National Park Service
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# Alpine vegetation composition, structure, and soils monitoring for Great Sand Dunes National Park and Preserve

## *2009 Summary Report*

Natural Resource Data Series NPS/ROMN/NRDS—2010/056

**ON THE COVER**
Hudson Lake viewed from Padilla Peak, July 2009, Great Sand Dunes National Park and Preserve
Photograph by: Phyllis Pineda Bovin

# Alpine vegetation composition, structure, and soils monitoring for Great Sand Dunes National Park and Preserve

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# Executive Summary

Alpine ecosystems are important monitoring targets for the Rocky Mountain Inventory and Monitoring Network (ROMN) for a number of reasons, including their value to park visitors, wildlife, and water resources in the West and because the alpine is particularly vulnerable to climate change. Here, we present a summary of our efforts in 2008-2009 to monitor vegetation composition, structure, and soils in the alpine of Great Sand Dunes National Park and Preserve (GRSA). We found the following:

- In 2008, an alpine monitoring site was established at GRSA following the guidance from the Global Observation Research Initiative in Alpine Environments (GLORIA) whereby the park became part of an international effort to monitor biodiversity and climate change in the alpine.
- In 2009, a GLORIA sentinel site was established at four unnamed peaks between Mount Herard and Music Pass varying in elevation from 3550 to 4000 m.
- There were 83 species of vascular plants identified from the four peaks. The peaks differed in the number of species present, specifically, the highest peak, SIX, supported only 46 species and the lowest peak HUK had 60 species.
- The four peaks are generally characterized by stable soils, high vegetation cover, low exotic species cover, and minimal human and herbivore disturbance.
- For the winter of 2008-2009, mean daily temperatures remained below freezing for most of the period between October and May. In 2009, we increased the network of temperature dataloggers in the alpine at GRSA and will track soil temperatures on the north, east, south, and west side of each summit.

In 2009, we found the alpine tundra at the four sentinel sites in GRSA to be a system little impacted by human disturbance or exotic species. Climate change and increasing atmospheric deposition of nutrients are the greatest threats to alpine systems in GRSA. Continued monitoring of the vegetation and temperature at sentinel sites will allow us to determine whether climate change correlates with changes in biodiversity in the alpine. Warmer temperatures in the future may contribute to the extinction of some plant species while simultaneously increasing the elevation and latitudinal limitations of other species.

# Acknowledgments

I thank all those that assisted with field work, particularly Phyllis Pineda Bovin, Kurt Chowanski, Brian Jacobs, Mike Britten, and Ula Bovin. I would also like to thank Fred Bunch and the staff at GRSA for being exceptionally helpful with logistics, housing, and accommodating our office needs. The staff at the GLORIA office have been invaluable, particularly Barbara Friedmann and Christian Klettner, by providing databases, field sheets, and methods. This manuscript was improved by comments from Amy Miller and Regina Rochefort.

# Introduction

The purpose of the National Park Service (NPS) Inventory & Monitoring (I&M) Program is to provide scientifically credible information on the current status and long-term trends of the composition, structure, and function of park ecosystems, and to determine how well current management practices are sustaining those ecosystems. The Rocky Mountain I&M Network (ROMN) identified vegetation composition, structure, and soils as a vital sign that can be used to better understand the condition of park ecosystems (Britten et al. 2007). The alpine, defined as the vegetation communities that exist above treeline, is represented in three of the ROMN parks: Glacier National Park, Rocky Mountain National Park and Great Sand Dunes National Park at 28%, 20%, and 3% land cover, respectively. The ROMN selected alpine ecosystems as an important vegetation monitoring target in these parks for a number of reasons, including their value to park visitors, wildlife, and water resources in the West and because the alpine is particularly vulnerable to climate change. Here, we present a summary of our efforts in 2008-2009 to monitor vegetation composition, structure, and soils in the alpine of Great Sand Dunes National Park and Preserve.

Since this was our initial monitoring effort, this report summarizes only the status of alpine in the park at four sentinel sites and does not explore trends. Sentinel sites are locations where monitoring will be long-term and is frequent and detailed (Britten et al. 2007). The long-term objectives of our alpine monitoring effort will focus on both status and trends. Specifically, our objectives are to:

(1) Determine the status and trend in **vegetation composition and structure** of four sentinel alpine peak communities at a range of elevations.

(2) Determine the status and trend in **cover of invasive/exotic plant species** at four sentinel alpine peak communities at a range of elevations.

(3) Determine the status and trend in **soil condition** based on a suite of physical and chemical properties that include: surface stability, soil carbon (C) and nitrogen (N) content, pH, texture, evidence of erosion, extent of bare (non-vegetated) soils, and compaction at four sentinel alpine peak communities.

(4) Determine the status and trend in **anthropogenic and natural disturbance** at four sentinel alpine peak communities at a range of elevations based a qualitative index of anthropogenic disturbances (e.g. distance to roads) and natural disturbance (e.g. evidence of fire) and the presence and frequency of feces, trampling, and browsing damage.

(5) Determine the status and trend in **soil temperature** and **snow cover** period of four sentinel alpine peak communities at a range of elevations.

# Methods

The ROMN adapted an alpine monitoring protocol from the Global Observation Research Initiative in Alpine Environments (GLORIA), an international monitoring network established in 2001 to assess and predict biodiversity and temperature changes in alpine communities in response to drivers such as climate (Pauli et al. 2004). The goals of the GLORIA program are to provide a global baseline for vegetation monitoring in alpine environments and to assess the risks of biodiversity loss and ecosystem instability from climate change. The methodology is extended by cooperators, such as the ROMN, to create a long-term monitoring network at the global scale. The ROMN Alpine Vegetation Composition, Structure, and Soils protocol follows established GLORIA protocols but adds components for soil condition, treeline movement, and human disturbances (Ashton et al. 2010).

## Sample Design

We followed the GLORIA monitoring design (Grabherr et al. 2000) which calls for the establishment of four sentinel sites on alpine peaks representing an elevation gradient within a target region (e.g. the Sangre de Cristo Mountains, CO). One GLORIA region includes four sites. The sites are established on the top of the peaks (summits) and the summits vary from just above treeline to the highest life zones of vegetation. Within one region, all four summits share qualitatively similar geology, climate, disturbance, and land-use history leaving vegetation differences among the summits to be driven primarily by elevation.

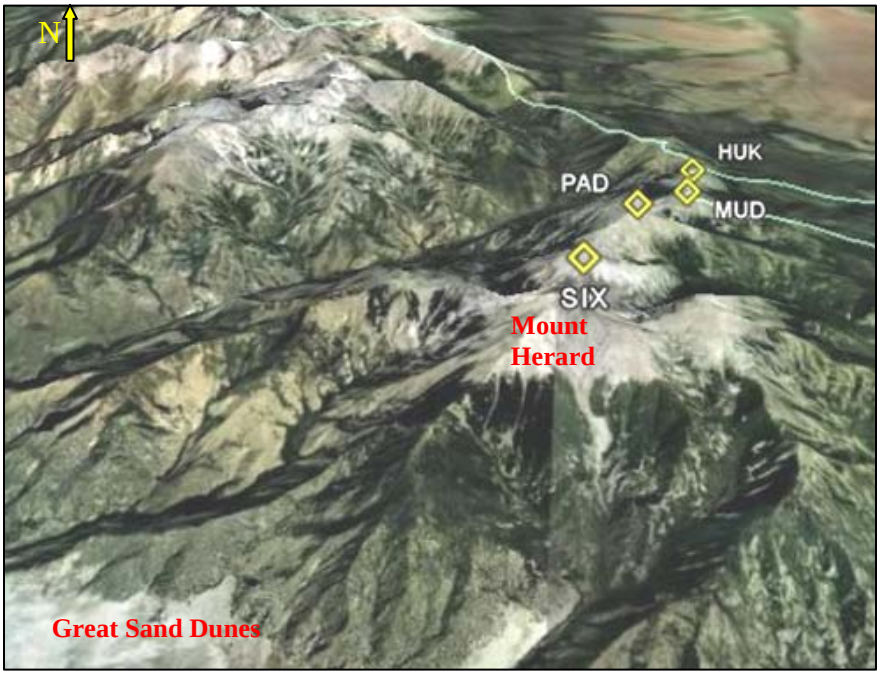


**Figure 1.** Locations of the four sentinel GLORIA peaks in Great Sand Dunes National Park and Preserve used to monitor the status of alpine vegetation and climate.

In 2008, we selected four summits within the Great Sand Dunes National Park and Preserve (US-GSD; Table 1). We examined topographic maps and photographs, discussed options with park managers, and hiked to potential sites to select the best summits. The summits we chose are within close proximity of one another (all within ~ 4 km) on a ridgeline that connects Mount Herard in the south to Music Pass in

the north (Figure 1). The four peaks have similar geology (Crestone conglomerate and felsic gneiss and granite), similar land-use history and disturbance levels, and a similar climate. In addition to selecting the summits, we placed one HOBO Onset pendant temperature logger (UA-001-64) on MUD peak as an initial test of the equipment and to acquire preliminary temperature data for the winter of 2008-2009.

**Table 1**. Name, location, elevation, and vegetation zone of the four alpine sentinel sites within the target region of GRSA.

| GLORIA Summit code | Summit name | Latitude (decimal degrees) | Longitude (decimal degrees) | Elevation (m) | Vegetation zone |
|---|---|---|---|---|---|
| SIX | Unnamed | 37.861501 | -105.492034 | 4000 | alpine/nival ecotone |
| PAD | Unnamed | 37.87965 | -105.478217 | 3870 | upper alpine |
| MUD | Unnamed | 37.887517 | -105.47665 | 3700 | lower alpine |
| HUK | Unnamed | 37.89615 | -105.473733 | 3550 | lower alpine/subalpine ecotone |

## Plot layout

In 2009, we established long-term monitoring plots on all four summits that we had selected the previous summer (Figure 2). For each peak, this entailed placing one marker (a rebar with a labeled aluminum cap) at the highest point on the summit, identifying and marking a 3 x 3 m quadrat cluster (Figure 3) in each cardinal direction at exactly 5 m in elevation below the summit (all four corners of the quadrat cluster are marked: one with capped rebar and 3 with nails; Figure 2), and identifying 4 lower and 4 upper summit area sections that describe each aspect to a distance of 10 m below the summit (e.g., the upper north section was the north side from the summit to 5 m below the summit and the lower was from 5 to 10 m below the summit).

## Vegetation, Soils, Temperature, and Disturbance Monitoring

The quadrat clusters each contain 9-1 $m^2$ quadrats (Figure 2, 3) that are used to measure fine changes in vegetation cover and frequency (Table 2). In addition, one temperature datalogger is buried in the center of each 9 $m^2$ quadrat cluster to measure changes in soil temperature over time and variation in temperature associated with aspect. The 1 $m^2$ quadrats are also used to record the presence and frequency of herbivore damage including trampling, scat, and browsing. The summit area sections are used to measure the exact dimensions of the peak (area and slope), the coarse-scale ground cover of the peaks (7 cover classes: solid rock, scree, vascular plants, lichens, bryophtyes, bare ground, and litter), and the presence of individual plant species used to estimate species diversity and exotic plant cover. For more details on the methods see the ROMN alpine monitoring protocol (Ashton et al. 2010).

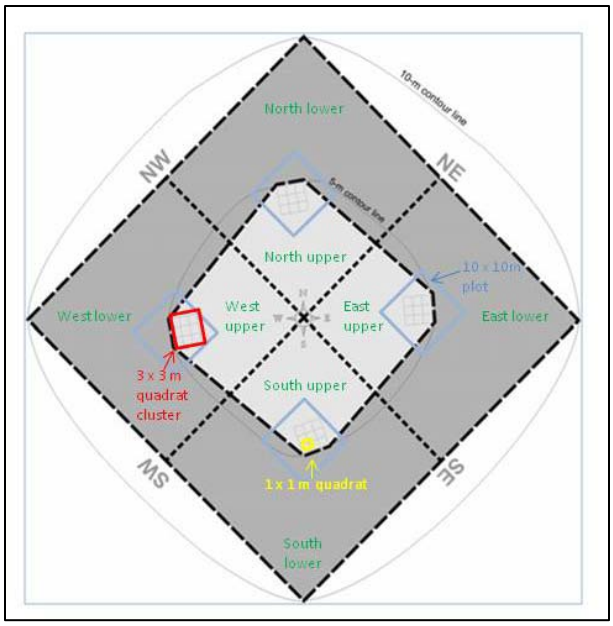


**Figure 2.** Field plot design for alpine monitoring. This design was replicated on four summits that varied in elevation. The design is centered by the highest point on the summit and extends to 10 m in elevation below the highest point. The 1 $m^2$ quadrats used to measure changes in plant frequency are indicated in yellow.

**Table 2.** Types of plots present on each GLORIA summit and data available for analyses. Each quadrat cluster contains 9 quadrats but only 4 are used for vegetation surveys.

| Plot type | Size | Number of plots per peak | Number of plots in GRSA | Available Data |
|---|---|---|---|---|
| Summit | Variable from 0 to 10m below highest point | 1 | 4 | Natural and anthropogenic disturbance |
| Summit Area | Variable from 0-5m and 5-10m below highest point for each direction | 8 | 32 | Species presence; Cover class |
| Quadrat cluster | 9 $m^2$ | 4 | 16 | Hourly soil temperature; Soil parameters |
| Quadrat | 1 $m^2$ | 16 | 64 | Cover class; Species cover; Species frequency; Frequency of herbivore damage |

After establishing and photographing the quadrats on all peaks, we installed 4 temperature loggers per peak buried 10 cm in the soil, measured plant cover and frequency in at least eight 1 $m^2$ quadrats per peak, and surveyed all summit area sections to determine changes in species diversity by elevation and aspect. We chose the lower left and upper right quadrats for sampling and priority will be given for sampling this subset in the future. Cover was measured in the quadrat by ocular estimate and frequency was measured as the presence of a species in one hundred 10 x 10 cm grid cells with the quadrat. We installed HOBO Onset pendant temperature loggers (UA-001-64) that are programmed to measure and record temperature every hour. To aid in identification, some plant specimens were collected, indentified using regional floras, and compared to specimens in the GRSA herbarium.

We also collected a bulk soil sample (an aggregate of 3 cores to 20 cm depth) from each of the quadrat clusters to characterize soil chemistry and texture. The soil samples were air dried and sent to a cooperating laboratory at Colorado State University for analysis. Soil aggregate stability was measured at the quadrat clusters using a soil test kit developed by Herrick et al (2005) using classes from 1 (unstable) to 6 (stable) based on the rate of degradation in water. In order to qualitatively describe disturbance, we documented the presence of potential stressors in and around each site. Using applicable metrics from the 2008 Human Disturbance Index developed by the Colorado Natural Heritage Program, (Rocchio 2007) and the California Rapid Assessment Method for Wetlands (Collins et al. 2008) we indicated a condition score for each site that ranges from 0 (pristine) to 100 (highly disturbed).

**Figure 3**. Phyllis Pineda Bovin, Isabel Ashton, and Brian Jacobs sitting on the highest GLORIA peak (SIX) at Great Sand Dunes National Park and Preserve. A divided meter tape outlines a 3 x 3 m quadrat cluster on the west side of the peak and a frequency plot-frame used to measure fine-scale changes in plant cover can be seeing lying above the cluster (July 7, 2009; photograph by Kurt Chowanski).

In total, the field work during 2009 took 18 days, seven of which were used for travel and access to and from backcountry campsites. It took four people (Pineda Bovin, Chowanski, Ashton, and Jacobs) five days to complete the establishment and data collection at the highest summit of which two days were spent packing in and out of Medano Lake. The lower peaks are all close to one another and accessed from the Hudson Ditch. In this case, two people worked two field days and one travel day to establish the three sites (Ashton and Chowanski) and two people worked 6 field days and 4 travel days to acquire the vegetation data at the three lower summits (Pineda Bovin and Ashton). We feel this timing allowed for an adequate sampling of the peaks. However, we measured only eight quadrats at the lower peaks (2 quadrats from each aspect) and twelve at the highest peaks (3 quadrats per aspect) rather than the full sixteen recommended by GLORIA and we were not able to complete the optional GLORIA sampling of 100 $m^2$ plots. These larger plots are intended to provide better cover estimates for the summit, particularly at sites with low vegetation cover. In the future, we expect the vegetation sampling to occur more quickly because we now have established species lists for each summit, but we will also allow for more days of field work to compensate for bad weather and short work days.

After field sampling, species lists were compiled, sent to the GLORIA offices, and fit to an international standard of nomenclature used by all GLORIA sites. The GLORIA office then customized and delivered to ROMN a data-entry database for the GSD target region and a separate photograph tracking database.

All photographs from the GSD region are now in the database and identified by date, location and purpose of the photograph, and photographer. We estimate the data entry process will take 60 or more hours and the process is ongoing. We expect all data to be entered, the QA/QC process to be completed, and the complete database returned to the GLORIA office in the winter of 2009-2010. Data for this report was entered directly from field sheets to Excel and while some QA/QC was performed, all results should be considered preliminary until data has been approved by the GLORIA office.

Data analyses were performed in R 2.9.2 (2009) using linear models (aov or lme). Models were designed to test for differences among peaks, aspects and an interaction effect (lm= variable~ summit*direction). Where appropriate, variables were log-transformed to meet assumptions of heteroscedasticity and normality. Post-hoc tests were done using Tukey's tests. For this report, we used these models to ask three types of questions: (1) Do summits differ significantly for a given variable? (2) Do aspects differ significantly for a given variable? (3) Was there a summit x aspect interaction?

# Results

## Vegetation Composition and Structure

### *Summit Area*

The four sentinel GLORIA summits varied in composition and ground cover classes (Figure 4; Table 3). SIX, the highest summit, has a large amount of bedrock and scree, particularly on the southern side which is a steep cliff face. The north side is a gentler slope and consequently has a much higher plant cover. PAD, the second highest summit is flat and large (Figure 5). It is well covered with vegetation and has fewer rocky slopes than the other peaks (see Figure 3 for a comparison to SIX), but it is characterized by larger patches of bareground and litter (Figure 4). In general, HUK and MUD are not as rocky as SIX but less vegetated than PAD. There is a large scree slope on the east side of HUK that limited the cover of vegetation.

**Table 3.** Analysis of variance results for solid rock cover on four alpine peaks in Great Sand Dunes National Preserve. The significant interaction effect was driven by SIX which had a very rocky southern aspect compared to other peaks which were more uniformly rocky.

| | df | SS | MS | F | *P* |
|---|---|---|---|---|---|
| Summit | 3 | 1.4 | 0.5 | 1.0 | 0.4019 |
| Direction | 3 | 5.6 | 1.9 | 4.1 | 0.0205* |
| Summit x Direction | 9 | 17.0 | 1.9 | 4.2 | 0.0038** |
| Residuals | 20 | 9.1 | 0.5 | | |

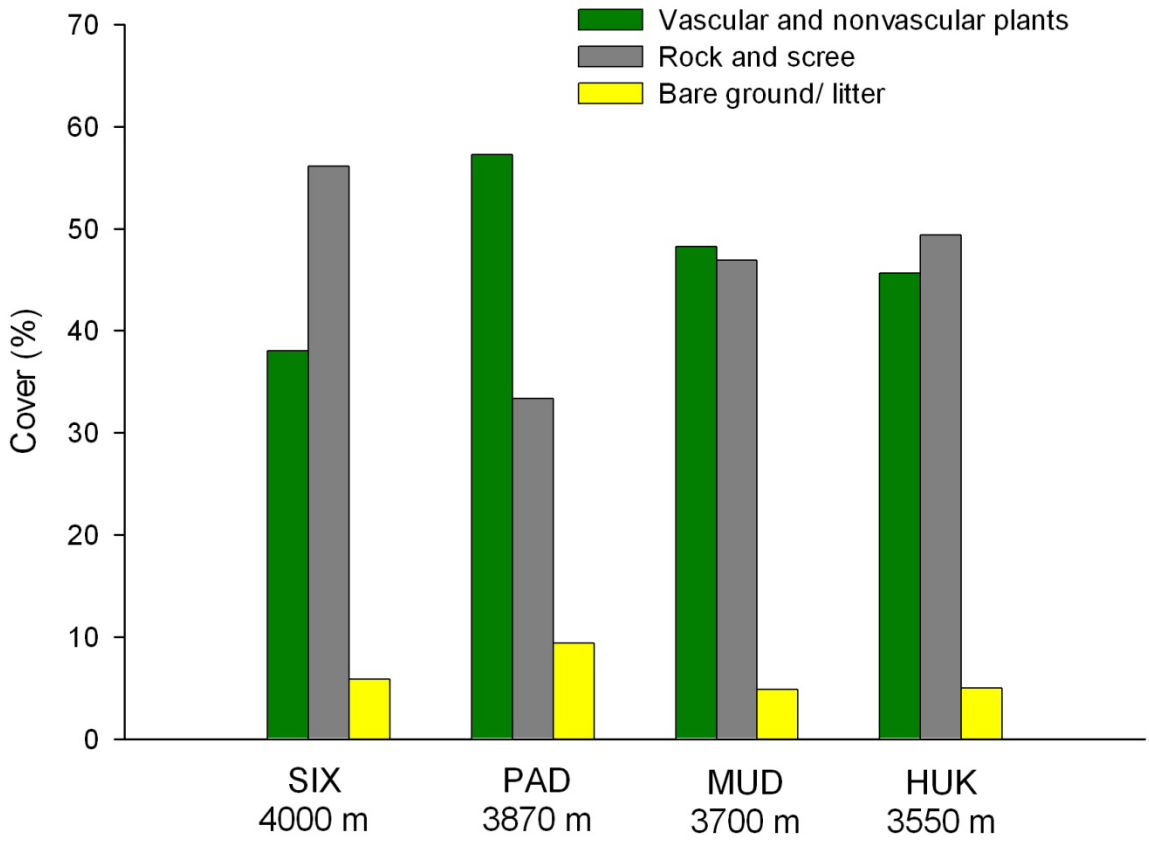


**Figure 4.** Mean vegetation, rock, and bare ground cover for each of the four sentinel GLORIA peaks at the Great Sand Dunes National Park and Preserve. The cover classes are averaged from the summit to 10 m below the summit.

A total of 83 vascular plant species were found on the four summits (Appendix 1). The number of species varied among peaks and generally followed a trend of fewer species at higher elevations (Table 4). For the lower summits, we found 5 additional species after surveying the sections from 5 to 10 m below the summit. This pattern is likely due to an increase in the presence of subalpine species in the lowest parts of the summit. Forbs and graminoids were the most common growth form found on the summits, but we did find some rare instances of shrubs (*Potentilla fruticosa*) and trees (a *Populus tremuloides* seedling and a small *Pinus aristata*). The most common species found on SIX were three graminoids: *Kobresia myosuroides, Carex rupestris,* and *Poa glauca* and one forb, *Trifolium nanum*. PAD was also dominated by *K. myosuroides* and *C. rupestris* but the most common forbs were *T. dasyphyllum* and *Minuartia obtusiloba*. MUD was similar to PAD but *C. rupestris* was not as abundant and instead, a forb *Arenaria fendleri var fendleri* was one of the most abundant species. Finally, *K. myosuroides* was also common on the lowest peak, HUK, and other common species included three forbs: *Potentilla pulcherrima, A. fendleri var. fendleri*, and *T. dasyphyllum.*

**Table 4.** Number of species present on four alpine sentinel sites within the target region of GRSA.

| GLORIA Summit code | Elevation (m) | Number of species to 5 m | Additional species found between 5 and 10 | Total number of plant species on summit |
|---|---|---|---|---|

| | | below summit | m below the summit | |
|---|---|---|---|---|
| SIX | 4000 | 45 | 1 | 46 |
| PAD | 3870 | 50 | 1 | 51 |
| MUD | 3700 | 49 | 5 | 54 |
| HUK | 3550 | 55 | 5 | 60 |

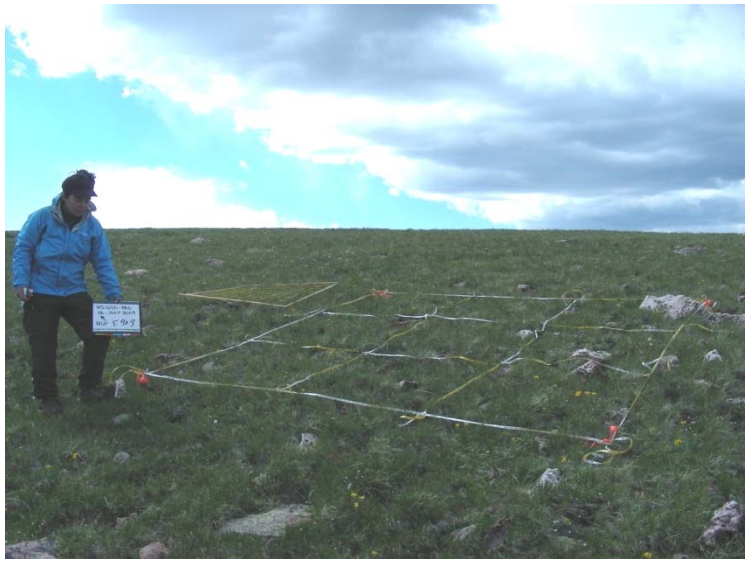

**Figure 5.** Phyllis Pineda Bovin on the east side of PAD peak in Great Sand Dunes National Park and Preserve (July 2009, Photograph by Isabel Ashton). The peak is flat and well vegetated compared to the others in the region, particularly SIX.

### *Frequency and Cover Quadrats*

An array of 1 $m^2$ quadrats on each aspect of each peak were used to measure the fine-scale variation in plant cover and frequency. Total plant cover in the quadrats differed among summits ($F_{3,20}$= 4.3, *P*=0.016), with PAD having the highest cover of vegetation. There was no significant difference by aspect for vegetation cover. In other words, the north, east, south, and west side had similar cover or ~ 42%. In contrast to this, we found no difference in total rock cover among the summits but rock cover differed by aspect ($F_{3,20}$= 4.1, *P*=0.020). Quadrats on the north side of peaks have lower cover of rock (~22%) than the south (~38%; *P*=0.019) and tend to have lower vegetation cover than the east (33%, *P*=0.056). These trends were similar to those seen in the larger summit areas.

As with the summit area data, we found that the number of plant species present in the quadrats also varied by peak ($F_{3,20}$= 30.2, P<0.001) where SIX had significantly fewer species than all other peaks (*P*<0.001). SIX averaged 13 ± 0.8 (mean ± 1 standard error) species per quadrat while PAD averaged 21 ± 1.0, MUD averaged 18 ± 1.4, and HUK averaged 19 ± 2.0 species. We found numerous showy flowers and cushion plants typical of the alpine tundra (Figure 6).

**Figure 6.** Four common alpine species found in the US-GSD region. Clockwise from upper left *Tetraneuris brandegeei* (Brandegee's four-nerve daisy), *Silene acaulis var. subacaulescens* (moss campion), *Eritrichium nanum* (Alpine forget-me-not), *and Castilleja haydeni* (Hayden's Indian Paintbrush). (July 2009; photographs by Phyllis Pineda Bovin and Isabel Ashton)

## Invasive/Exotic Plants

Of the 83 species identified from the US-GSD region, only one species of exotic plant was found: *Taraxacum officinale* (dandelion). *T. officinale* was present on the lower peaks with a scattering of individuals on the north and east aspect of MUD and the east side of HUK. There were no exotic species present on SIX or PAD.

## Soil Condition

In general, the soils in the alpine at the sentinel sites in GRSA were thin and rocky. The soils at the sites are comodore (shallow, well-drained, stony loam) soils range from 0-20 inches thick. On the highest peak, where scree and rock covered large portions of the summit, there was relatively little soil. PAD, a large flat summit, had the most stable and developed soils. We found no evidence of soil erosion in the form of rills, gullies, or pedestals at sites. There was however, a great deal of soil disturbance at MUD peak presumably caused by elk and burrowing rodents (Figure 7). HUK was characterized by a great deal of scree and steep slopes, limiting soil development.

**Figure 7.** A view to the east from MUD peak at Great Sand Dunes National Park and Preserve (July 2009; photograph by Isabel Ashton). Patches of bare soil are apparent in the lower portions of the photograph and likely indicate disturbance from elk or small mammals.

Soil aggregate stability is a direct measure of the ability of the soil to adhere to cohesive units (peds), it is a function of soil type and condition and requires ongoing inputs of carbon (plant biomass) to bind soil particles together (Herrick et al. 2005). Soil aggregate stability was measured on each aspect of all four peaks using an index from 1 (unstable) to 6 (stable). We found there was no significant difference between aspect but there was a difference among peaks for subsurface stability ($F_{3,47}$= 3.4, $P$=0.025). PAD, the peak with the most vegetation cover, had the most stable soils particularly in comparison to HUK (Figure 8).

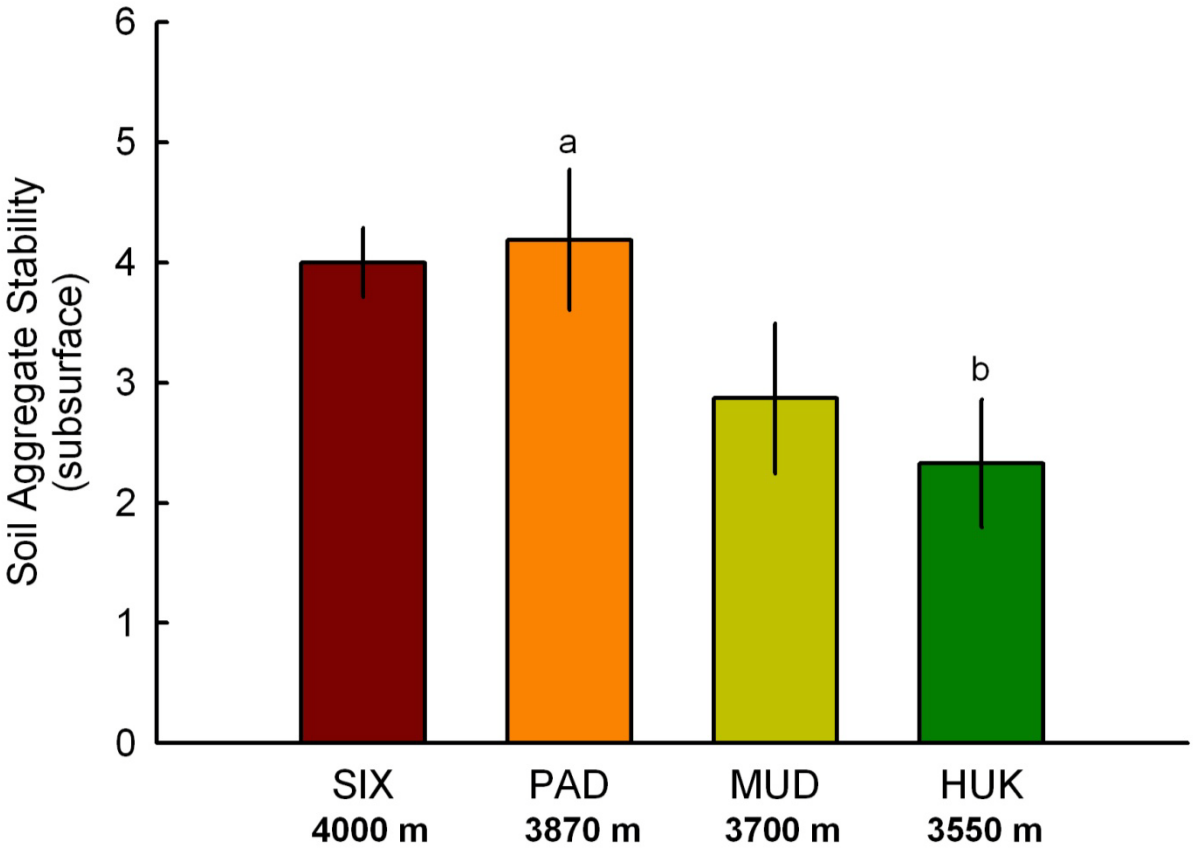


**Figure 8**. Subsurface soil aggregate stability at four sentinel peaks in Great Sand Dunes National Park and Preserve. Bars indicate means ± 1 standard error and different letters indicate means that are significantly different from one another.

## Anthropogenic and Natural Disturbance

### *Disturbance in quadrats*

Disturbance was measured as the frequency of visible trampling (hoof prints, flattened plants), browsing (broken stems and/or missing flower heads), and scat in 1 $m^2$ quadrats on all summits. In general, we found little evidence of trampling or browsing within the quadrats and there was no significant difference in trampling across peaks or by aspect. While still rare, we found that browsing did differ among peaks ($F_{3,20}$= 8.2, $P$<0.001) where MUD averaged a rate of 3.25% of the quadrat browsed while the other peaks were closer to 0. Scat was fairly common on all peaks but the frequency found in quadrats varied by peak and direction ($F_{9,20}$= 2.5, $P$=0.045). The east side of MUD peak had the highest frequency of scat, with a mean frequency of 14% of the quadrat. Elk, marmots, and ground squirrels were seen on the peaks during the sampling period. Elk were particularly abundant on MUD peak and marmots were common on the summit of SIX.

### *Qualitative disturbance indices*

In addition to measures of disturbance at the quadrat scale, we also conducted a qualitative assessment of anthropogenic and natural disturbance on the site to ~ 1 km around the site. Using these assessments, we found all four summits to be pristine (Figure 9). In other words, the landscape was void of disturbances such as nearby roads, intense recreation, or logging pressures. Moreover, the area was unfragmented, dominated by native vegetation, and there were not hydrologic or physical modification

of the landscape. Natural disturbances were more common. We found there to be a moderate level of disturbance at SIX due to frost heave, rodents, and native herbivory (Figure 9). Rodent disturbance was characterized by burrows and disturbed soil. Native herbivory was characterized from wallows, browsed and trampled vegetation, and hoof punching. There was little to no natural disturbance visible at HUK and the two middle peaks, PAD and MUD, showed some evidence of rodents and native herbivores.

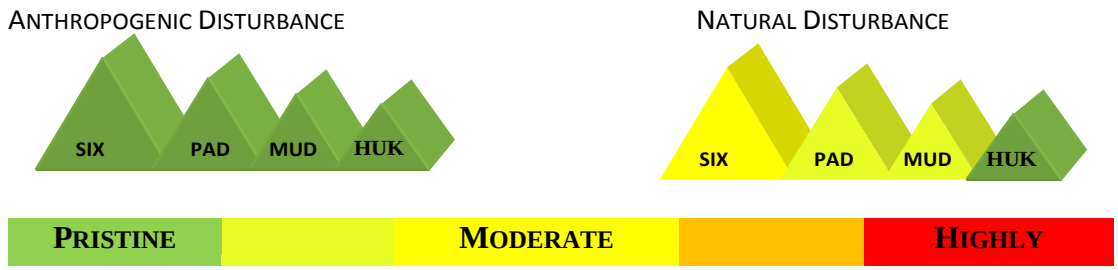


**Figure 9.** Scales of natural and anthropogenic at four sentinel peaks in Great Sand Dunes National Park and Preserve.

## Temperature

The temperature datalogger measured hourly temperatures under a rock pile on the summit of MUD peak from July 2008 to July 2009. The temperatures were generally very cold on MUD peak (Figure 10). Freezing temperatures began in October 2008 and were common through May and June 2009. February was the coldest month with an average daily temperature of -8.1 °C (17.3° F), and August was the warmest with mean temperatures of 9.8°C (49.6°F). The average temperature range per day was about 8°C (14°F), with the greatest range found on February 28, where the difference between the minimum temperature and maximum was 18°C (32°F). Strong daily variation in temperature suggests snow cover was less than 50 cm.

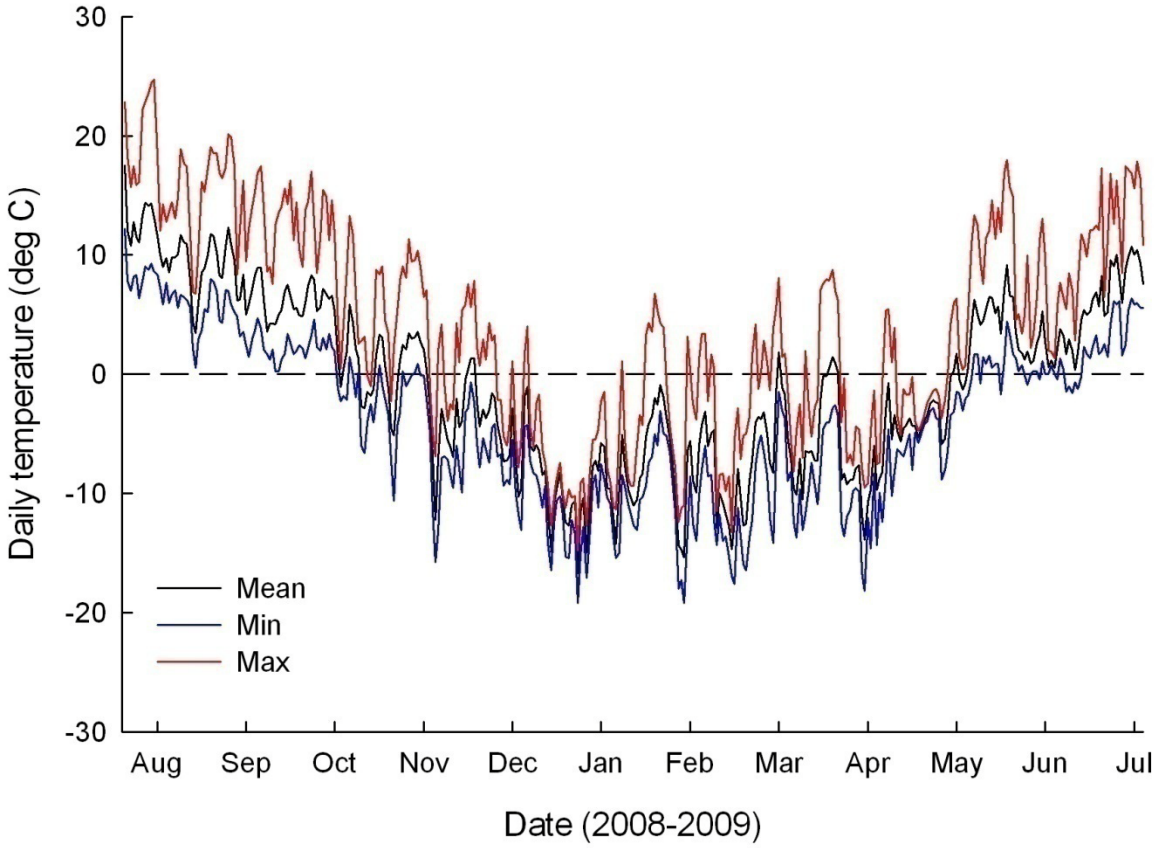


**Figure 10.** Daily temperatures from July 2008 to July 2009 at the summit of MUD peak (3700m) in Great Sand Dunes National Park and Preserve.

# Discussion

The goal of our alpine monitoring effort in GRSA is to determine the status and trend in five parameters: vegetation composition and structure, invasive/exotic cover, soil condition, and disturbance, and soil temperature. As of 2009, we have completed the first full season of field work and while we have increased our understanding of the status of the alpine at the four sentinel sites, we cannot yet describe trends. Since our sampling was conducted at only four sites we cannot make park-wide inferences on the status of the alpine. Below, we summarize the results from above and highlight some of the most interesting aspects of the alpine monitoring program.

We found the vegetation structure and soils of the alpine tundra in GRSA to be typical of fell-field and alpine turf communities (Zwinger and Willard 1996) as it was dominated by sedges and grasses with a high diversity of forbs. Compared to other grassland types, the alpine tundra shows high local diversity (Gough et al. 2000) and this was certainly true of our sites. In one quadrat on PAD we record 26 species in a 1 $m^2$ area. Trees and shrubs were rare in the sites, but not completely absent. We found woody species at the two lowest peaks, but the site lowest in elevation, HUK, was the only where we found trees (one aspen seedling and a small bristlecone pine). We found the fewest species on the highest peak which is consistent with the general pattern that diversity often declines with elevational, a pattern which is thought to be driven by a reduction in area at high elevations (Rahbek 1995).

Climate changes may affect biodiversity and species richness in the alpine by contributing to the extinction of some species while simultaneously increasing the elevation and latitudinal limitations of other species. A survey of summit sites in the Alps of Switzerland showed that vascular plants have been establishing at higher altitudes than recorded earlier (Grabherr et al. 1994). Thus, it is assumed that an upward and northward migration of plants, induced by recent climate warming, is an already ongoing process in some areas. In the future we will monitor changes in species distribution, particularly woody species, to determine if species are migrating upward in this region. We expect the greatest changes to be seen at the lowest peak, HUK, where woody species and some subalpine species are already present. In the short-term, we are likely to see increases in number of species observed at the lower peaks, but over the longer term it is possible that some alpine species will be lost from these sites.

In addition to the upward migration of species, climate change may allow for the spread of exotic/invasive species into the alpine where they are typically limited by the harsh environment (Pauchard et al. 2009). We found only one exotic species in GRSA at the two lower alpine sentinel sites and no exotics at the sites at higher elevation. *Taraxacum officinale*, or common dandelion, the exotic present at the lower sites, originated in Eurasia and is considered naturalized throughout the United States. It is one of the few exotics that is found in the alpine and has also been found in GLAC and ROMO GLORIA sentinel sites. On the peaks where we found *T. officinale* there was a co-occurring and rarer native dandelion, *T. eriophorum.* It is unknown whether these two species directly compete, but future work will include monitoring the presence and abundance of the native with an effort to determine if there is a correlation between increasing abundance of the exotic and a decline in the native. Work from the alpine in Chile suggests *T. officinale* can compete with native alpine wildflowers for pollinators and affect their reproduction potential, but only when present in high densities (Muñoz and Cavieres 2008). If climate changes continue and temperatures warm at GRSA, we expect that sampling in future years will reveal an increase in the frequency of *T. officinale* and an increase in the number of other exotics present.

Observing and documenting land use and natural episodic events can provide insight into understanding status and trends in vegetation composition, structure, and soils. Disturbance can act as a strong driver of

change and cause direct alterations in community composition and disturbances may be of particular interest to park staff because they may be able to reduce disturbances through changes in land management (e.g., reroute trails). In the alpine regions of GRSA current anthropogenic disturbances are minimal (Figure 8). Historically the area was used for sheep grazing and there is some evidence of mineral exploration. Currently, none of the sentinel peaks have trails to the top, although we did find a cairn and hiker log on SIX. Still, the last entry was more than 3 years ago, suggesting very few people access these sites. The largest user group is most likely hunters, but any localized disturbance caused by them (e.g. garbage, trails, camps) was restricted to below treeline.

In high elevation systems with historically low nitrogen availability, the influx of nitrogen (N) from pollution has caused changes in vegetation, soil, snow, and water chemistry (Fenn et al. 2003). Field measures of N deposition are beyond the scope of our qualitative assessment of anthropogenic impacts. The National Atmospheric Deposition Program (NADP) measures wet deposition of inorganic N (ammonium and nitrate) in two nearby locations which may be used to infer loadings in GRSA. In 2008, 0.33 kg/ha of inorganic N fell in Alamosa (2298 m) and 2.9 kg/ha fell at Wolk Creek Pass in Pagosa Springs, CO (3292 m) (NADP 2009). For Alamosa this level is the lowest since the program began in 1980. For Wolf Creek Pass, deposition is the lowest it has been since 2003. Both are lower than those found in northern Colorado (NADP 2009). In the future, we will continue to track N deposition rates in the area to determine whether they may be affecting the vegetation at the four sentinel summits.

As with anthropogenic disturbance, we found little evidence of natural disturbance at the four sentinel peaks. Elk, marmot, and ptarmigan scat was found at all the sites but there was little evidence of browsing or trampling damage. Elk browse heavily on willow species and can dramatically impact the structure of communities (Baker et al. 2005). Surprisingly, we did not find any willow species at our sites and this may be related to high historic herbivory rates by elk or sheep. However, there are many alternative explanations for the lack of willows including low water availability and dispersal limitations. Our qualitative index of disturbance suggested that the highest summit, SIX was subjected to the greatest amount of disturbance (although still moderate) and this was in the form of frost heave, elk, and rodent disturbance.

The alpine at GRSA is characterized by extremely cold temperatures and a short growing season (Figure 8). Compared to temperatures in Alamosa (2299 m a.s.l.) for the index period of 1971-2000, monthly maximum temperatures on MUD peak (3700 m) averaged 9.3°C (16.8° F) cooler. The data we reported came from a pilot test of only one temperature logger. We do not have data to compare MUD peak to the other sentinel sites, nor do we have temperature data from different aspects of the peaks. We placed 16 temperature loggers into the alpine of GRSA (4 per summit) in July 2009, and will download these data in the summer of 2010. We expect that temperatures will decrease with increasing elevation, but the close proximity of HUK, MUD, and PAD make it likely that temperature patterns are quite consistent across sites. SIX is the highest and further south of the other peaks and while we assumed it is in the same climate region as the other peaks (a prerequisite of a GLORIA target region), the data from 2009-2010 may be used to verify this assumption. It remains unknown whether temperatures differ by aspect on any one peak, however the variation in vegetation across aspects and experience in the field suggest that the west side may be the coldest. Overtime, the temperature records collected at these sites will greatly add to our understanding and documentation of climate change in the alpine at GRSA.

In summary, the four sentinel sites at GRSA represent stable and healthy alpine ecosystems. We found 83 vascular plant species in the target region and only one exotic species. The soils were generally thin but stable, vegetation cover was high and human and herbivore disturbance was minimal. As with much of the alpine zone in the Rocky Mountains, mean daily temperatures remained below freezing for most

of the time period between October 2008 and May 2009. We found the most variation in vegetation and cover was across the peaks, rather than among aspects, and differences tended to correlate with elevation. For instance, the highest peak SIX had the fewest species and the lowest peak HUK had the greatest number of species. This implies that low temperatures are currently limiting the expansion of species upward. Future monitoring efforts should document change at these alpine sentinel sites with a particular focus on species diversity and climate change.

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# Appendix 1: US-GSD target region species list

| Species | SIX 5m | SIX 10m | PAD 5m | PAD 10m | MUD 5m | MUD 10m | HUK 5m | HUK 10m |
|---|---|---|---|---|---|---|---|---|
| Achillea millefolium L. var. occidentalis DC. | | | | | | | | X |
| Allium geyeri S. Watson | | | | | | | | X |
| Androsace chamaejasme Wulfen | X | X | X | X | X | X | X | X |
| Androsace septentrionalis L. | X | X | X | X | X | X | X | X |
| Antennaria rosea Greene | | | | | | | | X |
| Arenaria fendleri A. Gray var. fendleri | X | X | X | X | X | X | X | X |
| Artemisia scopulorum Gray | X | X | X | X | X | X | X | X |
| Besseya alpina (Gray) Rydb. | | | | | | | | |
| Calamagrostis purpurascens R. Br. | X | X | X | X | X | X | X | X |
| Campanula rotundifolia L. | | | | X | X | X | | |
| Carex albonigra Mack. | | | | X | X | X | X | |
| Carex rupestris All. var. drummondiana (Dewey) Bailey | X | X | X | X | X | X | X | X |
| Castilleja haydenii (A. Gray) Cockerell | | X | X | X | X | X | X | X |
| Castilleja occidentalis Torr. | | | | | | | X | X |
| Cerastium beeringianum Chamisso & Schlechtendal | | | | | | | | |
| Cirsium scopulorum (Greene) Cockerell ex Daniels | | | X | X | X | X | X | |
| Claytonia megarhiza (Gray) Parry ex S. Wats. | X | X | X | X | X | X | X | X |
| Cruciferae in US-GSD | | | | | | | X | X |
| Danthonia intermedia Vasey | | | | | | | | |
| Deschampsia cespitosa (L.) P. Beauv. | X | X | X | X | X | X | X | |
| Draba aurea Vahl ex Hornem. | X | X | X | X | X | X | X | X |
| Draba streptocarpa A. Gray | X | X | X | X | X | X | X | X |
| Elymus scribneri (Vasey) M.E. Jones | X | X | X | X | X | X | X | X |
| Erigeron pinnatisectus (Gray) A. Nels. | X | X | X | X | X | X | X | X |
| Erigeron simplex Greene | X | X | X | X | X | X | X | X |
| Eriogonum flavum Nutt. | | | | | | | X | X |
| Eritrichium nanum (L.) Schrad. ex Gaudin var. aretioides (Cham.) Herder | X | X | X | X | X | X | X | X |
| Erysimum capitatum (Dougl. ex Hook.) Greene | | | | | | X | X | X |
| Festuca brachyphylla J.A. Schultes ex J.A. & J.H. Schultes | X | X | X | X | X | X | X | X |
| Frasera speciosa Dougl. ex Griseb. | | | | | | | | |
| Geum rossii (R. Br.) Ser. var. turbinatum (Rydb.) C.L. Hitchc. | X | X | X | X | X | X | X | X |
| Heterotheca pumila (Greene) Semple | | | | | | | | |
| Heuchera parvifolia Nutt. ex Torr. & Gray | X | X | X | X | X | X | X | X |
| Kobresia myosuroides (Vill.) Fiori | X | X | X | X | X | X | X | X |
| Lewisia pygmaea (Gray) B.L. Robins. | | | | | | | | |
| Lloydia serotina (L.) Rchb. | X | X | X | X | X | X | X | X |
| Luzula spicata (L.) DC. | X | X | X | X | X | X | X | X |
| Mertensia lanceolata (Pursh) DC. | | | X | X | X | X | X | X |
| Minuartia macrantha (Rydb.) House | | | | | | X | X | X |
| Minuartia obtusiloba (Rydb.) House | X | X | X | X | X | X | X | X |
| Oreoxis alpina (Gray) Coult. & Rose | X | X | X | X | X | X | X | X |
| Species | SIX 5m | SIX 10m | PAD 5m | PAD 10m | MUD 5m | MUD 10m | HUK 5m | HUK 10m |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Oxyria digyna (L.) Hill | X | X | X | X | X | X | X | |
| Paronychia pulvinata A. Gray | X | X | X | X | X | X | X | X |
| Pedicularis parryi A. Gray | | | | | | X | X | X |
| Penstemon whippleanus Gray | | | | | | | | |
| Phacelia hastata Dougl. ex Lehm. | | | | | | | | X |
| Phleum alpinum L. | X | X | X | X | X | X | | |
| Phlox condensata (Gray) E. Nels. | X | X | X | X | X | X | X | X |
| Phlox multiflora A. Nelson | | | | | | | | |
| Pinus aristata Engelm. | | | | | | | | |
| Poa alpina L. | | | | | | | | X |
| Poa glauca Vahl subsp. rupicola (Nash ex Rydb.) W.A. Weber | X | X | X | X | X | X | X | X |
| Poa sp. in US-GSD | | | | | X | X | X | X |
| Polemonium viscosum Nutt. | X | X | X | X | X | X | X | X |
| Polygonum bistortoides Pursh | | | | | | X | X | X |
| Populus tremuloides Michx. | | | | | | | | |
| Potentilla diversifolia Lehm. | X | X | X | X | X | X | X | X |
| Potentilla fruticosa L. | | | | | | | | |
| Potentilla ovina Macoun | X | X | X | X | X | X | X | X |
| Potentilla pulcherrima Lehm. | X | X | X | X | X | X | X | X |
| Potentilla subjuga Rydb. | X | X | X | X | X | X | X | X |
| Primula angustifolia Torr. | X | X | X | X | X | X | X | X |
| Pulsatilla patens (L.) Mill. subsp. multifida (Pritz.) Zämelis | | | | | | | | |
| Rhodiola integrifolia Raf. | X | X | X | X | X | X | X | X |
| Saxifraga bronchialis L. subsp. austromontana (Wieg.) Piper | X | X | X | X | X | X | X | X |
| Saxifraga chrysantha Gray | X | X | X | X | | | | |
| Saxifraga flagellaris Willd. ex Sternb. | X | X | X | X | X | X | X | X |
| Saxifraga rhomboidea Greene | X | X | X | X | X | X | X | X |
| Sedum lanceolatum Torr. | X | X | X | X | X | X | X | X |
| Selaginella densa Rydb. | X | X | X | X | X | X | X | X |
| Senecio soldanella Gray | X | X | X | X | X | X | X | |
| Silene acaulis (L.) Jacq. var. subacaulescens (F.N. Williams) Fern. & St. John | X | X | X | X | X | X | X | X |
| Solidago nana Nutt. | | | | | | | | X |
| Taraxacum eriophorum Rydb. | | | | | | | | |
| Taraxacum officinale Weber | | | | | | | | |
| Tetraneuris acaulis (Pursh) Greene var. caespitosa A. Nelson | | | X | X | X | X | X | X |
| Tetraneuris brandegeei (Porter ex A. Gray) K.F. Parker | | | X | X | X | X | X | X |
| Thlaspi montanum L. var. montanum | X | X | X | X | | | | |
| Tonestus pygmaeus (Torr. & Gray) A. Nels. | | | | | | | | |
| Trifolium dasyphyllum Torr. & Gray | X | X | X | X | X | X | X | X |
| Trifolium nanum Torr. | X | X | X | X | X | X | X | X |
| Trisetum spicatum (L.) K.Richt. | X | X | X | X | X | X | X | X |
| Vaccinium caespitosum Michx. | | | | | | X | | X |