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Mapping vegetation communities across home ranges of mountain goats in the North Cascades for conservation and management

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LandSat 5TM; mountains; non-hierarchical classification; *Oreamnos americanus*; thematic classification

Nomenclature
Pojar & MacKinnon 2004

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Abstract

Question: What is the composition of vegetation communities found across mountain goat ranges? Can we use LandSat 5TM to model those vegetation communities across a mountain range to guide conservation and management plans?

Location: The Cascade Mountains of Washington, USA.

Methods: We surveyed vegetation across previously undocumented home ranges of mountain goats, which we determined via GPS telemetry and tracking. We used non-hierarchical cluster analysis to identify vegetation communities found therein. We linked the results of the fieldwork to a supervised classification of three LandSat 5TM (bands 2: 0.52–0.60 µm, 3: 0.63–0.69 and 4: 0.76–0.90 µm) images acquired consecutively on 29 July 2005 and to aerial imagery with 1-m resolution from the National Agriculture Inventory Program (NAIP) to create a map of vegetation communities across the Cascade Mountain range. Finally, we evaluated the success of the classification accuracy after transforming categorical land cover into percentage cover classes at a resolution that matches the positional error of the GPS telemetry collars.

Results: Field reconnaissance and analysis identified eight vegetation communities across mountain goat home ranges: montane forest, sub-alpine forest, heather, huckleberry, east-side shrub, sparse meadow, dense meadow and cryptogram (talus). Analysis of imagery linked the vegetation communities found on mountain goat ranges to specific thematic classes and projected the classification across the entire range. We identified a scale of analysis (ca. 2 ha) that achieved balance between bias and precision resulting in an accuracy of ca. 80% based on comparison with 1-m digital aerial imagery and survey results.

Conclusions: Our results demonstrate that common and readily available data can be used to produce reliable maps of percentage cover type in mountainous terrain for specific applications. Our work is the first to describe the type and distribution of vegetation communities occurring within and across mountain goat ranges along the length of the Washington Cascades.

Introduction

Delineation and classification of land-cover types are common objectives for natural resource management. Methodologies relying on integration of field data and LandSat 5TM data for predictive purposes often are required to meet project goals and objectives. Implementation of field-based vegetation assessments in mountains regions, however, can be challenging because of access restrictions by both ground and air. Generation of reliable maps of land cover in mountainous terrain is also difficult using existing techniques and technologies because of technical challenges, including altered spectral response due to variable slopes, aspects and illumination (Colby 1991; Dymond & Shepherd 1999; Dorren et al. 2003). Nonetheless, a variety of techniques and data are becoming

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more readily accessible, both monetarily and computationally, for conducting vegetation mapping and land classification efforts around the world (Colby 1991; Dymond & Shepherd 1999; Dorren et al. 2003). Development and implementation of straightforward processes to overcome the logistical and technical drawbacks of land classification studies offer an opportunity to advance both basic and applied research in vegetation science. For example, knowledge about the availability and quality of habitat resources is needed for sound wildlife management and conservation decisions. Characterizing the distribution and abundance of vegetation resources is a fundamental step in evaluating habitat for many wildlife species, such as declining populations of mountain goats (*Oreamnos americanus*) across the Cascades of Washington, USA (Rice & Gay 2010).

Studies of mountain goat habitat are complicated by a lack of reliable vegetation surfaces with thematic resolution, both in terms of cover class and percentage cover that match the ecological requirements for the species. The remote and rugged terrain inhabited by mountain goats (Shelford 1963; Dailey et al. 1981; Peek 1999; Festa-Bianchet & Côté 2008), and other species of mountain ungulate, challenges researchers addressing both basic and applied ecological questions (Photo S1). Consequently, our past work describing mountain goat habitat (Wells et al. 2011; Shirk et al. 2010) did not assess the contribution of forage resources to patterns of habitat selection. Existing data layers, including the Interagency Vegetation Management Plan (IVMP; O'Neil et al. 2002) and the GAP Analysis (Sandborn 2006) depicting vegetation resources that cover the full extent of the region broadly describe the distribution and composition of vegetation. The IVMP was specifically designed to assess habitat for studies of the Northern Spotted Owl (*Strix occidentalis*), while the GAP project described vegetation resources for the entire species assemblage of the region. These data sets do not adequately describe nor fully quantify the composition of the subalpine and high-alpine regions in terms of the vegetation resources relevant to mountain goat ecology (Johnson 1983; Gaines et al. 1994; Peek 1999). Likewise, existing literature describing in detail the composition of vegetation communities in the higher elevations of the North Cascades is sparse and not spatially explicit (Douglas 1972; Douglas & Bliss 1977). Therefore, we sought to determine the composition of vegetation communities across mountain goat ranges, and to produce a reliable, scale-dependent model of the spatial distribution of the vegetation communities across the landscape for modelling and management purposes.

Our primary objective was to produce a vegetation map that was relevant to modelling habitat selection by mountain goats using readily available remote sensing products. To accomplish our primary objective, we: (1) collected field data to identify vegetation communities occurring within mountain goat home ranges; (2) developed LandSat 5TM imagery to thematic classes representative of those vegetation communities; and (3) developed a scale-dependent approach for evaluation of the accuracy and reliability of the thematic classes as continuous variables. This straightforward approach produced simple yet reliable maps of the distribution of vegetation resources in mountainous terrain across a broad extent of the North Cascades for conservation and management purposes.

Methods

Study area

From 2003 to 2008, the Washington Department of Fish and Wildlife deployed Vectronic-Aerospace GPS collars (GPS plus collar v6; Vectronic-Aerospace GmbH, Berlin, Germany) on mountain goats across the Cascade Mountain range in Washington, USA (Rice & Hall 2007). We used the GPS data to estimate home ranges and utilization distributions of 53 mountain goats, based on kernel density estimators (R package version 1.8.1, available at: http://CRAN.R-project.org/package=ks), which spanned the Mount Baker-Snoqualmie National Forest, Wenatchee National Forest, Gifford Pinchot National Forest, North Cascades National Park and Mount Rainier National Park. Mountain goats used elevations from ca. 300–3000 m. The region extends west to east over the crest of the Cascade Mountain range and north to south from the US–Canadian border to the Washington–Oregon state border along the Columbia River (49°0′ N to 45°30′ N, 120° 10′ W to 122°30′ W; Fig. 1).

Field data and analysis

The process we employed included four steps: (1) partitioning of vegetative communities based on field data (Gauch 1982); (2) implementation of a supervised classification based on reflectance including an illumination-based topographic correction model (Dorren et al. 2003) to LandSat 5TM imagery; (3) accuracy assessment of cover classes based on field data (Cingolani et al. 2004; Jensen 2005; Díaz Varela et al. 2008); and (4) objective and scale-dependent reclassification of cover classes to percentage cover classes.

We used a gradient-directed or 'gradsect' approach (Gillison & Brewer 1984; Sandmann & Lertzman 2003) to stratify the home ranges of mountain goats by aspect and elevation for field sampling of vegetation communities. The field survey protocol was adapted from methods developed by Henderson & Lesher (2003) to identify the plant associations and potential spatial distribution of plant species. In particular, we were interested in the sub-alpine region and areas above the tree line where data from

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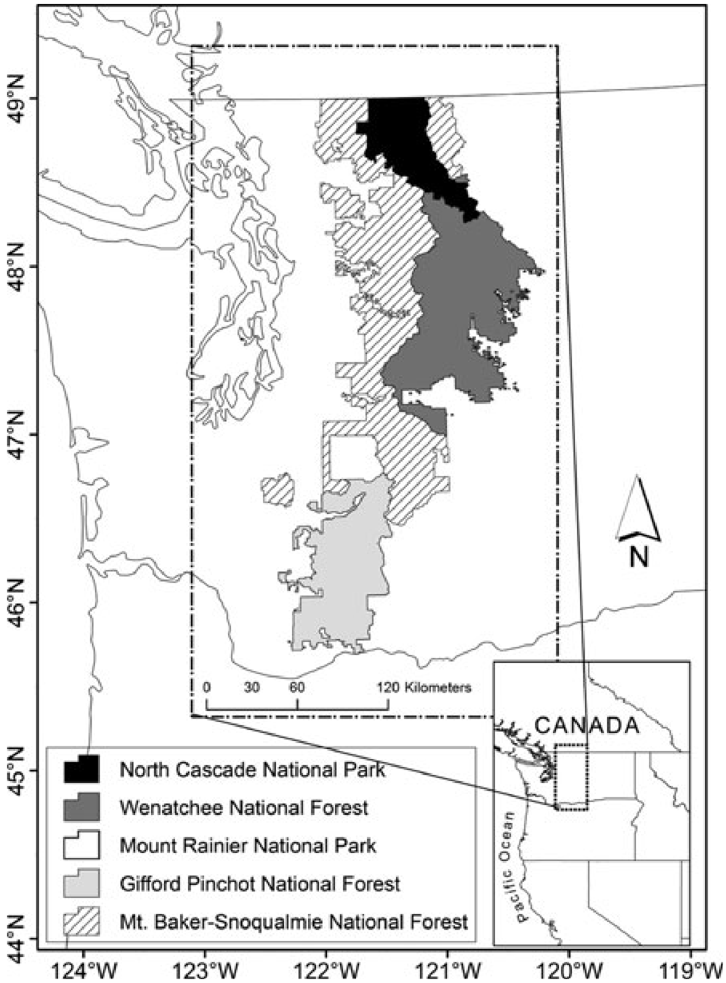

Fig. 1. Location of study area (Cascades of Washington, USA) showing domain of public lands included in the study (Note: Mount Rainier National Park is shown in white within the interior of the cross hatching designating the Mount Baker-Snoqualmie National Forest).

previous mapping projects (Henderson et al. 1992; Henderson & Lesher 2003; Sandborn 2006) are limited and mountain goats most often occur. The field data consisted of a taxonomic survey of all vascular and non-vascular plants to species at each sample site (Harlow et al. 1996; Parish et al. 1996; Pojar & MacKinnon 2004). We used variable circular plots (10–100 m) based on stocking density (trees·ha^{-1}) to estimate overstorey cover, and we visually estimated the percentage cover of understorey species within a circular plot with a fixed radius of 5 m. Variable circular plots were used to ensure that sampling included trees in areas with sparse forest cover (i.e. the greater the density of trees, the smaller the plot size and *vice versa*). We used the field data to define vegetation community types representative of mountain goat ranges and as reference sites for the supervised classification.

We analysed vegetation measurements collected in the field with multivariate cluster analyses. We grouped the vegetation data from species into structural groups based loosely on growth form (i.e. trees, shrubs, forbs, grass, ferns, heather and cryptograms) and we reviewed the literature (Rideout & Hoffman 1975; Campell & Johnson 1983; Peek 1999; Festa-Bianchet & Côté 2008; Hamel & Côté 2007) to assess which species to include as representative forage items for mountain goats. We transformed the percentage cover values to Z-scores to standardize the field data across sites (Krebs 1999). Because we were interested in assigning samples to community types (Gauch 1982), we used non-hierarchical partitioning (k-means) in program R (R Development Core Team, R Foundation for Statistical Computing, Vienna, AT) for assignment of cluster types. We derived the optimal number of clusters from the data based on a comparison of the change of sum-of-squares variance within clusters (Everitt & Hothorn 2006). We defined the vegetative community based on the relative percentages of species composition in each community. Species prevalence, the range of values

(% cover), mean cover (%) and median value (%) of individual species provided insight and a means by which to provide a formal definition, or name, to the vegetation communities. To integrate the field data into the image classification, we used the field-derived vegetation communities at known sample sites as a basis for the supervised image classification.

Imagery and analysis

We evaluated three spatially contiguous, cloud-free LandSat 5TM images acquired on 29 July 2005 (WRS path 46 row 26, 27 and 28), and integrated a 10-m digital elevation model (DEM) during topographic correction. We used the vegetation communities defined by our field data to supervise the image classification procedure based on reflectance values. We used bands 2 (0.52–0.60 μm), 3 (0.63–0.69 μm) and 4 (0.76–0.90 μm) during our analysis and generated spectral signatures for each vegetation community we observed in the field. Additional classes of glacier and water were identified based strictly on analysis of the imagery by assignment of spectral signatures. By linking the vegetation communities derived from field data to land-cover classes derived from images, each class related to a mean and a range of percentage cover of specific species composition.

The images were geo-rectified and pre-processed to level L1T by the Earth Resources Observation Systems (EROS) data centre. Unfortunately, the meta-data files from EROS indicated that the cubic convolution re-sampling algorithm was implemented during the standard geo-rectification process rather than nearest-neighbour re-sampling (USGS, EROS 2010). Implementation of cubic convolution resampling results in alteration of the original digital numbers acquired by the LandSat 5TM system, thereby introducing an additional source of error into a spectral analysis (Jensen 2005). We radiometrically corrected the images and calculated reflectance values following the approaches of Chander et al. (2009).

To compensate for topographic illumination (Dymond & Shepherd 1999), we applied the Sun-Canopy-Sensor correction (SCS; Dorren et al. 2003) to the LandSat 5TM scenes. The SCS correction is similar to the cosine correction (Jensen 2005) and suffers from the same limitations. That is, as slopes approach 90°, the denominator in the correction factor approaches zero, resulting in a correction factor that approached infinity. Much of the terrain within the home ranges of mountain goats contained slopes that approached 90°, which resulted in the topographic correction producing brightness values outside of the expected range of values. Therefore, we modified the SCS correction factor by adjusting the denominator with a constant to avoid the indeterminate form.

To evaluate the accuracy of the supervised classification, we generated a matrix of the land-cover classes against the known vegetation communities identified by analysis of the field data. We assigned each sample site (n = 280) to a vegetative community definition based on the non-hierarchical partitioning of the field data and a thematic class based on the supervised classification of the LandSat 5TM data. We tabulated the agreement between cluster assignment and image assignment in a matrix to calculate user's accuracy, producer's accuracy and overall accuracy. We aggregated our land-cover classes into simpler classes to reflect expected differences in habitat selection by mountain goats between summer and winter and revaluated our error matrix. From our GPS data, we observed mountain goats utilizing lower elevations during time periods reflecting winter conditions, while summer ranging tended to be at higher elevations (Rice 2008).

We compared these aggregated land-cover classes to hand-digitization of aerial imagery to again evaluate accuracy. For comparison, we manually digitized land classification types at field sites based on 1-m digital imagery from the National Agriculture Inventory Program (NAIP) acquired in 2006. In our GIS, we calculated the proportional area of each vegetation community within a circular buffer around field sample sites that was equal to the size of our expected error in location accuracy of the GPS telemetry collars. The buffer decreased the spatial resolution of our analysis window to ca. 2.3 ha (26 30 × 30 m pixels). The buffer was based on the expected error in location or 95% circular error probable (Lewis et al. 2007) associated with data acquired from the GPS collars used during the telemetry study (Wells et al. 2011). To assess accuracy at this resolution, we tabulated the correlation between visually digitized classes (on the NAIP imagery) and classes based on supervised classification within the buffers. We averaged the individual correlation coefficients to generate an overall correlation coefficient between hand-digitized cover types and the classification based on LandSat 5TM imagery at the scale at which these data would be applied.

Results

Vegetation communities within mountain goat ranges

During the summers (June–September) of 2008–2010, we visited sample sites (n = 331) to collect data on the type and distribution of forage resources in mountain goat habitat across the Washington Cascades. The list of species identified during taxonomic surveys of the forage resources included >350 species, but only about two dozen occurred with sufficient regularity (>12 sites) to be considered common in mountain goat habitat. Nearly all species

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identified in the field were represented in the literature as forage items used by mountain goats, with the exception of mountain avens (*Dryas* sp. L.; Festa-Bianchet & Côté 2008). The remaining species that occurred rarely (less than three sites) usually were evident on a limited number of plots, but were also identified in the literature as forage items used by mountain goats.

The non-hierarchical partitioning analysis (k-means) revealed eight different vegetative communities across the home ranges of mountain goats in the Cascades. The aggregated vegetation communities that we defined that were relevant to habitat selection by mountain goats included: two forest communities (Table 1, montane and sub-alpine), two shrub communities (Table 2, huckleberry and eastside), two meadow communities (Table 3, dense and sparse) and two talus communities (Table 4, heather and cryptogram or talus). Specific composition of cover types (see Appendices S1–S4) based on the field data provided working definitions of the vegetation communities.

The montane community was typical of lower elevation, mesic forests. The sub-alpine forest community defined vegetation compositions that occurred at higher elevations where the montane forest gives way to sub-alpine forests and parklands. The sub-alpine forest community also appeared as secondary growth at lower elevations, but we ignored this point because the entire classification objective and process were directed at mountain goat ranges that occurred at higher elevations. The results indicated a relatively similar species composition of forbs and grasses between both meadow types that we defined, but with differing amounts of overall cover distinguishing the two. The major compositional difference was the contribution of mountain juniper (*Juniperus communis*) to the sparse meadow type, which was virtually absent in the dense meadow community. The two shrub communities differed primarily on the abundance of representative species, in particular, *Vaccinium* spp. Huckleberry species were present in the eastside shrub community but exhibited <30% cover ($\bar{x} = 4\%$), in contrast, they were ubiquitous across all sites within the huckleberry community type. The heather cluster provided the most precise and clearly delineated grouping of vegetative communities. The partitioning of field data into the cryptogram type resulted from the dominant and unequivocal contribution of mosses and lichens (50–100%; $\bar{x} = 51\%$). There was a high degree of variability of forb species in the cryptogram community. A number of other species of herbaceous plants were also represented in the cryptogram community, but were not identified with any regularity across the

Table 1. Summary of cover (%) of the montane and sub-alpine forest communities found across home ranges of mountain goats in the Washington Cascades, USA.

Growth form	Montane			Sub-Alpine		
	Range	Mean	Median	Range	Mean	Median
Tree	0–100	61	55	0–100	72	80
Shrub	0–100	22	12	0–93	29	15
Fern	0–31	9	10	0–10	2	1
Forb	0–86	25	18	1–40	10	7
Graminoid	0–60	12	1	0–17	1	1
Heather	1–2	1	1	1–3	1	1
Ground cover	3–100	65	65	1–98	55	50

Table 2. Summary of cover (%) of the huckleberry shrub and eastside shrub communities found across home ranges of mountain goat in the Washington Cascades, USA.

Growth form	Huckleberry			Eastside shrub		
	Range	Mean	Median	Range	Mean	Median
Tree	0–85	9	0	0–25	5	0
Shrub	30–100	63	65	35–96	63	60
Fern	0	0	0	0	0	0
Forb cover	1–92	36	36	2–44	20	18
Graminoid	0–60	8	4	0–61	23	23
Heather	0–40	4	0	<1	<1	<1
Ground	5–100	85	90	45–100	78	80

Table 3. Summary of cover (%) of the dense and sparse meadow communities found across home ranges of mountain goats in the Washington Cascades, USA.

Growth Form	Dense meadow			Sparse meadow		
	Range	Mean	Median	Range	Mean	Median
Tree	0–75	4	0	0–25	4	0
Shrub	0–65	4	0	0–29	5	2
Fern	0–7	<1	0	0	0	0
Forb	0–100	52	41	2–70	35	12
Graminoid	0–90	20	10	0–50	10	5
Heather	0–30	5	0	0–10	1	0
Ground cover	3–100	64	70	0–80	35	30

Table 4. Summary of cover (%) of the heather and talus communities found across home ranges of mountain goats in the Washington Cascades, USA.

Growth form	Heather			Talus		
	Range	Mean	Median	Range	Mean	Median
Tree	0–20	3	<1	0–70	8	0
Shrub	0–15	1	<1	0–100	32	23
Fern	0	0	0	<1	<1	<1
Forb	0–50	10	7	0–48	11	7
Graminoid	0–35	4	1	0–35	5	1
Heather	15–100	57	60	0–60	5	0
Ground cover	15–100	77	80	0–100	43	45

cryptogram sites. The high variability of plant species present in this community suggested that there was some confusion in the community assignment between high-elevation sites typically dominated by cryptogram (i.e. areas of alpine talus and scree) and lower-elevation sites also dominated by cryptograms, such as the exposed bedrock or boulder fields beneath cliffs in the montane forest. Therefore, the cryptogram community coincided with two distinct vegetation communities distinguished largely by elevation and the surrounding forest communities.

Analysis of the LandSat 5TM data produced eight image classes based on the eight vegetation communities defined by analysis of field data (Fig. 2). The corresponding spectral signatures showed minor variation among spectral reflectance values for bands 2, 3 and 4 (Fig. 3). The accuracy assessment of the original eight classes against the corresponding vegetation communities on a per pixel basis showed a low overall accuracy and low within-class agreement (Table 5). To improve the accuracy, we aggregated the eight vegetation communities and the eight corresponding image classes into three simpler variables. We aggregated the two forest community types into one variable; the heather, sparse meadow and talus community types into a second variable; and the dense meadow, huckleberry and east side shrub into a third variable. The final three variables of mountain forage were therefore forest, shrub-meadow and talus (Fig. 4). Snow was retained as a fourth variable based strictly on image interpretation. The point level accuracy of the merged land-cover classes with field data was still low (Table 6).

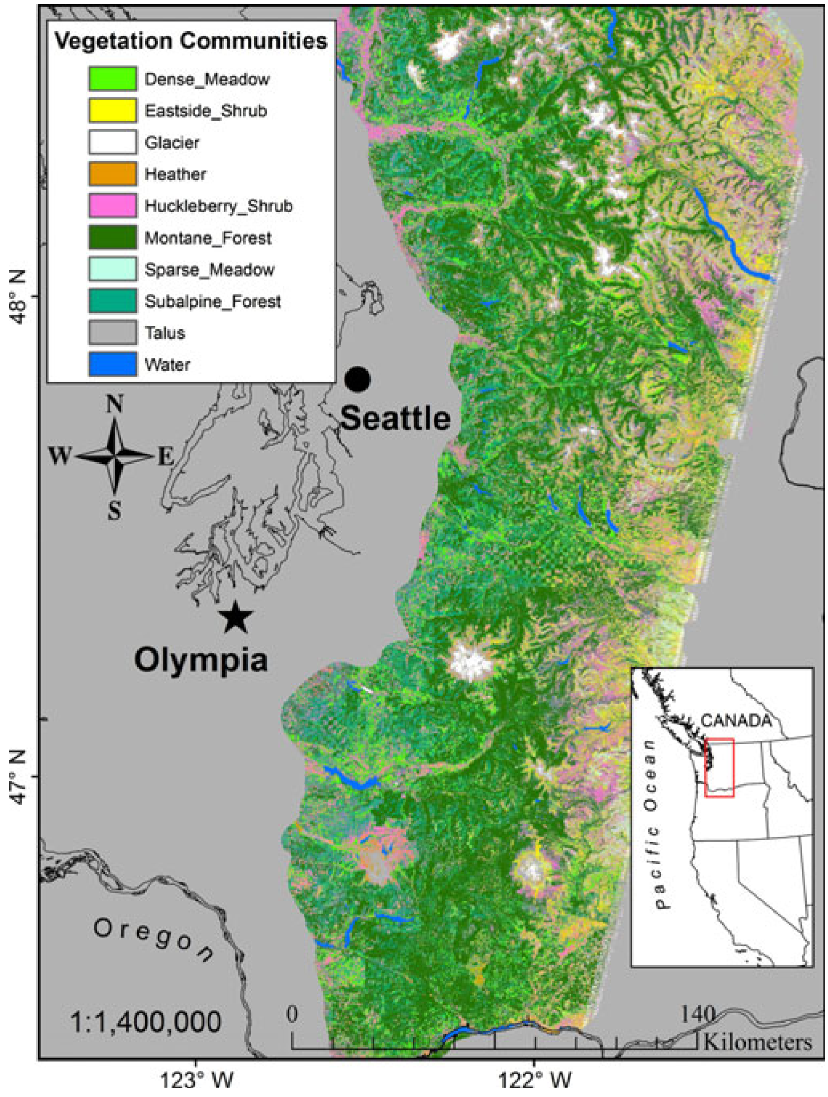

Fig. 2. Thematic classes derived from three spatially adjacent LandSat 5TM images acquired in July of 2005 based on supervised classification of field-derived vegetation communities across home ranges of mountain goats in the Washington Cascades, USA.

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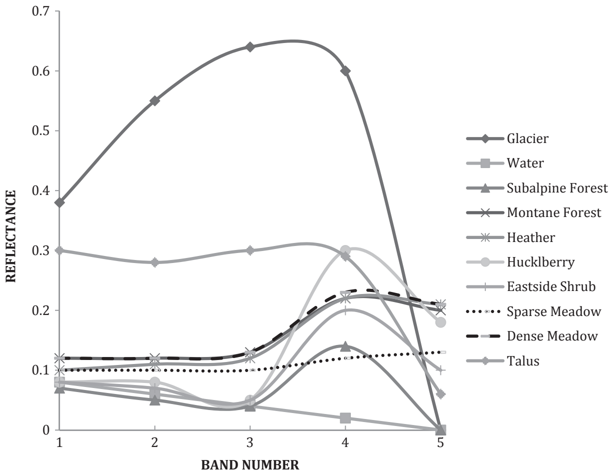

Fig. 3. Spectral signatures from LandSat 5TM imagery of eight vegetation and two non-vegetated (glacier and water) communities identified across home ranges of mountain goats in the Washington Cascades, USA.

In our final comparison of percentage cover classes at the resolution of our expected positional error in the GPS telemetry collars (ca. 2.3 ha), we documented an overall increase in our estimate of accuracy. The correlation between variables derived from thematic classes based on LandSat 5TM imagery and hand-digitization of NAIP imagery at known sample sites ($n = 32$) was relatively high ($r = 0.78$, $P < 0.001$). The individual classes had high correlations, as well: forest ($r = 0.75$, $P < 0.001$), shrub-meadow ($r = 0.72$, $P < 0.001$), talus ($r = 0.75$, $P < 0.001$) and snow ($r = 0.91$, $P < 0.001$). Consolidation of the vegetation communities and thematic classes into simpler variables at an appropriate resolution for future modelling and mapping of mountain goat habitat across a broad extent increased the accuracy of the land classification and also provided a more concise database for subsequent use in our particular application.

Discussion

We overcame the common obstacles associated with working in mountainous terrain and produced a useful map of the distribution of vegetation community types for modelling and mapping mountain goat habitat across a large area of rugged terrain. Our results provided a land classification map (Fig. 2) with an extent that is broad sufficient to cover the entire Cascade Range, and we used a suitable resolution for analysis to produce reliable predictions of percentage cover classes (Fig. 4). The resolution matched that of our empirical observations (i.e. location errors of the data collected by the GPS collars). Altering the scale of our analysis to match the expected errors of our telemetry data resulted in a higher correlation between vegetation communities

Table 5. Accuracy assessment of the original eight land-cover classes against field-derived vegetation communities.

GIS cover type	Field cover type									
	Dense meadow	Eastside shrub	Heather	Huckleberry shrub	Montane forest	Sparse meadow	Sub-alpine forest	Talus	Grand total	User's accuracy
Dense meadow	**17**	1	6	10	2	1		6	43	0.40
Eastside shrub	10	**2**	6	3	1	3	1	1	27	0.07
Heather	17	1	**7**	5	1	2		5	38	0.18
Huckleberry shrub	22	2	5	**3**	3	13	3	9	60	0.05
Montane forest	2		1	2	**3**		10	1	19	0.16
Sparse meadow	3		3	3		**2**			11	0.18
Sub-alpine forest	6	2	2	1			**9**	4	24	0.38
Talus	20	2	7	3	1	14	2	**9**	58	0.16
Grand total	97	10	37	30	11	35	25	35	**280**	
Producer's accuracy	0.18	0.20	0.19	0.10	0.27	0.06	0.36	0.26		**0.19**

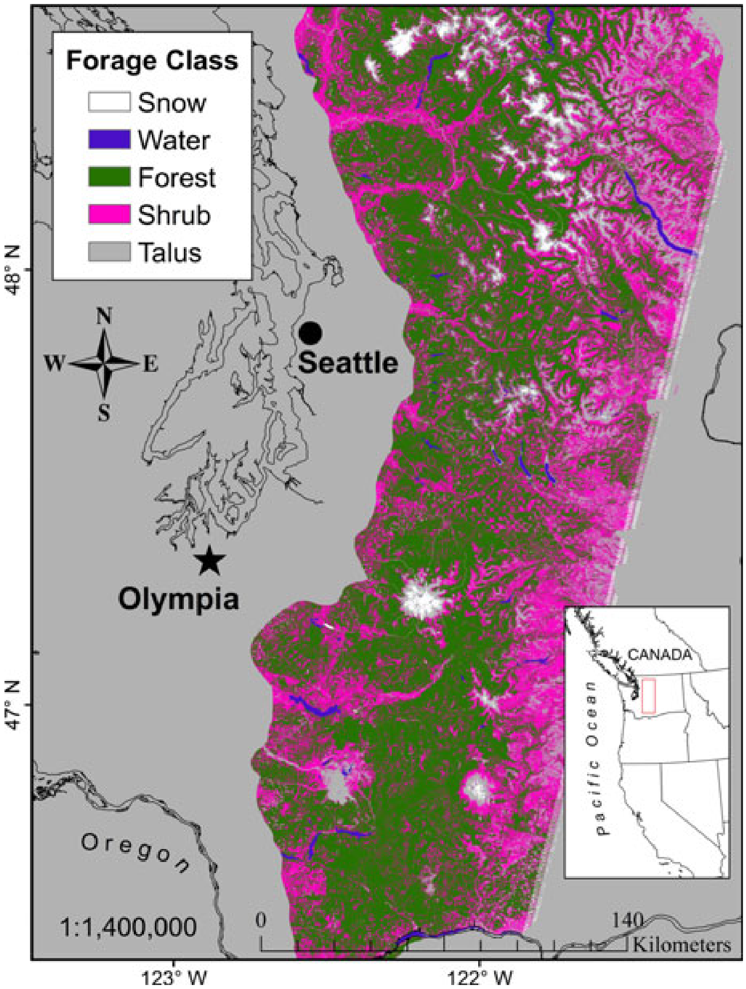

Fig. 4. Simplified classification for accuracy assessment and potential application of the results to future studies designed to address specific questions regarding use and availability for mountain goats in the Washington Cascades, USA.

Table 6. Accuracy assessment of the aggregated land-cover classes against field-derived vegetation communities.

	Forest	Meadow shrub	Talus	Grand total	User's
Forest	**22**	13	8	43	0.51
Meadow shrub	10	**70**	50	130	0.54
Talus	4	54	**49**	107	0.46
Grand total	36	137	107	**280**	
Producer's	0.61	0.51	0.46		**0.50**

based on LandSat 5TM data and field observations. We believe that adjusting the resolution of our analysis not only improved the accuracy of our land-cover map, but also honestly incorporated uncertainty in locations of animals based on GPS collars, which is important for our application of the vegetation analyses. Our map embraces a landscape-level scale for attempts to prioritize and identify potential areas where sufficient vegetation resources can accommodate the differing seasonal needs of mountain goats.

Our work provided a detailed understanding of vegetation communities within home ranges of mountain goats and a basis for classification of cover types and prediction of the distribution of vegetation communities using LandSat 5TM data. Analysis of our field data provided a detailed description of the expected vegetation communities, and consequently forage items, available to mountain goats in the Cascades. We defined eight vegetation communities within home ranges of mountain goats throughout the Cascade Range based on intensive field sampling. Although cluster analysis has some inherent subjectivity when selecting the number of communities (Pfitsch 1981), the eight vegetation communities we identified were relevant to our application: montane forest, sub-alpine forest, eastside shrub, huckleberry shrub, heather, dense meadow, sparse meadow and talus. The difference in timing of

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acquisition between satellite and field data presented little concern due to the slow rates of growth of sub-alpine and high-elevation ecosystems (Franklin et al. 1971; Price & Waser 2000). In our initial efforts, we were unable to effectively link the vegetation communities derived from fieldwork, however, to the original eight land cover classes at the point level (i.e. resolution of a single pixel; Table 5) because the accuracy was too low. To improve our ability to discriminate the land-cover classes, we grouped the eight vegetation communities into three variables for use in modelling habitat selection and space use by goats: forest, shrub-meadow and talus. The accuracy of the grouped land-cover types, again at a point level resolution, was not satisfactory for application of the land-cover map (Table 6). When we decreased the resolution of our analysis during accuracy assessment, however, our ability to identify the relative percentage cover class increased markedly. The coarser scale of our work allowed us to develop a useful model to describe the distribution of vegetation communities across the broad extent of the Cascades.

While our mapping effort suffices for the intended application, the process was not without flaws. Utilization of supervised classification resulted in unique yet not entirely separate spectral signatures among the image classes (Fig. 3). Although overlap existed with some bands across signatures, the form of the curves and differing response across bands 2, 3 and 4 allowed for extrapolation of themes across the study area. Spectral profiles of the classes overlapped due to spectral mixing of the different plants present within pixels. Likewise, past efforts, while quite detailed and thorough, to identify vegetation communities in the area (Douglas 1972; Douglas & Bliss 1977; Pfitsch & Bliss 1985) were not capable of widespread prediction based on LandSat 5TM data. For example, the fine discrimination of *Carex* communities presented by Douglas & Bliss (1977) provides little support for the required variation in reflectance to discriminate among *Carex* communities based on imagery data.

An additional source of error encountered during development of our classification map was associated with the topographic correction process. The indeterminate form of the SCS correction formula as slopes approach zero resulted in the failure of the topographic correction process to work in areas with extreme topography. Typically, areas with steep slopes tend to have less soil formation, limiting the development of vegetation, and thus eliminating the need to correct for illumination differences among cover types. This generalization might hold some merit, but is certainly not universal, as small features (i.e. ledges and cracks) occur in areas with steep topography that likely result in differing spectral signatures within the 30-m spatial resolution of LandSat 5TM imagery. Considering the nature of mountain goat habitat (extremely steep and rugged terrain), this generalization of non-vegetated surfaces on slopes approaching 90º was undesirable. The topographically corrected and uncorrected results were almost indistinguishable. Additionally, we could not remove deep shadows created by topographic features from the images with this technique. Removal of shadows from the classification map would require manual digitization and interpretation.

Our vegetation maps will assist in developing fine-scale habitat maps for mountain goats across the North Cascades utilizing GPS telemetry, topographic data and GIS tools for specific time periods of interest. All in all, improved metrics and interpretation of habitat models offers a greater capacity for understanding and predicting movements and habitat selection by mountain goats. Our approach for creating a scale-dependent land classification map in mountainous country can be applied to creation of variables for modelling and mapping habitat relationships and testing ecological hypotheses. In particular, our application was designed to be used in conjunction with GPS telemetry data collected from free-ranging wildlife. This approach demonstrates a process for using existing data and technologies to produce site-specific thematic classes for directed modelling objectives and applied conservation projects.

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Supporting Information

Additional supporting information may be found in the online version of this article:

Appendices S1–S4. Vegetation communities and vegetation species identified therein across home ranges of mountain goats in the Cascades of Washington, USA. Presence (%), mean cover (%) and median (%) are given for each of the forest communities (Appendix 1) shrub communities (Appendix 2), meadow communities (Appendix 3) and talus and heather communities (Appendix 4).

Photo S1. Mountain goat in typical habitat occupied by the species (white dot in centre on top of peak in foreground).

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