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Influence of geological substrate on mountain goat forage plants in the North Cascades, Washington State

Final Report

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Abstract:

We addressed 3 questions relevant to patterns in abundance of mountain goats in Washington's North Cascades: 1) What are forage preferences of mountain goats during summer? 2) Are abundances of goat forage species predicted by site-specific geological characteristics? and 3) Are indices of nutritional quality and digestibility of 2 preferred goat forage species (*Carex spectabilis* and *Polygonum bistortoides*) predicted by these geological characteristics? These questions were motivated by observations that historical abundance of mountain goats in

Washington, accounting for habitats generally documented as suitable for them, was greater in atop some geological substrates than others. Goats ate primarily sedges, secondarily rushes, and made surprisingly little use of grasses. Goats ate a wide variety of forbs, with none showing overwhelming preference, but *Penstemon* spp. and *Polygonum bistortoides* were seemingly favored. Despite their abundance in many landscapes near mountain goat escape terrain, *Vaccinium* spp. were rarely consumed, and other shrubs in Ericaceae avoided entirely. Geological substrate explained only a small proportion of variability in goat forage abundance. Categorized by geological origin, sedges had greater canopy cover atop sedimentary and shale substrates than atop plutonic substrates. Categorized by geochemistry, sedges had greater canopy cover atop sedimentary than atop potassium-feldspar substrates. Sodium-rich substrates generally supported less vegetation than other substrates across all forage categories. Neither nutrients nor digestibility of the 2 focal species were predicted by geological type. Our study suggests that geological substrates in the North Cascades vary slightly in their production of forage plants valued by mountain goats, but do not affect the nutritional quality of 2 key forage plants.

Key words: dietary preference, geological substrate, habitat suitability, mountain goat, North Cascades, nutritional quality, *Oreamnos americanus*, Washington

Mountain goats (*Oreamnos americanus*), the emblematic species of Washington's North Cascades and the primary large mammal of its alpine zones, are estimated to have declined some 70% relative to historic abundance levels (Rice and Gay 2010, WDFW 2014). Because mountain goats recolonize slowly and natural rates of increase are slow, an inter-agency group of stakeholders was organized in 2009 as the North Cascades Mountain Goat Restoration Group (NCMGRG), with the goal of planning and implementing reintroductions where needed. The

NCMGRG identified a number of candidate reintroduction sites, and ranked them based on patch size, proximity to other mountain goat core areas, estimates of previous abundance, implementation logistics, potential conflicts with other land-uses, and a qualitative, expert-opinion assessment of biological capacity. The NCMGRG also completed a quantitative assessment of all past mountain goat reintroductions within North American native range. This work (Harris and Steele 2014) highlighted the fact that reintroductions with larger numbers of seed animals were more likely to succeed than those with fewer, and that habitat quality was likely responsible for most residual variation in success.

Most scientists studying mountain goats (Hamel and Côté 2007, Festa-Bianchet and Côté 2008) have taken the view that although summer habitat selection is critical in that goats must obtain nutrition to support them most of the year in only a few months, goats are catholic with regard to the specific plants they select. Habitat analyses for mountain goats have emphasized proximity to escape terrain, aspect, and seasonality of forage acquisition (Beus 2010; Wells et al. 2011, 2012), but have largely assumed that goat consume the best available forage regardless of forage-class.

GIS-based analyses we conducted have suggested that habitat suitability for mountain goats within the North Cascades may be more heterogeneous than earlier believed. In short, we have developed evidence suggesting that mountain goats do better on habitats overlaying certain types of geological substrates than others. Here, we overview analyses that have generated this hypothesis. We examined a proxy for historical mountain goat abundance: accumulated records of recreational harvest (collected over during 1948-70, when mountain goats were still abundant throughout their native range in Washington, and largely before North Cascades National Park was established), adjusted by size of area. We supplemented this with examination of recent helicopter surveys in both North Cascades National Park, the Mount Baker-Snoqualmie National Forest, and the Gifford Pinchot National Forest (conducted in 2000, 2002, 2012, 2013 and 2014), which showed very similar geographical patterns of relative abundance. (This supplementary data provided confidence that geographic patterns suggested by the historic harvest data were not strongly biased by patterns of access or historic hunting management, but largely reflected overall abundance). These abundance patterns evinced some striking anomalies: In large areas that appeared suitable for mountain goats (based on elevation and topography) but were underlain by specific geologic types, abundance was much lower than atop other geological substrates (Fig. 1). Even allowing for imprecision in definitions and geographic locations of historical harvest, it seems clear that some types produced relatively larger goat populations than others. In particular, geological types summarized into the broad category igneous, common in North Cascades National Park, supported relatively few mountain goats (using harvest as a proxy), whereas relatively more goats were harvested atop other geological substrates.

How geologic substrate might affect goat habitat suitability remains conjectural. One hypothesis is that landforms overlaying plutonic formations are less conducive than others to producing moist meadows that provide nutritious summer forage for goats. Alternatively, nutrient levels of vegetation growing in soil derived from differing bedrock may vary due to substrate chemistry. Littke et al. (2011) found that soil overlaying sedimentary parent material had significantly greater N and C than those atop plutonic formations in Cascade Range Douglas-fir plantations. Morford et al. (2011) also showed similar relationships from parent material, through soil, to plants.

In this study, we build on existing field and remote sensing analyses conducted by Wells et al. (2011,2012) of mountain goat habitat suitability in the North Cascades, by adding 1) analysis of mountain goat diets, as sampled using plant fragments found in feces, 2) additional field plots, and 3) geological substrates, obtained from existing digital sources.

Study area

Following Wells et al. (2012), we defined the study area as high elevations within the Cascade Mountain range within Washington State, extending south from the Canadian border to the Oregon State line along the Columbia River (49° N to 45° 30N, approximately 120° 10’ E to 122 ° 30’ E, Fig. 2). We focused most sampling effort within the northern portion of this large study area. During our 2015 sampling, we restricted our attention to polygons that had previously been mapped by Wells et al. (2011; Table 6) as summer mountain goat habitat.

Methods

Definition and identification of geological substrates

To identify and locate geological substrates, we used the surface geology layer managed by the Washington State Department of Natural Resources Division of Geology and Earth Resources (WDGER 2014). We considered two typologies of geological substrate: one we termed “geological origin”, and one we termed “geochemistry”. Within geological origin, we recognized the categories deposit, plutonic, sedimentary, shale, various, and volcanic. Geochemistry included the same plots for categories deposit, sedimentary, shale, and various. However, within igneous types, we followed http://www.appstate.edu/~abbottrn/rck-id/ignchrt.html, which resulted in sub-types sodium-rich (diorite, andesite), calcium-rich (gabbro, basalt) , potassium-feldspar (e.g., granite, rhyolite, obsidian), and unknown, and within origin type volcanic, we recognized the same 3 subtypes as well as unknown, intermediate, and simply volcanic.

To locate field plots within mapped geological substrates, we mapped feasible ground routes (i.e., hiking trails) that accessed patches of mountain goat habitat (Wells et al., 2011) overlaying each of the common geological types of interest. We established zones of potentially sampled areas for each of the common geological types, ensuring that none was located > 500m from mountain goat escape terrain (i.e., likely to be available to mountain goats, Hamel and Côté 2007), and none was located on slopes > 25º (to maintain field crew safety). We then identified plot centers using ArcGIS ensuring that each was no less than 200 m from a geological substrate boundary (to minimize the chance that either mapping or field error would result in the plot not corresponding to the intended geological type), and had field crews attempt to reach each. At each plot center, field crews established temporary vegetation sampling plots of 5 m radius (~ 247 m^2) using a flexible tape measure to delineate the outer boundary of the plot. We could not always control the selection of plots by other topographic attributes, and instead treated possible influences of slope and aspect (as well as the date of sampling) a posteriori by including these in statistical models.

Presence and abundance of vegetation by species

Following Wells et al. (2012), at each plot we recorded slope, aspect, elevation, and visually estimated the canopy coverage of each species. Crews made visual estimates of the proportion of vegetation consisting of grass (subdivided into the genera *Festuca* and *Poa*, documented as preferred by mountain goats in Washington [Pfitch and Bliss 1985, Fiedler and McKay 1984]), sedge (most of which was *Carex* spp.), rush (primarily *Juncus* and *Luzula* spp.), ericaceous shrubs (shown as avoided by mountain goats in other studies), other shrubs, other forbs, and conifers.

Percent cover of vegetation was always non-normally distributed, with the most common coverage being zero in almost all cases. Such distributions were unlikely to be successfully transformed; rather, we interpreted them as resulting from 2 related but separate processes, one determining whether or not the taxon would be present at all, the other determining the taxon's relative abundance if present. We thus examined relationships between vegetation and geology in a 2-step way: First, we used logistic regression to test associations with plant species presence in the plot. If present, we used conventional linear models to test associations of abundance, defined as the natural logarithm of the relative abundance excluding plots in which the taxa was absent entirely. In both approaches, we included the Julian date of sampling, the elevation of the plot, and the aspect of the plot (defined as the absolute value of the deviation from 180º [due south] in degrees) in all models to account for temporal and site effects other than geological substrate. Statistical analyses were conducted using JMP 11.2.0 (JMP 2013). Due to possibility of erroneous inference arising from multiple unplanned comparisons, we considered associations significant only when $P < 0.01$.

Mountain goat diets

We collected freshly deposited fecal pellets from maternal groups we observed in 2 areas (Ptarmigan Ridge near Mt. Baker, and Three Fingers), combining group that appeared to come from 6-8 animals into a single composite sample. We sampled at Ptarmigan Ridge because recent surveys had indicated the goat population there had recovered to what we considered a healthy density (WDFW 2015); the ease with which we encountered large groups of goats in this area while collecting samples corroborated our surveys. Samples we collected in the Three Fingers area were intended to represent a newly recovering population; this area had few goats in the early 2000s, but surveys since 2013 indicated 100-150 goats in the area. Samples collected in early July 2015 were considered to represent “early summer” diets; samples collected in late August or early September 2015 were considered to represent “late summer” diets. Pellets were placed in paper bags, and analyzed using micro-histological fragment analyses at the Wildlife Habitat Nutrition Laboratory, Washington State University, Pullman, WA. Plants were identified to the finest possible taxon; percent volume was calculated from 100 views on each slide.

We declined to attempt statistical inferences on differences between abundances of plants in goat diets and abundances of those plants on the landscapes (e.g., the significance of proportion used vs. proportion available) for a number of reasons. First, dietary percentages were expressed in relative volume, whereas species-specific abundances were measured in relative cover; we had no way to reformulate vegetation metrics to a biomass basis. Secondly, our vegetation plots were designed to characterize vegetation types (Wells et al. 2011) or, in 2015, vegetation as a function of geological types. Although goat fecal pellets could be associated with these types, we had no way of knowing where the goats producing these pellets actually consumed the vegetation. Thus, we had only an approximate spatial matching of diets with landscapes. Thirdly, differences between forage used and forage available can be informative, but can also be misleading. Although it is reasonable to assume importance and positive selection when a species uncommon on the landscape is common in the diet, the reverse logic may not hold. Animals may elect to spend time where a preferred (or even critically important) plant species is abundant, and if so, there may be little or no difference between use and availability. Instead, we simply report our raw data, and temper our interpretations with the understanding that sampling error may hide true dynamics while suggesting others that have no biological meaning.

Nutritive value of 2 goat forage species by geology

We clipped and collected stems and leaves of 2 species used as forage by mountain goats: *Carex spectabilis* and *Polygonum bistortoides* (Fiedler and McKay 1984, Pfitch and Bliss 1985). Samples were analyzed separately for each location and date for percent crude protein, percent in vitro dry matter digestibility (IVDMD), percent acid detergent fiber (ADF), percent neutral detergent fiber (NDF), acid insoluble ash, and acid determent lignin (ADL; Hamel and Côté, 2007) at the Habitat and Nutrition Laboratory at Washington State University, Pullman, Washington, USA.

We examined linear models with data from both species aggregated, using species as a fixed factor. We investigated possible associations with geological substrate at the same 2 levels of resolution as used in examining species-specific occurrence and abundance: 1) categorized by geologic origin, and 2) geochemistry. To account for temporal and site effects other than geological substrate, we included Julian date, elevation, and aspect in all models. Statistical analyses were conducted using JMP 11.2.0 (JMP 2013).

Results

Site and vegetation characteristics

We visited 504 sites that were quantified in terms of both vegetation and geology. Elevation of sites averaged 1,723 m (SD = 288 m), slopes averaged 28.8° (SD = 13.6), and aspects (defined as absolute difference from due south) averaged 67.9° (SD = 48.0). We found no associations between proportion cover of sedges and elevation, slope, or aspect. However, rushes as group were negatively associated with steepness (slope $\beta = -0.051$, SE = 0.018, t = -

2.82, P = 0.050) and positively associated with northerly aspects (difference from south β = 0.013, SE = 0.005, t = 2.54, P = 0.011). *Vaccinium* spp. shrubs were negatively associated with steepness (slope β = -0.516, SE = 0.112, t = -4.58, P < 0.001) and positively associated with southerly aspect (difference from south β = -0.090, SE = 0.024, t = -3.72, P = 0.0002). In contrast, heather species, while also negatively associated with slope, were positively associated with northerly aspects (difference from south β = 0.189, SE = 0.032, t = 5.99, P < 0.001).

Mountain goat diets

Mountain goats in both sample areas consumed primarily sedges (family Cyperaceae, genus *Carex*), and secondarily rushes (family Juncaceae) during both early and late summer, 2015. A diverse variety of dicots (forbs), grasses, ferns, leaves from shrubs, and mosses rounded out their summer diets. Early summer (July) samples taken from the recovered population near Mt. Baker (Ptarmigan Ridge, Table 1) consisted, on average, of 57.1% from the genus *Carex* (about half of which could be identified as the *C. spectabilis*, the other half could be identified only to genus). An additional 23.1% of these diets consisted of the rushes *Juncus mertensianus* and *Luzula parviflora*. Taken as a group, sedges and rushes constituted > 80% of diets by volume for Ptarmigan Ridge goats. Similarly, July diets of the recovering mountain goat population in the Three Fingers area (Table 2) consisted primarily of *C. spectabilis* (29.2%), other *Carex* spp. (17.1%), *J. mertensianus* (7.8%), and *L. parviflora* (2.9%); i.e., a total of 57.0% in these two forage groups.

Grasses as a category made up only 1.6% of July diets on Ptarmigan Ridge, although constituted 8.2% of July diets for Three Fingers goats (and of these grasses, 72% were from the genus *Poa*). Dicot forbs as a group (consisting of 27 uniquely identified species or genera) constituted 14% of summer diets at Ptarmigan Ridge, and 17.7% at Three Fingers; individually, most were < 1% of diets. The most common dicot forbs in July diets were *Penstemon* spp. (3.9% of diets at Ptarmigan and 0.8% at Three Fingers) and *Polygonum bistortoides* (1.4% at Ptarmigan, and 3.8% at Three Fingers). Ferns (primarily *Pterdium aquilinum* and *Cystopteris fragilis)* constituted 4.2% of July diets at Three Fingers, but were not documented from diets at Ptarmigan Ridge. Despite their abundance on the landscape, vegetation in the family Ericaceae was relatively rare in July goat diets. Leaves and stems from *Vaccinium* spp. together comprised 3.0% of diets at Ptarmigan and 3.3% at Three Fingers. No identifiable fragments from other heather species (e.g., *Phyllodoce* spp. and *Cassiope* spp.) were documented, despite their relative abundance in both study areas (Tables 1, 2).

Early fall diets of goats (in late August at Three Fingers and early September at Ptarmigan Ridge) were largely similar to July diets. At Ptarmigan Ridge, proportion of diets consisting of *Carex* spp. declined slightly (to 47.1%), of rushes increased (from 21.3% to 29.5%), and use of grasses (mostly *Poa* spp.) increased to 5%. At Three Fingers, use of *Carex* spp. increased (to 68.1%), and use of forbs (aggregated as a category) declined to 3.6%. Use of *Vaccinium* spp. declined further in early fall, to 0.8% at Ptarmigan Ridge, and undetected levels at Three Fingers.

Forage plants and site-specific geology

Geological origin — Logistic regression models accounting for Julian date, elevation, and aspect predicted that sedge was more likely (β =1.52, SE = 0.34, P < 0.01) to be present on sedimentary than other types, although predictive power was weak (Fig. 3; r^2 = 0.06). Among plots where sedge was present, geologic origin did not predict its relative abundance. For the sedge species *C. spectabilis*, presence was more likely on shale than other types ($P < 0.01$, $r^2 = 0.07$; Fig. 3). In addition, pairwise comparisons predicted that its presence was more like on sedimentary than plutonic, various, or volcanic types. Among plots where *C. spectabilis* present, geological origin did not predict its abundance. Log odds predicted that heather, like sedge, was more likely to be present on sedimentary than other types ($P < 0.01$, $r^2 = 0.11$). In addition, pairwise comparisons predicted that heather was also more likely to be on plutonic than volcanic substrates ($P < 0.01$). Among plots with heather present, canopy cover of heather was higher on plutonic origins than volcanic origins (Tukey HSD pairwise comparison: percent canopy cover difference = 0.61, SE = 0.19, $t = 3.23$, $P = 0.02$). We found no significant predictors of either presence or abundance of rush, *P. bistortoides*, or *Penstemon* spp. by geologic origin. Figure 3 presents occurrence of each taxon by geologic type unadjusted for covariates. Although rarely encountered ($n = 17$), *Poa alpina* was more abundant on plots were it was documented atop sedimentary than plutonic substrates (5.6% difference, log odds 1.72, SE = 0.6, $P = 0.07$).

Geological type chemistry — Logistic regression models accounting for Julian date, elevation, and aspect predicted that sedge was more likely (log odds $P < 0.01$) to be present on sedimentary than other types (Fig. 4), although predictive power was weak ($R^2 = 0.08$). Additionally, pairwise comparisons predicted that sedge was more likely (log odds $P < 0.01$) to be present on intermediate than on deposit, sodium-rich, and various substrates; sedge was also more likely to be present on type calcium rich than types deposit or various. Among plots where sedge was present, geochemical subtype origin did not further predict its relative abundance. For the sedge *C. spectabilis*, presence was less likely on potassium-feldspar than other types ($P < 0.01$, $R^2 = 0.08$; Fig. 4). Among plots where *C. spectabilis* present, geologic subtype origin did not further predict its abundance. Log odds predicted that heather was less likely to be present on sodium rich substrates than other types ($P < 0.01$, $r^2 = 0.12$). In addition, pairwise comparisons predicted that heather was also more likely ($P < 0.01$) to be present on sedimentary than deposit types. We found no significant predictors of either presence or abundance of rush, *P. bistortoides*, or *Penstemon* spp. by geochemical type. Figure 4 presents occurrence of each taxon by geochemical type unadjusted for covariates.

Nutritive characteristics of two species of mountain goat forage

Crude protein did not differ between the 2 species (*C. spectabilis*, $n = 34$, and *P. bistortoides*, $n = 27$). As expected, crude protein declined with the advance of time through the growing season ($\beta = -0.08$, SE = 0.02, $t = -3.41$, $P = 0.001$); similar phenological dynamics were consistently observed in all models. Crude protein also increased with elevation ($\beta = 0.003$, SE = 0.002, $t = 2.03$, $P = 0.047$). However, we found no significant associations of crude protein with geological substrate at either level of categorization. Similarly to crude protein, IVDMD did not differ between the 2 species, and declined as the season progressed (slope on Julian date = -0.16, SE = 0.04, $t = -2.60$, $P = 0.012$). Neutral detergent fiber was higher in *C. spectabilis* ($\bar{x} = 60.9$) than *P. bistortoides* ($\bar{x} = 41.1$, $t = 16.9$, $P < 0.01$), but was not associated with geological type. Lignin was greater in *P. bistortoides* than *C. spectabilis*, but did not vary with time. We quantified no other associations of nutritive indices with geological substrate.

Discussion

We found that mountain goats in 2 recently recovered populations eat primarily sedges and rushes. Where studied elsewhere, goats in summer have shown a preference for Graminoids (Brandborg 1955, Hibbs 1967; Pfitsch and Bliss 1985, Houston et al. 1994) although in some areas, forbs have been preferred over graminoids (Dailey et al. 1984). Equally noteworthy, we found that these goats make almost no use of species within the family Ericaceae, which likely account for more understory biomass than any other within North Cascades goat habitat (Douglas 1972). It is likely that heathers (primarily *Cassiope mertensiana, Phyllodoce empetriformis,* and *P. glanduliflora*), in addition to being quite fibrous, contain secondary compounds that reduce the nutritional quality otherwise available to goats (Gonzalez-Hernandez et al. 2003; see also McArthur et al. 1993). Villamuelas et al. (2016) found that Pyrenean chamois (*Rupicapra pyreniaca*), closely related to mountain goats, tended to avoid the fibrous plant common heather (*Culluna vulgaris*).

In addition, this study was designed to assess our hypothesis that patterns evident in historic mountain goat abundance that were correlated with underlying geology could be explained on the basis of presence, abundance, or nutritive quality of preferred forage species. We found some indication that sedges, the single most utilized forage class by goats in summer, were more likely to be present on sedimentary than plutonic formations, although effect size was not large and the total variability explained by our best statistical models was weak. However, we failed to find meaningful associations between any nutrient characteristics of the 2 species we sampled and geological substrate. Taken together, our results are suggestive that forage valued by mountain goats is more common on sedimentary and shale than on plutonic geologic origins, and that plutonic formations characterized by potassium-feldspar chemistry were particularly unlikely to support these species. That said, our results also suggest that our hypothesis was inadequate to explain satisfactorily the distributional patterns we'

Sedimentary parent material underlying coniferous forests were found by Littke et al (2011) to have greater nitrogen and carbon content than those of glacial or igneous origins. We were surprised therefore to find no difference in crude protein in our plant sample among any geological types. In contrast, Kranabetter and Banner (2000) found lower nitrogen concentrations in in forest soils atop limestone than schist or gneissic diorite. Unlike Littke et al (2011), we were unable to analyze soils as well as geology; thus we do not know if there were no important differences in the chemical composition among bedrocks we examined, if any differences did not extend to soils, or if differences in soils did not extend to the 2 plant species we sampled. Notable in this regard are the findings of Castle and Neff (2009), who found differences in a number of macro- and micronutrient concentrations in bedrocks, but not in the foliage of either aspen (*Populus tremuloides*) and 2 conifer species examined.

Our results suggest some rationale for mountain goats to do less well on plutonic substrates than sedimentary, shale, or some volcanic geological formations, but likely explain only part of the patterns we observed. Ultimately, studies that combine detailed examination of habitat characteristics with long-term demographic responses will be needed to fully understand patterns in mountain goat population performance (e.g., Garshelis 2000).

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TABLE 1. Diets of mountain goats in the Ptarmigan Ridge area, near Mt. Baker, Washington, 2015 from fecal micro-histological fragment analysis. Shown are dietary proportions of major forage categories for early (column b) and late (column c) summer diets, and percent cover of the same taxa as estimated from vegetation plots in the Ptarmigan Ridge area (column d). Goat diets are expressed in mean percent volume and each contains pellets from ~ 6-8 different animals; vegetation availability metrics are expressed in percent cover (and thus can sum to > 100%); not detected in plots = tr.

Vegetation category	**Early summer mountain goat**	**Late summer mountain goat**	**Early summer canopy cover**
	-------------------- **Diets**	-------------------	
a	*b*	*c*	*d*
	------- Graminoids -------		
Carex spp.	57.1	47.1	13.3
Rushes[1]	23.1	29.5	3.6
Poa spp.	1.2	4.2	tr
Other grasses	0.4	0.8	3.1
	------- Ericaceae shrubs -------		
Vaccinium spp.	3.5	0.8	21.8
Other heathers[2]	0.0	0.0	29.3
	---------- Dicotyledons ---------		
Anemone occidentalis	0.0	0.0	tr
Epilobium angustifolium	0.8	0.0	tr
Erigeron spp.	0.4	0.0	0.3
Fragaria vesca	0.6	1.9	tr
Hieracium gracile	0.4	1.3	1.4
Luetkea pectinata	0.8	0.0	16.2
Lupinus spp.	0.8	0.8	12.1
Penstemon spp.	3.9	0.8	0.6
Phacelia hastata	2.1	1.3	tr
Phlox diffusa	0.0	0.0	5.9
Polygonum bistortoides	1.4	1.3	3.9
Saxifraga spp.	0.2	0.4	1.9

[1] *Juncus* and *Luzula* spp.
[2] *Cassiope* and *Phyllodoce* spp.

TABLE 2. Diets of mountain goats in the Three Fingers area, Washington, 2015 from fecal micro-histological fragment analysis. Shown are dietary proportions of major forage categories for early (column b) and late (column c) summer diets, and percent cover of the same taxa as estimated from vegetation plots in the Three Fingers area (column d). Goat diets are expressed in mean percent volume and each contains pellets from ~ 6-8 different animals. Vegetation availability metrics are expressed in percent cover (and thus can sum to > 100%); not detected in plots = tr.

Vegetation category	**Early summer mountain goat**	**Late summer mountain goat**	**Early summer canopy cover**
	------------------ Diets	**--------------------**	
a	*b*	*c*	*d*
	------------ Graminoids	----------------	
Carex spp.	46.3	68.1	18.6
Rushes[3]	10.7	18.2	1.4
Poa spp.	3.8	3.0	tr
Other grasses	4.3	5.7	10.6
	----------- Ericaceae shrubs	------------	
Vaccinium spp.	4.1	0.0	28.7
Other heathers[4]	0.0	0.0	43.6
	----------- Dicotyledons	----------------	
Anemone occidentalis	3.5	1.0	tr
Epilobium angustifolium	0.0	0.0	tr
Erigeron spp.	0.0	0.2	2.1
Fragaria vesca	0.1	0.4	tr
Hieracium gracile	0.0	0.0	1.9
Luetkea pectinata	0.0	0.0	22.6
Lupinus spp.	0.0	0.0	12.2
Penstemon spp.	0.0	0.0	tr
Phacelia hastata	0.0	0.0	tr
Phlox diffusa	0.0	0.0	1.8
Polygonum bistortoides	3.8	1.7	13.7
Saxifraga spp.	0.0	0.0	tr
Valeriana sitchensis	0.0	0.0	3.2

[3] *Juncus* and *Luzula* spp.
[4] *Cassiope* and *Phyllodoce* spp.

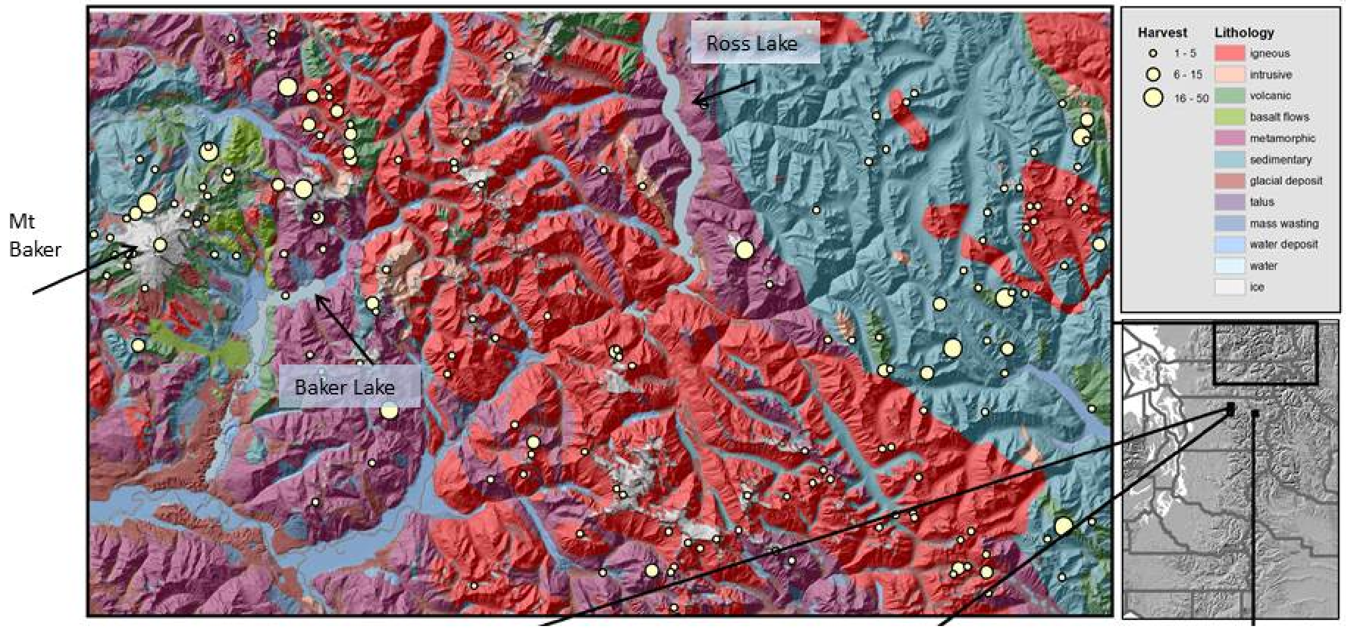


Figure 1. Geological types in the North Cascades region of Washington State, USA, summarized into broad categories, with approximate locations and number of mountain goats harvested during 1948-70 (size of yellow circles illustrates number of goats harvested).

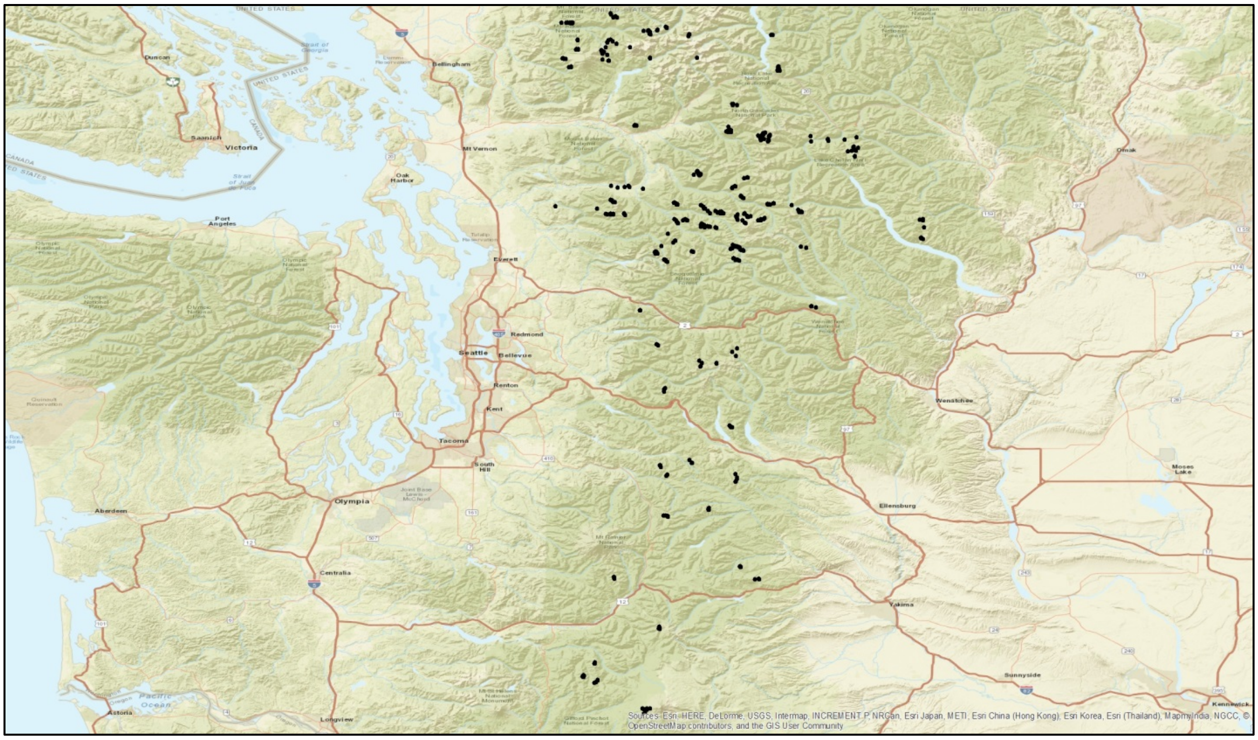
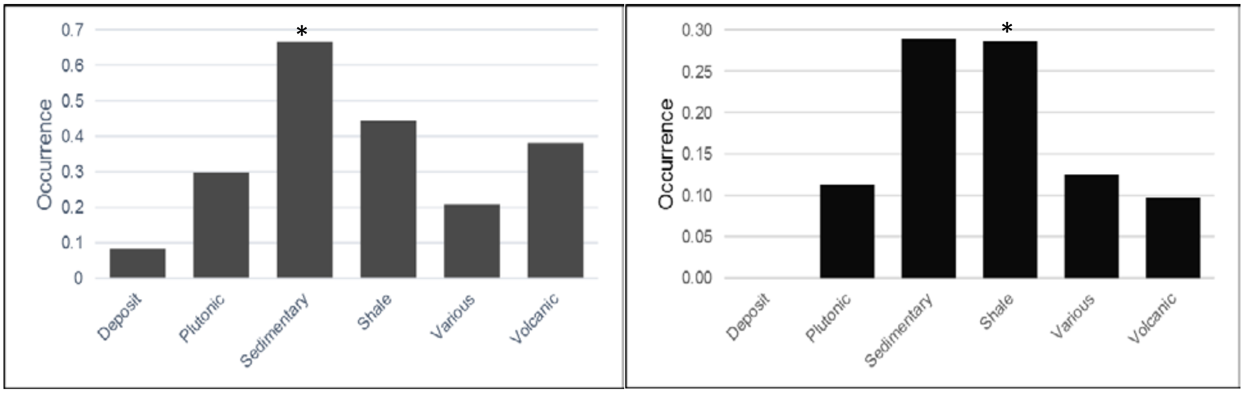


Figure 2. Locations of 504 vegetation plots examined during 2008 and 2009 and used in this study (*n* = 292; Wells et al. 2012), and 2015 (this study, *n* = 212), in the Cascade Mountains of Washington State, USA. Shown are major highways and large cites in Washington.

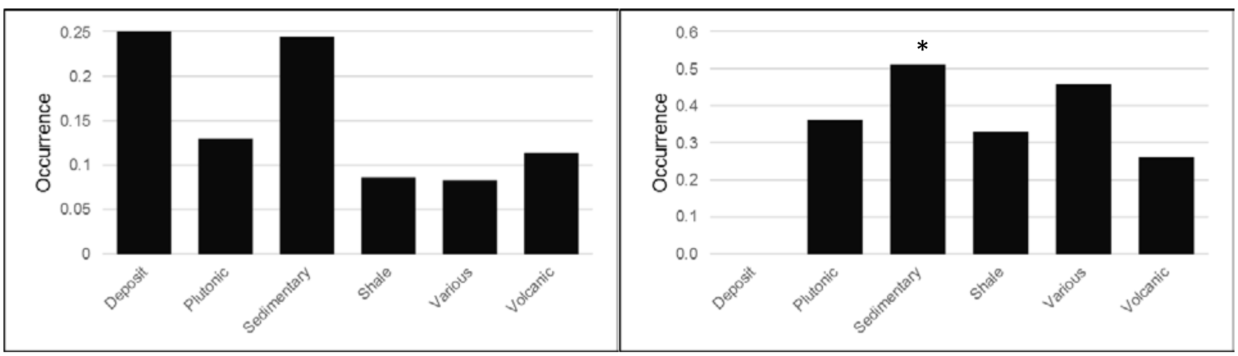
a. Sedge



b. *Carex spectabilis*

c. Rush

d. Heather



e. *Polygonum bistortoides*

f. *Penstemon* spp.

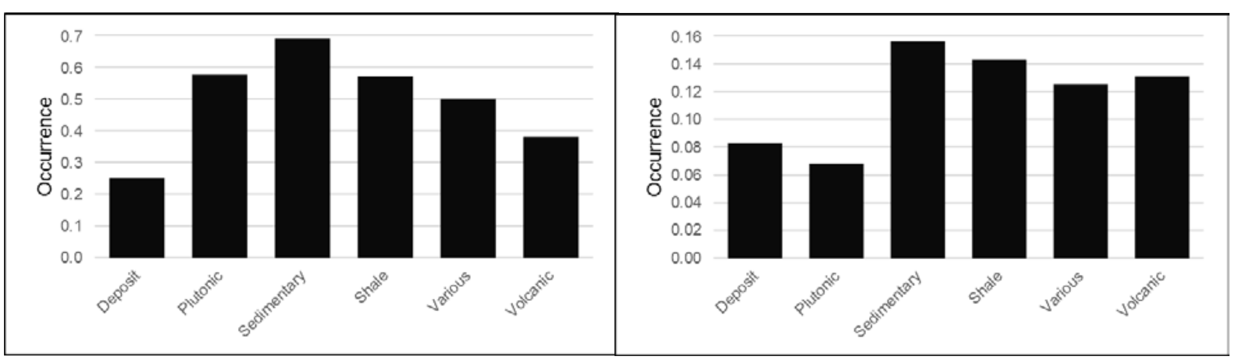
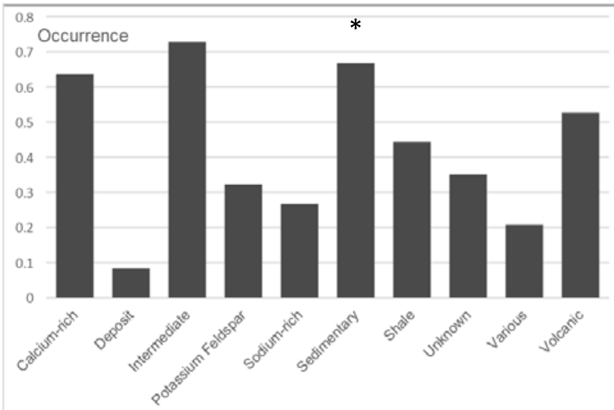
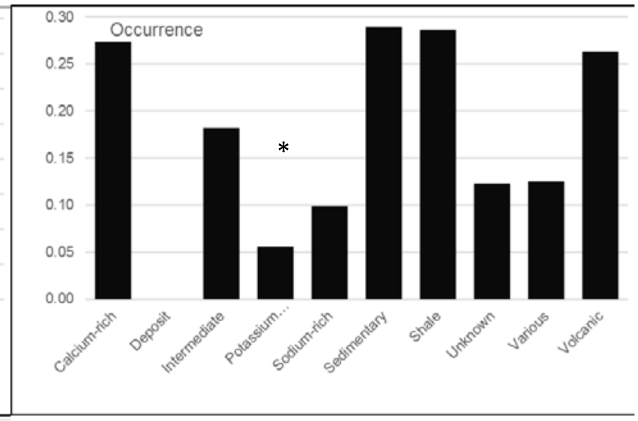


Figure 3. Histograms showing proportional occurrence of 6 plant taxa of importance to mountain goats by geological origin subtype, as estimated from 504 x m^2 vegetation plots inspected during summers 2008-2015. Subtype sample sizes: deposit = 12, plutonic = 177, sedimentary = 45, shale = 70, various = 24, volcanic = 176. Symbol "*" represents significant predictor, $P < 0.01$ from logistic regression model incorporating Julian date, elevation, and aspect.

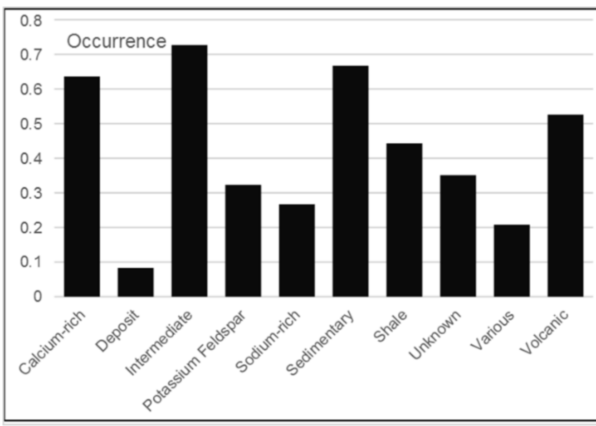
a. Sedge



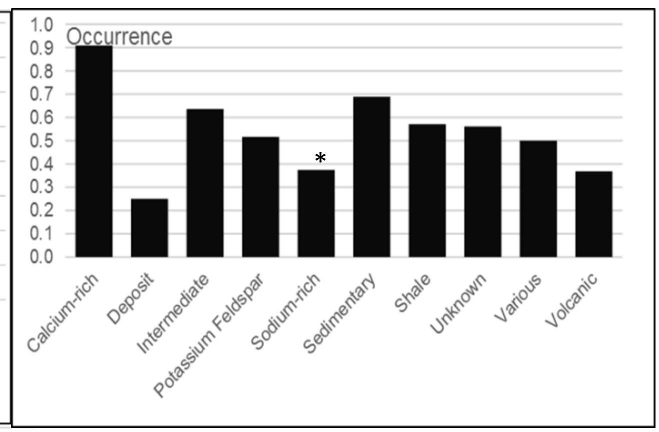
b. *Carex spectabilis*



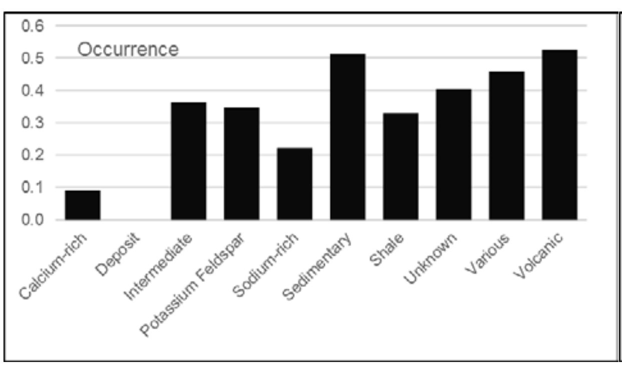
c. Rush



d. Heather



e. *Polygonum bistortoides*



f. Penstemon spp.

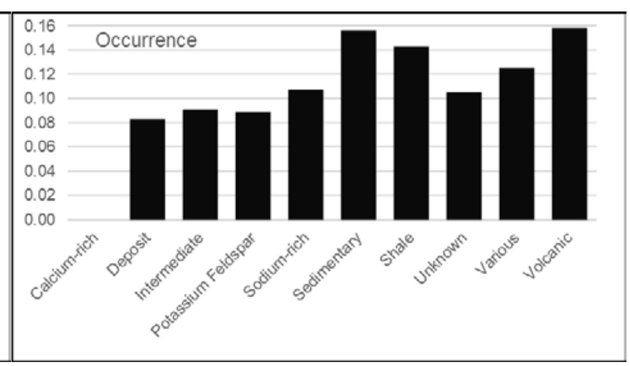


Figure 4. Histograms showing proportional occurrence of 6 plant taxa of importance to mountain goats by geological origin subtype, as estimated from 504 x m^2 vegetation plots inspected during summers 2008-2015. Subtype sample sizes: Calcium-rich 11; Deposit 12; Intermediate 11; Potassium-Feldspar 124; Sodium-rich 131; Sedimentary 45; Shale 70; Unknown 57; Various 24; Volcanic 19. Symbol "*" represents significant predictor, $P < 0.01$ from logistic regression model incorporating Julian date, elevation, and aspect.