation because of weight restrictions in the backcountry. In addition, the summer of 2018 experienced intense smoke conditions from wide-spread forest fires occurring across the Pacific Northwest and British Columbia. The heavy smoke conditions prevented the research team from surveying some marmot meadow habitats in the southern range of the study area that we originally intended to survey and compare with the northern marmot meadow habitats.

This research focused on the east side of the ONP, selecting sites on a north to south continuum, from the Hurricane Ridge in the North to Lena Lakes in the South (Map 2b). Suitable marmot meadow habitat was identified with a GIS-based modeling approach developed by Sue Griffin (2007) as part of her dissertation work. A total of 386 meadow habitat units were identified. Meadow units were numbered and grouped into "meta-clusters" (called "trips" in the citizen science protocol) and then "clusters" of meadow habitat units (see terminology and scale details in Appendix A) (Figure 3). Sites were selected after consultation with local area expert, Dr. Patti Happe, based on location, accessibility and historic marmot presence/absence. For this research, eight meadow clusters were selected and out of those clusters, 56 habitat units (meadow polygons) were randomly selected, using a random number generator, to survey. Specifically, in each cluster, meadows of each designation type (occupied, abandoned and no sign) were selected to survey, if all three types existed within the cluster, beyond that the meadows were selected to survey using a random number generator ranking system to avoid sampling bias.

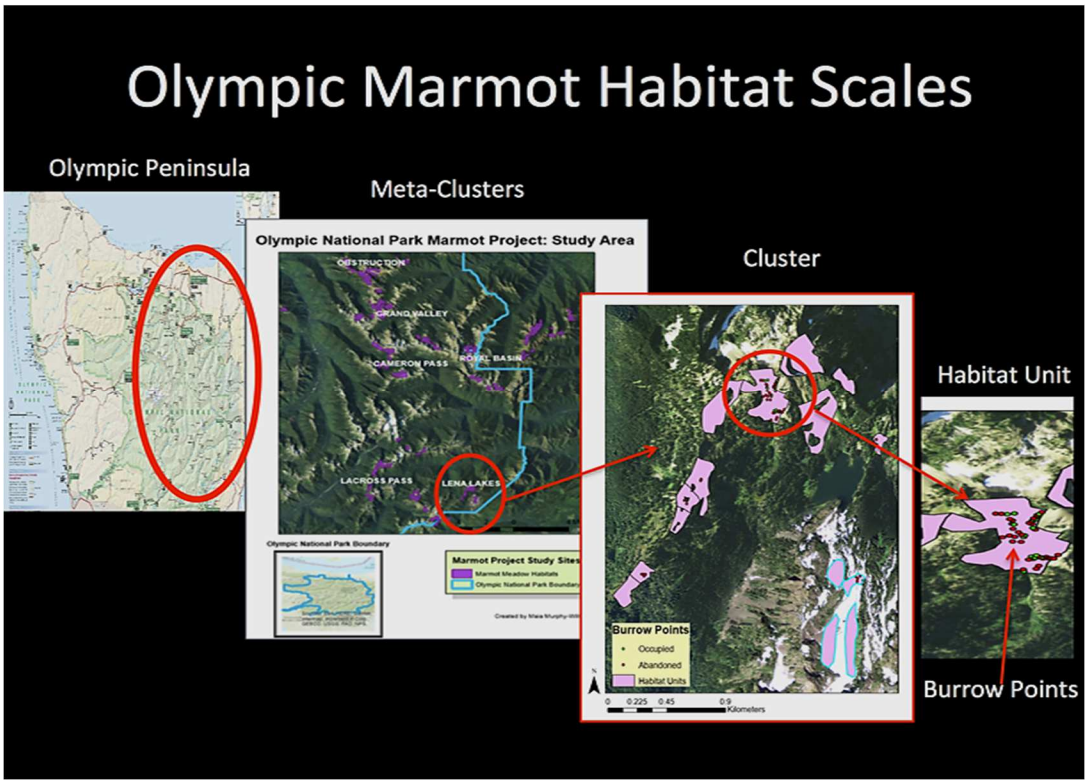


Figure 3. Olympic marmot habitat scale.

1.8 Field protocol

Habitat variables were measured at 56 meadow units throughout the study area (Table 1). The original goal was to sample and compare meadow units in the north where marmots are persisting, to meadow units in the south where they are disappearing. However, due to heavy smoke conditions later in the season, access to some remote southern field sites was not possible. Of these variables, density and abundance of occupied burrows at each meadow site were used as a continuous variable of marmot use/abundance in each area. Using number of occupied burrows as a proxy for total marmot count allowed us to visit each meadow unit only once and at any

time throughout the day, even at times when marmots are not active (middle of the day), and still get an estimate of marmot use of a habitat unit. Number, sex and age of marmots was still recorded at each meadow surveyed but since some meadows were surveyed during marmots active times (generally morning and late afternoon), and some surveyed in the middle of the day when marmots are typically sleeping in the burrows to avoid the hot conditions outside, we cannot accurately compare using this metric. Vegetation data were collected at each marmot meadow habitat unit surveyed in order to procure detailed habitat preference data (Table 1).

Table 1. Overview of environmental characteristics and variables measured at each marmot meadow surveyed.

Response Variables (measures of marmot use of a meadow unit)	**Topographical Variables**	**Tree Encroachment Variables**	**Ground cover proportions (meadow-wide estimates)**
Density occupied burrows per meadow unit (hectare)	Slope	Transect total trees (total trees recorded in meadow transect)	Trees
Abundance of occupied burrows per meadow unit (raw count)	Elevation (m)	Belt trees (trees under 2 m at meadow perimeter)	Shrubs
Meadow status (occupied, abandoned, no sign)	Aspect	Dominant tree species	Herbs and grass
Marmot count	Obstruction (proxy for predation risk)	Other tree species	Bare ground
	Area of meadow unit (hectares)		Rock
	Average plant height (m)		Snow
			Water

1.9 Survey techniques: vegetation data collection within each meadow

Vegetation transects (ground cover proportion measurements)*:* 100-meter vegetation transects were performed in each of the four cardinal directions starting from a designated center point within each habitat unit, determined by the GPS centroid point. Every 10 meters, a 1x1 m quadrat was dropped randomly on the ground. Ground cover percentages were assigned for general ground cover substrate categories such as tree, shrub, bare-ground, rock, herb, grass,

lichen, tree, little, water and snow (See supplementary materials for details). In addition, average plant height and three dominant plant species were recorded at each quadrat. This process was repeated for every 10 m along the transect until the transect reached 100 m or the edge of the meadow, whichever came first (Figure 4). Data were later aggregated to obtain overall percent cover proportions for the whole meadow unit.

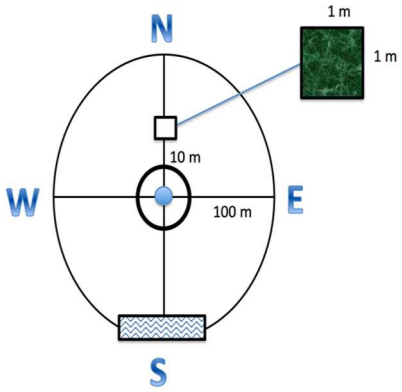


Figure 4. Diagram of basic study design of vegetation transects.

Tree encroachment: Tree encroachment was measured by counting the number of seedlings with heights less than or equal to 1 m in a belt transect at the end of each transect or at the edge of the meadow (Figure 4, perpendicular to the end of the transect). Belt transects were 10 x 20 m rectangular plots at the edge of the meadow. Photos were taken facing the forest, and seedling species were also recorded.

Predation risk— obstruction of visibility (percent obstructed): In previous marmot research, the ability of predators to sneak up on marmots undetected was a significant determinant of mortality risk (Blumstein et al. 2006). The more open and unobstructed a meadow was, the more likely a marmot was to spot an approaching predator, let out a warning whistle to other marmots, and avoid death by predation. With this in mind, a study technique was adopted to measure the level of visual obstruction in each marmot meadow, nicknamed "the coyote vs. the marmot." To conduct this, one researcher lowers herself to approximate marmot height (35-45 cm off the ground) with a compass in hand, the other researcher walks out to a distance of 25 m and commences to walk in a circle (using a GPS unit to maintain the 25 m distance), around the "marmot" researcher in the center. As the "coyote" walks around the circle, the "marmot" observes whether she can see the lower half (below the knees) of the "coyote" at each 45-degree wedge of the 360-degree compass. Each wedge was determined as obstructed or unobstructed from a marmot-height view, which gave an indication of the openness off each habitat unit (Blumstein et al. 2006). The result is a measure of the relative "obstructiveness" of each meadow, a proxy for predation risk.

General habitat composition: General meadow observations and composition were also recorded. The general composition and conditions of the meadow were noted in order to gain a more comprehensive look at the makeup of the entire habitat unit and to later compare these

characteristics to marmot use of each meadow. Variables such as meadow elevation, steepness, weather, temperature, aspect, and other meadow composition details were recorded ((See supplementary materials for details).

Methods for determining marmot use of meadow habitat units: Because of limited time and resources the wilderness area constraints of this project, it was not feasible to obtain an accurate total marmot population estimate for each meadow surveyed. Instead, abundance of occupied burrows was used as a metric for marmot use of a habitat unit. Marmot use of a meadow area was measured by counting the total burrows in a meadow unit, recording if they were occupied, abandoned or long abandoned. We used the established protocol used by the marmot citizen science team to determine the occupancy status of each burrow, looking for signs of current use such as fresh digging, clipped grass, feces and trampled vegetation (See supplementary materials for details and photos). For some burrows, it was unclear whether or not the burrow was abandoned or occupied, or if a burrowing animal besides a marmot made the burrow. To account for this variable, for each burrow designation was accompanied by a confidence level of high, medium or low. In the data analysis, all low confidence burrows were thrown out. In order to determine rates of burrow occupancy for each meadow unit, a GPS waypoint and photo of each burrow was taken. Information such as orientation, slope, marmot sign and status (abandoned, occupied and long abandoned) were recorded. To obtain a proxy for abundance of marmots in the occupied burrows for each meadow unit, the number of occupied burrows were counted for each meadow unit. Marmot usage of each meadow was also measured by counting marmots seen during the survey and recording their age-class and sex. Another way in which marmot abundance/use of a habitat unit was measured, was to determine the density of occupied burrows in a meadow unit, which was found by dividing the total number of occupied burrows by the total area (in hectors) of the habitat unit. This approach allows us to go beyond the previously used binary occupancy modeling of simply occupied vs. abandoned, adding more detail to how marmots are using each meadow unit.

1.10 Data management and statistical analysis

All data were collected by hand and recorded in the field on paper. Data were then entered into a Microsoft Access database created for this project. After data were entered, a different person (whoever didn't originally enter the data) did quality control checks on the data entered, cross-referencing all data with the original data sheet to verify correctness. After data were entered into the Access database, data analysis was conducted by doing query searches on aspects of the data, extracting a CSV file and reading it into R for further statistical analysis. The non-parametric, Krustal-Wallis one-analysis of variance sum-rank test was also conducted to test for significant differences in groups. Although the Krustal-wallis has low statistical power, it was selected as a test of variance because our data satisfied the assumption of a non-normal distribution and independent variables. All statistical analyses of the data were evaluated in R (v2.14.1) (2011) and significance was accepted at $\alpha \leq 0.05$. ESRI ARC GIS was used for all geographic data analysis and processing.

Regression-tree prediction model: When collating data from multiple meadows, the marmot abundance and meadow characteristic relationships may not be immediately apparent using

standard multivariate regression models. Therefore, this study used a multivariate statistical method that utilizes a binary division of sample populations to create tree-like regression models (Therneau et al. 2011) to determine the correlations and thresholds of marmot habitat preferences. Since binary regression trees are a non-parametric technique, they do not suffer from linear regression requirements for normalized distributions, and the initial distribution of the data can be used without the constraints of traditional transformation of any non-normal data (Lemon 2003).

The binary regression-tree statistical method was used as the conceptual framework to identify significant splits within the compiled dataset. The binary regression-tree statistical tree method revealed relationships between multiple variables within the data that might have been overlooked using other analytic techniques. This approach was chosen to easily convey results of the statistical model and quickly identify significant splits in a complex dataset. Continuing development and wide use of this statistical method—not just within the environmental sciences but within health sciences, social sciences, statistics, computer science and other fields—speaks to its general acceptance as an exploratory regression method.

To build a regression tree, the sample population was split into two distinct groups based on an identified significant division of the data by choosing one of the predictive factors. This process was then applied again, treating each new group as its own distinct entity and finding the next set of variables that best divides the input population into another two new groups for each initial grouping. The process was carried out continually or recursively until a minimum size was reached or a subgroup could no longer be significantly subdivided (Therneau et al. 2011). It can be said that each successive split adds a new level that isolates each node, making it resistant to multi-collinearity among the predictor variables (Loh 2006).

The model's relative error was used to assess and ensure that a regression was not over-fitted to the data. Regression trees with a relative error close to zero produce a good prediction while a relative error around, or greater than, one produces a poorer prediction (Cukjati et al. 2001). The number of nodes or splits to be used within the regression tree is determined by choosing a complexity parameter that minimizes the cross-validation prediction error. The complexity parameter may increase as additional splits are introduced to the fitted tree. This value is expressed within the RPART library (Therneau and Atkinson 2011) using the **printcp** command, which will print a table showing the distinct complexity parameter, the number of splits and the associated cross-validation error (Everitt and Torsten 2010). Classification and regression trees are non-parametric with no assumptions made about the underlying distribution of the predictor variables (Lewis 2000; Tittonell et al. 2008).

RESULTS

1.11 Within-meadow comparison of vegetation and topographical variables

Habitat variables and marmot use were measured at 56 meadow units sampled throughout the study area (Table 1), with the goal of identifying which variables were correlated with high marmot abundance or abandonment of a meadow. The relationship between marmot use and habitat variables was examined using two indices— density of occupied burrows and number of occupied burrows (Figure 5). The two response variables are highly correlated with each other, which is to be expected because they measure (and are a proxy for) the same thing-–marmot use of a meadow habitat (Figure 5). Two habitat variables were also highly correlated: saplings in transect and number of trees in belt transect. Total number of occupied burrows in a meadow unit was positively correlated with the area of the meadow habitat unit, meaning that the larger the meadow, the higher the number of occupied burrows will be (Figure 5). There was a strong negative correlation between number of occupied burrows (measure of marmot use) and percent obstruction; as the amount of obstruction in a meadow unit increased, the number of occupied burrows per meadow unit decreased (Significant at a 95% confidence interval according to parson's correlation coefficient table, df = 55).The other variables were insignificant at a 95% confidence. In addition, there were significant, positive correlations between the number of saplings measured in the transect and meadow area, elevation and meadow area, plant height and tree height. The significant negative correlations are between plant height and elevation, meaning that as meadows increase in elevation, the average height of plants decreases. The same effect is seen for tree height, with smaller trees occurring at higher elevations. It should also be noted that this research only focused on sites on the eastside of the Olympics, therefore the results are only applicable on the eastside and may not be valid on the Westside of the Olympics.

LEGEND	
Density of occupied burrows per meadow unit	DNSTY
Total occupied burrows (abundance)	ABND
Area of Meadow Habitat Unit (hectares)	AREA
Elevation (meters)	ELVN
Level of Obstruction in Meadow Unit	OBST
Plant Height (meters)	PLNT
Number of Saplings in Meadow Transect	TREET
Number of Trees in Belt Transect	TREEB
Tree Height (meters)	TREEH

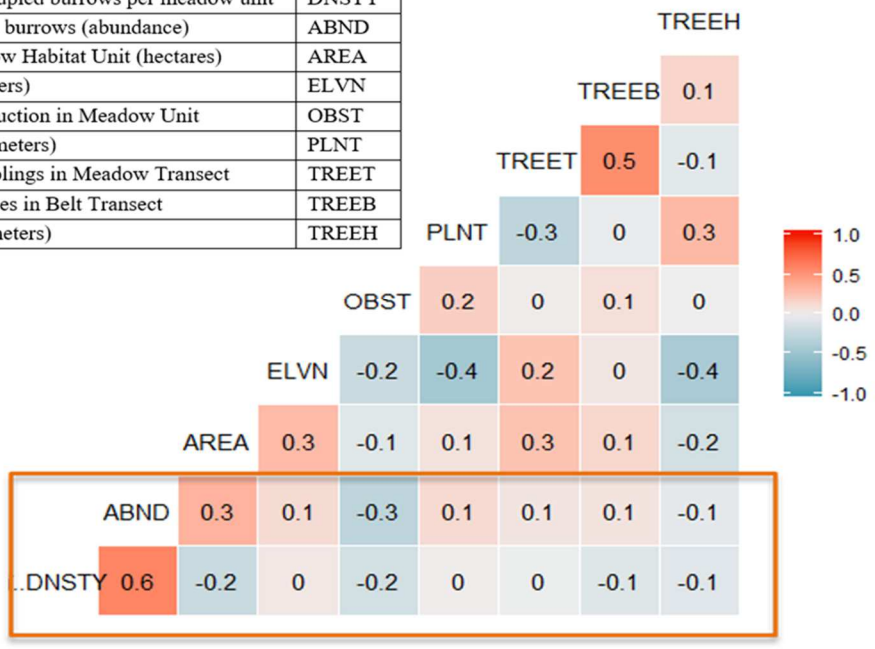


Figure 5. This correlation matrix shows all continuous, numerical topographical parameters recorded in each meadow unit and their correlation coefficient values compared with each other and with the response variable: abundance of occupied marmot burrows and density of occupied marmot burrows, used as a proxy for marmot use of a meadow unit (emphasized with the red box).

Correlations between percentages of ground cover types, averaged across the meadow unit, are shown in Figure 6. This figure shows the correlation coefficient values (r^2) for the meadow-wide ground cover percentage estimations for each meadow unit. Each variable is compared to occupied burrow abundance and to density of occupied burrows per meadow. When comparing to total occupied burrows (our proxy for marmot abundance), the most significant positive correlation is with shrubs, with herb and grass being a close second. There is also a strong negative correlation with rock, trees, bare ground, snow and water. Among the predictor variables, there is a strong positive correlation between snow and rock. There are also quite a few significant negative correlations, the most notable is -0.7 between rock and herbs and grass, this indicates that with increased abundance of rock, there's a decrease in herbs and grass.

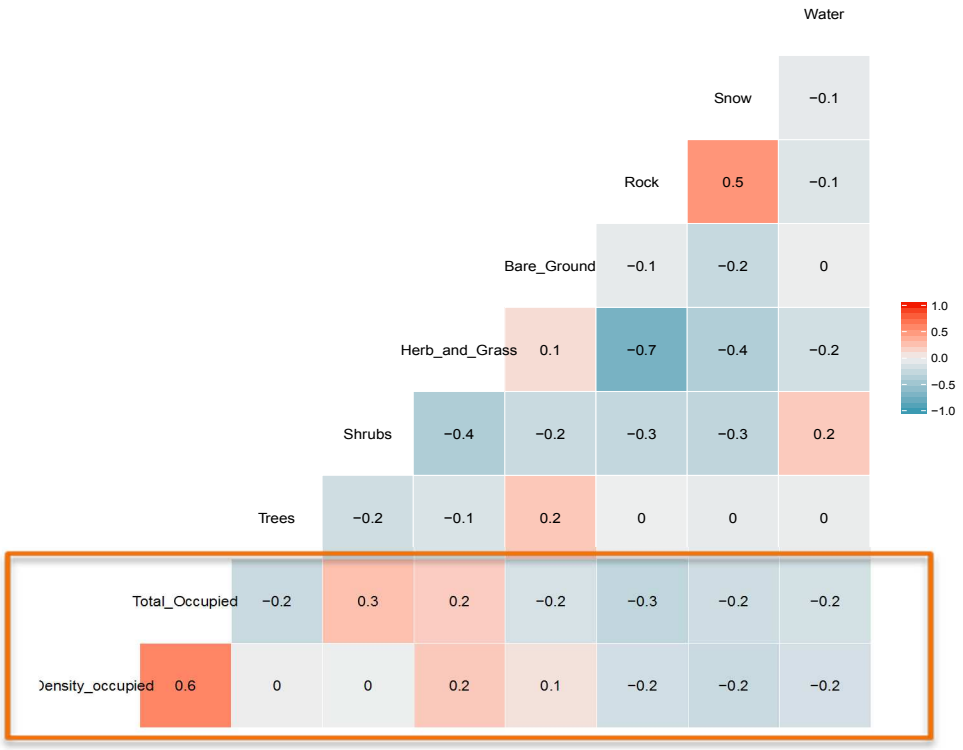


Figure 6. This matrix shows parson's correlation coefficient values (95% significance) for ground cover percentages averaged across meadow units (independent variables) and compared to measures of marmot abundance, total occupied burrows in meadow unit and density of occupied burrows per meadow unit (dependent variables), emphasized with the red rectangle.

1.12 Exploring relationships between habitat variables and marmot abundance

In addition to correlation matrices, each variable was individually graphed against the response variables to check for any non-linear relationships that may not be picked up by the correlation coefficients or linear regressions. The variable of elevation of the meadow in meters (Figure 7) had a potentially curvilinear shape to the distribution. Greater numbers of occupied burrows were generally found at higher elevations, whereas meadows with no sign of significant marmot activity were found at lower elevations. For example, meadows with a high number of occupied burrows tended to be clustered between 1676 and 1828 meters in elevation, suggesting a range of elevations where marmots are most prevalent.

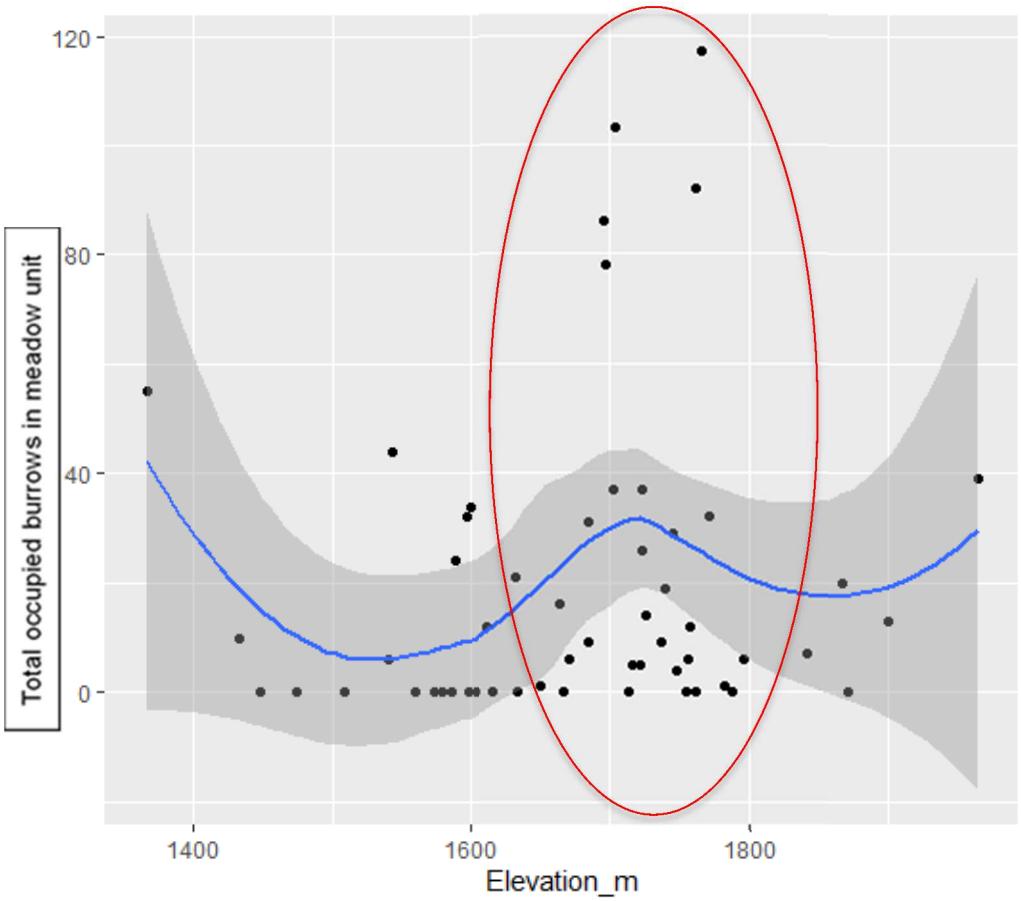


Figure 7. Elevation (m) of marmot meadows compared to response variable, total number of occupied burrows per meadow unit.

1.13 Categorical variables: slope, aspect and percent obstructed

Categorical variables measured in the field but not added to correlation matrix were also analyzed: Slope and Aspect (see Figure 8). Meadows with high numbers of occupied burrows are primarily northeast facing, with some southwest facing but with a high degree of variance. Also, meadows with low numbers of occupied burrows also have a strong negative trend for meadows facing southeast and west (Figure 8). The non-parametric, Krustal-Wallis one-analysis of

variance sum-rank test was conducted to test for significant differences in groups. When comparing occupied burrows to slope, the p-value was 0.833, meaning we accept the null hypothesis at 95% confidence and conclude that there is no significant difference between degrees of slope. When comparing occupied burrows to aspect, the p-value was 0.355, meaning we accept the null hypothesis and conclude that there is no statistically significant difference between meadow aspects. Kristal-Wallis tests were also calculated for aspect and slope with density of occupied burrows as the response variable. P-values were above 0.05 and therefore no significant difference was found. Level of obstruction was also tested and found a p-value above 0.05 show no statistical difference among sample groups.

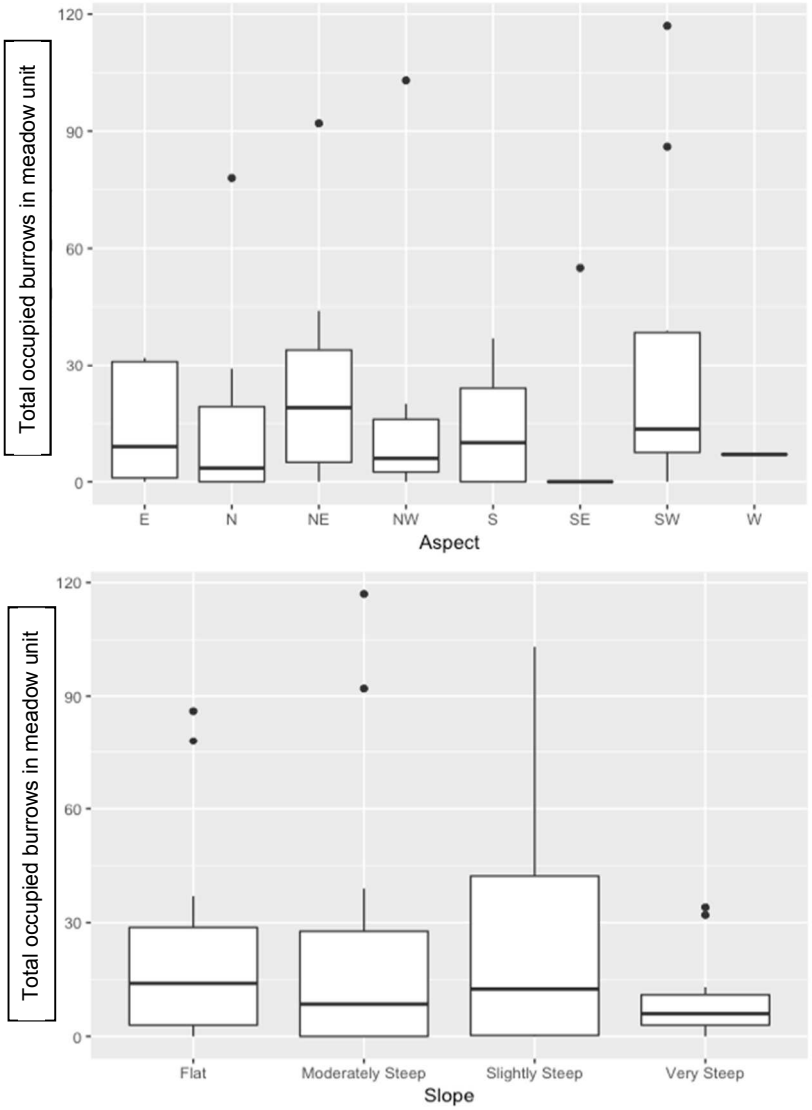


Figure 8. Variables aspect (top) and slope (bottom) compared to total occupied burrows in each meadow unit.

Trends with the obstruction variable (measure of predation risk) and marmot occupancy are shown in Figure 9, with interesting results. A logistic trend in the data is shown with low occupancy in highly obstructed meadows and medium occupancy in unobstructed meadows. The

highest occupancy by a large margin is seen with meadows that are 25% obstructed, indicating marmots prefer meadows that are somewhat visually obstructed but not too much so.

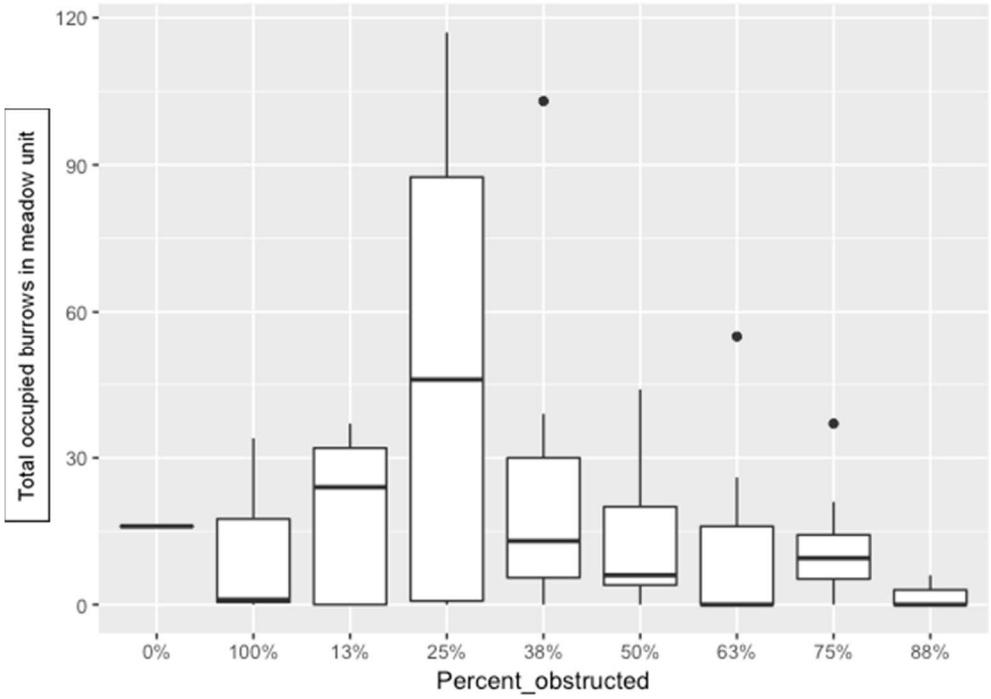


Figure 9. Obstruction variable compared with grand total occupancy.

1.14 Meadow-wide ground cover percentages

We estimated cover of trees, shrubs, herbs/grass, water, snow, bare-ground and rock in each meadow unit, with the total of the categories adding up to 100%. Exploratory data analysis showed that rock, trees, shrub and herbs/grass were most correlated with marmot abundance (Table 1). For rock, there is a slight negative trend for abundance of marmots, with most high-abundance meadows found in the range of 0-20% rock ground cover. For shrubs, there is a slight positive trend, with more high occupied burrows in meadows having a higher percentage of shrub; however there is significant variation. For herbs and grass, no significant trends resulted; however, a sigmoidal relationship of a clump of high-density meadows having 0-25% herbs and grass, and another clump was detected at 50-75% herbs and grass. Finally, trees show a negative trend, with most high marmot abundance meadows found between 0- 0% tree ground cover (Figure 10).

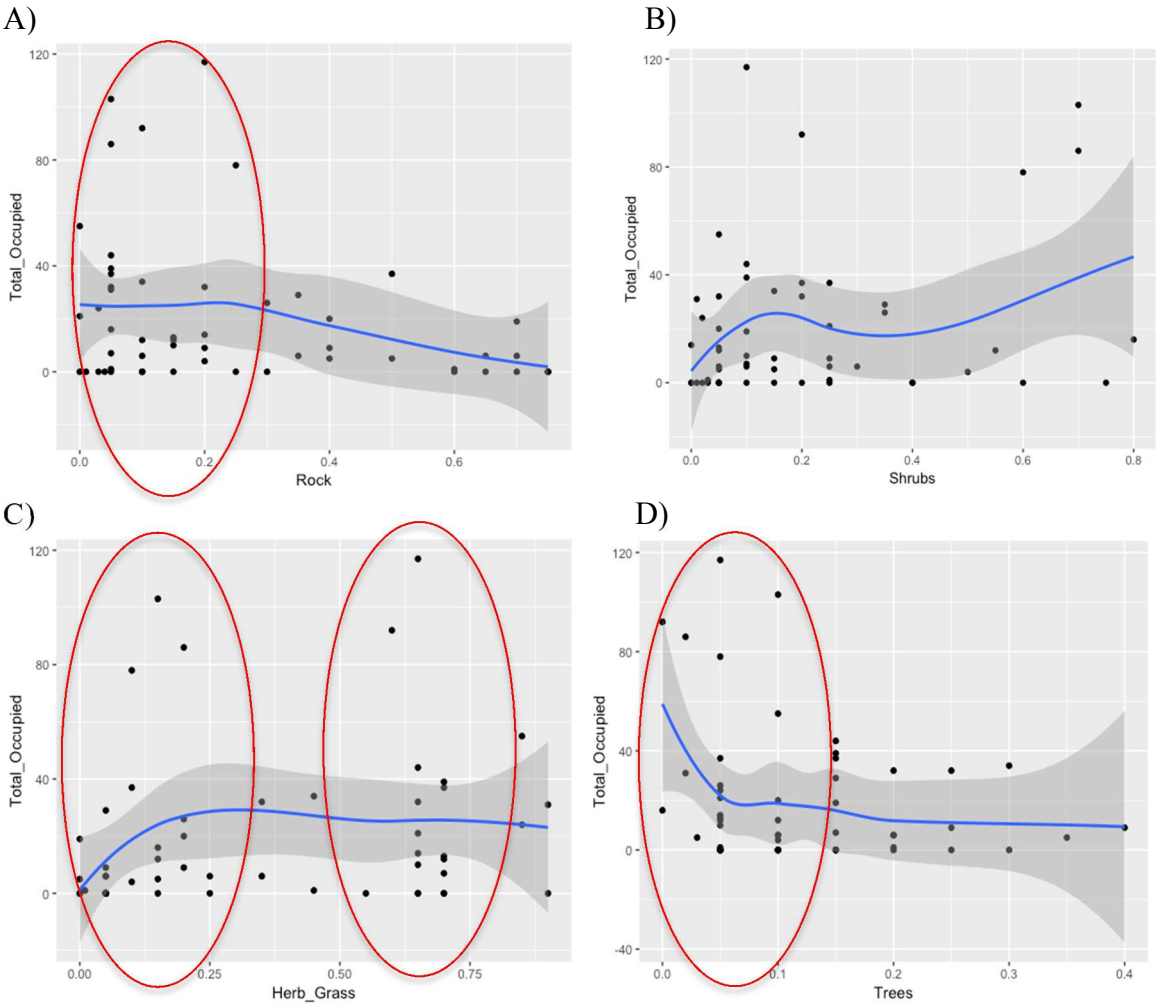


Figure 10 (a-d): Scatter plots for each statistically significant ground cover estimate variable, with the x-axis showing the proportion of each specified ground cover variable in each meadow unit and the y-axis showing the total number of occupied burrows for each meadow unit.

Table 2. Environmental characteristics of marmot meadows surveyed. Response variables include both continuous and categorical metrics for marmot abundance in a meadow unit. Red text indicates variables that are negatively correlated with abundance of occupied marmot burrows; green text indicates variables that are significantly positively correlated with abundance of occupied burrows at 95% significance.

Response variables (measures of marmot use of a meadow unit)	Topographical Variables	Tree Encroachment Variables	Ground cover proportions (meadow-wide estimates)
Density occupied burrows per meadow unit (hectare)	**Slope**	**Transect total trees** (total trees recorded in meadow transect)	Trees
Abundance of occupied burrows per meadow unit (raw count)	**Elevation** (meters)	**Belt trees** (trees under 2 m at meadow perimeter)	Shrubs
Meadow **status** (occupied, abandoned, no sign)	**Aspect**	**Dominant tree species**	Herbs and Grass
Marmot count	**Obstruction** (proxy for predation risk)	Other tree species	Bare Ground
	Area of meadow unit (hectares)		Rock
	Average **plant height** (meters)		Snow
			Water

1.15 CART decision tree analysis: threshold identification

Multiple regression decision trees were created in order to identify the environmental variables most strongly correlated with marmot abundance. Of the two regression trees created, abundance was the response variable in one (Figure 11), and density was the response variable in the other (Figure 12). Based on this regression analysis, the variables that are most predictive of high number of occupied burrows are area, aspect and percent obstructed. The highest marmot use of meadows was found in meadows larger than 3.5 ha in size and around 17.4% obstructed (Figure 11). The CART analysis shows the following variable importance scores. Variables are listed in order of their importance to the response variable: area (25), percent obstructed (23), plant height (12), aspect (12), shrubs (10), elevation (8), herb and grass (4), rock (4), and total trees (1). The regression tree analysis shows that those meadows that have highest marmot occupancy are grouped together and meadows with the lowest occupancy are grouped together based on area of meadow and percent obstructed.

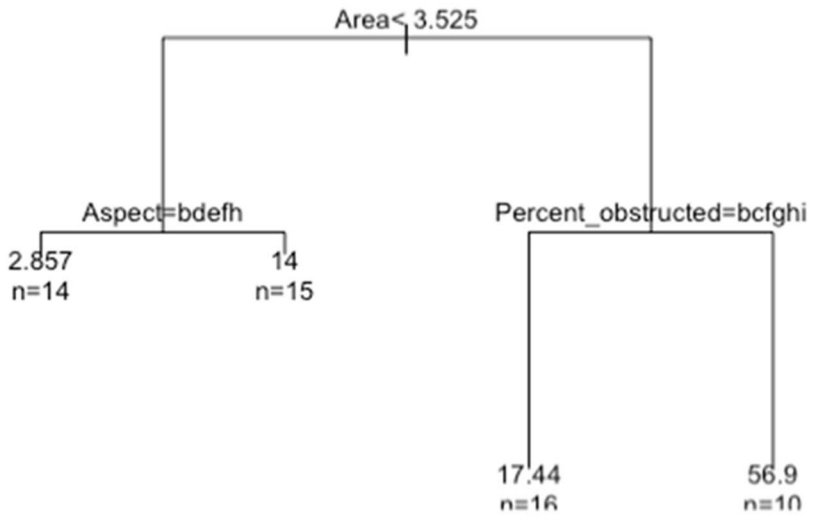


Figure 11. Regression decision tree with total number of occupied burrows as the response variable. According to this analysis, variables that best predict a high number of occupied marmot burrows in a meadow unit were the total area of meadow unit, aspect of meadow unit, and the degree to which the view of the meadow is obstructed.

For the regression tree with density as a response variable, slightly different results where produced (Figure 12). When herb and grass cover is less than 7.5 %, the data are split, and the predicted density of burrows is 1.205. If it's greater than that, we move to the second most significant variable, which is elevation, then meadow area. The highest density predicted (16.1 occupied burrows per meadow unit), was explained by a combination of variables that included herbs and grass, elevation and area of the meadow unit.

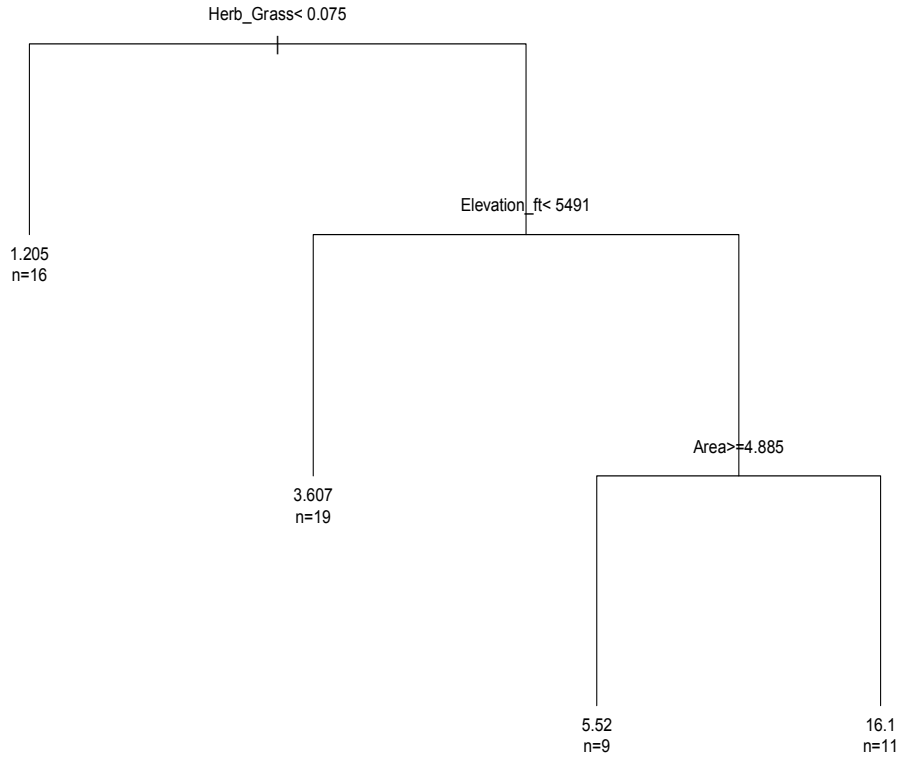


Figure 12. Regression decision tree with density of burrows as the response variable.

DISCUSSION

Climate change is having a proportionally greater effect on cold, sensitive ecosystems, including alpine and subalpine ecosystems (Jia et al. 2019) (Dirnböck et al. 2011). Many native species found at these high elevations are of conservation interest since these they are hypothesized to maintain the resilience of ecosystems (Harrison and Noss 2017). Understanding how their ecological range is being altered due to climate change and how to manage impacts is critical as the climate continues to warm (Beard et al. 2005, Vogt et al. 2012, IPCC 2019). Mountain meadows are also essential for proper ecological functioning of mountain ecotones, maintaining biodiversity and hydrologic regulation through the seasonal release of snow melt into streams (Lubetkin et al. 2017). Acting as "water towers" for lower elevation habitats, alpine meadows provide water throughout the year. Throughout the western U.S., there's evidence of unique flora depending on alpine meadows, and fauna using meadows as a food source and refuge from predators (Thelin 2018).

Reports have documented the decrease in the population density and abundance of Olympic marmots that are mainly found inhabiting high alpine areas in ONP of Washington State (Griffin 2007). In the last 100 years, mountain meadow vegetation has changed as trees are growing into alpine meadows in the Pacific Northwest U.S. (Woodward et al. 1995, Inouye et al. 2000, Frenzel 2003, Lubetkin et al. 2017). There are also many examples of widespread woody plant encroachment into ecologically important alpine and subalpine meadows (Woodward 1995). These vegetative changes are not only influencing the distribution of flora and fauna that depend on these meadows but are also having far-reaching, negative ecological impacts, such as altering the regulatory hydrological services meadows provide along the forest-meadow ecotone (Lubetkin et al. 2017).

1.16 Climate change impacts on marmot habitat: 1) changes in meadow vegetation composition and 2) reduction in landscape-level connectivity

The effects of climate change on marmot habitat in ONP are thought to occur at two spatial scales. The first is at the habitat level when food sources change within the meadow habitat units due to changes in vegetation/habitat composition in the meadows resulting from changing climatic conditions (Figure 13). As the climate warms in alpine and subalpine areas, annual snowpack level is decreasing and summer precipitation is decreasing, causing drought conditions to dramatically increase and produce changes in the timing and patterns of seasonality of weather conditions (Inouye et al. 2000). These changes to the alpine environmental template are leading to changes in meadow vegetation composition. Since marmots depend on specific plant composition in alpine meadows for food, bedding and shelter from predators, changes in vegetation may be a factor in marmot population decline (Figure 13) (Thelin 2018). The second impact of climate change is at the landscape level—the reduction of landscape-level connectivity. Habitat reduction and fragmentation through tree encroachment into alpine meadows may lead to reduction in connectivity. This change to meadow structure through the loss of meadow area, and therefore marmot meadow habitat, may have a large negative effect on marmot meta-population dynamics (Figure 13). However, this is not the focus of this paper and will be discussed in a subsequent paper.

1.17 Main research focus: impact of habitat-level characteristics and topographical difference influencing marmot abandonment of, or persistence in, a habitat unit

Previous research and this current research project indicate that Olympic marmot population decline is being caused by a combination of predation pressure by invasive coyotes (Witczuk 2013) and changes to their sensitive meadow habitat structure and function caused by the changes to the environmental template that affect both connectivity between populations and vegetation composition within the meadow units (Figure 13). This research project focuses specifically on the impact of changing climates on the habitat-level environmental characteristics and topographical differences that influence marmot abandonment of or persistence in a habitat unit. The results show that certain meadow habitat unit characteristics were correlated with marmot abundance, the specifics of which are discussed in the next section. To examine this, we compared vegetation between meadows with active marmot colonies to meadows where marmot colonies historically existed but now have gone locally extinct.

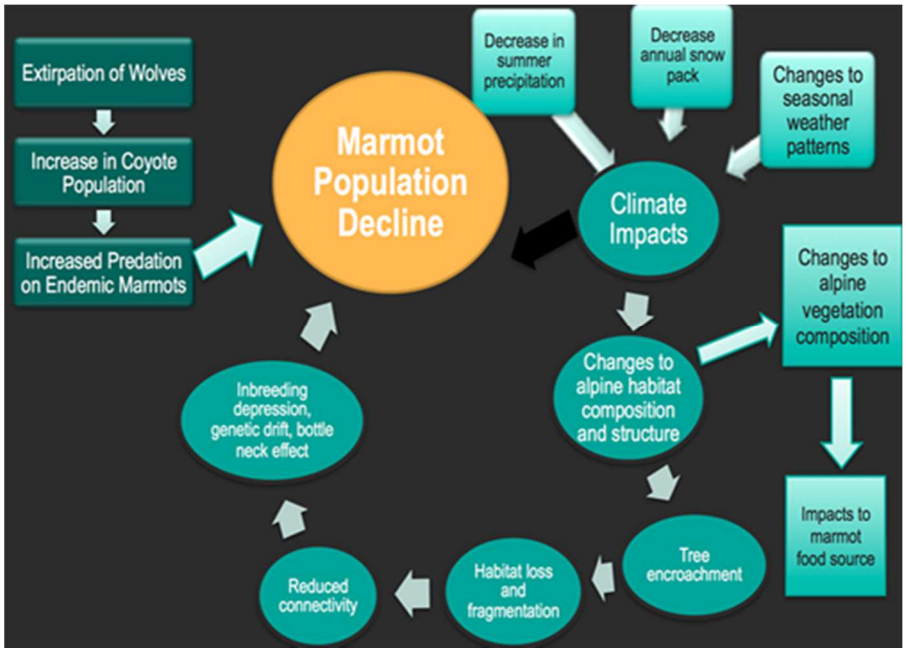


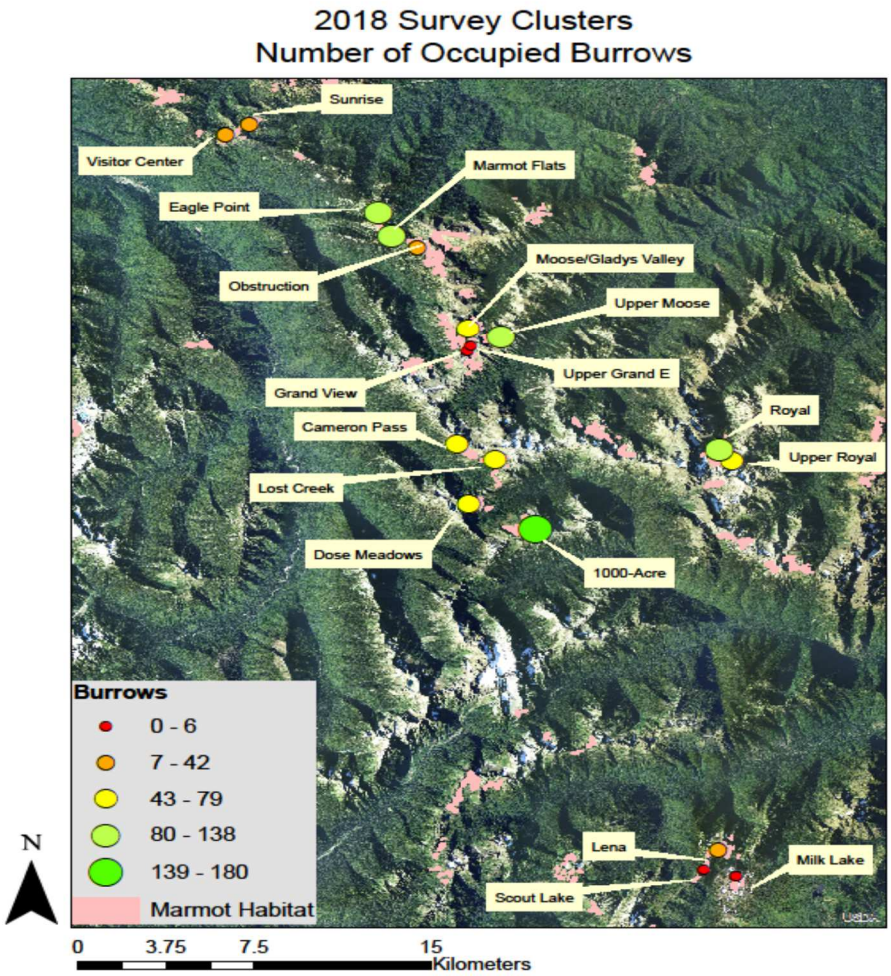
Figure 13. Holistic conceptual diagram describing reasons for Olympic marmot decline.

Although research on Olympic marmot demography has been conducted periodically since 1973 (Barash 1973, Griffin 2007, Witzcuk 2013), scant research has been done on marmot habitat characteristics over time. It's important to establish baseline data to examine if climate-induced changes in alpine meadow characteristics and vegetative composition influence the resilience of marmot colonies. Marmots are ecologically important, altering their environment and possibly changing the soil chemistry and hydrology of the alpine meadows in which they reside (Armitage 2013). Assessing these links and identifying what factors produce thresholds that will reduce marmot survival rates has been challenging due to the paucity of long-term records of their abundance linked to landscape-level records of vegetative community shifts.

Although this effect has yet to be studied, if marmots disappeared from the alpine meadows of the Olympics there may be unforeseen and far-reaching ecological consequences. One of the goals of this current research project was to collect baseline habitat and vegetation data and link that to marmot occupancy patterns.

For this research, a holistic lens was used to determine what causal factors may be correlated with the decline of the Olympic marmot population in ONP. Alpine habitats in ONP contain unique ecosystems and a high degree of endism. Previous research showed that there is a spatial pattern to where Olympic marmots have historically existed and where they currently exist (Griffin et al. 2007). This research attempts to ascertain the underlining ecological reasons for the marmot decline to better manage the species in the future and to contribute to an understanding of how climate change will affect alpine meadows.

The spatial patterning of the decline of the Olympic marmot from 2010 to 2017, based on occupancy data collected by the Olympic Marmot Citizen Science project, is shown on Map 1. This suggests clear spatial patterning of marmot subpopulations disappearing from the south but persisting in the northern parts of the ONP. Subsequently, we collected data on the number of occupied burrows in each meadow surveyed (56 meadow units) in 2018. The 2018 data provide a more nuanced picture of where marmots are thriving and where they are at risk of disappearing compared to the binary occupied/unoccupied metric for marmot abundance provided by the citizen science project. In Map 3, some areas have very high marmot abundance, whereas some do not. Specifically, Lena Lakes in the south has much lower abundance of occupied marmot burrows than Royal Basin or Marmot Flats in the north. In the next section, we will discuss the results and potential reasons for marmot decline. This current study used abundance of occupied marmot burrows as a method of measuring marmot use of a meadow habitat unit.



Map 3. Occupied burrow abundance in each meadow unit surveyed during the 2018 survey.

1.18 Environmental/habitat thresholds: habitat variables correlated with marmot abundance

A lack of knowledge of an ecosystem's pre-novel context (Seastedt et al. 2008) or the interconnectivities of complex drivers of change (Scullion et al. 2014) limits our understanding of ecosystem resilience. How an ecosystem responds to disturbance indicates whether ecological systems have recovered within their historical range of conditions or have shifted to a different state less suitable for an endangered species. Additional knowledge may be needed to identify system parameters that maintain functionality within the "safe operating space" where a stress or disturbance does not trigger the system to cross a threshold of recovery beyond the historical range of variation (Scheffer et al. 2015). This is why it's essential to collect baseline vegetation and habitat data, in order to be able to track change over time. In fact, identifying the safe operating space for ecological systems would probably be even more challenging with the multitude and complexity of connections that exist between them. Identification of thresholds

provides an evidence-based decision-making framework for spatially disparate natural resources and where interconnectivity is crucial for maintaining an endemic species. This research identified the environmental thresholds necessary for Olympic marmot population resiliency. We identified habitat characteristics correlated with marmot abundance vs. marmot abandonment of meadow habitats.

For this study, the following environmental and topographical variables were found to be important for explaining changing patterns in marmot occupancy. Meadows with abundance of marmots (measured through number and density of occupied burrows in each meadow unit) were highly correlated with size (area) of the meadow unit, and with a high percentage of ground cover of shrubs, herbs and grass in each meadow unit. Number of occupied burrows was positively correlated with **area of meadow**, meaning that that larger the meadow, the higher the marmot abundance of occupied burrows. This indicates that a meadow needs to be large enough to sustain a viable marmot population, based on the needs of marmots for adequate food and burrowing conditions that their habitat provides. The decision tree analysis indicates that the ideal meadow size for increased marmot abundance is 3.4 hectares or greater (Figure 11). In addition, the regression analysis and data plotting showed **elevation** to be an important factor in marmot abundance. The highest marmot occupancy rates were found at elevation ranges between 1,676 and 1,829 meters in elevation, showing that this particular elevational band is currently important for marmot abundance. This is important information for natural resource managers—particularly in selecting habitats for local marmot reintroduction.

Ground cover proportion measurements were also taken at each meadow site. When comparing marmot abundance to ground cover proportions, a strong, positive correlation was found with high ground cover proportions of **herbs/grass**. Herbs and grass were lumped together because of the difficulty differentiating the two groups from far distances in the field. This result is congruent with previous research on marmot dietary needs: marmots depend on herbivorous plants and grasses as their primary food source (Griffin 2007, Barash 1989). This dietary need supports the relationship between a high amount of herbs and grass and greater marmot survival and abundance. In addition, a high ground cover proportion of **shrubs** was positively correlated with marmot abundance. Although marmots do not generally eat shrubs, they may provide important structure for marmot meadows, providing shelter from predators and reducing erosion in alpine meadows.

The results of this study showed that high marmot abundance meadows are negatively correlated with a high ground cover proportion of **rock**. The negative correlation with high amounts of rock in a meadow suggests the more rock found in a meadow, the less herbs and grasses are able to grow in the same meadow. However, this is an interesting finding because other marmot species, such as the Hoary marmot (*Marmota caligata*) and the yellow-bellied marmot (*Marmota flaviventris*) depend on large, rocky substrate to dig their burrows in because it prevents ground-digging predators from excavating their burrows (Griffin 2007). In contrast, it appears that, for the Olympic marmots, the risk of burrow excavation by predators is not as great of a threat as lack of edible vegetation. The Olympics do not have burrowing predators such as badgers or wolverines, so excavation is less of a threat. Marmot abundance in a meadow is more correlated with high amounts of herbs and grass and negatively correlated with amount of rock. The results also showed a strong negative correlation between marmot abundance and **percent obstruction (i.e., predation risk)**, meaning as the degree of obstruction in a meadow unit

increases, occupied burrow abundance decreases. In fact, further data analysis showed a left-skewed Gaussian trend with the highest marmot abundance in meadows with a 25% obstructed view (Figure 9). These findings are congruent with previous research on the importance of predation in marmot decline (Witczuk 2007, Blumstein et al. 2006) and will be discussed further in the following paragraphs.

The Olympic marmot, characterized as naïve and slow moving, has many predators in the Olympics such as the Golden eagle, bobcat and cougar (Griffin 2007). However, these species co-evolved, and marmots adapted to deal with native predators effectively. They employed strategies such as digging burrows and living in colonies in which they warn each other of approaching predators by vocalizations. Some other research also argues that marmots are not often eaten by ONP native predators due to the abundance of other food sources (Witczuk 2007). However, since the 1930's, there has been a new predator in the Olympics, the generalist, invasive and highly successful coyote. In the early 1900's, predator control led to the extirpation of the wolf in Washington State, including within ONP. Without the competition from wolves, invasive coyotes arrived in the Olympics. Predation on the Olympic marmot by coyotes has been shown in previous research to be a significant factor in marmot decline (Figure 1) (Witczuk et al. 2013, Griffin et al. 2008). Witczuk et al (2013) found that for all scat sampled that contained marmot remains, 85% of them confirmed coyotes as the predator. Among other lines of evidence, they concluded that, as an invasive generalist, coyotes appeared to be the primary terrestrial predator of the endemic Olympic marmot. Griffin (2007) also reported predation to be a significant factor in marmot decline.

Returning to the findings of this research, data analysis of the obstruction variable in comparison to marmot abundance shows that the ideal level of obstructedness in a meadow should be around 25% (Figure 9). This means that the meadow should have some visual obstruction but not more than 25% of the view from the marmot's perspective. This finding makes sense because if there was no visual obstruction at all the meadow would provide no shelter or opportunities for marmots to hide from predators. However, if the meadow is more than 25% visually obstructed, the meadow may be too obstructed for marmots to notice the approach of a predator, giving predators a plethora of opportunities to sneak up on their unsuspecting marmot prey. This finding is similar to a study in Colorado on the yellow-bellied marmot *(Marmota flaviventris*), which found that environmental variables associated with visibility and safety (obstruction of meadow) determined whether or not a site was occupied by marmots better than environmental variables associated with food (Blumstein et al. 2005). The study also found that the level of obstruction in the meadow was a strong predictor of long-term population persistence among the marmot population (Blumstein et al. 2005). This highlights the importance of visibility and safety in marmot meadow habitats as a determinant of long-term success of marmot populations and should be taken into consideration when managing the Olympic marmot.

Overall, the results identified factors producing thresholds of vulnerability and where marmot populations would persist. The preferred habitat for marmots includes: meadows with a high proportion of herbs, grass and shrub as a dominant ground cover type as well as a total meadow area 3.5 ha or larger in size. Rock as a ground cover type was negatively correlated with high marmot occupancy as well as visual obstruction levels over 25%. In addition, the highest marmot occupancy rates were found at elevation ranges between 1,676 and 1,829 meters in

elevation. These results suggest that food availability (dominant ground cover type), risk of predation (obstruction) and elevation are the most important factors in predicting marmot abundance in a habitat unit, although additional research is recommended.

1.19 Loss of meadows but not marmots due to tree encroachment

The climate change-induced increase in temperatures in the alpine areas is encouraging the in-growth of trees into meadows, reducing the area of meadows dominated by herbs and grasses (Inouye et al. 2000, IPCC 2019, Jia et al. 2019). One hypothesis for marmot decline is the loss of meadows caused by tree encroachment in alpine meadow habitats that reduces connectivity between meadows. This is reducing dispersal capability for meadow species such as the Olympic marmot. Tree encroachment, as a habitat characteristic, was measured, but found not to be correlated to marmot abundance in a meadow unit at this time. Tree encroachment into each meadow unit was measured in two ways—total number of trees counted in the vegetation transect and the number of trees less than 2 meters tall counted at the edge of each transect (edge of the meadow unit) (Table 1). Dominant tree species were also recorded, with subalpine fir being by far the most abundant, while mountain hemlock and Alaska yellow cedar were also present. Although at this time there was no correlation between amount of tree encroachment and marmot abandonment of meadows, there is evidence that in the future, as the climate warms and trees grow, encroachment may become more of an issue for the Olympic marmot as it is for other alpine meadow communities (Lubetkin et al. 2017). The seedling growth may also eventually become an important factor for the loss of meadows but currently, marmots are being impacted by other factors and are not yet being impacted by in-growth of trees into their meadows. This is important information to keep in mind for natural resource managers in the long term as alpine trees grow very slowly.

Additional factors may also be important in the future. This research suggested that habitat characteristics such as topographical variables (e.g., slope, aspect) and average plant height were not strongly correlated to marmot abundance (Table 1). However, as the climate warms, topographical variables such as slope and aspect may have an impact on marmot abundance because of their effect on snowpack conditions, which, in turn, affect the vegetation composition and meadow topology of the meadows on which the marmots depend (Armitage 2013). Groundcover proportions that were measured but weren't correlated with marmot abundance were trees, bare ground, snow and water. However, the amount of snow was measured at each meadow throughout the summer period so the comparison between meadows may be unreliable because it was measured in each meadow at different times throughout July and August 2018.

CONCLUSIONS

Climate change impacts are challenging to research since there is a displacement in time and space when a species responds to perturbations and when the impacts are detected. Climate change can cause habitat range shifts across the landscape, sometimes resulting in novel environmental conditions no longer capable of supporting native species (IPCC 2019). To determine possible intervention points to restore, reintroduce or manage a declining species requires knowledge of what triggered ecosystem change. Based on previous research on Olympic marmot population trends and observations of climate impacts in alpine meadows, this study was originally designed to examine the impact of tree encroachment on marmot population decline. However, our findings showed that as of now, tree encroachment does not seem to be the driving causal factor in marmot population decline, although as tree in-growth progresses it may become a significant driver. Instead, this study was able to identify other environmental factors that may better explain the patterns of marmot abandonment of historically occupied meadow habitat units. By focusing on identifying thresholds, it is possible to design enhanced management plans for species of conservation interest that are losing their habitats. Such an approach identifies meadow characteristics that maintain the habitat requirements of marmots within the "safe operating space" they need when faced with climate change as a disturbance (Scheffer et al. 2015). By understanding threshold and range of variation that may trigger marmot meadow abandonment, a more effective conservation plan can be implemented. Identifying thresholds provides an evidence-based decision framework for maintaining marmot populations at this stage of climate change impacts on the high alpine ecosystems.

The goal of this research was to fill the gap in knowledge and develop a list of habitat characteristics and environmental thresholds that are indicative of optimal marmot habitat for the Olympic marmot population in Olympic National Park, Washington State. Marmots are important for maintaining the structure and function of their high alpine meadow ecosystems (Armitage 2013). With this information, managers will be able to make better informed decisions for management of the species. Specifically, managers should be able to 1) potentially identify "at risk" habitat areas on which to focus management and monitoring efforts; and 2) identify optimal marmot habitat patches that may be good candidates for local reintroductions to augment the Olympic marmot population. The data presented in this research provide insight on climate-induced changes occurring in alpine meadows and will hopefully serve as baseline vegetation data for future research.

In summary, high-occupancy meadows are highly correlated with the following variables: area of meadow unit, amount of shrubs, and amount of herbs/grass in the meadow unit. High marmot occupancy meadows are negatively correlated with high levels of obstruction and a large amount of rock as a ground cover proportion. This research suggests thresholds and conditions in which marmot populations are more likely to persist; they seem to prefer meadows that have a high proportion of herbs, grass and shrub as a dominant ground cover type as well as a total meadow area that's 3.45 hectares or larger. Rock as a ground cover type is negatively correlated with high marmot occupancy. Elevation should be between 1,676 and 1,829 meters and obstruction (predation risk) should be around 25%.

1.20 Management recommendations and future research

Although this paper does not focus on landscape-level connectivity and tree encroachment and impacts on the marmot population, these are still important factors that should be researched further. Habitat reduction and fragmentation through tree encroachment into alpine meadows may lead to reduction in landscape level connectivity. This change to meadow structure through the loss of meadow area and therefore marmot meadow habitat through climate change may have a very large effect on marmot meta-population dynamics. Marmots live in high alpine meadow habitats in colonies consisting of 3-20 individuals, sometimes isolated from each other by dense forests. Typically, when marmots reach two to three years of age, they will disperse to other colonies to breed and maintain the population. As trees encroach into alpine meadows, connectivity between alpine meadow habitats could be reduced, restricting the ability of marmots to disperse to other subpopulations. The loss and fragmentation of habitat leading to reduction in dispersal across their range can lead to a variety of genetic issues including genetic drift, the bottle neck effect and inbreeding depression. Although this is not a driving factor of marmot decline as of now, tree encroachment and meadow interconnectivity should be researched and monitored in the future.

In addition, future research will be needed to determine whether climate change is reducing the number and extent of meadows with suitable habitat and climatic conditions required by marmots. This study should be expanded into areas not included in this study to evaluate their suitability for local re-introduction programs for marmots in high alpine meadows. In the future, the baseline vegetation data gathered in this study should be revisited and a follow-up study conducted to see how alpine meadows have changed overtime.

Appendix

Appendix A

Terminology and scale in order of geographic size (to be applied throughout the paper) See Conceptual Diagram 1 (appendix item)

Olympic Peninsula: total range of the Olympic marmot, found only on the Olympic peninsula with 90% of its range found in Olympic National Park

Study Area: The East side of Olympic National Park: from Hurricane Ridge in the North, to Dose Wallops in the South. Surveyed areas include viable alpine and subalpine meadow of elevations higher than 1400 meters (Griffin et al., 2009).

Meta cluster (trip): Clusters of habitat units grouped together based on geographic proximity and accessibility. Meta cluster habitat units are typically less than 1 kilometer apart. They are a Cluster of clusters, and may indicate a subpopulation of marmots. Meta clusters were surveyed at the same time.

Cluster: habitat units grouped together based on close geographic proximity. Usually these are almost completely touching or within 500 meters of other habitat units within the cluster.

Habitat Unit (polygon): Terminology used for each individually designated habitat area. These habitat units consist of meadow or open rocky area and have been previously designated by the Olympic National Park citizen science marmot monitoring project.

Burrow Point: This is the finest scale that the study reaches. Each burrow point is a marmot burrow that has been marked on the GPS with a designated status of occupied (green) or abandoned (red).

Appendix B- Data Sheet 1: General Meadow Sheet (see supplementary materials packet)
Appendix C- Data Sheet 2: Meadow Transect Data Sheet (see supplementary materials packet)
Appendix D- Data Sheet 3: Marmot Burrow Survey Sheet (see supplementary materials packet)
Appendix E- Data Sheet 4: Burrow Mapping Sheet (see supplementary materials packet)
Appendix F- Photos of occupied, abandoned and long abandoned burrows

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