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MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Rachel N. Kreb

A Project Presented in Partial Fulfillment
of the Requirements for the Degree
Masters of Science
in Environmental Biology

REGIS UNIVERSITY
May, 2019

MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Rachel N. Kreb

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CHAPTER 1. LITERATURE REVIEW: RECRUITMENT TRAITS INFLUENCE SUCCESS OF ALPINE RESTORATION

Alpine environments are unique in that plant populations persist in high elevations where moisture fluctuates and climate varies interannually (Jonas et al., 2008; Krautzer et al., 2012; Billings & Mooney, 1968). To thrive in extreme alpine condition species implement distinctive strategies during early life stages (Forbis & Doak, 2004; Chen et al., 2017; Zoller & Lenzin, 2004; Roach & Marchand, 1984). Typical alpine strategies include slow growth rates and short growing seasons; alpine plants take a long time to develop (Willard and Marr, 1971; Agakhanyantz & Lopatin, 1978; Billings & Mooney, 1968; Wager, 1938). Slow growth rates pose an obstacle to the long-term goal of restoration after disturbance; to develop a self-supporting and resilient ecosystem without further maintenance takes longer with slow-growing plants (Urbanska et al., 1997). However, an understanding of the species traits that promote the recruitment, establishment, and succession of alpine plants informs restoration strategies to promote native plant diversity in alpine systems.

A trait is defined as a quantifiable measure of a function and can be used comparatively across species (Stokes et al., 2009; Silvertown et al., 1993). Quantifiable trait distinctions between species can be used in selecting target plant species for revegetation (Stokes et al., 2009; Pywell et al., 2003). Differences in timing and magnitude of traits vary widely across species and likely affect the success of restoration projects considerably. Negative consequences associated with failed establishment could be amplified in disturbed or extreme alpine environments. New plant recruitment can create bottlenecks inhibiting long-term revegetation (Bell & Bliss, 1980). Germination, seedling growth, stabilizing roots, and the ability to facilitate

succession influence plant recovery after disturbance. These defining traits differ significantly between species, and understanding them can provide insight into which species to use in efforts to mitigate disturbance and increase biodiversity.

SEEDLING RECRUITMENT

Seedling recruitment plays a vital role in plant regeneration and is increasingly critical in the face of human disturbance (James et al., 2011). Recruitment is defined as the process by which new individuals initiate a new population, and patterns differ with species' life history strategies (Franco & Silvertown, 1996). Plants are more susceptible to disturbance in earlier stages, yet plants that survive past those early life stages often have high longevity. Recruited individuals have high survival rates in alpine systems, and therefore recruitment shapes community composition and controls plant recovery rates in newly established populations. The early life stages, therefore, pose a major bottleneck to revegetation in alpine systems (Bakker et al., 1996) and recruitment patterns should be considered in restoration planning and monitoring.

Alpine seedling recruitment is critical to understand because restoration efforts to establish new populations often fail due to high seedling mortality. Additionally, plant growth and recovery after disturbance are slow in alpine conditions. Current research centers around management methods including seeding, transplanting, and substrate stabilization, but little research exists regarding the species-specific demographic processes that drive seedling recruitment in alpine systems and their relative rates of success. Measuring seedling recruitment probabilities is critical to understanding ecological processes that influence the persistence of new populations. Using recruitment likelihood, adaptive management can avoid selecting ineffective recruiters and reduce long-term costs associated with failed establishment.

Seedling recruitment varies widely depending upon species characteristics and life history traits. Chambers et al. (1990) first connected the life history of alpine species and the ability to recruit after disturbance. Six alpine species were seeded in disturbed areas, and investigators found significant differences in the number of recruited individuals, depending upon the species. Chambers et al. (1990) also observed a distinct relationship between the time after restoration and new plant recruitment. Species differ both in the magnitude of recruitment and in progression over time. Species demographic research could improve large-scale seeding and transplanting outcomes aimed at native revegetation.

GERMINATION

Native revegetation relies on the successful germination of new individuals from seed mixes or seed via transplanted individuals. Germination is defined as the growing development from seed and is critical in establishing new plant populations from seed to seedling (Bliss, 1958). Germination timelines differ between species, and for many, the window of germination is narrow (Hoyle et al., 2015). Varying and narrow germination opportunities pose a challenge to recruitment in alpine systems that experience variable and extreme environmental conditions.

Hoyle et al. (2015) investigated variation in the germination strategies of alpine plants. Half of their investigated species only germinated after a cool, wet period, suggesting cold stratification eased a dormancy mechanism. Delaying germination until the spring after seeds are dispersed allows individuals to avoid risky and harsh winter conditions before seedlings reach a substantial size. If a seed were to germinate late in the growing season, there would be limited time to accumulate the biomass required to persist in harsh alpine winter conditions. Delaying germination until the following spring allows individuals to take advantage of the entire growing season to accumulate biomass. On the other hand, in milder conditions,

individuals may benefit by germinating immediately, beginning to accumulate biomass, and flowering within the first season (Hoyle et al., 2015). In conclusion, germination strategies vary widely between species. To identify species with a high likelihood of establishment requires research on plant demographics and differences in germination strategies between alpine species.

SEEDLING GROWTH

Alpine environments are considered harsh habitats, and species implement a range of adaptations to deal with the extreme climatic conditions. Under such conditions, plants face trade-offs in allocating limited resources for competing functions (Forbis & Doak, 2004). In botany, the allocation of scarce resources is often evaluated by comparing relative biomass accumulation in different functional parts of an individual plant (McConnaughay & Coleman, 1999). Biomass is the amount of living material in a given area, habitat, or region, and when biomass is compared between functional structures and species, areas of higher biomass can indicate higher importance of functions and life history patterns (Lavorel & Garnier, 2002). Management plans that take species type into account to manipulate the allocation of energy towards desired functions are more likely to lead to positive restoration outcomes.

Grime (1977) proposed that plants facing stressful environments tend to emphasize the stability of adult stages at the expense of growth and fecundity in early stages. Other studies align with this perspective; alpine plants exhibit a negative correlation between adult survival and fecundity, suggesting low rates of recruitment (Charnov, 1991). A contradiction exists between research showing that low growth during early life stages increases longevity and the observation that restoration success depends on high growth rates, even at early stages when healthy populations might exhibit low recruitment. Knowing how readily different species recruit can inform species choices in seed mixes and transplant material. Beyond that,

understanding their unique and specific patterns of recruitment allows us to better monitor populations and measure the progress of re-establishment in alpine systems, even with slow growth rates and unpredictable mortality.

STABILIZING ROOTS

Erosion commonly poses a challenge to establishment and an ideal plant would be effective in developing roots to slow runoff. Alpine plants persist on steep slopes that are prone to high erosion, especially when the vegetation cover and upper soil layer are disturbed. Roots influence stability, infiltration capacity, density, texture, and organic content of soil (Stokes et al., 2009). Roots increase soil texture roughness by creating small pores in the soil which slow the volume and velocity of runoff. Additionally, roots bind to soil particles, creating friction and further slowing low runoff (Stokes et al., 2009). Even more, stabilized soil traps seeds better, promoting recruitment. Species-level distinctions in root structure and function could be instrumental in identifying appropriate species to reduce erosion and trap seed.

Root size and structure vary considerably between different species. Highly competitive root systems are characterized by high root lengths per soil volume; these roots take advantage of soil exhaustively (Caldwell & Richards, 1986). In comparison, less competitive root systems have lower density of root length per soil volume, and while their roots cover long distances, they are not able to utilize soil as exhaustively. In infertile soils, less competitive root systems may be advantageous as they are better suited to inconsistent or spatially sparse resources (Fitter et al., 1988; Fitter, 1991). Additionally, coarse roots are better suited to penetrate hard soils and access deep water resources, providing better anchorage than finer roots. To conclude, assisted revegetation aims to reduce erosion, and selecting species based on root morphology could stabilize soil and promote native biodiversity.

Studies show that newly-colonized soil stabilizes as new plants recruit (Angers & Caron, 1998; Tisdall & Oades, 1979; Cochran, 1969). However, little research focuses on the influences of rooting type on improving rates and magnitude of revegetation in alpine plants. In extreme environments with slow growing plants, poor soil stabilization could be limiting recruitment. Mulch is used in restoration to reduce the loss of water and increase substrate temperatures to promote plant recovery (Cochran, 1969). Significant costs could be reduced if target species have specific root morphologies that stabilize soil, increasing soil recruitment and reducing the amount of mulch needed.

FACILITATING SUCCESSION

High biodiversity is widely accepted as a measure of ecosystem health (Ruiz & Aide, 2005). Higher species diversity in newly revegetated communities improves the ability to achieve the definition of long-term restoration to develop an ecosystem that is self-supporting and is resilient without further maintenance (Urbanska et al. 1997). Land managers use nurse plants to increase native plant diversity (Ren & Lui, 2008). Nurse plants facilitate the growth and development of other species by providing microhabitats ideal for germination and recruitment (Ren & Lui, 2008). Nurse plants are recommended in restoring plant diversity of degraded sites, especially in alpine conditions that limit recruitment and establishment.

Cushion plants serve as nurse species in alpine systems by modifying microenvironments to facilitate the establishment of other native plant species. Cushion plants' shape allows the plants to trap water and heat, cycle nutrients, provide shelter from wind, attract fungal and bacterial communities in their roots and rhizomes, and provide resources for arthropods and insects (Chen et al., 2017). By modifying their microenvironment, cushion plants improve growth and establishment conditions, increasing the survival probabilities of individuals and

essentially acting as a keystone species in alpine establishment. Nurse species increase germination and seedling establishment (Griggs, 1956), and therefore establishing nurse species would have significant long-term benefits to native diversity. In conclusion, cushion plants enable succession after disturbance and influence long-term native plant diversity.

Strength of facilitation varies across nurse species and selecting the right nurse species can define which new species establish, consequently determining the success or failure of restoration (Gómez-Aparicio et al., 2004; Sánchez Velásquez et al., 2004). Since early establishment acts as a bottleneck to revegetation, the ideal nurse species would provide optimal environmental conditions for overall recruitment. Alpine plants have short, and specific germination requirements and therefore the type of microhabitat a nurse species provides likely benefits some species more than others. Determining nurse species that are likely to facilitate establishment should be incorporated into alpine management to promote higher plant diversity.

MANAGEMENT IMPLICATIONS

In conclusion, human disturbance diminishes alpine plant biodiversity along montane recreational areas by limiting seedling establishment and population growth (Willard et al., 2007; Willard & Marr, 1970; Chambers et al., 1990). Human trampling near montane recreational trails eliminates plant cover over time and significantly diminishes soil stabilization, resulting in gaps of bare substrate with high erosion, which is not optimal for seedling recruitment (Chambers et al., 1990). Therefore, human disturbance threatens native plant communities in alpine areas, and this is an especially urgent problem in areas like Colorado with high levels of recreational activity. Few studies have assessed plant recovery of previous alpine trails or the effect of disturbance on recruitment and long-term restoration.

Recruitment patterns including germination, growth, soil-stabilizing roots, and the ability to facilitate succession of other native plants likely shape the long-term community composition in alpine systems in response to disturbance. Early life stages of alpine plants differ and can significantly influence establishment outcomes. Few studies exist that make clear distinctions between species' life history traits, particularly in the early stages of alpine plants. Species trait distinctions in early life stages remain prevalent in deciding which species are best suited to mitigate the effects of disturbance and loss of plant diversity.

Long-term monitoring can indicate whether species that germinate immediately or species that exhibit dormancy periods are better suited for plant recovery in alpine environmental conditions. Some argue for using a combination of germination patterns to increase the likelihood that at least one species will persist in spite of varying environmental conditions. However, little research exists relating demographic patterns to the success of alpine management.

Alpine plants face limited resources, especially new seedlings on disturbed soil. Unfortunately, high seedling mortality is common in efforts to revegetate previously-disturbed soil. Poor timing of growth could result in establishment failure, especially in harsh winter conditions. Comparing the timing and relative rates of growth between species and identifying ideal growth patterns could have beneficial results in the long-term.

Erosion impacts plant recruitment, species performance, and future colonization in moderate climates (Bell & Bliss, 1973). In response, selecting target species with higher soil-stabilizing properties in restoration planning would further promote long-term recovery (Ghestem et al., 2011). Others propose that using a diversity of root types to multiply soil texture at different depths and pore sizes is a better method of reducing erosion (Pohl et al.,

2009). Alternative viewpoints suggest that root type needs to be considered alongside germination patterns. Hagen (2002) tested several species based on their germination success rate and their rooting ability. Investigators concluded that the most effective strategy uses species with a combination of both high germination rates and high rooting ability (Hagen et al., 2002).

The long-term goal of restoring areas after disturbance is to establish a healthy, self-sustaining ecosystem with a high diversity of native plants. A nurse plant's capacity to support and promote establishment of other native species creates diverse community compositions over the long-term in alpine systems. The ability to do so differs among species, and quantifying the probability of facilitation could inform species decisions in seeding and transplanting. In conclusion, understanding ideal species traits that promote the recruitment, establishment, and succession of other native plants helps inform restoration efforts after disturbance. Research comparing population dynamics, germination strategies, growth rates, root-stabilizing properties, and the ability to facilitate succession between species would improve overall alpine restoration efficacy and promote native plant diversity.

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CHAPTER 2. GRANT PROPOSAL: ECOLOGICAL RESTORATION:
CUSHION PLANT FACILITATION ON ALPINE TRAILS

URSC COVER SHEET

Student Research and Scholarship Grant

Name(s): Rachel Krebs

Note: If multiple names, please indicate the primary contact person with an asterisk.

CBE CC&IS CCLS Regis College RHCHP

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Name and email of Faculty Advisor:

Dr. Catherine Kleier, ckleier@regis.edu

Project Title (Limited to 120 characters, including spaces)

Ecological Restoration: Cushion Plant Facilitation on Alpine Trails

This project involves (check all that apply):

Human Subjects (Attach IRB approval letter)

Vertebrate animals (Attach IACUC approval letter)

No Yes, I received funding for an URSC research grant in the past 2 years.

N/A No Yes, The funding I received in the past 2 years addressed the same research question that the current proposal addresses.

Applicant signature and date:

Rachel Krebs

April 10, 2018

Faculty Advisor signature and date:

ECOLOGICAL RESTORATION: CUSHION PLANT FACILITATION ON ALPINE TRAILS

ABSTRACT

Hiking trails serve as important infrastructure for nature-based tourism, and visitation to popular hiking trails continues to rise globally. Unfortunately, the trampling from hiking causes plant loss and soil disturbance. Alpine ecosystems are particularly susceptible to disturbance, yet little is known about the resiliency of their plant communities. I will monitor the progress of the Old Denny Gulch trail that was restored by the Colorado Fourteeners Initiative using cushion plants in their restoration efforts. Cushion plants are proposed for use in restoration because they are highly adapted to alpine conditions and can survive despite soil destabilization. Most interesting, however, is that cushion plants act as ecosystem engineers and support the plants living in their canopy. I will measure the success of restoration – paying attention to which species and plant traits perform best. I will also document the species and abundances of plants living in the cushion’s canopy, since little is known about these communities. Literature lacks the research necessary to inform effective restoration in those alpine areas affected by recreation. The project will use plant ecology research to inform adaptive restoration strategies in an ecosystem notoriously difficult to revegetate.

BACKGROUND/RATIONALE/SIGNIFICANCE

Colorado experiences heavy recreational activity along popular hiking trails in alpine mountain areas, causing significant loss to native plant diversity. This human-induced

biodiversity loss is a growing concern, especially as foot traffic on Colorado's trails continues to rise. Above the treeline, harsh conditions impede the restoration of plant diversity, ecological function, and resilience, so restoration efforts often fail (Urbanska, 1997). However, understanding factors that enable plants to persist in extreme alpine conditions and after heavy disturbance can improve our ability to mitigate human impact. Cushion plants are strong candidates for mitigating human impact because of their adaptation to extreme environmental conditions, their ability to persist in disturbance, and their role in supporting other native plants (Ren et al., 2008). Investigating how cushion plants respond to human-caused disturbance along recreational trails and what communities they support can be useful to inform adaptive management strategies in mountain environments.

CUSHION PLANTS

Cushion plants grow low to the ground, grow slowly, and can live up to 3,000 years old (Wickens, 2013). Their hemispherical shape allows them to persist in high wind conditions. They are called "ecosystem engineers" because they modify their microclimate by trapping heat, moisture, and nutrients. Their "engineering" benefits the cushion's own survival, and also creates favorable environments for other native plants (Figure 1). Since cushion plants support other species in their canopy, they could be advantageous to creating diverse communities after disturbance.

Cushion plants have fascinated botanists for their ability, even in stressful environments, to colonize bare soil, create "mini-ecosystems," and host communities of plants. Yet, little research has been done to assess the use of cushion plants in alpine restoration. Ecological theory predicts that as stress increases in an ecosystem, mutualisms become more prevalent and competitive interactions fade (Bertness & Callaway, 1994). This concept, referred to as the *stress*

gradient hypothesis, suggests that in human disturbance, mutualistic relationships become more common. If cushion plants exhibited more mutualisms in disturbed areas, that could have direct applications to developing restoration plans. The magnitude and diversity of the plant communities they facilitate would shape the long-term species composition, and are critical to understand.



Figure 1. Cushion plant canopy supporting other non-cushion plant species.
Photo credit: Alpadino, University of Basel

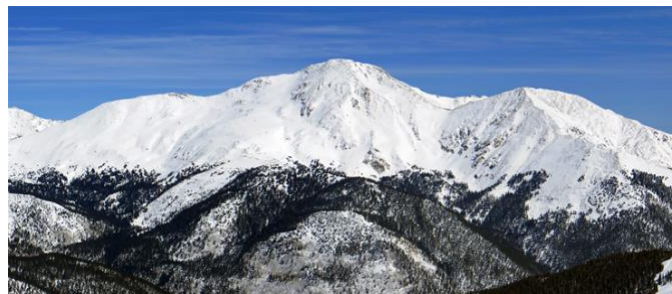


Figure 2. Mt. Yale's peak. Mt. Yale is a popular Colorado Fourteener in the Collegiate Peaks
Photo credit: 14ers.com

LOCAL RESTORATION MONITORING

The restoration of the Old Denny Gulch trail at Mt. Yale (Fig. 2.) poses an exceptional opportunity to study cushion plant performance. The Old Denny Gulch trail (38.8442° N, 106.3139° W) was a popular fourteener trail visited by hikers. Overuse of the trail has led to diminished plant cover, high levels of erosion, and decreased soil stability. To limit human impact, during the summer of 2011, the volunteers of the Colorado Fourteeners Initiative constructed a second trail to Mt. Yale's peak and closed off the Old Denny Gulch trail for restoration. Mature cushion plants and non-cushion plants were extracted from the surrounding area and transplanted in the trail. Since this initial revegetation effort, my research advisor, Dr. Catherine Kleier, and Regis University students have monitored aspects of the ecology along the trail. With their monitoring data and new botanical information on the species and abundances, we can get a better understanding of their success.

MISSION ALIGNMENT

Regis University emphasizes social responsibility, the search for truth, and the larger question of “how ought we to live?” If we aim to live justly, it is essential to have a sense of how our societal actions positively and negatively affect people, organisms, and ecosystems. Authentic living requires an awareness of the interconnectedness of our relationships with each other and the planet we depend upon. This study aims to use scientific research to recognize the effects of human impact to native ecology, to understand the complexities of restoring degraded ecosystems, and to develop methods for mitigating human impact to native communities in Colorado. This project’s relevance to larger issues of conservation and environmental stewardship align seamlessly with the mission and values of Regis University and socially responsible living.

PURPOSE AND SPECIFIC AIMS

The primary objective of this research is to monitor the success of revegetation of the Old Denny Gulch trail. As time progresses, I expect cushion plants will colonize soil more effectively. Since the initial restoration, I predict an increase in vegetation coverage and newly recruited individuals. However, I also anticipate significant differences in recruitment between different cushion plant species; understanding the relative performance of specific species is critical to developing land management strategies.

The monitoring of this trail can help us study the plant functional traits that result in the highest success. I expect smaller cushion plants to perform better than larger plants because their taproot serves a smaller area. I expect that as cushion plants grow, their canopy will maintain a higher diversity and abundance of other plants. Consistent with the *stress gradient hypothesis*, I

also expect to find that mutually beneficial interactions become more dominant in high-stress areas.

The third objective of this study is to determine whether cushion plants develop roots that reduce erosion. Erosion hinders revegetation and is especially high in alpine areas since there are no trees to slow runoff; therefore, an ideal plant would reduce erosion. I expect the roots of cushion plants and roots of the plants in their canopy to hold soil in place and reduce erosion. Therefore, in areas of more cushion plant coverage, I anticipate less erosion. I will characterize soil characteristics off trail, and each transect on trail (water tension, soil moisture, pH) to understand the environmental stress of the plant communities.

Accomplishing research goals to understand cushion plant dynamics and their use in the restoration of trails will be a major accomplishment in the field of ecology since limited literature exists on restoration of recreational trails above treeline with cushion plants, nor the diversity of plants they facilitate.

METHODS

Site Description

Mt. Yale, near Buena Vista, Colorado, is an alpine peak sitting above treeline at 14,196 feet elevation. The Collegiate Peaks are typically snow-covered from at least September through May.

Field Data Collection

Data for this project will be collected during three 3-day trips to Mt. Yale. I will measure out two sets of transects each consisting of a 10-meter sample area as wide as the trail with 90 meters in between each sample area. There will be one set of transects along the length of the trail. There will be a parallel set of transects that are not on the trail, but approximately 10

meters away in the adjacent plant community. I will repeat measurements taken by Dr. Catherine Kleier and Regis University students as a continuation of the ecological monitoring underway (Kleier, 2017). I will record the diameter of cushion plants, the number of non-cushion species in their canopy, and percentage cover of cushion plants. Additionally, new data will give a new perspective to previous data since I plan to identify all plants to the species level.

At the beginning of the field season, I will install instruments called erosion pins to measure erosion, following well-validated methods by Haigh (1977). To install erosion pins, iron rods are put into the substrate, and zinc washers go around the rod. The level of soil is measured at the beginning and the end of the field season, allowing for an estimate of the rate of erosion.

Data Analysis

I will sort cushion plant samples into age classes based on their diameter for demographic analysis (Benedict 1989). All statistical analysis will be performed using R version 3.4.3 and RStudio (RStudio Team, 2015). Using a linear regression model comparing cushion age over time, I will assess if new cushion plant recruitment has increased over time. With independent t-tests, I will evaluate differences in recruitment between cushion plant species. Performing another linear regression model comparing cushion size and species richness, I will determine whether the diversity and number of plants a cushion supports increases as their canopy grows. Using a multiple regression, I will assess how the effect of canopy size on diversity and number of plants a cushion plant can support varies between cushion plant species. To assess the *stress gradient* hypothesis, I will perform an independent t-test looking at total species richness to understand whether there is more facilitation in the trail compared to undisturbed areas. Lastly, I

will use an independent t-test to evaluate whether higher coverage of cushion plants exists in areas with lower rates of erosion.

WORK PLAN

I will conduct fieldwork during three 3-day trips (June 2-5, July 2-5, July 25-28) to the Old Denny Gulch trail at Mt. Yale. From June 2-5, I will establish 10-meter-long transects and install erosion pins. I will also collect plant data, and a full floristic survey of the area will be completed. From July 2-5, I will photo document cushion plant species, and species living in their canopy, take measurements from the erosion pins, and collect all plant data. From July 25-28, I will take final measurements from the erosion pins, remove them, and collect all plant data. After fieldwork is completed, I will perform statistical analysis and write a report of my results. Lastly, I plan to present findings at a scientific conference.

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URSC PROJECT BUDGET JUSTIFICATION TABLE

Name(s): Rachel Krebs

Project Title: Ecological Restoration: Cushion Plant Facilitation on Alpine Trails

Items <i>(Please itemize amounts below)</i>	Description	Funds requested from URSC	Funds requested from other sources	Source of other funds
Supplies				
1 100-meter field measuring tape	To measure transects			Will loan from Regis University Biology Department
3 60-inch measuring tapes	To measure transects			Will loan from Regis University Biology Department
Book: <i>Colorado Flora: eastern Slope</i> . 2001. William A. Weber and Ronald C. Whittmann. University of Oklahoma Press.	For plant ID			Will loan from Regis University Library
Book: <i>Guide to Colorado Wildflowers: Mountains</i> . Volume 2. 2005. G.K. Guennel. Westfliffe Publishers.	For plant ID			Will loan from Regis University Library
Book: <i>Rocky Mountain Flora</i> . JE Ellis. Colorado Mountain Club Press	For plant ID			Will loan from Regis University Library
Book: <i>Alpine Flower Finder</i> . JL Wingate and Loraine Yeatts. (Colorado Native Plant Society)	For plant ID		\$13.50 \$3.00	Colorado Native Plant Society
Book: <i>A Simplified Guide to Grasses</i> . JL Wingate. (Colorado Native Plant Society)	For plant ID		\$3.50	Colorado Native Plant Society
1 roll of flagging tape (Amazon)	To mark transects		\$4.75	Colorado Native Plant Society

1 clipboard	For data collection			Will loan from Regis University Biology Department
10 cast iron rods (Grainger Industrial Supply)	For erosion pins		\$162 +\$25.15 (S&H)	Colorado Native Plant Society
10 zinc plated washers (Home Depot)	For erosion pins		\$3.33	American Alpine Club
1 Hammer	To install erosion pins			Will loan from Regis University Biology Department
Gas for travel to field site	regular unleaded gasoline for 3 trips (292 mi. x 3 = 876 mi.) (876 mi. x \$0.535 = \$468.66)	\$110.42	\$358.04	Colorado Native Plant Society (263.95) American Alpine Club (94.09)
2 128GB San Disc Memory cards (Amazon)	For photo documentation (\$63.79 x 2 memory cards = \$127.58)		\$127.58	American Alpine Club
32GB Memory Card	For photo documentation (\$24.15)		\$24.15	Colorado Native Plant Society
Camera for photo documentation	For photo documentation in field			Will use personal DSLR
Altitude Meter (Sun Company)		\$74.25		
12" Jet Fill Tensiometer (Ben Meadows)	To measure soil water tension	\$149.00 + \$9.00 (S&H)		
Soil pH and moisture meter (Forestry Suppliers)	To measure pH and moisture levels in soil	\$119.95 + \$9.00 (S&H)		
The Globe Soil Color Book (Forestry Suppliers)	Portion of cost - To analyze qualitative soil characteristic \$65.00 + \$9.00 (S&H)	\$28.38		

Stipend for field assistant	Stipend for 2 assistants for one 3-day trip of 3 trips		\$1,000	American Alpine Club
Total		\$500.00		

Amount requested from URSC: \$500.00

Please list any additional grants or sponsorships you are applying for and the amount(s) received:

American Alpine Club – Applied and Received
\$1,225.00

Colorado Native Plant Society – Applied and Received
\$500.00

URSC PROJECT BUDGET JUSTIFICATION NARRATIVE

Supplies:

Gas to the field site

I plan to complete data collection within three backpacking trips to Mount Yale with Regis University students and Dr. Catherine Kleier. As a result of short growing seasons in alpine conditions, I am limited to collecting sufficient data within a relatively short time frame. Species flower at different times and 3 trips allow me to collect all data and identify species based on flower structure.

I can use some funds to cover a portion of the total gas required, so the remaining request is \$110.42.

Altitude meter

Colorado poses a great opportunity to study how ecology changes with elevation, and transects are set up at different elevations. An accurate measurement of the elevational changes in this study would allow us to accurately compare plant success at different elevations. This research is in alpine regions, where environmental stress is directly associated with elevation. This tool could have a number of applications to the research and teaching in the Regis Biology Department.

Can be purchased from the Sun Company for \$74.25.

12" jet fill tensiometer

This scientific instrument measures soil water tension. A tensiometer provides an estimate of how difficult it is for plants to physically extract water from the soil. The availability of this instrument to Regis' Biology department could be useful in field studies and student research in the future. The ability to measure the availability of water to vegetation is important to understanding ecosystem health.

Can be purchased from Ben Meadows for \$149.00 + \$9.00 (shipping and handling) = \$158.00

Soil pH and moisture meter

Plants have specific pH ranges for optimal growth. Soil that is too acidic or too basic decrease the availability of important nutrients plants need. Again, there are a number of applications of this instrument to studies of environmental biology in the Regis Biology Department.

Can be purchased from Forestry Suppliers for \$119.95 + \$9.00 (shipping and handling) = \$128.95

Globe soil color book

Soil color reflects the minerals present and the organic content. These factors influence plant biology and will be important to measuring success of restoration.

Can be purchased Forestry Suppliers for \$65.00 + \$9.00 (shipping and handling)

Research Assistant(s):

TBD

Other:

NA

Total Amount Requested from URSC: \$496.58

RELEVANCE TO COURSEWORK/CAREER GOALS

My research focuses on how plant functional traits influence restoration and mitigate human impact to ecosystem health. The study encompasses my interests in understanding how botany and ecology can inform restoration. The project fits in with skills I'm developing in Advanced Field Ecology Lab, Environmental Biostatistics, Ecological Modelling and Research Design at Regis University, enabling me to execute it successfully. Since I'm pursuing a career in ecological research that mitigates human impact, this project aligns seamlessly in reaching that goal. Additionally, I'll use writing and analytical skills to prepare reports and present findings at a conference. This year's celebration of scholarship was lovely, and it made me appreciate the diverse range of study the University Research and Scholarship Council supports. If awarded, I would welcome the opportunity to present research at the event.

CHAPTER 3. JOURNAL MANUSCRIPT: CUSHION PLANT REVEGETATION
AND RECOVERY AFTER RECREATIONAL TRAMPLING ON A
COLORADO FOURTEENER

ABSTRACT

Cushion plants are candidates for revegetation on former alpine trails as they are well-adapted to extreme environmental conditions, persist through disturbance, and facilitate the establishment of other plants. This 7-year study monitored cushion plant transplants and grass transplants used to restore a closed trail on Mount Yale. Overall, the grasses saw more population growth than the cushion plants. Almost all of the cushion plant transplants died, but recruits established on their own. *Minuartia rubella* became the most dominant cushion plant to establish on the revegetated trail. The cushion plants that came into the trail facilitated species from varying elevation and soil moisture preferences. However, cushion plant species did not support distinct canopy communities. Therefore, rather than focus on particular cushion plant species during revegetation, managers should prioritize the cushion plant that contributes the most plant cover to stabilize the soil. With such low success using cushion plants as transplants, land managers should consider alternative methods of seeding and transplanting younger cushion plant individuals.

Cushion Plant Revegetation and Recovery After Recreational Trampling on
a Colorado Fourteener

Colorado experiences heavy recreational activity along hiking trails in alpine mountain areas, causing significant loss of native plant diversity. This human-caused biodiversity loss is a growing concern as foot traffic to Colorado's trails continues to rise, increasing damage to off-trail areas. Above the treeline, harsh environmental conditions with long winters and high winds slow new plant growth, so short-term revegetation efforts often fail (Urbanska, 1997). However, finding novel revegetation techniques and understanding what enables plants to persist in extreme conditions can improve our ability to mitigate human impact. Cushion plants are candidates for alpine revegetation because of their adaptation to extreme environmental conditions, their ability to persist in disturbance, and their role in supporting other native plants (Ren et al., 2008).

Cushion plants are found on every continent. There are 1,309 recorded species of cushion plants covering 63 plant families (Aubert et al., 2014). North America hosts 87 of the 1,309 cushion plant species. Cushion plants are unique mat-forming plants found in alpine environments that earn their name from the dense dome of vegetation they create. Their dome structure buffers changes in temperature (Kyakatay & McGeoch, 2008), provides wind protection (Cavieres et al., 2006), collects moisture (Nunez et al., 1999), and increases soil nutrients (Cavieres, 2008). As the cushion plants provide those services, they create microhabitats that facilitate other plant species, ultimately increasing species diversity (Butterfield, 2013; Cavieres et al., 2014). Investigating the success of transplanting mature cushion plants to promote plant cover after disturbance and studying the communities they support will inform management of mountain environments degraded by frequent hikers.

In 2001, the Colorado Fourteeners Initiative (CFI) compiled US Forest Service data and found that attempts to climb fourteeners (peaks over 14,000 feet) had increased 300% over ten years (Conlin & Ebersole, 2001). In 2014 they used infrared sensors to count hikers and have found a 6-7% increase in visitation each year. The CFI reported 334,000 people hiked fourteeners during the 2017 hiking season. Increased visitation to Colorado's recreational hiking trails negatively affects mountain ecosystems. Hikers step on parts of plants and over time rip entire plants from the ground. Trampling not only reduces vegetation cover, but can also decrease the height of plants, alter the abundance of particular species (Bayfield, 1971; Bell & Bliss, 1973), and even eliminate rare species (Zika, 1991). Trampling widens montane trails and eliminates plant cover over time which diminishes soil stabilization, resulting in gaps of bare substrate with high erosion, conditions not optimal for seedling recruitment (Chambers et al., 1990). Therefore, human disturbance threatens native plant communities and becomes an especially urgent problem in places like Colorado with high levels of montane recreation. CFI constructs sustainable trails to prevent soil erosion, maintain plant cover, and preserve plant diversity. However, as sustainable trails are created, it is equally important to revegetate closed social trails. Revegetating closed trails proves challenging above treeline because of the combination of harsh environmental conditions and high levels of disturbance and erosion which prevent seedling establishment.

Cushion plants live in the mountains above the treeline, characterized by high elevation, climate variability, frequent moisture fluctuation, rocky substrate, low nutrient availability, and erosion (Korner, 2012). Given these conditions, several factors have to be just right for new plants to grow within a short growing season, persist through harsh winters, and reproduce to maintain healthy populations (Billings, 1974). Cushion plants grow low to the ground, grow

slowly, and can live up to 3,000 years (Wickens, 2013). Cushion plant growth rates can also vary tremendously from year to year and plant to plant (Kleier et al., 2015). Their unique semi-hemispherical structure and low height shelter these plants from the extremes of wind and temperature. Their canopy traps heat so efficiently that temperatures inside the plants have been observed up to 15 degrees higher compared to the air directly above, allowing them to resist fluctuating temperature and climate (Antonsson et al., 2009). Cushion plants would be excellent in restoration efforts due to their ability, even in stressful environments, to colonize bare soil, create “mini-ecosystems,” and host communities of plants (Molenda et al., 2012).

Cushion plants provide a habitat for plants that might not otherwise colonize bare soil, a process called facilitation. Because of their facilitating ability, cushion plants are considered a foundation species: a species that shapes the community structure by stabilizing local environments for other species (Dayton, 1972). Little is known about the recovery and succession of cushion plants following disturbance. I anticipate differential establishment between cushion plant species: some species are likely better adapted to the local conditions than others. Understanding the relative recovery of specific species is critical to plan effective revegetation. I expect cushion plant species support distinct communities of non-cushion plants, which has not been previously studied. Because cushion plants are a pioneer species that shapes alpine community structure, understanding which cushion species recover best, and the diversity of plants they support can shed light on the direction of plant communities after disturbance.

Ecological theory predicts that as stress increases in an ecosystem, mutualisms become more prevalent and competitive interactions fade (Bertness & Callaway, 1994). This concept referred to as the *stress gradient hypothesis* suggests that when plants experience human disturbance, mutualisms increase. Therefore, on the trampled substrate, I predict cushion plants

will support a greater diversity of plants than would otherwise thrive in undisturbed areas. If cushion plants exhibit more mutualisms in disturbed areas, that could have direct applications to developing restoration plans. A finding of more mutualisms in stressed conditions might suggest that cushion plants bring a greater diversity of plant species into disturbed areas, and promote greater plant diversity, which is a common goal of restoring degraded ecosystems.

The primary objective of this research is to measure the success of using cushion plants to revegetate trampled alpine areas. As time progresses after revegetation, I expect cushion plants will colonize soil more effectively. I also predict an increase in recruited individuals. However, I also anticipate significant differences in recruitment between different cushion plant species. The role of cushion plants in supporting other plants could make them appropriate candidates for restoring plant communities. I expect that as cushion plants grow in size, their canopy will maintain a higher diversity and abundance of other plants. Consistent with the stress gradient hypothesis, I also expect to find more facilitative relationships with cushion plants in stressed areas.

In 2011, to reduce human impact to a popular fourteener trail, the CFI created a sustainable trail to Mount Yale's peak which relies on a rock base, rather than trails where visitors trample directly on soil which leads to erosion. After creating the trail, the CFI placed signs to cut off foot traffic to the Old Denny Gulch trail and then revegetated it using mature cushion plants and grasses from the adjacent plant community and replanting them into the closed trail. In this study, I compare the recovery of the six cushion plant species observed on the trail following revegetation (*Phlox condensata*, *Minuartia obtusiloba*, *Minuartia rubella*, *Paronchia pulvinata*, *Silene Aucaulis*, and *Trifolium nanum*). Species likely differ in the magnitude of recruitment and progression over time. Species demographic research could

improve large-scale seeding and transplanting outcomes aimed at native revegetation. The strength of facilitation also likely varies across cushion plant species and selecting the right nurse species can define which non-cushion species establish, determining the success or failure of restoration (Gómez-Aparicio et al., 2004; Sánchez Velásquez et al., 2004). Grasses are commonly used to revegetate disturbed areas because their root systems are well-adapted to harsh environments and frequent change. Comparing the cushion plant transplantation to grasses serves as a measure against a known technique. However, using cushion plants in alpine revegetation is novel and untested.

This study will address the following questions:

- Did the mature cushion plants transplanted into the closed trail survive?
If cushion plants can persist in disturbance, the cushion plants transplanted into the trail will survive.
- How did the population growth of cushion plants compare against grasses?
If grasses are early successional species in alpine environments, they will experience more population growth than cushion plants.
- Which cushion species established best and facilitated the most diverse canopies?
No research to date has documented which cushion plant species are at Mount Yale or the broader Collegiate Peaks Wilderness. This study will serve as a general botanical survey.
- Do cushion canopy communities change with the size of cushion plant, cushion plant species, elevation, slope, and soil moisture?
I expect canopy communities are shaped by the size of cushion plant, cushion plant species, elevation, slope, and soil moisture.

- Do cushion plants facilitate more species in a stressed environment or an undisturbed environment as would be consistent with the stress gradient hypothesis?

Consistent with the stress gradient hypothesis, I expect cushion plants will facilitate more species in the trampled area compared to the untouched area.

Alpine revegetation proves challenging; evaluating new techniques can promote restoration efforts. The proposed study is one of the first to investigate the use of cushion plants in revegetating closed hiking trails and can be valuable to organizations committed to trail maintenance and revegetation in Colorado and more broadly in alpine mountains across the world. Further, no one before has compared cushion species recovery after disturbance, nor the plant communities they support. This information contributes to a growing knowledge of alpine successional communities following human disturbance.

METHODS

Site Description

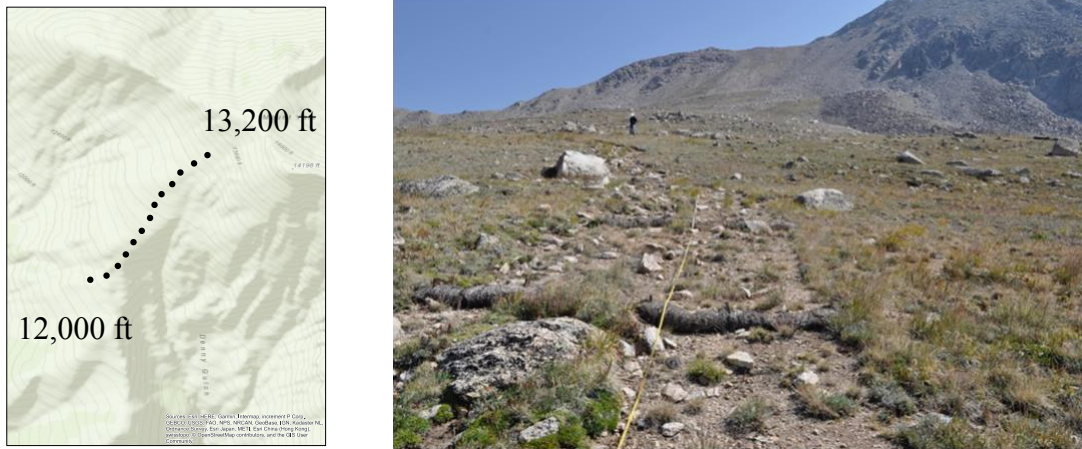


Figure 1. Site location with each black dot representing a data collection plot. 13,200-12,000 feet elevation. On the right, the closed and revegetated trail with measuring tape used to establish plots.

Mount Yale, near Buena Vista, Colorado, is an alpine peak sitting at 14,196 feet elevation. Mount Yale is in the Collegiate Peaks of the San Isabel National Forest, which are typically snow covered from at least September through May. Overuse of the Old Denny Gulch trail has led to diminished plant cover, high levels of erosion, and decreased soil stability. In the summer of 2011, volunteers with the Colorado Fourteeners Initiative constructed a second trail for hikers to Mount Yale's peak and closed off the Old Denny Gulch trail for restoration. Revegetation included extracting mature vegetation plugs made of grasses and cushion plants from the surrounding area and transplanting them into the former trail. Volunteers transplanted these plugs, and as such, the size of plugs varied from 8 to 30 cm in diameter. During this initial effort and for several years following (2011, 2012, 2014, 2015, 2017, and 2018), Dr. Catherine Kleier, monitored the population of cushion plants and grasses along the trail (Kleier & Trenery, 2017).

Plant Species

Table 1. Cushion plant species observed in the revegetated trail.

Cushion plants	Common name
<i>Minuartia rubella</i>	beautiful sandwort
<i>Minuartia obtusiloba</i>	twinflower sandwort
<i>Silene acaulis</i>	moss campion
<i>Paronchia pulvinata</i>	rocky mountain nailwort
<i>Trifolium nanum</i>	dwarf clover
<i>Phlox condensata</i>	dwarf flox

Table 2. Non-cushion plant species observed in cushion plant canopies in the revegetated trail.

Non-cushion plants	Common name
<i>Cedum lanceolatum</i>	spearleaf stonecrop
<i>Tonestus pygmaeus</i>	pygmy serpentweed
<i>Sibaldia procumens</i>	creeping sibaldia
<i>Trifolium perryi</i>	parry's clover
<i>Bisorta vivipora</i>	alpine biswort
<i>Geum rossii</i>	ross' avens
<i>Festuca brachyphylla</i>	alpine fescue
<i>Trisetum spicatum</i>	spike trisetum
<i>Carex</i>	sedge species
<i>Castilleja</i>	indian paintbrush
<i>Kobresia myosuroides</i>	bellardi bog sedge
<i>Gentiana algida</i>	whitish gentian
<i>Artemesia borealis</i>	northern sagewort
<i>Lusulia spicata</i>	spiked woodrush

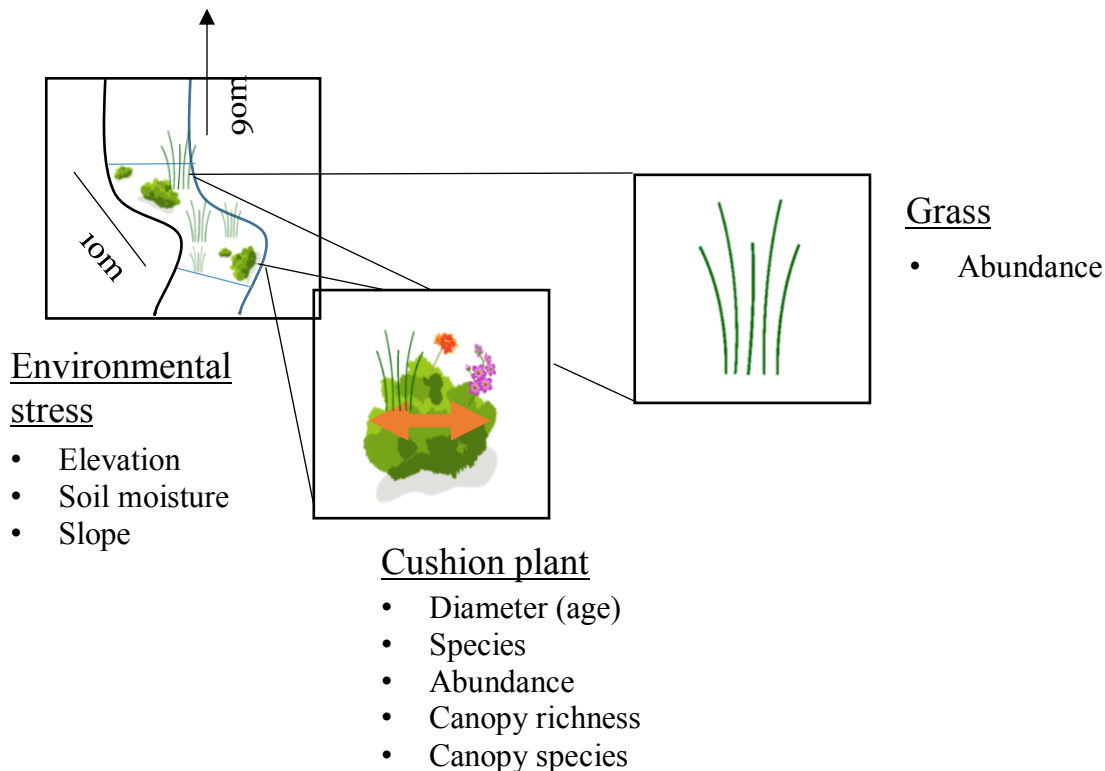


Figure 2. Study design. At each plot, we collected soil samples, elevation, and GPS locations to measure environmental stress. Each cushion plant individual was identified and measured. All the plants growing in cushion plant canopies were identified. Grass abundances in each plot were recorded.

Data Collection

I collected data during three 3-day backcountry trips with volunteers to Mount Yale in the summer season. At 13,200 feet elevation, the new trail branches off from the closed trail. Starting there, following the length of the closed trail downwards in elevation, I established plots every 90 meters. Each plot ran 10 meters the length of the trail and as wide as the trail's edges. A second set of plots of equal size, slope, and elevation were created parallel to the trail, 10 meters away in the adjacent plant community. We sampled a total of 13 plots before reaching treeline at 12,000 feet elevation.

In 2018, I repeated grass and cushion plant measurements taken by Kleier in previous monitoring years (2012, 2014, 2015, 2017) (Kleier & Trenery, 2017). Since botanists use the

diameter of cushion plants as a proxy for age and biomass of cushion plants (Benedict, 1989), I recorded the diameter of each cushion plant. In 2018, with the expertise of botanist Mike Kintgen, I identified cushion plants growing in the trail to the species level. I also identified the non-cushion plant species living inside those cushion plants to the species level. Canopy richness was calculated by summing the number of canopy species in cushion plants growing in the trail and cushion plants growing off the trail.

One way to evaluate a new technique is to compare it against a recognized one. Because grasses transplant well, I compared the population growth of the grasses with that of the cushion plants. In the final monitoring year, I recorded grasses either as transplants or recruits based on their size. In the last year, I estimated the overall vegetation cover in the trail as a percentage of each plot.

Elevation was recorded at the top of each plot using an altimeter. I used a Garmin GPS Map 62s to record GPS location at the top and bottom of each plot. Using GPS coordinates, ArcMap, and the National Map elevation layer at 1 arc-second resolution, I estimated the vertical and horizontal distance between the top and bottom point to calculate the slope at each plot (US Geological Survey, 2017). Soil samples were taken using a corer to 5cm depth. With 24 hours of sampling, I weighed the soil samples before and after drying at in a standard drying oven 100° for 48 hours to calculate the percentage of moisture in each soil sample.

Data Analysis

Each cushion plant was considered one of the transplants or a recruited individual. I considered cushion plants larger than 8cm in diameter to be the original transplants. Any plants smaller than 8cm in diameter were considered recruits that established since the revegetation. I used bar graphs to illustrate how the populations of the original transplants and newly established

cushion plants changed over time. I compared the community each year to the baseline monitoring year (2012) to calculate the percentage growth since the revegetation. In the final monitoring year, I sorted the cushion plants into size classes based on their diameter. To compare the cushion plant transplants and grass transplants, I calculated the percentage of the population that had survived since the baseline year.

I summed the number of individuals of each cushion plant species in the trail community to measure abundance. As a proxy for biomass, I estimated the surface area of each cushion plant based on its diameter. I summed the surface area of cushion plants of each cushion plant species. Importance values, commonly used in forestry describe the dominance of species based on biomass and abundance were used to compare the dominance of cushion plant species. Therefore, I calculated importance values for each cushion plant species in the trail community. For each cushion plant species, I calculated the maximum number that an individual plant facilitated, the average number of plants facilitated per individual, and the range of species that was facilitated.

I created a community matrix of the cushion plant species surface area. I used the community matrix to generate a distance matrix using a Bray-Curtis dissimilarity index. I used nonmetric multidimensional scaling (NMDS) ordination to assess the effect of elevation, soil moisture, and slope on the cushion plant community structure. The number of dimensions used to describe the community composition in the ordination was selected to minimize stress.

I performed a second NMDS ordination to describe how the non-cushion canopy communities among cushion plant species, with the size of the cushion plant, elevation, soil moisture, and slope. The community matrix used presence-absence data of plants living in cushion plant canopies. I again used a Bray-Curtis dissimilarity index to create a distance matrix

for ordination. The number of dimensions used to describe the community composition in the ordination was decided upon to minimize stress. Lastly, to test whether cushion plants facilitate more non-cushion plant species, I used a one-sample t-test to compare canopy richness of between cushion plants in the revegetated trail and the adjacent community. All statistical analyses were performed using R statistical software (R Core Team, 2013).

RESULTS

Cushion plants that the CFI transplanted into the trail didn't survive well. In the final monitoring year (2018), the population of the original transplanted cushion plants fell to only 14% of the baseline monitoring population (Fig. 3a). However, there was promising recruitment. By the final monitoring year, the population of newly recruited cushion plants since transplantation had grown to 180% of the baseline population (Fig. 3b). I compared the cushion plant population each year to the first year's population (Fig. 3c). The majority of cushion plants in the final year were smaller, younger plants, with a mean diameter of 4.4 cm (Fig. 3d). By the final monitoring year, the population of all cushion plants rose to 156% of the baseline population. Comparatively, the grasses rose slightly more to 192% of its baseline population.

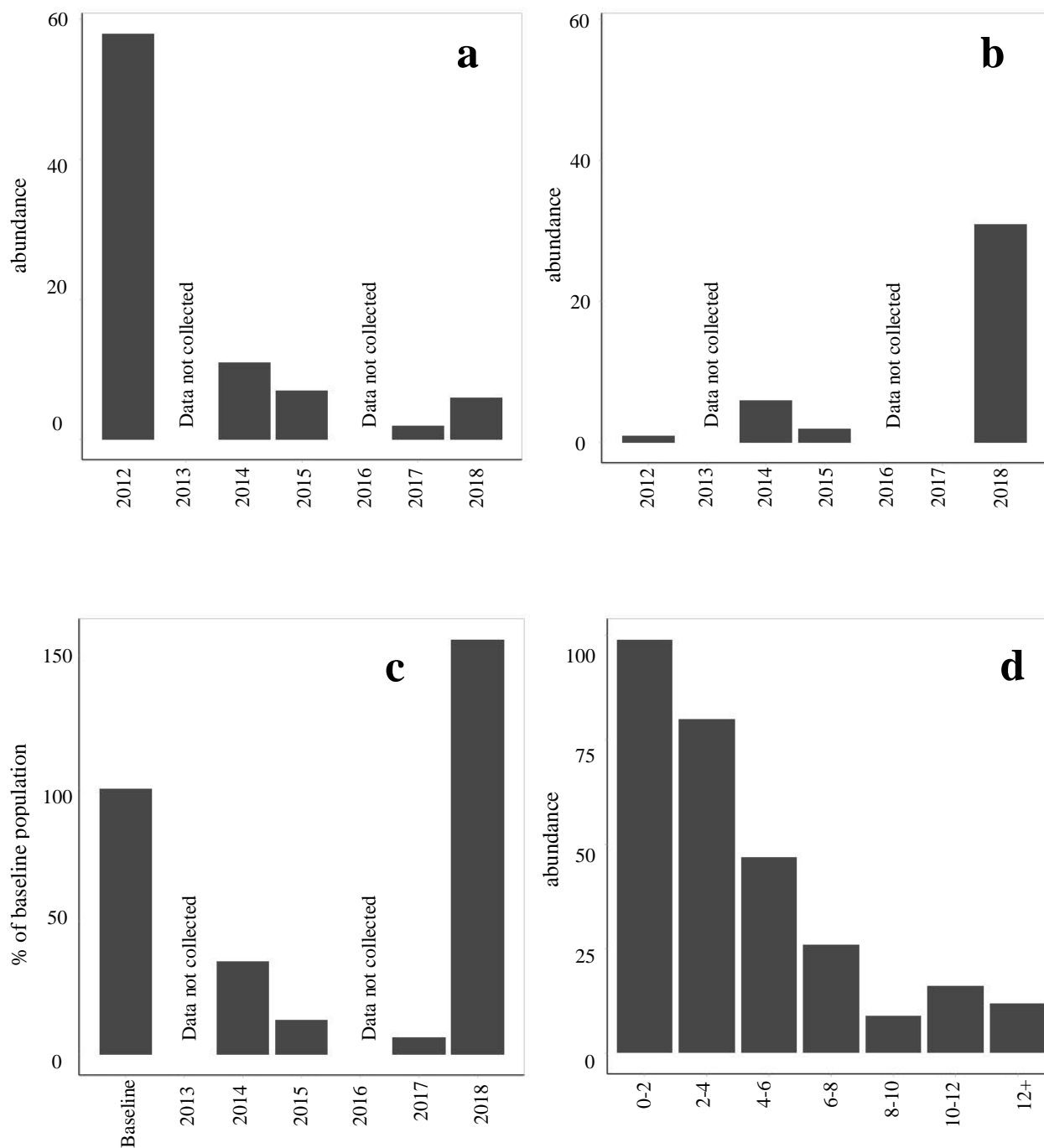


Figure 3. (a) Number of cushion plants that were transplanted into the trail in 2011 (individuals with diameters larger than 8cm). (b) New cushion plants that established into the trail since 2011 (individuals with diameters smaller than 8cm). (c) Percentage of population since the baseline monitoring year (2012). (d) Number of cushion plants in 2018 sorted into size classes according to diameter length (cm).

According to the importance values, *Minuartia rubella* was the most dominant, followed by *Minuartia obtusiloba* and *Silene acaulis* (Table 3). *Silene acaulis* facilitated the highest maximum number of species per individual plant (4), followed by *Trifolium nanum* (2). When considering the species as a whole, *Silene acaulis* facilitated the broadest range of non-cushion species (9), followed by *Minuartia rubella* (4). *Plox condensata* facilitated, on average the highest number of species per cushion plant (0.33), followed by *Silene acaulis* (0.30) and *Trifolium nanum* (0.21). *Paronchia pulvinata* was the only species found not to facilitate any non-cushion species.

Table 3. Calculated importance values for each species of cushion plant.

Cushion plant species	Importance value
<i>Minuartia rubella</i>	1.206
<i>Minuartia obtusiloba</i>	0.496
<i>Silene acaulis</i>	0.214
<i>Paronchia pulvinata</i>	0.118
<i>Trifolium nanum</i>	0.057
<i>Phlox condensata</i>	0.016

Elevation ($p=0.048$) significantly influenced the composition and abundance of cushion plants in the trail (Fig. 4., NMDS ordination). Alternatively, slope ($p=0.593$) and soil moisture ($p=0.717$) did not significantly influence the composition and abundance of cushion plants that established into the trail. At the highest elevation, *Minuartia rubella* was most commonly found, followed by *Trifolium nanum*. Elevation ($p=0.001$) and soil moisture ($p=0.001$) significantly influenced the composition and abundance of plants living in cushion plant canopies (Fig. 5., NMDS ordination). Slope ($p=0.094$) and size of cushion plant ($p=0.860$) did not significantly affect the composition and abundance of plant living in cushion plant canopies. Species of cushion plants did not facilitate distinct non-cushion plant communities (Fig. 6.).

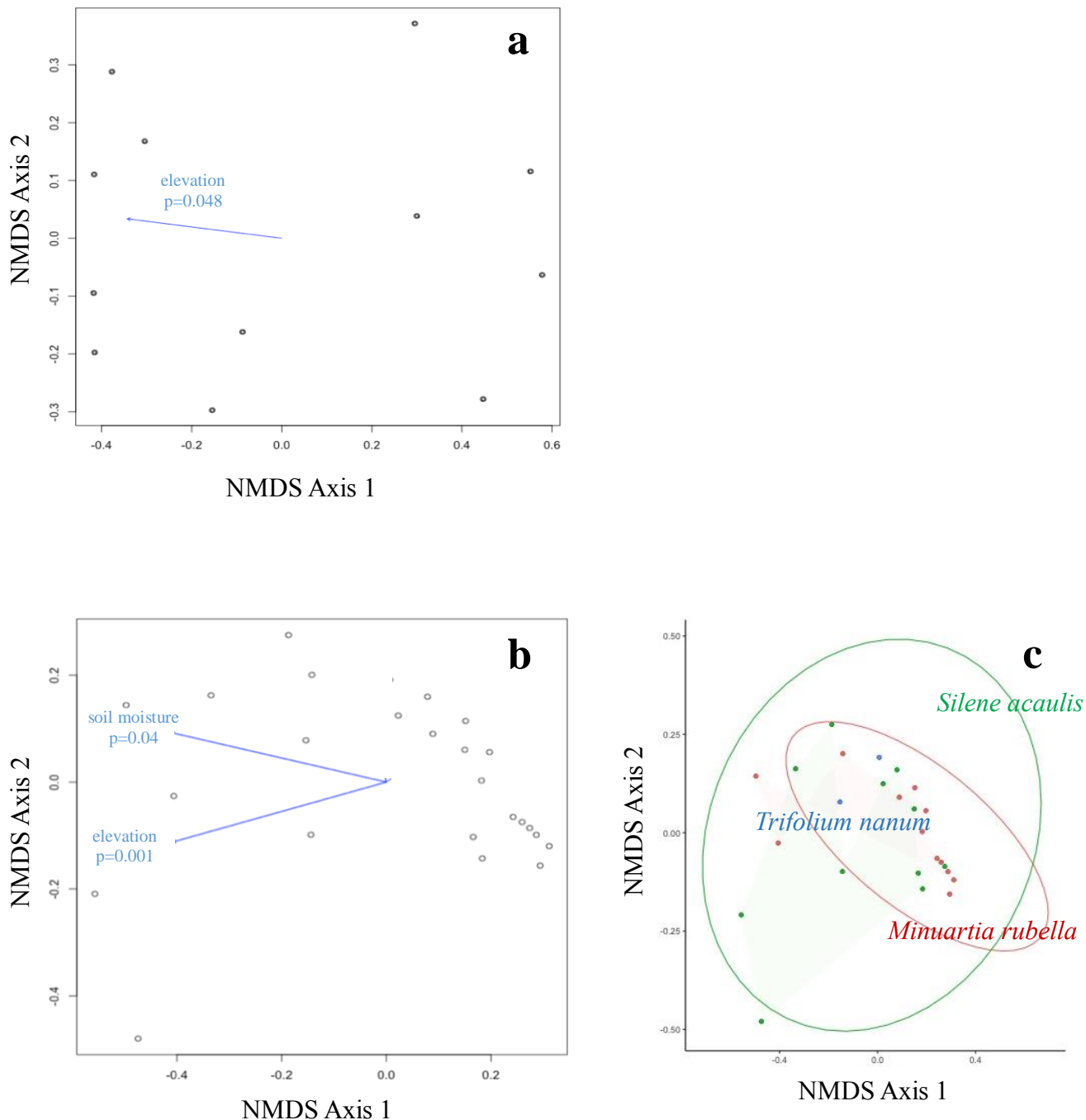


Figure 4.

(a) NMDS ordination using a Bray-Curtis distance matrix of the cushion plant species and sizes that established in the trail. The 2 NMDS axes explained approximately 87% variation in the community composition. (b) NMDS ordination using a Bray-Curtis distance matrix of cushion plant canopy species living in cushion plants. The 2 NMDS axes explained approximately 97% variation in the community composition. (c) NMDS ordination using a Bray-Curtis distance matrix of cushion plant canopy species living in each species of cushion plants. The 2 NMDS axes explained approximately 97% variation in the community composition.

Lastly, cushion plants in the trail facilitated on average, approximately <1 more cushion species than cushion plants in the adjacent unstressed community ($p=0.028$, one-sample t-test).

DISCUSSION

Transplanting mature cushion plants was not effective as most died after only seven years. Because cushion plants develop long taproots, it is possible that while transplanting, volunteers were unable to dig up entire roots, leaving the plants unable to absorb soil water and nutrients. However, since cushion plants are known to persist in disturbance, it was unsurprising that recruitment was so strong, suggesting cushion plants will establish on their own if given time. During the seven-year study, Dr. Catherine Kleier observed flowering of the transplanted cushion plants, so it is possible seed material came from those mature cushion plants. It is unclear whether recruited cushion plants established from the seed of the transplanted cushion plants, seed from the adjacent plant community, or the soil seed bank. However, this study cannot answer the question of where cushion plants facilitated from but poses an opportunity for further study.

Options other than transplanting mature individuals should be considered to revegetate former alpine trails. Grasses transplanted well and can be used to provide plant cover and stabilize soil, yet do not offer the benefit cushion plants provide by bringing in higher species diversity. Cushion plants are still important pioneer species in early successional stages. One New Zealand study followed the succession of an alpine community following disturbance (Brown et al., 2006). Because their research spanned 24 years, it was unique because it encompassed primary and secondary stages of succession. In the last 11 years, the researchers noticed that succession accelerated. In the second half of the study, the researchers noticed grasses that were abundant in the early stages decreased, and they saw an increase in other

species as overall plant cover increased. So, while the transplanted grasses survived well and their overall population increased, they are early pioneer species that could fade during secondary succession. Therefore, ensuring other species are introduced and can establish should be a goal of alpine revegetation. Further, this shift in the plant community after 11 years emphasizes a need for long-term monitoring to document the stages of succession. Alpine cushion plants may facilitate plant species in early successional stages, but become overrun as the species they facilitate flourish (Connell & Slayter, 1977).

Collecting and dispersing local cushion plant seed could be a viable option; however, few have attempted this with high success at alpine sites. Collecting seed and growing young cushion plants in greenhouses or growth chambers and transplanting them while still young would allow for the entire root to be transplanted and could also be considered. Until better methods are substantiated with future studies documenting their efficiency, passive restoration might be plausible, especially since we observed strong recruitment after only seven years. However, future study is still needed to better understand how to actively restore degraded alpine sites to minimize time, resources, and energy expended.

Ultimately, while the plants that were facilitated by cushion plants changed with elevation and soil moisture; different cushion plant species did not facilitate distinct plant communities. Therefore, focusing on certain cushion species may not alter the direction of the plant community. However, the cushion plants did differ in the number of species they facilitated and in how dominant they became in the trail. After seven years, *Minuartia rubella* became the most dominant in the trail but wasn't the best facilitator. *Phlox condensata* and *Silene acaulis* facilitated the most species per plant on average but made up a much smaller portion of the trail community. *Minuartia rubella*, the most dominant cushion species did,

however, facilitate the broadest range of non-cushion plant species, second only to *Silene acaulis*.

In this study, *Silene acaulis*, the popular cushion plant, facilitated the widest range of non-cushion plant species overall and the second highest number of non-cushion plant species per plant. This is not surprising, as *Silene acaulis* is well known in scientific literature for its facilitating ability (Molenda et al., 2012; Boananomi, 2016), especially in early successional stages (Kjaer 2018). One study found that of all the cushion plant species, researchers have published most on *Silene acaulis* at 12 publications, followed by *Azorella monantha* with 7 publications (Reid et al., 2010). Far less gets written about the ecology of *Minuartia rubella* and *Phlox condensata*. It surprised me that no literature exists about the two most dominant cushion plants we encountered on the trail. The lack of literature on these cushion plant species highlights a knowledge gap and reflects the early stages of alpine botany research.

Because cushion plants did not support distinct communities, one could argue that revegetation should focus on the cushion plant that establishes the fastest and persists longest. The idea being that because any cushion species will be able to support a range of non-cushion plants, the one that contributes the most plant cover and stabilizes soil would be advantageous. Besides the grasses, there were no non-cushion plants seedlings outside of cushion plants, suggesting these plants cannot establish yet in the degraded area and still rely on a nurse plant to recruit in the early stages. A common goal of restoration is to re-introduce diversity to degraded areas. Therefore, one could alternatively argue that the most important cushion plant to re-establish is the one that facilitates the highest number of other plants, or the broadest range of species because it would bring in the most number of non-cushion plant species. However, that may be flawed; in this study the species that facilitated the best made up a small portion of the

cushion plant cover. Lastly, if a specific plant species was desired to reintroduce in restoration, one could focus on cushion plants that were known to facilitate that desired species.

One limitation of this study is that it captured only seven years following disturbance, a timeframe that encompasses only early successional stages. Future studies could evaluate the long term successional stages of the alpine plant community. As previously mentioned, a New Zealand study monitored the plant community of an alpine cushion field over 24 years and saw that after 11 years, the succession accelerated with a decrease in the grasses that were abundant in the early stages, and an increase in other species as plant cover increased. Therefore, short term monitoring provides a limited view of recovery, and longer studies can indicate more about the progression of alpine communities over time. Lastly, cushion plants statistically facilitated more cushion species on average in the degraded area; however, the difference was less than one species and not ecologically significant. Our finding did not align with the stress gradient hypothesis, consistent with other studies (Cavieres et al., 2006).

To conclude, transplanting cushion plants is not the best way of revegetating closed trails, but since cushion plants live well in disturbed areas they will establish on their own. Consistent with other studies, alpine revegetation is challenging and often fails, necessitating more research on alpine restoration techniques. Compared to other cushion plant species, *Minuartia rubella* recovered the best in terms of abundance and biomass; however, it did not facilitate the most diverse canopies. Alpine seedling establishment depends on soil stability (Chambers et al., 1990), therefore, even though *Minuartia rubella* didn't directly facilitate the most diverse canopies, it could be an important cushion species to promote because it contributes the most plant cover and stabilizes soil in early stages of succession. This paper is one of the first to assess the cushion plant community following disturbance and suggests more research is needed

to identify better alpine revegetation methods and understand the successional stages following disturbance.

As ecologists develop knowledge about how positive plant interactions structure communities in a range of ecosystems, these interactions can be integrated into restoration and land management. Researchers found that salt marsh restoration was much more successful when the restoration efforts focused on maximizing positive interactions by creating areas where plants improved soil conditions for other plants (Halpern et al., 2007). Comparatively, salt restoration was far less successful when plants focused on minimizing negative interactions by spacing out plugs to avoid competition. Therefore, incorporating positive plant interactions into restoration strategies could maximize their efficacy. Studying the structure of successional communities to identify advantageous ecological interactions and specific plant traits could be broadly useful in addressing the recovery of degraded ecosystems.

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CHAPTER 4. ENVIRONMENTAL STAKEHOLDER ANALYSIS: CREATING SUSTAINABLE TRAILS AND REVEGETATING ALPINE AREAS DEGRADED BY RECREATION

INTRODUCTION

Alpine areas provide ecosystem services humans rely on. Mountain regions retain water as snow during cold seasons, purify it, and release it in the late summer. Over half of the humans on earth depend on water resources from mountain regions (MA 2005). Alpine ecosystems are considered more sensitive to disturbance than other ecosystems (Geneletti 2008). Mountain areas are also popular travel destinations. While outdoor recreation provides important value to society, visitation also poses a threat to wilderness preservation. As Colorado continues to attract outdoor enthusiasts to recreational hiking trails, increased traffic degrades protected wild places. Many land managers seek ways to reach a healthy balance between human visitation and wilderness preservation; this is especially of concern in sensitive mountain environments with water resources humans rely on.

One problem land managers face is the deterioration of informal trails created by visitors. Social trails are informal trails not a part of any official trail network. Instead, they are created over time by consistent trampling and foot traffic by people and animals. Because visitors and not land managers create these social trails, they are not strategically planned to minimize erosion and impact to vegetation. Trampling eliminates plant cover and destabilizes soil causing erosion (Pickering & Growcock 2009, Willard et al. 2007). Intact vegetation retains sufficient water by holding water in place, slowing it and reducing erosion. Alpine plant cover, rare native

plant species, plant diversity, and water resources are at stake if unsustainable social trails continue to go unaddressed.

Land managers have several options to address damage from unofficial social trails. Managers could close off social trails altogether and impose fines for violations. Often popular or historic trails are closed for months or years at a time, but generally are closed only temporarily to conduct maintenance. However, alpine plant growth is slow and to revegetate disturbed places would take so long that the time frame for closing would be indefinite. Permanently closing trails would reduce foot traffic allowing for plant regrowth, it would be costly to hire someone to enforce that trails weren't used for an indefinite period of time. Limiting access to social trails without creating an alternative route would upset hikers and other users of the trail, and be unfeasible in places reliant on revenue from recreation.

Managers could also consider diverting some unstable sections of a social trail to more stable areas. This solution would allow the already established social trail to be used while cutting off access to problem areas. This would allow managers to cut off access to degraded areas, while still maintaining parts of the social trails that some hikers may already be familiar with. It would cost time and money to employ a team to identify problem areas and divert the trail to more sustainable areas. Depending on the terrain, it could prove challenging to connect parts of the trail to new sections, and in some places be impossible. An additional drawback to this option is that, even well-planned trails can erode with large increases in foot traffic.

Another option would be to completely close off degraded social trails from foot traffic and create sustainable trails – this is my recommendation. Hikers familiar with those social trails may be upset at first with the closing of a trail, however, creating an alternative trail to the same peak could appease some hikers. Cutting off social trails would allow for vegetation to regrow

without any continued trampling, while creating formal trails that are sustainable would minimize any further degradation long-term.

In hopes of mitigating human impact, the Colorado Fourteeners Initiative (CFI) is one of the organizations using novel trail creation and revegetation techniques. The CFI creates more sustainable trails made of large boulders and rocks to limit trampling directly onto the substrate. This boulder-based trail creation was a response to increased traffic on popular fourteeners. Others make efforts to design native-surface trails to mimic native traits, but the CFI is the first to use boulder-based trails in the alpine.

The CFI uses this technique to address significantly increasing foot traffic on trails to peaks of fourteeners (mountain peaks over 14,000 feet elevation). In 2001, the CFI compiled unpublished data from the US Forest Service and found that attempts to climb fourteeners in Colorado had increased 300% over ten years (Conlin & Ebersole 2001). Later in 2014 they used infrared sensors to count hikers and found a 6-7% increase in visitation to fourteeners each year. The CFI reported 334,000 people hiked fourteeners during the 2017 hiking season and the growth is expected to continue. As the CFI creates sustainable trails, it's equally important to restore the closed trails where damage has already occurred. In alpine conditions, revegetating heavily disturbed areas proves challenging (Chambers 1997). Since alpine ecology is slow-growing and challenging to restore, the CFI also tests new techniques to restore alpine botany after trampling. The CFI along with other organizations and land managers continually seek new ways to revegetate degraded areas.

STAKEHOLDERS

Colorado Mountain Club, American Alpine Club, Colorado Fourteeners Initiative

Members of these organizations are hikers, backpackers, climbers, skiers, and general outdoor enthusiasts. Part of each of these organizations mission is to promote the sustainable use of natural places. They are service-oriented organizations that organize volunteer trips to maintain and improve hiking trails. Therefore, they have a vested interest in finding better ways of minimizing human impact. Closing well-used social trails to create sustainable ones could be a feasible option to maintaining the long-term use of trails by the public. Additionally, testing new revegetation techniques could significantly influence their efforts, planning, and use of time and monetary resources to restore the integrity of disturbed alpine areas.

The Colorado Mountain Club (CMC) advocates for policy changes to promote a balance of recreation and conservation of natural resources. They contribute in an advisory capacity in creating management plans and sustainable policy with the Grand Mesa Uncompahgre Gunnison National Forest, Rio Grande National Forest, BLM Eastern Colorado, Pike/San Isabel National Forest, San Juan Wilderness Act, Browns Canyon Monument, and the Continental Divide Wilderness. Closing trails to allow them to revegetation, while offering an alternative trail that minimizes damage aligns with their mission. CMC could propose or support projects to close off well-used trails to create sustainable trails.

The American Alpine Club (AAC) is also involved in policy for protecting wild places. Their main advocacy goals are 1) protecting public lands, 2) ensuring lands are open, and 3) safeguarding fragile mountain & climbing environments. They support staff and interns devoted to these policies. The AAC awards over \$150,000 annually in grants to support individuals in

their outdoor pursuits, and also supports research grants for projects concerned with conserving mountain ecosystems.

The CFI is specific to high altitude fourteeners in Colorado. Their mission is to protect native alpine ecosystems from harm while making peaks accessible to a wide range of people. The CFI partners with the US Forest Service, Bureau of Land Management (BLM), and volunteers. In 2018, they involved over 1,000 volunteers who gave over 2,150 days of service through trail construction, maintenance, and habitat restoration. They experiment with novel restoration techniques and connect with scientists to evaluate their success (Kleier & Trener 2017). Better understanding which methods work best to revegetate disturbed areas would maximize volunteer efforts and monetary resources to maintain integrity of recreational trails and protected wild places.

Hikers and trail runners

Hikers want accessible and safe trails in recreational areas. In places without designated trails, hikers will create informal social trails out of necessity. Colorado hosts trail running races which are dependent on safe, well-maintained formal trails. The Leadville 100 is a 100-mile race ranging from 9,000-12,000 feet in elevation. Trail races are not plausible on social trails because their limited accessibility is dangerous. Trail races on social trails would pose a safety concern with potential liability risk. Hikers can easily hike boulder-based trails. However, trail runners might find the large boulders more challenging than other trails directly on the substrate.

Hunters

Hunters may find informal social trails to be a nuisance. Areas without formal trails would be expected to have less human traffic, increasing opportunities for game hunting. However, as social trails are created, it allows more people access to previously quieter places.

More traffic and human noise reduce game hunting opportunities. Creating social trails could alter wildlife residence and movement as they avoid human activity.

State of Colorado

The state of Colorado is experiencing an increase in not only population size, but also recreational activity to mountain areas. The state gains revenue from the use of recreational land, and so maintaining it is of interest to continue to profit from recreation. Maintaining recreational areas could mean making it more accessible – adding roads, infrastructure, and formal trails. Maintaining it could also mean closing informal trails and creating more sustainable ones to support increasing visitation in the long-term.

US Forest Service, Colorado Division of Wildlife

The US Forest Service manages land and official trails in US Forests. As they strive to minimize damage to property, a better understanding of how to revegetate disturbed areas would be advantageous. Created social trails bring more human traffic and noise which deters some wildlife. Adding trail systems could create barriers animals cannot move through as they avoid human activity. Change in wildlife as trails become more accessible could have rippling effects on ecosystem health (Taylor & Knight 2003). Because designated trails make hiking easier, it allows more people to see Colorado's high-elevation mammals such as yellow-bellied marmot (*Marmota flaviventris*), American pika (*Ochotona princeps*), American elk (*Cervus canadensis nelsoni*), and Rocky Mountain bighorn sheep (*Ovis canadensis*). Ultimately, the US Forest Service supports and relies on well-maintained and well-established trails, because without them, they would lack infrastructure they need to draw visitors into park to gain revenue, while also ensuring public safety.

Emergency Response

Social trails are undefined and would be more challenging for emergency response teams to navigate compared to formal designated trails. Designated trails with maps would make places easier to find, shortening response time. Designated trails are also officially and regularly maintained by whoever manages that land, ensuring safe conditions.

Botanists, Colorado Native Plant Society, wildlife enthusiasts

Botanists, native plant societies, and wildlife societies would be concerned about considerable damage to alpine vegetation threatening diversity and rare/endangered plant species. For example, the Colorado Native Plant Society (CONPS) works with private and public organizations to conserve native plants. They are dedicated to appreciation and conservation of native plants and habitats in Colorado. CONPS funds conservation research grants and implements a number of volunteer-run conservation projects. They train and educate the public on restoration effective techniques and are therefore concerned with finding better ways to promote plant diversity and abundance. As social trails are created, wildlife enthusiasts may gain more accessibility to new places, however, increased human activity in those areas also impacts vegetation and ecosystems. Therefore, they would likely support projects to create sustainable trails that prevent further damage to alpine vegetation.

RECOMMENDATION

Mountains, wild places, and wildlife draw people to Colorado. Colorado needs to address a growing population and increased recreational use. To address the problem of eroded, degraded social trails, it would be ideal to prevent new social trails from being created in the first place. When visitors create social trails, location and use are not considered. This approach results in

trails too close to erodible areas. Maintaining and creating formal trail systems in increasingly popular areas could prevent the creation of more social trails. Plant growth is so slow in the alpine that revegetating disturbed areas is a long-term process, thus avoiding the need for revegetation of alpine areas is preferred to restoration.

Some could argue creating formal trails introduces intentional damage during trail construction. However, as tested by the Colorado Fourteeners Initiative, trails using boulders as trampling surface, rather than directly on the substrate reduces trampling impact and limits erodibility. The drawback is that using this method which relies on boulders rather than direct ground is more labor intensive (CFI 2017). It allows hikers accessibility while reducing further impact from social trails. Creating better trails could result in more human visitation to wild places; and the impact will be reduced. It also allows more people to spend time in wild places that they might not otherwise. As people spend more time in nature, they are more likely to advocate for its protection.

Planning formal trails in stable areas while cutting off access to sensitive areas could help meet a balance between use and preservation. Land managers can analyze the property to implement a trail system that allows for maintaining rare and endangered species and habitat heterogeneity. They could also design trail systems that limit interaction with sensitive wildlife and minimize blocking of wildlife corridors.

There is a need for better ways of restoring degraded alpine ecosystems when social trails are closed and replaced by formal sustainable trails. Because alpine plants grow so slowly, long-term monitoring projects should be implemented and monitored to understand how plant communities recover after disturbance. Further research on how to better revegetate disturbed alpine areas could significantly improve our ability to maintain sustainable trail systems.

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