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Rock Climbing Impact on Soil Properties and Invasive Plant Species in the Gunnison Valley, Colorado

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by

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Thesis

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Rock Climbing Impact on Soil Properties and Invasive Plant Species in the Gunnison Valley, Colorado

Rhyann Lowrey

Abstract

The sport of rock climbing is growing at a fast rate, roughly 13 percent per year (NPD Group 2017), and as these new climbers venture outside, the potential to negatively impact the health of ecosystems increases. This impact can come in the form of damage to native vegetation and soils, but the extent to which is relatively unknown. My thesis project quantifies rock climbing impacts on the base of cliff areas by studying 1) native vs. non-native vegetation composition and cover aboveground and in the soil seed bank, and 2) general soil health such as gravimetric moisture and bulk density in climbed and adjacent undisturbed areas. These objectives were addressed in areas with rock climbing impact and ecosystems particularly sensitive to disturbance, the sagebrush steppe and mid-elevation forests of Colorado (US EPA 2015). As the sport of rock climbing grows, the need for scientific research grows as well. The results of this study suggest that rock climbing traffic to climbed cliff base areas has a strong negative effect on graminoid and shrub presence. In addition, areas disturbed by rock climbing traffic also have a significant impact on soil bulk density and seed bank growth potential. There is no significant influence of rock climbing disturbance on non-native vegetation percent composition aboveground, but there was a significant difference in germination of non-native and native species in disturbed transects' soil seed bank in comparison to undisturbed transects. The goal for my thesis project is to increase ecological knowledge of rock climbing impact and to share and publish this information. Using this research, mitigation plans for rock climbing areas can be based on science, creating sustainable recreation areas for future generations to enjoy.

Background

Outdoor Recreation

Outdoor recreation is becoming a large part of life in the United States, with 146.1 million Americans participating in at least one outdoor activity in 2017 ("Outdoor Participation Report" 2018). In fact, the outdoor recreation industry in 2017 accounted for 2.2 percent of the U.S. current-dollar gross domestic product ("Outdoor Recreation Satellite Account, U.S. and

Prototype for States, 2017" 2019). Not only is the outdoor recreation industry popular, but it is also growing. The outdoor recreation economy grew faster than the U.S. economy as a whole in 2017, with 3.9 percent growth ("Outdoor Recreation Satellite Account, U.S. and Prototype for States, 2017" 2019). The sport of rock climbing is growing along with the outdoor recreation industry. Over 5 million Americans participated in indoor rock climbing in 2017, with many of these individuals venturing out of the gym to try the sport outside ("Outdoor Participation Report" 2018). In addition, 50 new climbing gyms opened up in the United States in 2018, a growth rate of 11.87 percent (Burgman 2019). With more people enjoying the outdoors in the U.S. each year, more impact occurs on the natural world. Outdoor recreational activities can have a negative impact on the health of ecosystems, and in particular rock climbing has the potential to damage fragile native vegetation and soils and disturb wildlife. What is the extent of this harm?

Current Research

Currently, most ecological research conducted in climbing areas has been on the impact of climbing on cliff vegetation. In Joshua Tree National Park, a study compared cliffs used for rock climbing versus cliffs not used and found that plant species richness on both cliff faces and the base of cliffs was greater for cliffs with no climbing than for cliffs with intensive climbing use (Camp and Knight 1998a). The number of individual plants also decreased with increased climbing use (Camp and Knight 1998a). In the cliff systems of Minnesota, a study of major local plant taxa found that total plant cover was significantly lower in climbed areas, and frequencies of most taxa were lower in climbed areas, although not significantly so (Farris 1998).

Furthermore, vascular plant species density and lichen species richness were significantly lower in climbed areas versus unclimbed areas, in a study of the Niagara Escarpment of Ontario, Canada (McMillan and Larson 2002). Eastern white cedar trees in this area have reduced numbers of older and younger age classes in climbed areas compared to unclimbed areas (Kelly and Larson 1997). This eastern white cedar harm is concerning, as some individual trees are over 1000 years old, and a higher percentage of human-caused damage was reported in climbing areas (Kelly and Larson 1997). In addition, a study of the limestone cliffs of the Swiss Jura mountains found that cover and species density of vascular plants was reduced in climbing areas (Rusterholz et al. 2004). Rock climbing also caused a significant shift in plant species composition, as well as altered the proportions of different plant life forms, suggesting threats to native plant communities (Rusterholz et al. 2004). However, not all rock climbing specific studies have found that climbing alters cliff plant communities (Baur et al. 2017, Boggess et al. 2017). Varied results could result from factors such as natural vegetation variation by site or infrequent climbing use (Boggess et al. 2017, Harrison 2020).

There is also evidence for negative impact from rock climbing on wildlife. The land snail communities of the Niagara Escarpment had lower density, richness, and diversity in climbed areas in comparison to unclimbed areas (McMillan et al. 2003). In Europe, Peregrine falcon *(Falco peregrinus)* breeding success and productivity were lower for nesting sites on cliffs frequented by climbers in comparison to nesting sites on unclimbed cliffs (Brambilla et al. 2004). Bird communities in Joshua Tree National Park are proposed to be disturbed by rock climbing activity. In a study of cliff nesting birds in the area, birds were more likely to be seen away from cliff faces at popular climbing cliffs (Camp and Knight 1998b). These birds were likely to be detected near cliff faces or perching on the face of cliffs in unclimbed stretches (Camp and Knight 1998b). However, in a study of small-footed bats in the eastern United States, activity did not differ between climbed and unclimbed cliffs that the bats used as habitat (Loeb and Jodice 2018). In the Loeb and Jodice (2018) study, bat species richness also did not differ between climbed and unclimbed areas.

There are gaps in the current ecological research surrounding the impact that the sport of rock climbing has on ecological systems. In regard to vegetation, most of the research has focused on impacts on the cliff itself and not on base areas. One of the few studies of cliff base impacts found that long-term trampling at the base of cliffs in the Swiss mountains reduced total aboveground vegetation cover and shifted the plant species composition (Rusterholz et al. 2011). Moreover, total seed density was lower, and seeds of ruderal and unintentionally introduced species were more common in the disturbed areas which were frequented by climbers (Rusterholz et al. 2011). Seed dispersal is likely heightened by climbers (Vogler and Reisch 2011). There is also little research on the impacts of climbing areas on invasive plant species. In a 2016 plant assessment report of Devils Tower National Monument, Wyoming, invasive species, particularly cheatgrass, were found on the summit of the tower, with a higher prevalence in rock climbing trafficked areas (Marriott and Mayer 2016).

Non-native Plants

Invasive plant species are a concern all over the world, as they often overtake native species and therefore create a loss of biodiversity (Getz and Baker 2008). In the U.S., cheatgrass (*Bromus tectorum*) is of large concern (Fig. 1), as it has achieved dominance in the intermountain west and has been reported even in some eastern states (EDDMapS n.d., Smith et al. 2008). Cheatgrass or Downy brome, is an invasive annual grass native to southern Europe, northern Africa, and southwestern Asia (Staver 2004). Cheatgrass can be found among a variety of plant communities and elevations, but has most affected the sagebrush, pinyon-juniper, and salt-desert communities of the western United States (Schupp n.d.), and dominates well over 7×10^6 ha of this terrain (Belnap et al. 2005). The affinity of cheatgrass for soil disturbance is of great concern, especially considering the possibility of rock climbing recreation disturbance to soils of route base areas. Cheatgrass depletes soil moisture and increases the incidence of wildfires, further perpetuating dominance and pure stands of the annual grass (Whisenant 1990, Smith et al. 2008). In a review of cheatgrass' effect on cattle grazing, it was reported that even the slight disturbance of rodents was enough to perpetuate cheatgrass in the range community (Young et al. 1987). Cheatgrass begins growth from fall to early spring depending on winter weather, earlier than most native perennials, and is an abundant seed producer contributing to both a transient and persistent seed bank (Smith et al. 2008). Seeds are dormant at dispersal and proceed to lose this dormancy through dry after-ripening under summer conditions (Smith et al. 2008). Therefore, cheatgrass seeds experience germination once exposed to autumn rains and early spring snow melt (Beckstead et al. 2007). Naturally dispersed seeds of cheatgrass do not persist beyond one year (Smith et al. 2008). Due to cheatgrass' tendency to thrive in disturbed areas, there is a potential of cheatgrass spread in rock climbing areas.

Other non-native plant species common in the Gunnison Valley include scentless chamomile (*Matricaria perforata*), common dandelion (*Taraxacum officinale*) and crested wheatgrass (*Agropyron cristatum*). Scentless chamomile, an introduced annual weed that exists perennially at higher elevations, prospers under high soil moisture and poorly drained soils (Blackshaw and Harker 1997, Woo et al. 2011). Creating a large soil seed bank, scentless chamomile reproduces entirely by seed, producing up to 1.8 million seeds per m^2 in dense stands, and is a serious competitor to native species (Woo et al. 2011). Common dandelion, also introduced to the Gunnison Valley, is a perennial herbaceous plant that produces abundant seeds with a large dispersal range (Honek et al. 2005). Established seedlings from a seed bank or dispersed seeds entering the soil is rare, as common dandelion seeds have high predation rates (Honek et al. 2005). Common dandelion germinates under a large variety of conditions in predominately grassy areas, from ruderal zones to roadsides (Stewart-Wade et al. 2011). Crested wheatgrass, a persistent, perennial, cold and drought-tolerant grass was introduced to the United States and Canada as forage from its native Siberia (Rogler and Lorenz 1983). The plant grows in many soil types, from sandy loams to clays, becomes dormant in hot, dry weather, and demonstrates persistence under disturbance (Rogler and Lorenz 1983). While beneficial for livestock feed, crested wheatgrass can push out native grass species. However, there is evidence that crested wheatgrass can resist cheatgrass competition, therefore giving a strong competitive advantage in cheatgrass management (Sharp et al. n.d.).

Impact on Soils

While there has been no specific study on soils in rock climbing areas, there is support that outdoor recreation has an effect on soils. Human trampling from recreation has a direct effect on soil compaction as well as exposure and displacement of soil particles (Monz et al. 2010). While soil compaction is typically increased in recreation areas, bulk density values differ. In a comparison study of recreation areas in Turkey, soil bulk density was slightly lower in recreation areas, an unexpected result (Ozturk and Bolat 2014). Soil bulk density was also found to be slightly lower in recreation areas in comparison to undisturbed forest sites in an additional Turkish report (Özcan et al. 2013). In contrast, a separate study found that bulk density significantly increased and total soil porosity decreased in moderately and highly trafficked recreation areas in comparison to undisturbed areas (Yüksek 2009). Overall, more research is needed on the direct effects of human trampling and recreation on soil properties.

Climbing Impacts in the Gunnison Valley

My research focuses on the sagebrush steppe and mid-elevation forests of the Gunnison Valley, Colorado, where rock climbing has a potential high impact, and the ecosystems are particularly sensitive to disturbance. The Gunnison Valley, which includes the towns of Gunnison, Almont, Crested Butte, and Mount Crested Butte, lies on the western slope of the Rocky Mountains in southwest Colorado. The area has multiple popular granite climbing destinations. The greater Gunnison area has 645 climbing routes, according to Mountain Project, a popular climbing website run by outdoor retailer REI (“Climbing in Gunnison” 2020). This area has reported cheatgrass presence according to EDDMapS, (Fig. 2; "Cheatgrass (Bromus tectorum)" 2020), is locally connected to Western Colorado University, and has potential for climbing impact. The areas of Hartman Rocks and Taylor Canyon were study sites for this research.

As outdoor recreation and the sport of rock climbing grow in the United States, the need to research impact to the natural world grows as well. The research objectives of my study are to quantify rock climbing impacts on the base of cliff areas by studying 1) native vs. non-native vegetation composition and abundance aboveground and in the soil seed bank, and 2) general soil health such as gravimetric moisture and bulk density in climbed and adjacent undisturbed areas. I expect that climbing areas will have more non-native plant species aboveground and in the soil seed bank, decreased soil moisture, and increased bulk density in comparison to undisturbed areas. The future of rock climbing areas depends on mitigation based on science, and it’s time that rock climbers and outdoor recreators work together with ecologists as teammates to protect beautiful ecosystems that can withstand sustainable recreation for generations.

Methodology

Study Sites

The Gunnison Valley, Colorado has an elevation between 2,300-2,800 meters, and encompasses both alfisol and mollisol soil orders (Panagos et al. 2011). In the city of Gunnison, at the south end of the valley, the mean annual temperature (MAT) ranges between -22 ºC to 26 ºC, with a mean annual rainfall of 27 cm and mean annual snowfall of 114 cm (“U.S. Climate Data, Gunnison” 2020). In the town of Crested Butte, at the north end, the MAT ranges between -22 ºC to 24 ºC, with a mean rainfall of 61 cm and a mean snowfall of 551 cm (“Weather averages, Crested Butte, Colorado" 2020).

I selected two individual sites in the Gunnison Valley to measure aboveground vegetation composition, soil health, and evaluate the soil seed bank. The sites are Hartman Rocks and Taylor Canyon (Fig. 3). Eight climbing cliffs were selected and assessed at Hartman Rocks and ten were selected and assessed at Taylor Canyon. I placed transects 0.5 m from the base of each climbed cliff to represent climbing disturbed areas. Adjacent transects were also placed 10 to 15 m out from the disturbed transects to represent undisturbed control areas. In total, 36 transects were placed and 18 climbing cliffs were studied.

The climbed cliffs were chosen at random using the random selection site *randomresult.com* from recorded routes in the guide book *Gunnison Rock* (Malloy 2007) (Table 1). All traditional and sport routes between the climbing grades of 5.0 and 5.11a (beginner through intermediate) were included, and bouldering problems were not included. This was to ensure more consistent usage, as more advanced and expect level climbs draw fewer users. Bouldering problems were not included due to variation of impact from required mats for fall protection. Routes with additional letter ratings PG, PG13, R, and X were not counted, as they also draw fewer users due to being more advanced. For the routes selected from the Malloy guide, only three star rated routes (from a scale of zero to three) were used for random selection. This insures popularity and increased climbing usage versus other cliffs in the area. The cliffs surveyed in Taylor Canyon had a southern aspect, and the cliffs in Hartman Rocks had south, southeast, and southwest aspects. I collected field data 48 hours after the most recent rain event to account for differences in soil moisture.

Aboveground Vegetation

To examine the impact of rock climbing on aboveground vegetation composition and species abundance, I used the line point intercept method to assess vegetation cover and composition (Godínez-Alvarez et al. 2009). Briefly, I ran a 10 m transect parallel to the cliff, at a distance of 0.5 m from the cliff base (Rusterholz et al. 2011). Beginning at 0.2 m on the transect line, I dropped a pin flag, less than 1 mm in diameter, 25 cm from the ground, every 0.2 m on the transect line (Herrick et al. 2005; Fig.4). At each dropped pin location, vegetation presence, species, number of hits of each species, and groundcover was recorded. This resulted in 50 dropped pin locations per transect. All live plant species that contacted the pin were recorded as hits (Godínez-Alvarez et al. 2009). The ground cover was recorded as rock, litter, lichen, moss, or bare soil (Herrick et al. 2005).

Soil Health

Soil samples were collected every 5 m along the 10 m transect line, at 0, 5, and 10 m using a 5 cm diameter cylinder to a 5 cm depth, resulting in a soil volume of 100 cm^3 (Rusterholz et al. 2011). The three soil core samples from each transect were pooled together for analysis, resulting in one soil sample per transect for a total of 36 samples. Soil health properties including mass, gravimetric moisture, and bulk density were measured from the collected soil samples.

The entire sample was weighed to get the bulk soil weight prior to sieving. Soils were then sieved with a 2 mm sieve to remove rocks and roots. Organic matter >2 mm was considered coarse fraction and was weighed and recorded after drying in a 65 ºC oven for a minimum of 48 hours. The volume of rocks and stones was determined through displacement. Finally, the post-sieved soil was weighed and recorded. All subsequential soil analyses were done using the less than 2 mm soil.

Gravimetric soil moisture was measured by drying 5 grams of soil in a 105 ºC oven for a minimum of 48 hours. Soil moisture (percent of dry weight) was calculated using the following equation, accounting for the weight of the tin:

$$\%\ soil\ moisture = 100\ \times\ \{(wet\ weight - dry\ weight) \div (dry\ weight)\}$$

Using the gravimetric soil measurements and core volume from the soil corer (subtracting rock volume), bulk density was also calculated using the equation:

$$Bulk\ density\ (g/cm^3) = ODE\ bulk\ soil\ weight\ (g) \div core\ volume\ (cm^3)$$

Oven dry equivalent (ODE) was calculated using:

$$ODE = moist\ soil\ bulk\ weight\ (g) \times \%\ soil\ (subsample\ dry\ weight \div subsample\ wet\ weight)$$

Soil Seed Bank

To determine potential for cheatgrass and other non-native species growth, I examined the soil seed bank from soil collected at the base of the climbed cliffs and their undisturbed counterparts. For the seed bank analysis, the seedling-emergence method of Ter Heerdt was used (Heerdt et al. 1996). Post-sieved soils were stored in the dark at 4ºC until lab analysis was possible (Rusterholz et al. 2011). The samples were washed through a 2 mm sieve, and then poured onto a 3 cm thick layer of steam-sterilized potting soil, resulting in approximately a 1-2 mm thick layer on top, in 55 x 35 cm seed trays for greenhouse cultivation (Heerdt et al. 1996, Rusterholz et al. 2011). The potting soil was steam-sterilized in an autoclave for 30 minutes. Six seed trays filled with only sterilized potting soil served as control (Rusterholz et al. 2011). Trays were exposed to 24-hour artificial light as well as daily sunlight. Trays were watered every other day, and the trays were rotated once weekly to avoid differences in sunlight exposure (Rusterholz et al. 2011). Seedlings were counted and removed as soon as they were able to be identified. After a four-week period with no new seedling emergence, the remaining seedlings were counted and removed.

Data Analysis

For all graphing and statistical analysis, R Studio software (R Core Team, Version 1.4.1106, 2021, Vienna, Austria) was used. Analysis of variance (ANOVA) was used to examine the effects of disturbance and site on gravimetric soil moisture and soil bulk density. Both the main effects of site and disturbance and the interaction between the two effects were tested. If necessary, data were log-transformed to obtain normal distribution. Tukey post-hoc tests were used to test multiple comparison between sites and treatments.

Negative binomial regression analysis was applied to test the effects of disturbance via rock climbing on native and non-native plant species and plant functional groups. This negative binomial regression was also applied to greenhouse seedling-emergence data, where disturbance effect on seedlings germination, individual species percent germination, and site were analyzed. Exploratory analyses indicated a modest Akaike Information Criterion (AIC) as well as a large mean to variance ratio, suggesting that the negative binomial regression model had more support than corresponding Poisson models (Lardner et al. 2015).

Results

Aboveground Vegetation

A total of 27 plant species was recorded at the base of 18 climbing cliffs and 18 undisturbed areas (Table 2). Of these 27 species, four were non-native, including cheatgrass (*Bromus tectorum*), common dandelion (*Taraxacum officinale*), crested wheatgrass (*Agropyron cristatum*), and scentless chamomile (*Matricaria perforata*) (Fig. 5). Of the non-native species, *Bromus tectorum* had the highest percent composition across all treatments, 23.88 ±SE 6.83 in Taylor Canyon, and 5.95 ±SE 3.78 in Hartman Rocks (Table 2). In total, 15 plant species were recorded in Taylor Canyon. *Bromus marginatus*, a native graminoid, was the most common species in Taylor Canyon (29.62 ±SE 7.80). Litter was the most frequent groundcover (59.4%

±SD 0.62) across of all Taylor Canyon transects. A total of 12 plant species were recorded in Hartman Rocks. The most common species documented in Hartman Rocks was *Cercocarpus montanus*, a native shrub (28.27 ±SE 7.91) . Bare soil in Hartman Rocks was the most common groundcover at 48.6% ±SD 0.76 across all transects.

Combining the data from both sites, there was significant difference in percent composition of graminoid and shrub functional groups in disturbed versus undisturbed areas (Table 3). Graminoids had higher percent composition in disturbed transects while shrubs had higher percent composition in undisturbed transects (Fig. 6). There was no significant difference in the presence of non-native plant species between disturbed and undisturbed transects (z *score* $= -0.41, P = 0.68$) (Fig. 7). In addition, there was no significant difference in total species composition aboveground between disturbed and undisturbed areas (Table 3).

Soil Health

In Taylor Canyon, mean ± SE soil bulk density (g/cm^3) in disturbed transects was 2.05 g/cm^3 ± 0.14, and 2.53 g/cm^3 ± 0.20 in undisturbed transects. The bulk density in soils from Hartman Rocks was lower than Taylor Canyon with a mean bulk density in disturbed transects of 1.31 g/cm^3 ± 0.25, and undisturbed transects measured at 1.81 g/cm^3 ± 0.32. Two-way ANOVA analyses showed a significant effect of disturbance ($F_{1, 2.1}=4.66, p = 0.04$) and site ($F_{1, 4.7}=10.46, p < 0.01$; Fig. 8) on bulk density. The interaction between disturbance and site was not significant ($F_{1,0.002} = 0.003, p = 0.95$).

In Taylor Canyon, mean ± SE gravimetric soil moisture (percent of dry weight (g) was 4.63% ± 0.80, and 7.02% ± 1.54 in disturbed and undisturbed transects, respectively. Gravimetric soil moisture in Hartman Rocks disturbed areas had a mean 7.98% ± 3.52, and 2.41% ± 0.71in undisturbed transects. Two-way ANOVA analyses showed no influence of site ($F_{1, 32} = 3.4, p = 0.07$) or disturbance ($F_{1, 32} = 0.06, p = 0.8$) on gravimetric soil moisture. The interaction was not significant ($F_{1, 2.2} =2.92, p = 0.09$).

Soil Seed Bank

Each transect's pooled soil samples were placed into one greenhouse tray. Therefore, one tray is equal to one transect. 16 out of 20 transect trays in Taylor Canyon and 9 out of 16 Hartman Rocks transect trays grew seedlings. All six control trays for both sites had no germination. Three forb species remain unidentified due to the individual seedlings dying before flowering at the later stages of the seedling-emergence study. There was no significant influence of site on seedling germination (*z score = 0, p = 0.99*). There was significance in disturbed transects' seedling percent germination (*z score = -2.72, p < 0.01*). All plant species in the seedling-emergence study were analyzed individually, resulting in percent germination of each species being greater in disturbed trays versus undisturbed trays (Table 4). Species seedling percent germination mean and standard error were calculated for native, non-native, and unknown species with combined data from both sites (Table 4). The species with the most germination include Unknown 1 (2.93 ±SE 2.60) and Unknown 3 (2.40 ±SE 1.38), while the species with the least germination was the non-native scentless chamomile (0.07 ±SE 0.07). The non-native species with the highest percent germination was cheatgrass (1.56 ±SE 0.69).

Discussion

The goal of this study was to quantify rock climbing impacts on the base of cliff areas by studying 1) native vs. non-native vegetation composition aboveground and in the soil seed bank, and 2) general soil health such as gravimetric moisture and bulk density in climbed and adjacent undisturbed areas. The results of this study suggest that rock climbing traffic to climbed cliff base areas has a strong negative effect on graminoid and shrub presence in the Gunnison Valley, Colorado. There is no significant influence of rock climbing disturbance on non-native vegetation percent composition, but there was a significant difference in germination of non-native and native species in disturbed transects' soil seed bank in comparison to undisturbed transects. In addition, areas disturbed by rock climbing also have a significant impact on soil bulk density, which was lower in disturbed areas, and seed bank growth potential, which was greater in disturbed areas.

Aboveground Vegetation

Long-term trampling at rock climbing sites has been shown to reduce total aboveground vegetation cover and shift plant species composition (Rusterholz et al. 2011). However, I found no difference in species composition between disturbed rock climbing areas and adjacent undisturbed areas. The Rusterholz et al. (2011) study was conducted in sub-alpine forests of Switzerland, an area with higher annual precipitation and different plant community than the

Gunnison Valley. In addition, the areas studied by Rusterholz et al. (2011) have much higher rates rock climbing traffic than that of Taylor Canyon and Hartman Rocks, Colorado. I also found that graminoids had higher percent composition in disturbed transects while shrubs had higher percent composition in undisturbed transects. This could be due to both graminoids and shrubs being a more common functional group in the sagebrush steppe and mid-elevation forest ecosystems studied, in comparison to the sub-alpine forests of the Rusterholz et al. (2011) study.

Although little research has been done on non-native plant species in rock climbing areas, a USDA statement of Devils Tower National Monument, Wyoming, did report higher prevalence of invasive species in heavily trafficked rock climbing areas (Marriott and Mayer 2016). Devils Tower encompasses a mid-elevation forest ecosystem, similar to that of Taylor Canyon, Colorado. In comparison, the present study found that combined site data did not reveal the same pattern. While non-natives are a threat to rock climbing areas, as well as the entire intermountain west of the United States (Smith et al. 2008), this study did not show that climbing areas had a greater number of non-natives. It is possible that the level of disturbance in the Gunnison Valley is not enough to significantly impact vegetation. In addition, since vegetation growth is generally low in the studied area, a large difference in climbed versus unclimbed areas may not be apparent. Degree of disturbance has been shown to affect the direction of plant community succession in sagebrush steppe ecosystems, resulting in different plant communities overtime (McLendon and Redente 1990). Restoration of native understory in sagebrush habitat also suggests slowed rate of sagebrush loss (Hemstrom et al. 2002). Other research of mid-elevation forests, like that of Taylor Canyon, revealed that human-caused disturbance had a greater influence on shrub species than dominant tree species (Kumar and Ram 2005). The results of the Kumar and Ram (2005) study are similar to what was found in my research.

Soil Health

Bulk density results showed a significant difference between sites and was significantly lower in disturbed areas. Soil bulk density results remained consistent with previous studies of bulk density impact from outdoor recreation; that bulk density measurements were lower at disturbed sites in comparison to undisturbed (Özcan et al. 2013, Ozturk and Bolat 2014). Lower bulk density at disturbed sites could be due to the soil type in the Gunnison Valley being sandy and quite dry, with very little clay content. This could possibly contribute to lower rates of compaction over time. Most of the literature on soil compaction of sandy versus clay soils has been done on the logging industry. While soils with higher clay content tend to have higher compaction and bulk density measurements, bulk density is not significantly different between clay and sandy soil types (Ampoorter et al. 2012).

Despite being lower in disturbed areas, the mean soil bulk density at each site and disturbance level was high. Soil bulk density measurements above 1.80 g/cm^3 have been shown to put restrictions on root growth in sandy soils, stagnate water movement, and increase erosion (USDA 2008). This suggests that although there is no direct impact from climbing use, further study of soil properties is needed in these areas to determine indication of soil compaction, soil health, and environmental quality (Ozturk and Bolat 2014). Measuring soil properties including infiltration rate, soil moisture in the field, and soil porosity would be beneficial to provide additional information on the impact of disturbance on soil health. There is also concern that due to the soils in both sites being extremely sandy and dry, extracting an accurate 100 cm^3 sample was difficult. This may have affected my soil bulk density measurements. Studies on soil bulk density measurement effectiveness have shown that the core sample method significantly underestimates soil bulk density at a fixed depth (Gross and Harrison 2018). Therefore, a more concise method for obtaining soil samples is needed if further study is completed.

Soil Seed Bank

A previous seedling emergence study of climbing areas resulted in findings of lower total seed density, as well as seeds of ruderal and unintentionally introduced species being more common in disturbed areas (Rusterholz et al. 2011). Although in the present study total seed density was not measured, seedling germination was significantly higher in disturbed transects in comparison to undisturbed. This could be due to seed dispersal from outdoor recreators or wind possibly stopping seed travel after it hits cliff faces. Furthermore, sport climbers have been recorded as unintentionally introducing disturbance-tolerant seeds to the limestone cliffs of the Swiss mountains (Pickering and Mount 2010, Rusterholz et al. 2011). In addition, all species had significantly higher percent germination in disturbed soils in comparison to undisturbed, including non-natives. There was not a significant difference in the number of native versus non-native seeds that germinated. This suggests that all species do have a larger seed bank in disturbed areas, which is of concern due to the fact that many non-natives are ruderal species, including cheatgrass (Colorado State University 2012). In an additional study on cheatgrass affinity to disturbance, it was found that disturbance had little effect on the potential germination of the grass (Roundy et al. 2007). The potential of disturbance to increase cheatgrass invasion was shown by a reduction in perennial herbaceous species resource use (Roundy et al. 2007). Invasive plant species are likely to reduce native diversity at the community scale, especially in communities were competitive interactions occur (Catford et al. 2012).

Management Implications

The future of rock climbing areas depends on mitigation based on science. In order to preserve rock climbing areas, management plans need to be designed and implemented effectively. This study could directly inform management decisions by highlighting the need to manage non-native plant species and aboveground vegetation growth. In addition, physical structures may need to be created to decrease disturbance. This can include trail building and maintenance, designated belay areas and platforms, and increased signage. Continued study of the impact of rock climbing on aboveground vegetation and soil properties is also crucial, as more data on cliff and base area vegetation and soil is needed to further our understanding of the true impact of climbing. Limitations of the present study included time, funding, and availability of study sites. Increasing these factors in future studies would contribute to implementing outdoor recreation management based on science. Rock climbers and outdoor recreators need to work together with ecologists as teammates to protect beautiful ecosystems that can support sustainable recreation for generations.

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Literature Cited

Ampoorter, E., A. de Schrijver, L. van Nevel, M. Hermy, and K. Verheyen. 2012. Impact of mechanized harvesting on compaction of sandy and clayey forest soils: results of a meta-analysis. Annals of Forest Science 69:533–542.

Baur, B., Baur, A., & Schmera, D. 2017. Impact assessment of intense sport climbing on limestone cliffs: Response of rock-dwelling land snails. Ecological Indicators 72: 260–267.

Beckstead, J., S. E. Meyer, C. J. Molder, and C. Smith. 2007. A Race for Survival: Can Bromus tectorum Seeds Escape Pyrenophora semeniperda-caused Mortality by Germinating Quickly? Annals of Botany 99:907–914.

Belnap, J., S. L. Phillips, S. K. Sherrod, and A. Moldenke. 2005. Soil Biota Can Change After Exotic Plant Invasion: Does This Affect Ecosystem Processes? Ecology 86:3007–3017.

Blackshaw, R. E., and K. N. Harker. 1997. Scentless Chamomile (Matricaria perforata) Growth, Development, and Seed Production. Weed Science 45:701–705.

Boggess, L.M., Walker, G.L., & Madritch, M.D. 2017. Cliff Flora of the Big South Fork National River and Recreation Area. Natural Areas Journal 37: 200–211.

Brambilla, M., D. Rubolini, and F. Guidali. 2004. Rock Climbing and Raven Corvus Corax Occurence Depress Breeding Success of Cliff-Nesting Peregrines Falco Peregrinus. Ardeola 51:425–430.

Burgman, John. 2019, April 29. Gyms and Trends 2018. https://www.climbingbusinessjournal.com/gyms-and-trends-2018/.

Camp, R. J., and R. L. Knight. 1998a. Effects of Rock Climbing on Cliff Plant Communities at Joshua Tree National Park, California. Conservation Biology 12:1302–1306.

Camp, R. J., and R. L. Knight. 1998b. Rock Climbing and Cliff Bird Communities at Joshua Tree National Park, California. Wildlife Society Bulletin 26:892–898.

Catford, J. A., C. C. Daehler, H. T. Murphy, A. W. Sheppard, B. D. Hardesty, D. A. Westcott, M. Rejmánek, P. J. Bellingham, J. Pergl, C. C. Horvitz, and P. E. Hulme. 2012. The intermediate disturbance hypothesis and plant invasions: Implications for species richness and management. Perspectives in Plant Ecology, Evolution and Systematics 14:231–241.

Cheatgrass (Bromus tectorum). (n.d.). . https://www.eddmaps.org/distribution/viewmap.cfm?sub=5214.

Climbing in Gunnison, Gunnison. (n.d.). . https://www.mountainproject.com/area/105802040/gunnison.

Colorado State University. 2012. Restoring Native Seedbanks To Control Cheatgrass.

Farris, M. A. 1998. The effects of rock climbing on the vegetation of three Minnesota cliff systems. Canadian Journal of Botany 76:1981–1990.

Getz, H. L., and W. L. Baker. 2008. Initial Invasion of Cheatgrass (Bromus tectorum) into Burned Piñon-Juniper Woodlands in Western Colorado. The American Midland Naturalist 159:489–497.

Godínez-Alvarez, H., J. E. Herrick, M. Mattocks, D. Toledo, and J. Van Zee. 2009. Comparison of three vegetation monitoring methods: Their relative utility for ecological assessment and monitoring. Ecological Indicators 9:1001–1008.

Gross, C. D., and R. B. Harrison. 2018. Quantifying and Comparing Soil Carbon Stocks: Underestimation with the Core Sampling Method. Soil Science Society of America Journal 82:949–959.

Harrison, G.R. 2020. The impact of rock climbing disturbance on cliff communities of the Linville Gorge Wilderness Area. M.S. thesis, Appalachian State University, Boone, North Carolina.

Heerdt, G. N. J. T., G. L. Verweij, R. M. Bekker, and J. P. Bakker. 1996. An Improved Method for Seed-Bank Analysis: Seedling Emergence After Removing the Soil by Sieving. Functional Ecology 10:144–151.

Hemstrom, M. A., M. J. Wisdom, W. J. Hann, M. M. Rowland, B. C. Wales, and R. A. Gravenmier. 2002. Sagebrush-Steppe Vegetation Dynamics and Restoration Potential in the Interior Columbia Basin, U.S.A. Conservation Biology 16:1243–1255.

Herrick, J. E., Van Zee, J. W., Havstad, K. M., Burkett, L. M., and Whitford, W. G. 2005. Monitoring Manual for Grassland, Shurbland, and Savanna Ecosystems. USDA - ARS Jordana Experimental Range, Distributed by the University of Arizona Press.

Honek, A., Z. Martinkova, and P. Saska. 2005. Post-dispersal predation of Taraxacum officinale (dandelion) seed. Journal of Ecology 93:345–352.

Kelly, P. E., and D. W. Larson. 1997. Effects of Rock Climbing on Populations of Presettlement Eastern White Cedar (Thuja occidentalis) on Cliffs of the Niagara Escarpment, Canada. Conservation Biology 11:1125–1132.

Kumar, A., and J. Ram. 2005. Anthropogenic disturbances and plant biodiversity in forests of Uttaranchal, central Himalaya. Biodiversity & Conservation 14:309–331.

Lardner, B., G. H. Rodda, A. A. Y. Adams, J. A. Savidge, and R. N. Reed. 2015. Detection Rates of Geckos in Visual Surveys: Turning Confounding Variables into Useful Knowledge. Journal of Herpetology 49:522–532.

Loeb, S. C., and P. G. R. Jodice. 2018. Activity of Southeastern Bats Along Sandstone Cliffs Used for Rock Climbing. Journal of Fish and Wildlife Management 9:255–265.

Malloy, Lee. 2007. Gunnison Rock. Sharp End Publishing.

Marriott, H., and C. Mayer. 2016. USDA. Devils Tower Plant Inventory and Vegetation Assessment:36.

McLendon, T., and E. F. Redente. 1990. Succession patterns following soil disturbance in a sagebrush steppe community. Oecologia 85:293–300.

McMillan, M. A., and D. W. Larson. 2002. Effects of Rock Climbing on the Vegetation of the Niagara Escarpment in Southern Ontario, Canada. Conservation Biology 16:389–398.

McMillan, M. A., J. C. Nekola, and D. W. Larson. 2003. Effects of Rock Climbing on the Land Snail Community of the Niagara Escarpment in Southern Ontario, Canada. Conservation Biology 17:616–621.

Monz, C. A., D. N. Cole, Y.-F. Leung, and J. L. Marion. 2010. Sustaining Visitor Use in Protected Areas: Future Opportunities in Recreation Ecology Research Based on the USA Experience. Environmental Management 45:551–562.

Outdoor Participation Report. 2018. . The Outdoor Foundation.

Outdoor Recreation Satellite Account, U.S. and Prototype for States, 2017. 2019. . News Release. https://www.bea.gov/news/2019/outdoor-recreation-satellite-account-us-and-prototype-states-2017.

Özcan, M., F. GÖkbulak, and A. Hizal. 2013. Exclosure Effects on Recovery of Selected Soil Properties in a Mixed Broadleaf Forest Recreation Site. Land Degradation & Development 24:266–276.

Ozturk, M. and Bolat, I. 2014. Transforming Pinus pinaster forest to recreation site: preliminary effects on LAI, some forest floor, and soil properties. Environmental monitoring and assessment 186:2563–2572.

Panagos, P., A. Jones, C. Bosco, and P. S. S. Kumar. 2011. European digital archive on soil maps (EuDASM): preserving important soil data for public free access. International Journal of Digital Earth 4:434–443.

Pickering, C., and A. Mount. 2010. Do tourists disperse weed seed? A global review of unintentional human-mediated terrestrial seed dispersal on clothing, vehicles and horses. Journal of Sustainable Tourism 18:239–256.

Rogler, G. A., and R. J. Lorenz. 1983. Crested Wheatgrass: Early History in the United States. Journal of Range Management 36:91.

Roundy, B. A., S. P. Hardegree, J. C. Chambers, and A. Whittaker. 2007. Prediction of Cheatgrass Field Germination Potential Using Wet Thermal Accumulation. Rangeland Ecology & Management 60:613–623.

Rusterholz, H.-P., S. W. Miiller, and B. Baur. 2004. Effects of rock climbing on plant communities on exposed limestone cliffs in the Swiss Jura mountains. Applied Vegetation Science 7:35–40.

Rusterholz, H.-P., C. Verhoustraeten, and B. Baur. 2011. Effects of Long-Term Trampling on the Above-Ground Forest Vegetation and Soil Seed Bank at the Base of Limestone Cliffs. Environmental Management 48:1024.

Schupp, Eugene W. (n.d.). Cheatgrass. http://www.usu.edu/weeds/plant_species/weedspecies/cheatgrass.html.

Sharp, W. C., A. H. Holmgren, N. H. Holmgren, L. Reveal, and P. K. Holmgren. (n.d.). Crested Wheatgrass. USDA, NRCS.

Smith, D. C., S. E. Meyer, and V. J. Anderson. 2008. Factors Affecting Bromus Tectorum Seed Bank Carryover in Western Utah. Rangeland Ecology & Management 61:430–436.

Staver, Carla. 2004. Invasion Biology Introduced Species Summary Project - Columbia University. http://www.columbia.edu/itc/cerc/danoff-burg/invasion_bio/inv_spp_summ/Bromus_tectorum.html.

Stewart-Wade, S. M., S. Neumann, L. L. Collins, and G. J. Boland. 2011. The biology of Canadian weeds. 117. Taraxacum officinale G. H. Weber ex Wiggers. Canadian Journal of Plant Science.

U.S. Climate Data, Gunnison. 2020. . https://www.usclimatedata.com/climate/gunnison/colorado/united-states/usco0175.

US EPA, O. 2015, November 16. Ecoregions. Data and Tools. https://www.epa.gov/eco-research/ecoregions.

USDA. 2008. Soil Quality Indicators. USDA Natural Resources Conservation Service.

Vogler, F., and C. Reisch. 2011. Genetic variation on the rocks — the impact of climbing on the population ecology of a typical cliff plant. Journal of Applied Ecology 48:899–905.

Weather averages Crested Butte, Colorado. (n.d.). . https://www.usclimatedata.com/climate/crested-butte/colorado/united-states/usco0093.

Whisenant, S. G. 1990. Changing Fire Frequencies on Idaho's Snake River Plains: Ecological and Management Implications. Intermountain Research Station, Forest Service, U.S. Department of Agriculture.

Woo, S. L., V. L. Harms, A. G. Thomas, D. P. Peschken, G. G. Bowes, D. W. Douglas, and A. S. McClay. 2011. The biology of Canadian weeds. 99. Matricaria perforata Mérat (Asteraceae). Canadian Journal of Plant Science.

Young, James A., Evans, Raymond A., Eckert, Richard E., and Kay, Burgess L. 1987. Cheatgrass. Rangelands 9:266–270.

Yüksek, T. 2009. Effect of Visitor Activities on Surface Soil Environmental Conditions and Aboveground Herbaceous Biomass in Ayder Natural Park. CLEAN – Soil, Air, Water 37:170–175.

Figures and Tables

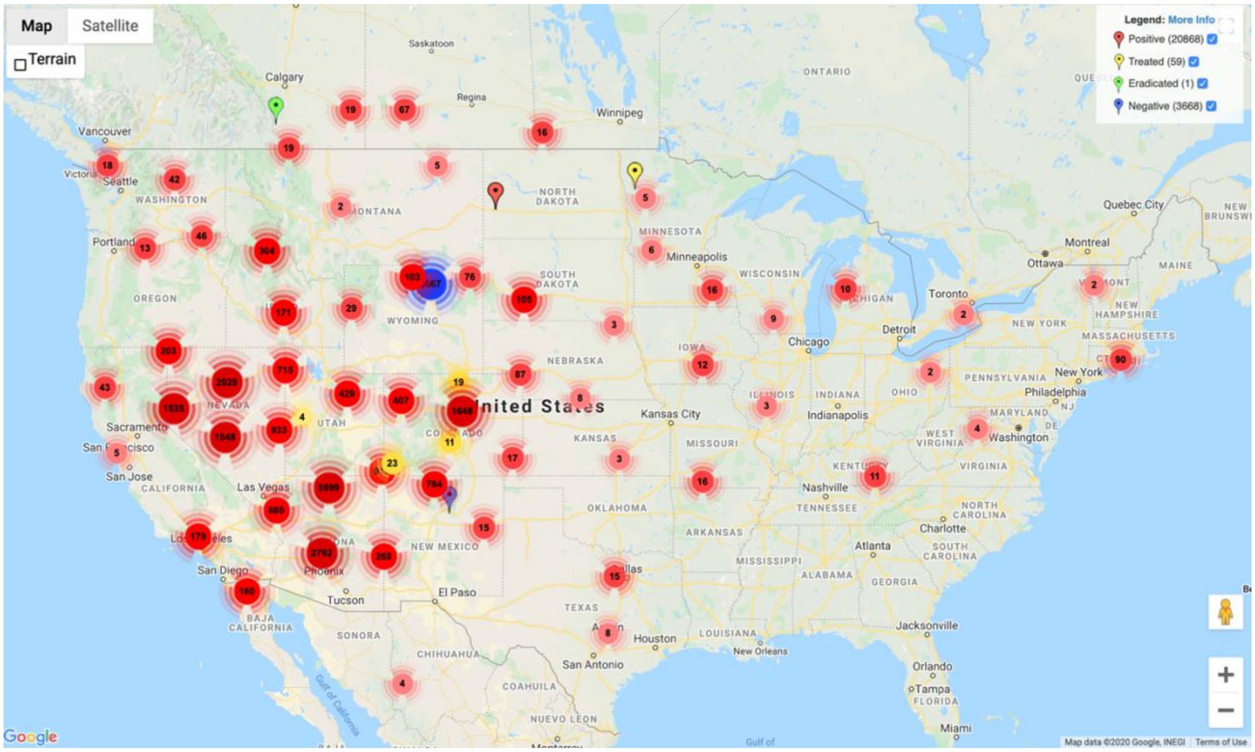

Figure 1. EDDMapS. Distribution and detection of cheatgrass *(Bromus tectorum)* in the U.S. Red clusters represent severity of cheatgrass distribution.

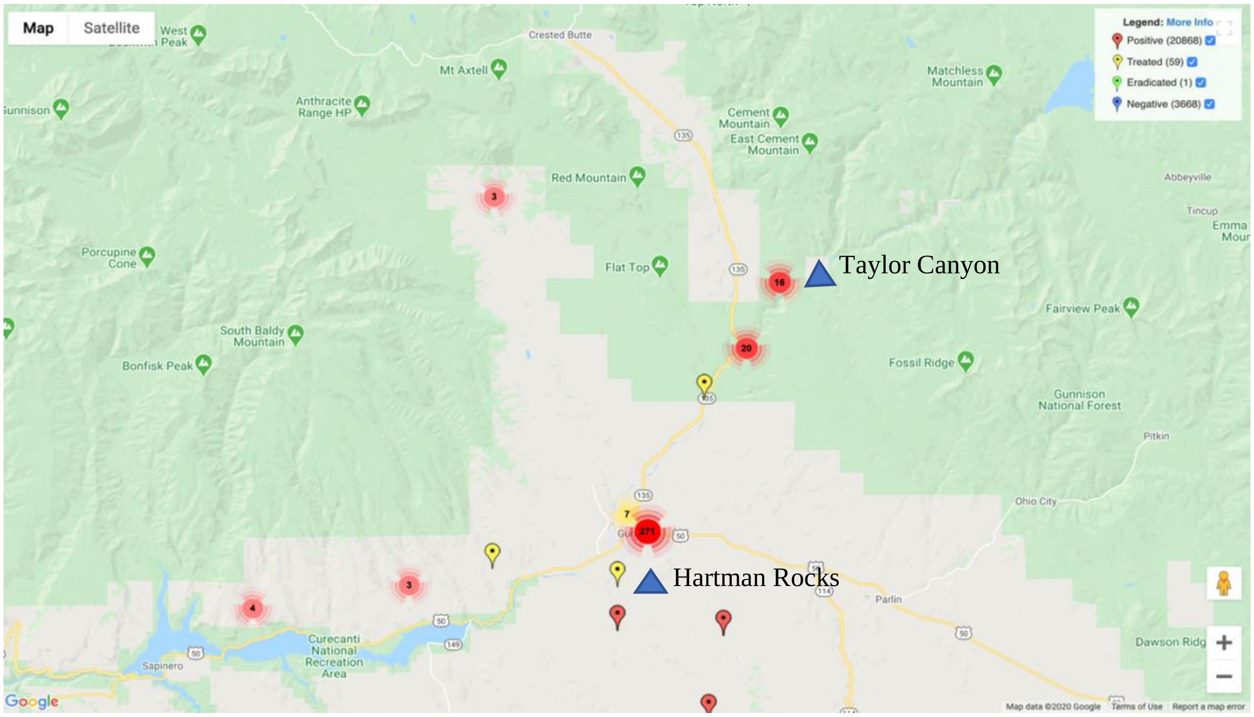

Figure 2. EDDMapS. Distribution of reported cheatgrass in the Gunnison Valley, Colorado. Blue triangles represent study sites Taylor Canyon and Hartman Rocks.

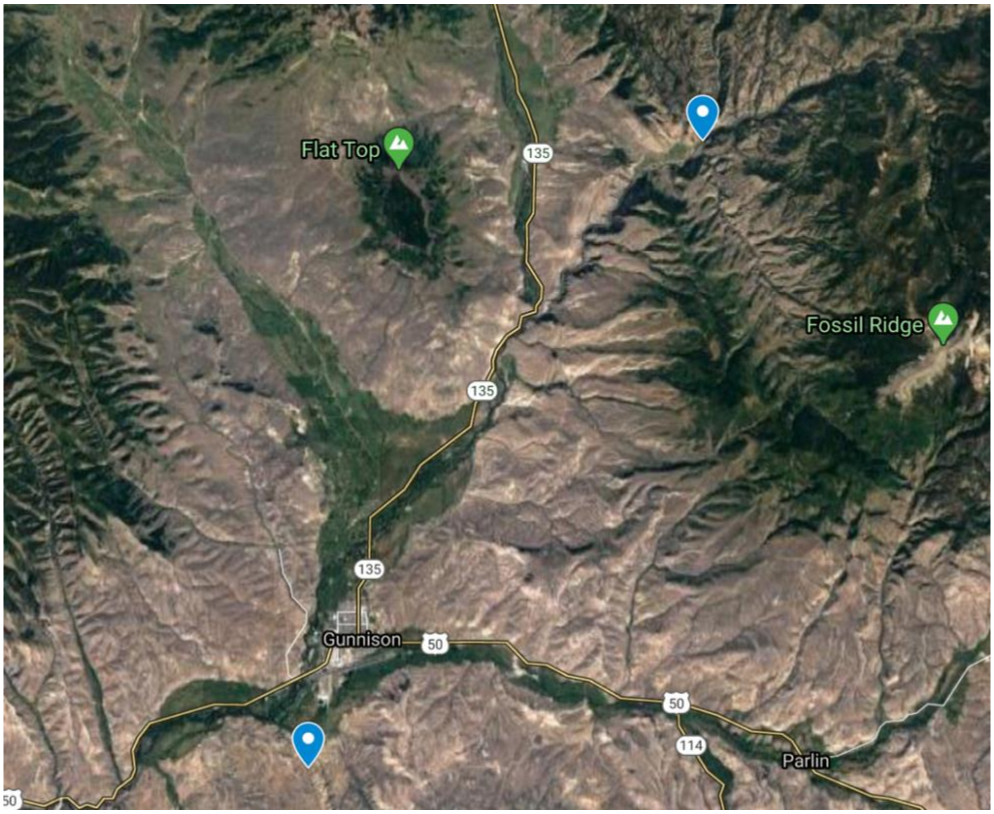

Figure 3. Map of study sites. Blue marker at the top of the image represents Taylor Canyon, and the blue marker at the bottom of the image represents Hartman Rocks.

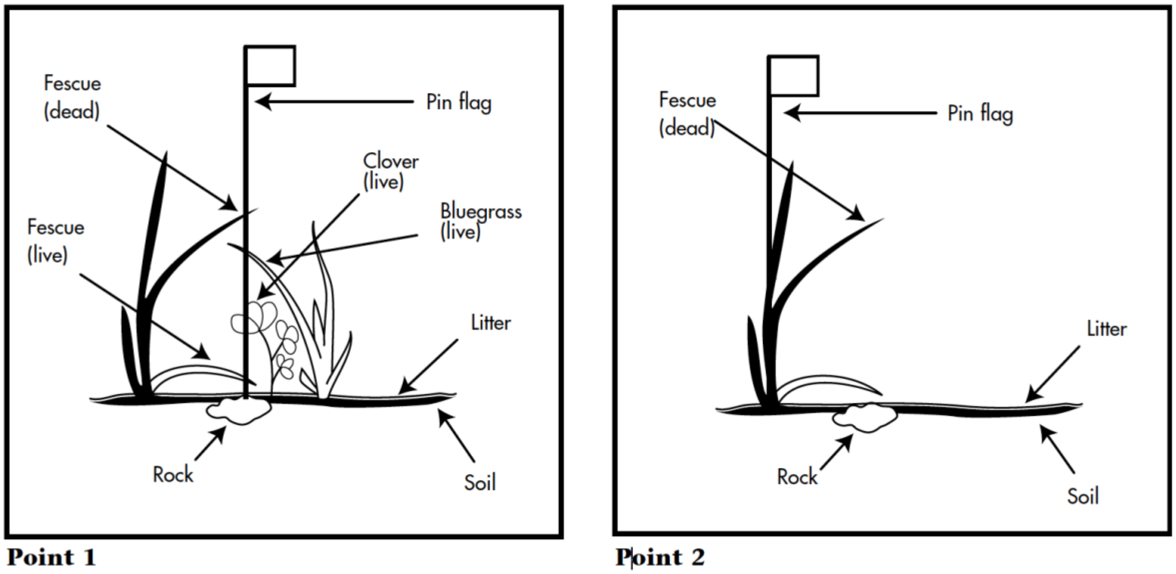

Figure 4. Line-point intercept method. (Herrick et al. 2005).

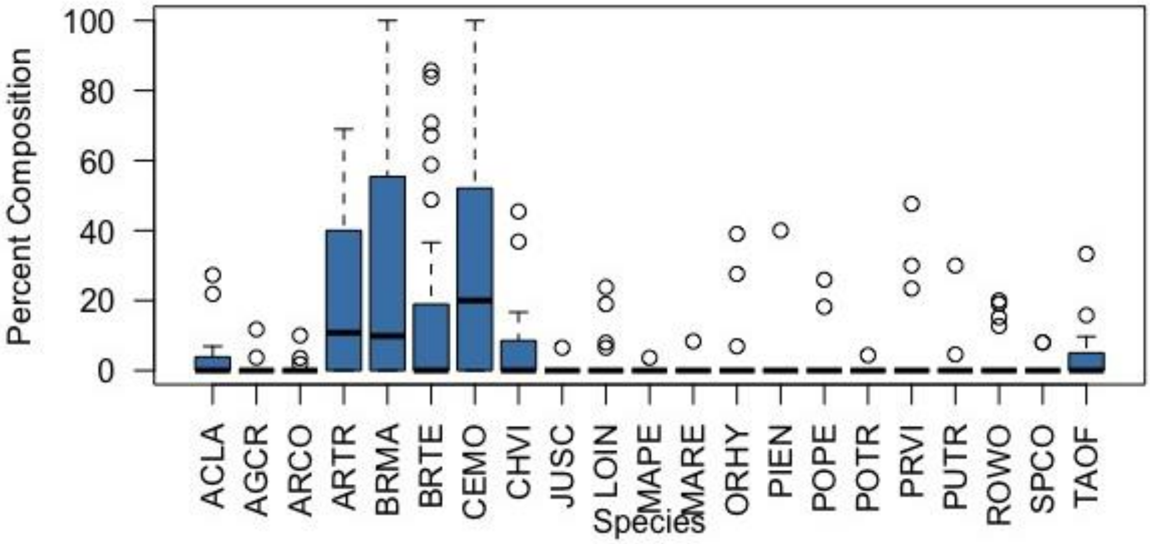

Figure 5. Percent composition of all aboveground plant species. Species code listed in Table 2.

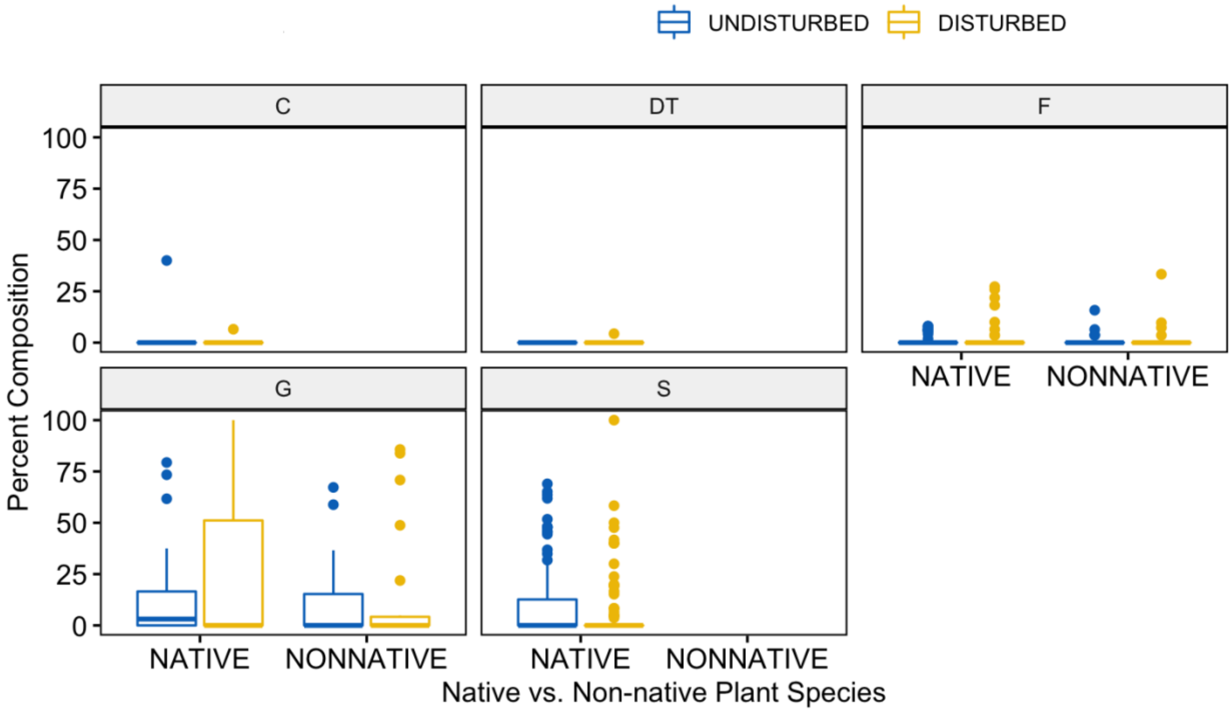

Figure 6. Native vs. Non-native aboveground percent composition of plant functional groups. C (conifer), DT (deciduous tree), F (forb), G (graminoid), S (shrub).

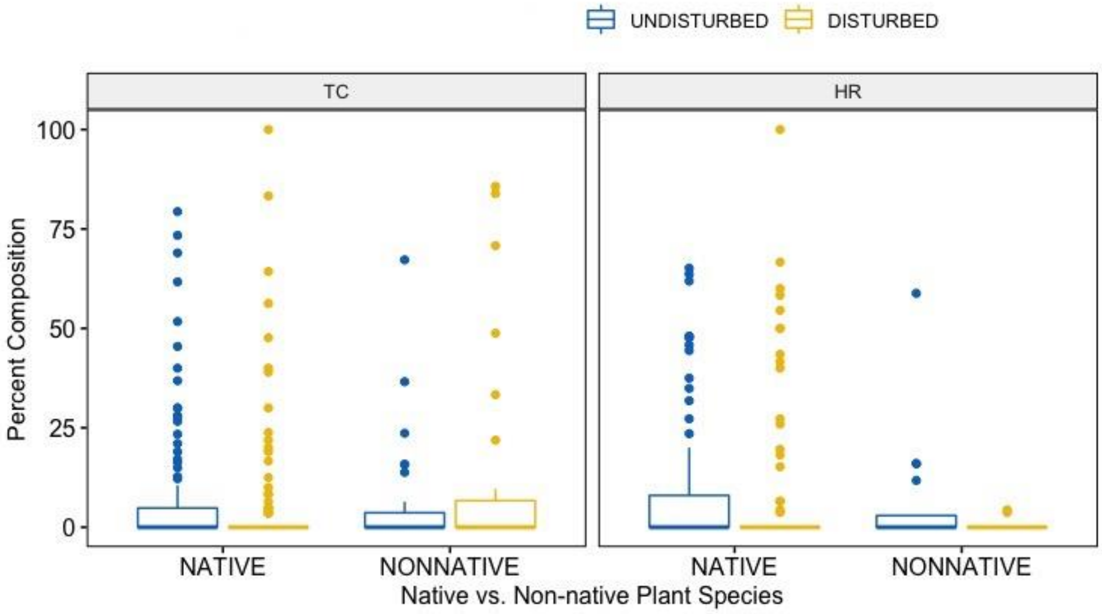

Figure 7. Native vs. Non-native aboveground percent composition of plant species in Taylor Canyon (TC) and Hartman Rocks (HR).

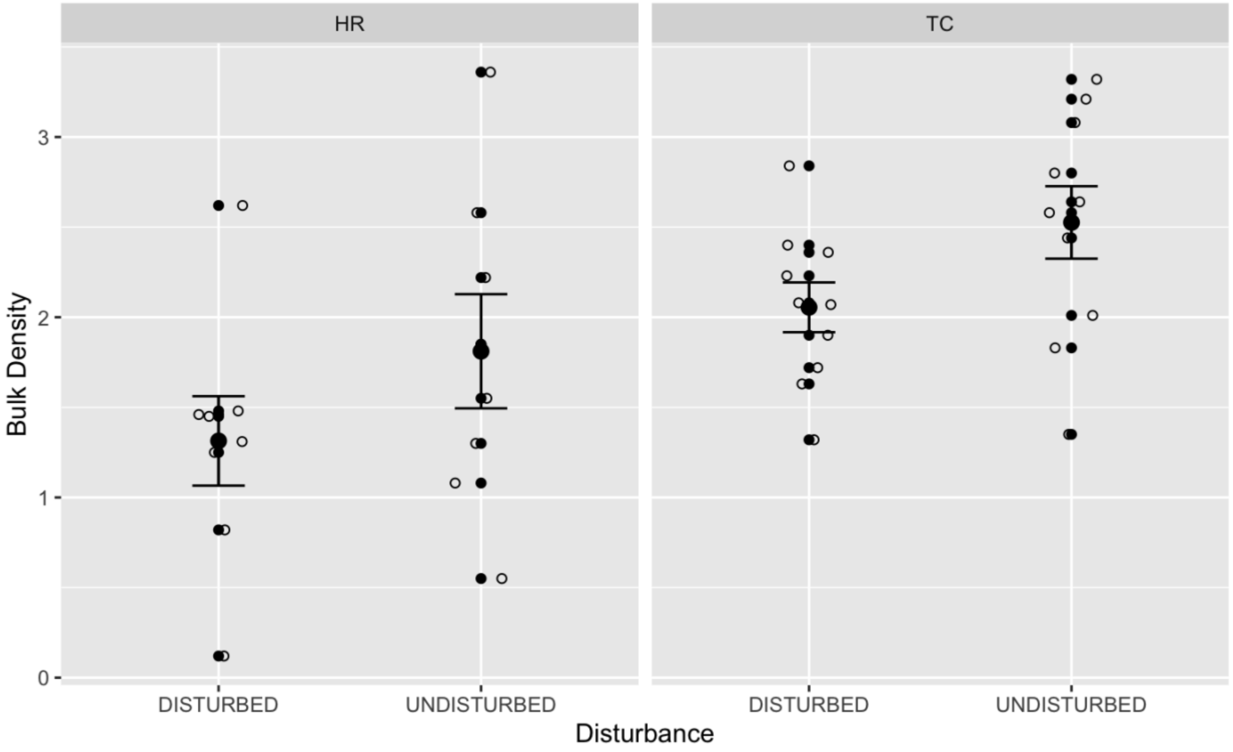

Figure 8. Bulk density (g/cm^3) in response to disturbance and site, Taylor Canyon (TC) and Hartman Rocks (HR).

Table 1. Gunnison Valley, CO Climbing Route Selection

Hartman Rocks	*Grade*	*Wall*
Buddha's Belly	5.9+	Buddha's Belly
Mystery Flake	5.9+	Resistance Wall
Resistance is Futile	5.8	Resistance Wall
Bajorn	5.7	Beginner Slabs
Neutral Zone	5.10a	Groove Rock
Pussy Foot	5.9	Tiger Wall
South Face Route	5.10+	Quintessential Pinnacle
The Pink Nipple	5.11a	Super Slab
Taylor Canyon		
Inner Space Traverse	5.9	First Buttress
Kindergarten Crack	5.4	First Buttress
Solo Crack	5.6	First Buttress
Left Hand Crack	5.8+	First Buttress
The Jackal	5.6+	First Buttress
Zigzag	5.9	First Buttress
Golithan	5.10b	First Buttress
Chuck E. Cheese	5.9+	Second Buttress
Angles Away	5.10a	Second Buttress
Nancy	5.11-	Second Buttress

Table 2. Recorded Plant Species. Mean and standard error of percent composition. Sites include Taylor Canyon (TC) and Hartman Rocks (HR).

Site	Species and Code	Mean ±SE	Common Name	Native or Non-native
TC	*Taraxacum officinale (TaOf)*	3.99 ± 1.82	Common dandelion	Non-native
TC	*Bromus tectorum (BrTe)*	23.88 ± 6.83	Cheatgrass	Non-native
TC	*Achillea lanulosa (AcLa)*	2.84 ± 1.18	Western yarrow	Native
TC	*Artemisia tridentata (ArTr)*	14.12 ± 4.34	Big sagebrush	Native
TC	*Chrysothamnus viscidiflorus (ChVi)*	6.55 ± 2.92	Douglas rabbitbrush	Native
TC	*Bromus marginatus (BrMa)*	29.62 ± 7.80	Mountain brome	Native
TC	*Oryzopsis hymenoides (OrHy)*	3.68 ± 2.33	Indian rice grass	Native

TC	*Purshia tridentata (PuTr)*	1.73 ± 1.51	Antelope bitterbrush	Native
TC	*Rosa Woodsii (RoWo)*	2.59 ± 1.44	Woods' rose	Native
TC	*Arnica cordifolia (ArCo)*	0.77 ± 0.52	Heartleaf arnica	Native
TC	*Matricaria perforata (MaPe)*	0.18 ± 0.18	Scentless chamomile	Non-native
TC	*Lonicera involucrata (LoIn)*	2.14 ± 1.48	Twinberry honeysuckle	Native
TC	*Prunus virginiana (PrVi)*	5.05 ± 2.90	Chokecherry	Native
TC	*Mahonia repens (MaRe)*	0.42 ± 0.42	Creeping Oregon grape	Native
TC	*Picea engelmannii (PiEn)*	2.0 ± 2.0	Engelmann spruce	Native
HR	*Artemisia tridentata (ArTr)*	27.34 ± 5.32	Big sagebrush	Native
HR	*Cereocarpus montanus (CeMo)*	28.27 ± 7.91	Mountain mahogany	Native
HR	*Bromus marginatus (BrMa)*	22.60 ± 6.30	Mountain brome	Native
HR	*Bromus tectorum (BrTe)*	5.95 ± 3.78	Cheatgrass	Non-native
HR	*Lonicera involucrata (LoIn)*	0.90 ± 0.62	Twinberry honeysuckle	Native
HR	*Rosa Woodsii (RoWo)*	0.95 ± 0.95	Woods' rose	Native
HR	*Populus tremuloides (PoTr)*	0.27 ± 0.27	Quaking aspen	Native
HR	*Juniperus scopulorum (JuSc)*	0.41 ± 0.41	Rocky Mt. juniper	Native
HR	*Potentilla pensylvanica (PoPe)*	1.53 ± 1.53	Pennsylvania cinquefoil	Native
HR	*Agropyron cristatum (AgCr)*	0.97 ± 0.76	Crested wheatgrass	Non-native
HR	*Achillea lanulosa (AcLa)*	2.33 ± 1.72	Western yarrow	Native
HR	*Sphaeralcea coccinea (SpCo)*	1.00 ± 0.68	Scarlet globemallow	Native

Table 3. Negative binomial regression analysis comparing plant functional groups between disturbed and undisturbed transects across both sites.

Coefficients	Std. Error	Z Score	p-Value
Total plant composition	0.32	-0.13	0.90
Deciduous trees	1.18	-1.30	0.19
Forbs	0.71	0.73	0.47
Graminoid	0.74	3.45	< 0.001
Shrub	0.66	2.73	< 0.001

Table 4. Seedling percent germination mean and standard error by species and negative binomial regression analysis on greenhouse seedling species percent germination. Data is combined from both sites. Percent germination refers to the percent of seedlings that germinated relative to the total number of seedlings germinated.

Coefficients	Mean ±SE	Std. Error	Z Score	p-Value
Native				
Arnica cordifolia	0.52 ±0.31	1.5e-01	-16.69	< 0.001
Artemisia tridentata	0.44 ±0.19	1.5e-01	-16.58	<0.001
Bromus marginatus	2.23 ±1.07	1.1e-01	-5.47	<0.001
Mahonia repens	0.15 ±0.09	1.2e-01	-11.25	<0.001
Rosa woodsii	1.45 ±0.85	1.3e-01	-4.77	<0.001
Non-Native				
Bromus tectorum	1.56 ±0.69	1.13-01	-8.61	<0.001
Matricaria perforata	0.07 ±0.07	3.5e-01	-12.66	<0.001
Taraxacum officinale	1.31±0.52	1.1e-01	-8.93	<0.001
Unknowns				
Unknown 1	2.93 ±2.60	1.3e-01	-10.47	<0.001
Unknown 2	0.13 ±0.13	1.8e-01	-15.07	<0.001
Unknown 3	2.40 ±1.38	1.1e-01	2.39	0.02