A Framework for Understanding Off-trail Trampling Impacts in Mountain Environments

Ross Martin and David R. Butler

Introduction

Many people visit mountain environments each year for the solitude and the challenge that they provide. Outdoor recreation has been steadily increasing this century, with a 12% increase in visitor-days to primitive areas from 2000 to 2008 (Cordell et al. 2008). Often mountain environments that are in remote locations or that display great biodiversity are chosen as destinations. Many hiking, mountain biking, or equestrian enthusiasts plan vacation time to carry out their respective activity in a unique mountain environment. People may choose to live in or near mountain environments so they can have access to mountain trails every day. The characteristics that make mountain environments attractive to outdoor recreation enthusiasts are often the very traits that are most impacted by human interaction with the environment. To preserve these areas and maintain the remote and diverse mountain recreation experience, it is vital that human impacts are well understood.

Trail systems provide networks so that recreationists can traverse the landscape to experience nodes of interest. Formal trails are designed, built, and maintained by the land managers. However, sometimes formal trails do not provide access to a desirable location, and informal trails are created by the trail user. Informal trails exist in a range of conditions, from a path of broken vegetation created by the trampling effects of one person to a highly eroded trail. Informal trails are one type of off-trail trampling. This paper discusses general trampling impacts of recreationists in mountain environments with a particular focus on how they might be more sensitive to off-trail trampling and informal trail propagation.

Mountain environments

Mountain environments were selected as the focus for this study based on the hypothesis that they are more sensitive environments, and therefore the impacts of off-trail trampling should be exacerbated there. The reality of this hypothesis will be discussed throughout this paper. Mountains exist as "islands' in the sky" that harbor biodiversity and sensitive species

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The George Wright Forum, vol. 34, no. 3, pp. 354–367 (2017).

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(Monz et al. 2010). Mountains exhibit high biodiversity with distinct changes in vegetation sequences or ecotones associated with changes in altitude (Brown 1994) or with specific geomorphic processes and settings (Butler et al. 2003). The distribution of vegetation on mountains exists primarily in lateral bands, with the most obvious boundary of vegetation change being the tree line (Butler et al. 2007).

Mountains have distinct weather and climatological patterns (Beninston 2006). Latitude determines amount and duration of sunlight. Altitude and topography result in orographic uplift and sometimes the rain shadow effect, where the slopes facing the incoming weather receive nearly all of the precipitation and the leeward side of the mountain receives little to no precipitation. This creates a contrast in vegetation with regard to aspect of the slopes.
No single factor can be used to empirically define a mountain. However, mountains are usually higher in elevation than the surrounding area, and have steep slopes, distinct zones of vegetation that change with elevation and microclimate, and a geologic origin.

Methods

This study is a qualitative analysis of the literature, resulting in the creation of a conceptual framework to understand off-trail trampling and informal trail propagation. The analytical method of this research includes "inductive analysis and creative synthesis." According to Patton (2005), this type of qualitative method is characterized by "immersion in the details and specifics of the data to discover important patterns, themes, and interrelationships" and is "guided by analytical principles rather than rules" to produce a "creative synthesis" (Patton 2005: 40–41). In this case the literature comprises the *data*; the *patterns and themes* are the variations, rates, and impacts of trampling; and the *creative synthesis* results in the formulation of a conceptual model of the evolution of off-trail trampling and informal trail propagation.

Research about trampling impacts was reviewed with regard to vegetation and soil impacts, and comparisons of impacts from different types of trail users. Impacts on vegetation and soils were analyzed to understand generally what those impacts consisted of, and if mountain environments are more sensitive to them. Literature about different types of trail users in mountain environments was evaluated in order to understand if the degree of impact was influenced by the type of trail user. The literature reviewed explicitly identified the study area as mountain, montane, sub-alpine, or alpine (see Table 1).

Literature about informal trails was reviewed to explore how they are created and propagated. The focus was on how and why informal trails are created, and the impacts associated with their creation. Because there were so few articles that discussed informal trails in mountain environments, this portion of the literature was not confined to those environments.

Formal and informal trails

Recreational trail systems function to connect nodes of interests or to provide routes across landscapes. From a management perspective, trails can be categorized either as artificially surfaced trails, or as naturally surfaced informal or formal trails (Marion and Leung 2011). Typically, surfaced trails exist in the highest-trafficked areas and are covered by gravel, as-

- *Mountain:* A general term, typically inclusive of all mountain ecologic zones.
- *Montane:* The ecologic zone generally marked by a transition from dense tree stands to sparser, hardier tree species (Price 1986).
- *Sub-alpine:* The ecologic zone immediately below the tree line; often krummholz are present.
- *Alpine:* The ecologic zone above the tree line; often includes meadows and tundra.

Table 1. Terms used to characterize areas identified for inclusion in this study.

phalt, or wood. Naturally surfaced trails, either formal or informal, stretch across the landscape and are often the only way to access remote areas. Natural surfaces connote that foreign material is not used on the trail surface; however, in some cases it may be reworked to facilitate water drainage. Formal trails function to concentrate and direct visitor traffic so their presence is more sustainable (Wimpey and Marion 2010). Informal trails are not subjected to a design process that considers environmental conditions, and in most cases they are not maintained (Wimpey and Marion 2010).

Wimpey and Marion (2010) found that informal trails in Great Falls Park, Virginia, have higher slopes, are located in steeper terrain, and are more closely aligned with the fall line than formal trails. Each of these factors add to the potential for trail incision and erosion by flowing water. Steep terrain and high slopes are obvious characteristics of mountain environments, so the potential for incision and erosion of informal trails is even greater there. Trail density also is a concern because trails can fragment landscapes and impact plants and wildlife (Knight 2000). Informal trails often result in duplicate routes that are in close proximity, which result in unneeded forest fragmentation (Wimpey and Marion 2011).

Informal trail creation begins with off-trail trampling. Off-trail trampling occurs when trail users go somewhere other than on a formal trail. Wimpey and Marion (2011) suggest seven reasons for off-trail trampling. Six are intentional: (1) to access areas unavailable to formal trails, (2) to avoid poor conditions on formal trails, (3) to explore, (4) to create a shortcut, (5) to investigate or photograph something, and (6) to engage in off-trail activities such as geocaching. The seventh reason is unintentional: people may go off-trail by accident, perhaps because of poor trail markings. These seven likely reasons for off-trail trampling do not include instances where people seek privacy (for any number of reasons), where users must step off the trail to allow others to pass, or where groups wait along the side of a trail. Thus, there are ten potential reasons for off-trail trampling. The results of off-trail trampling include trail widening and the creation of new trails.

The potential for degradation depends on topography, slope, and vegetation and soil properties. Depending on the resistance of the vegetation to trampling, only a few off-trail users can create a visual cue that subsequent users might interpret as a trail. Visual cues include broken vegetation and soil exposure. Once present, visual cues can lead to an increase of off-trail traffic, as trail users begin to identify a path or area as all right to use. In order to reduce the propagation of informal trails, the sensitivity of an area to off-trail trampling must be considered by management. From a process perspective, informal trails are not any different than formal trails.

Impacts on vegetation

Vegetation responds to trampling in many ways. The most obvious impact is the breaking of vegetation and reduction of vegetation cover. Other impacts include a change in species diversity and reduction in reproductive ability. Hill and Pickering (2009) compiled data from several vegetation studies (Cole 1995a, b; Liddle 1997; Monz et al. 2000; Littlemore and Barker 2001; Monz 2002; Gallet et al. 2004; Growcock 2005) to show that the montane zone was the most susceptible to trampling, followed by the alpine, subalpine, and temperate zones, with the subtropical zone being the most resistant.

Different vegetation types react to trampling differently (Cole 1995a, b; Whinam and Chilcott 2003; Barros et al. 2013). Plant height and morphological structure appear to be strongly associated with resistance to trampling (Sun and Liddle 1993). Under experimental conditions, Cole (1995b) showed that vegetation stature and physiognomic type (shrubs, graminoids, or forbs) explained the majority of the variance for the resistance to trampling. Under experimental conditions in a Mediterranean environment, Andres-Abellan et al. (2006) found that species composition had the greatest impact on the decrease of percent vegetation cover, number of species, and plant height response to trampling. They found that the plant species factor was followed by trampling intensity in terms of overall impact (Andres-Abellan et al. 2006). Whinam and Chilcott (2003) showed that plant morphology was the major factor in determining the impact of trampling regardless of slope, aspect, or altitude. Cole 1995(a) revealed that most types of vegetation experience constant, nearly linear, rates of loss, whereas more resistant species experience highly curvilinear rates of vegetation loss when compared with trampling intensity.

The general trend of resistance to trampling is graminoids > trees > forbs > shrubs (Yorks et al. 1997; Hill and Pickering 2009). Whinam and Chilcott (1999) found shrubs to be more vulnerable that grasses or graminoids in an alpine/sub-alpine environment on the Central Plateau of Tasmania. Their follow-up analysis of the same site (Whinam and Chilcott 2003) shows that shrubs, graminoids, and cushion plants experienced a sustained impact, whereas tufted graminoids and low-growing shrubs were more resistant to trampling. Under experimental conditions in a subalpine environment in northwest China, Mingyu et al. (2009) described areas with low shrub vegetation, which were highly vulnerable to trampling damage, whereas graminoid grasslands were more resistant. Barros et al. (2013) revealed that most grasses and shrubs were not as tolerant to trampling when compared with native herbs. They found that some native herb species responded positively to trampling, suggesting evolutionary adaptation to disturbance or a reduction in less resistant and competitive plant species. In post-trampling assessments, Whinam and Chilcott (1999, 2003) discovered that trampling increased species diversity at some sites, suggesting that the reduction in cover of some species gave competing species the opportunity to grow. In contrast, Rusterholz et al. (2011) found that species richness and total plant cover was reduced in trampled areas, with a larger proportion of the species found in trampled areas being more competitive and stress tolerant. The changes in species richness are likely highly dependent on the types of vegetation and the degree of competition between types that naturally occur at any given location. The response by vegetation cover continues for some time after trampling impact, peaking days, weeks, or even a year after treatment, depending on the resistance of the vegetation (Cole 1993; Cole and Bayfield 1993).

In addition to the reduction of less-resistant vegetation by the mechanical forces of trampling, species richness can be impacted by changes in reproductive ability. Shorter growing seasons makes this an especially important consideration in mountain environments (Pickering and Growcock 2009). The potential for sexual reproduction can be reduced because of reduction in fruit production in trampled sites (Rossi et al. 2006, 2009). Under experimental conditions, Pickering and Growcock (2009) found trampling to reduce species height. They suggest that height has far-ranging impacts in mountain environments because it directly affects the photosynthetic area of the plant. This is especially crucial in the spring, when montane plants experience the most growth; with decreased photosynthetic area and correspondingly lower carbohydrate reserves, the plants may fail to produce seeds (Pickering and Growcock 2009).

A secondary impact of trampling on a plant's ability to reproduce is that it can affect seed dispersal. Trampling can distribute seeds of open-habitat species into the forest interior (Hamberg et al. 2010). The introduction of new plant species into a trampled area can change the competition dynamics. Rusterholz et al. (2011) showed that soil seed density was negatively correlated with trampling intensity.

Impacts on soil

In mountain environments, soil disturbance by trampling is greatest in cols and on summit ridges because of the more limited development of soil horizons in these areas (Grieve 2000). In general, soil is less developed on high slopes, and increases downslope. When vegetation cover is reduced, the soil becomes impacted, which in turn affects future vegetation growth, thus triggering a feedback loop. For example, in alpine and subalpine zones of Aconcagua Provincial Park (Argentina), Barros et al. (2013) deduced that sedge abundance was reduced likely because of trampling-induced losses of soil moisture. Under experimental conditions in the northern Rocky Mountains, Cole and Spildie (1998) found that mineral soil exposure after trampling was dependent on vegetation type because the thickness of the soil organic-horizon was dependent on vegetation type.

Under experimental conditions, Korknac (2014) showed that short-term impacts have minimal impact on most soil properties, however, at a higher trampling intensity (200–500 passes) there was decreased total porosity and increased soil penetration resistance. Kutiel and Zheveleve (2001) documented a fourfold increase in soil compaction and a 21% decrease in soil moisture in a picnic area when compared with surrounding undisturbed forest. Scott et al. (2007) found that increased trampling intensity led to an increase of water loss. Lucas-Borja et al. (2011) noted higher compaction and carbon/nitrogen ratio on trampled trail areas compared with adjacent untrampled areas. De Gouvenain (1995) found that the soil of a trampling-impacted site had finer grains and more bare ground surface. In contrast, Grieve (2000) found that unvegetated trampled sites had increased stone abundance and less organic matter, iron, and soil moisture. In Yosemite National Park (California, USA), Malin and Parker (1976) found a platelike hardpan structure 3–5 cm beneath trampled areas.

Soil compaction reduces infiltration and can initiate overland water flow. In mountain environments where slopes are abundant, any overland flow has the capacity to entrain sediments. This erosion can remove the top layer of soil and expose mineral horizons.

Comparison of trampling types

In mountain environments several types of recreational activity can result in off-trail trampling. Horses, mountain bikers, and hikers are probably the most common trampling forces, especially in national and state parks and other preserved lands. Although all of these activities create and require trails, the impact of a specific user type is important to understand. Different user types express different forces on the landscape; however, the result still is characterized by the previously discussed trampling impacts to vegetation and soil. It is necessary to consider the mechanics of motion and weight distribution of various trampling agents. The differences in impacts of various user types are ones of scale or of how quickly the impact might occur.

Mingyu et al. (2009) showed that the user type is a more dominant factor than vegetation, although differences in user type are less drastic when more resistant vegetation species are involved. Under experimental conditions, Cole and Spildie (1998) compared hiker, horse, and llama trampling. They found that horse trampling impact was significantly higher than those of llamas and hikers, which were significantly similar. They found that vegetation type and trampling intensity played a role in vegetation cover loss, but if these two factors were accounted for, the horse impact on vegetation cover was substantially greater than that of either hikers or llamas. In shrub-type vegetation, no mineral soils were exposed by hikers or llamas, but mineral soils were exposed in as few as 25 passes by horses. Cole and Spildie concluded that because the weight of a horse is approximately six times greater than that of a person, and because the distribution of that weight is by means of a hoof that has half the surface area of person's boot or shoe, the horse impact is greater because of the increase in pressure per area.

Under experimental conditions, Whinam and Chilcott (1999) compared horse with hiker trampling and found that after 30 passes the percentage of broken biomass caused by hikers was 0.1% compared with 39.2% for horses. Reduction of vegetation cover by horses persisted longer, and one year after trampling there was a substantial difference in rates of recovery between horse and hiker impacts.

Pickering et al. (2011) showed in experimental trampling conditions that mountain bike riding produced a reduction in vegetation height in as few as 25 passes. Mountain biking also produced a reduction in percent vegetation cover and species richness similar to other trampling activities. The authors found that the impact of bikes was higher on slopes compared with flat ground. Bikers produced soil compaction much faster than hikers, but had a smaller impact on absolute cover of vegetation. Bikers had a greater impact on leaf litter, but these differences only occurred at the highest levels of trampling tested (500 passes).

Summary of impacts

The literature suggests that mountain environments are indeed more sensitive to off-trail trampling. Vegetation response includes a reduction in species richness and abundance. Shrubs and forbs are more sensitive to off-trail trampling. Seed availability is also negatively impacted in trampled areas. If mountains are regarded as isolated "islands in the sky," the reduction of seed availability presents a unique challenge, since there is a smaller spatial extent of suitable species to provide replacement seeds and reproductive resources.

Soil impact, including compaction and loss of soil moisture, can negatively impact plant growth. Soil in mountains is less developed on slopes and those slopes provide more potential energy for downslope erosion of soils. The erosive capacity for overland water flow is greater because of the steeper slopes.

Horses cause the greatest impact because of their larger mass being distributed by means of a small hoof area. A mountain biker compacts the soils faster, possibly because a bike is in relatively constant contact with the ground, whereas hikers and horses leave gaps between their steps. The biker produces less impact on overall vegetation cover likely because the front tire is followed by the rear tire, creating a narrower tread width of a few inches, whereas hiker's feet move side by side, creating a wider tread path. Another factor that must be considered is how each trampling agent moves while in groups. The trampling pattern of two agents moving side-by-side will be different from one following another. Clearly, horse impact has the highest degree of impact, with hiker and biker impact roughly equal. However, it is likely that more hikers and bikers visit mountains for recreational purposes. Therefore, in many areas the greater net impact may be from many hikers and bikers, rather than a few horses.

Trampling evolution

Trampling occurs in stages. To gain a broader understanding of trampling, it is useful to loosely define the stages of its impact. It should be noted that these stages are not discrete, but a convenient way to divide and describe a continuum of impact. Figure 1 provides a graphic depiction of the hypothetical trampling evolution model associated with hikers, bikers and horses. The first stage of trampling occurs with the first impact to vegetation. In this stage the trampling agent breaks or crushes the plants in the tread area. The degree to which impact occurs in this stage is dependent primarily on the trampling agent type, vegetation type, and the trampling intensity. As the trampling progresses, more vegetation is lost, with more-resistant species remaining longer than the less-resistant ones. As vegetation is lost, the trampled area becomes more visually apparent.

The second stage of trampling occurs as vegetation is lost and soils become exposed to impacts. At this point, the trampled area may visually be identified as a trail. This may cause impact to increase, because users are more likely to take a route that is recognizable as a path. In this stage there is further vegetation loss, dead plant matter may litter the trail, and the soil becomes compacted and loses its storage capacity. Compaction and reduction of storage capacity can cause further vegetation loss.

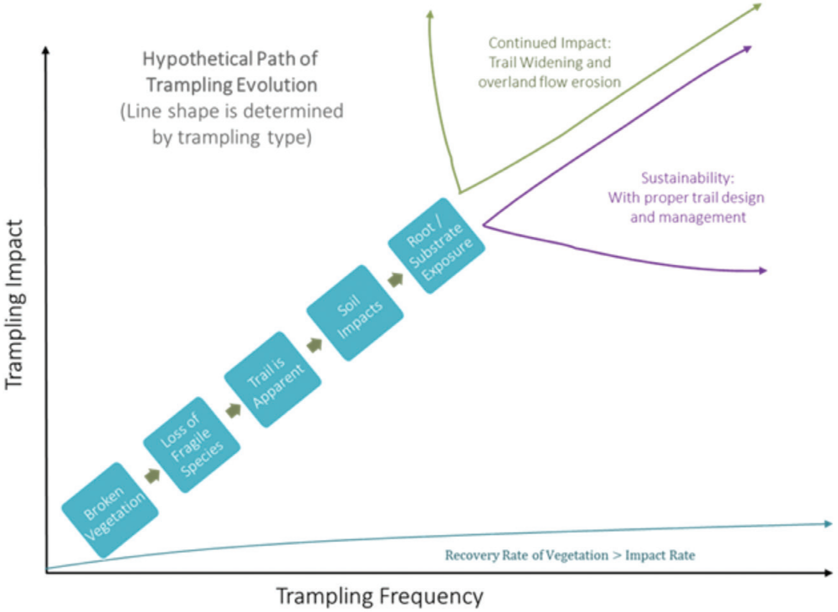

Figure 1. Hypothetical evolution of trampling.

What happens after these initial two phases is largely dependent on user type and intensity. At this point the trampling becomes an obvious trail, if it is a linear pattern of trampling. If the trampling was limited in scale, there is likely to be some recovery of vegetation. However, the extent of recovery is dependent upon the intensity of the trampling and on the vegetation type as well as climatic factors (Willard et al. 2007). If the trail is used often, it continues to experience soil and vegetation impacts along its margins. There is likely a threshold of trampling intensity that will determine if the trail will be characterized by recovery or continued impact. The threshold would be dependent on vegetation and substrate conditions.

Increased traffic widens and deepens a trail, the extent of which is dependent on both vegetation and substrate type (Morrocco and Ballantyne 2008). An increase in trail usage will likely cause an increase in likelihood that the margins of the trail become trampled. This can occur by having to pass someone going the same direction, by stepping off the trail to allow oncoming traffic to pass, or by walking or riding two or three abreast. The impacts of this stage are the same impacts that occur in the initial stages—soil compaction and reduction of vegetation—only now the impact spreads to adjacent areas. The further evolution of the trail is now dependent on the use type and the terrain sensitivity. Morrocco and Ballantyne (2008) indicated that the terrain sensitivity is dependent on vegetation and substrate.

Two critical thresholds exist in regard to off-trail trampling and informal trail creation. These thresholds are difficult to quantify and likely vary greatly across different environments. The literature, as previously discussed, makes it clear that the initial impact to vegetation is reduction in height and breakage, which occurs after relatively few passes. Vegetation sensitivity plays a major role in how many off-trail trips create visual cues. However, the type of trampling agent (or trail user) plays the biggest role in how much off-trail trampling it takes to create visual cues. The visual cues afforded by the reduction of vegetation represent the initial threshold in off-trail trampling. If those visual cues present themselves, additional off-trail trampling is likely to occur as other trail users now identify it as a trail, or as a place that is "okay" to go to. However, vegetation can recover from this low-level impact, and with expedient management efforts the trampled vegetation will recover. If, however, there is continued trampling, there will be a reduction in vegetation abundance in addition to further breakage, and soils begin to be impacted. The impact to soils represents the second crucial threshold. Impacted soils can reduce vegetation growth, and it takes much longer for soils to recover. With broken vegetation, impacted soils, and reduced vegetation growth, the area is certainly visibly acknowledged as a trail and it will continue to be used as such unless management strategies are put in place to prevent use and restore vegetation.

One of the general impact-use patterns observed in the field of recreation ecology is the sigmoidal response curve, show in Figure 2 (Monz et al. 2013). This research suggests that off-trail trampling in mountain environments follows that curve, with the vegetation impact and soil impact represented by the primary and secondary inflection points.

Mountains are unique environments, and because of their extreme conditions trampling impacts can be amplified. The initial impacts that lead to the first inflection point occur with only a few off-trail tramplers. By damaging vegetation and soils, areas of off-trail trampling become more attractive to other trail users. The secondary threshold is crossed, resulting in informal trail creation and further degradation. These thresholds are both visual and physical, and are present because of impact to vegetation and soil.

Management strategies

Insights into how trampling changes a landscape and how that impact can change over time can be very valuable to trail management initiatives. Proper management of recreational trampling-related activities is crucial. Management techniques and considerations that may reduce impact and increase the sustainability of mountain recreational trampling activities are considered here.

One important concept to define is the difference between plant *resistance to trampling* and *resilience*. Resistance to trampling is how the plant reacts to the initial trampling

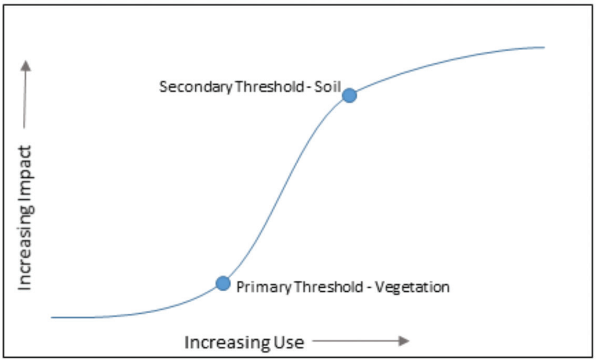

Figure 2. Generalized use-impact response curve. Adapted from Monz et al. 2013.

force, whereas resilience is how quickly that plant community can rebound if the trampling force is removed (see Cole 1995b). For example, Pickering and Growcock (2009) noted that in their Australian alpine study location there was a moderate resistance to trampling but low resilience, meaning that a few initial trampling activities have minimal impact, but once the impact is present it is difficult for the vegetation to rebound. In situations such as this, it is important to make sure that users stay on the trail. Barros et al. (2013) suggest signage and visual trail boundaries to reduce trail widening and the formation of informal trails, especially in alpine meadows. Kim and Daigle (2012) also suggest that defining trail boundaries is crucial to re-establish vegetation, referring to vegetation recovery in areas up to 70–80m away from the formal trail. In an interesting result, Barros et al. (2013) found that braided trails in meadows were twice as wide as trails in steppe sites. The control sites showed nearly complete vegetation coverage in the meadows and approximately two-thirds coverage in the steppe sites. They deduced that the woody vegetation in the steppe sites restricted trail users to narrower paths, while the meadow vegetation did not restrict users in that way, resulting in lateral spreading of impacts.

Horses are shown to have the biggest impact on soils and vegetation, with bikers having only slightly higher overall impact that hikers. It is common practice for trail systems to require bikers to yield to all other users. When a biker has to yield to a hiker, the biker must decelerate much more quickly than a hiker. The deceleration can be associated with skidding and increased shear stress, resulting in erosion of the trail surface. Then, one of the parties, usually the person yielding, must step off-trail to allow the other to pass. In sensitive mountain environments, this study suggests that perhaps this rule should be re-evaluated, since the impact of a hiker coming to a stop and stepping off-trail is a lesser impact than that of a biker being forced to do so.

Whinam and Chilcott (1999) show that the rotation or temporary closure of trails is sometimes not a useful form of management because of very slow recovery rates of some types of vegetation. However, if trail closure is chosen as a management strategy, the condition of soils should be considered before reclamation or restoration of trampled sites is undertaken, because the changes in soil characteristics may provide a better habitat for plant species other than those present before the trampling disturbance (de Gouvenain 1995). Restoration and management efforts should consider re-establishing vegetation from nearby populations and from seeds collected on site (Rossi et al. 2006), and forethought exercised in establishing seed banks at impacted recreation areas (Rossi et al. 2009).

Geographic Information Systems (GIS) and other geospatial technologies provide powerful tools that can be used to describe environmental sensitivity and monitor restoration efforts. Tomczyk (2011) demonstrated a method of GIS assessment of environmental sensitivity that includes the USLE (Universal Soil Loss Equation). This assessment showed areas of potentially increased soil erosion. A study by Morrocco and Ballantyne (2008) found relationships between terrain (vegetation and substrate) and trail morphology. Although they did not discuss the use of GIS in their paper, the terrain index analysis they employed is very friendly to GIS applications. Their analysis could be easily taken to the next level of predicting trail morphology, at least qualitatively, based on terrain index. Remote sensing could be used to analyze vegetation trends and mineral soil surface exposure. Kim and Daigle (2012) successfully demonstrated a methodology using NDVI (Normalized Difference Vegetation Index) and GIS to monitor vegetation impact and recovery in sub-alpine Cadillac Mountain at Acadia National Park, Maine, USA.

Conclusions

In terms of physical processes, the dichotomy of informal and formal trails holds little meaning. Trails exist on a continuum from lightly trampled vegetation to highly incised and eroded pathways. The primary difference is that the formation process of informal trails is unlikely to consider environmental conditions. In highly trafficked parks and wilderness areas, it is important to minimize informal trail formation to reduce negative impacts such as habitat fragmentation and erosion. When discussing trampling impact and off-trail trampling in mountain environments, the evolution of a trail must be considered. Because vegetation is more sensitive in mountain environments, fewer off-trail passes may result in the visual appearance of a trail that may entice other recreationists to also traverse that route.

Consideration must be given to the processes involved in trampling impact. It is possible to mitigate negative recreational impacts by recognizing the processes of trampling evolution in mountain environments. More research into the impact of specific user types in various terrain types is needed. Future research should consider the applicability of utilizing GIS and remote sensing to monitor trampling impact in remote mountain areas. Additionally, by approaching trampling within a biogeomorphic framework, it may be possible to predict trail conditions for an area before enabling recreation enthusiasts to use it, allowing land managers to avoid trampling impact in the most sensitive environments.

References

Andres-Abellan, Manuela, Francisco R. Lopez-Serrano, Francisco A. Garcia-Morote, and Antonio Del Cerro-Barja. 2006. Assessment of trampling simulation impacts on native vegetation in Mediterranean sclerophyllous forest. *Environmental Monitoring and Assessment* 120: 93–107.

Barros, Agustina, Jorge Gonnet, and Catherine Pickering. 2013. Impacts of informal trails on vegetation and soils in the highest protected area in the southern hemisphere. *Journal of Environmental Management* 127: 50–60.

Barry, R.G. 1994. *Past and Potential Future Changes in Mountain Environments*. London and New York: Routledge.

Beniston, M., Mountain weather and climate: A general overview and a focus on climatic change in the Alps. *Hydrobiologia* 562: 3–16.

Brown, D.G. 1994. Comparison of vegetation–topography relationships at the alpine treeline ecotone. *Physical Geography*15: 125–145.

Butler, David R., George P. Malanson, Stephen J. Walsh, and Daniel B. Fagre. 2007. Influences of geomorphology and geology on alpine treeline in the American West—More important than climatic influences? *Physical Geography* 28(5): 434–450.

Butler, David R., Lynn M. Resler, Dianna A. Gielstra, and Dawna L. Cerney. 2003. Ecotones in mountain environments: Illustrating sensitive biogeographical boundaries with remotely sensed imagery in the geography classroom. *Geocarto International* 18(3): 63–72.

Cole, David N. 1993. *Trampling Effects on Mountain Vegetation in Washington, Colorado, New Hampshire and North Carolina.* Research Paper INT-464. Ogden, UT: US Department of Agriculture–Forest Service Intermountain Research Station.

———. 1995a. Experimental trampling of vegetation: (2) Predictors of resistance and resilience. *Journal of Applied Ecology* 32: 215–224.

———. 1995b. Experimental trampling of vegetation: (1) Relationship between trampling intensity and vegetation response. *Journal of Applied Ecology* 32: 203–214.

Cole, David N., and Neil G. Bayfield. 1993. Recreation trampling of vegetation: Standard experimental procedures. *Biological Conservation* 63: 209–215.

Cole, David N., and D.R. Spildie. 1998. Hiker, horse and llama trampling effects on native vegetation in Montana, USA. *Journal of Environmental Management* 53: 61–71.

Cordell, H. Ken, Carter J. Betz, and Gary T. Green. 2008. Nature-based outdoor recreation trends and wilderness. *International Journal of Wilderness* 14(2): 7–13.

de Gouvenain, Roland C. 1996. Indirect impacts of soil trampling on tree growth and plant succession in the north Cascade Mountains of Washington. *Biological Conservation* 75: 279–287.

Gallet, S., S. Lemauviel, and F. Roze. 2004. Responses of three heathland shrubs to single or repeated experimental trampling. *Environmental Management* 33: 821–829.

Grieve, Ian C. 2000. Effects of human disturbance and cryoturbation on soil iron and organic matter distributions and on carbon storage at high elevations in the Cairngorm Mountains, Scotland. *Geoderma* 95: 1–14.

Hamberg, Leena, Minna Malmivaara-Lamsa, Susanna Lehvavirta, Robert O'Hara, and Johan Kotze. Quantifying the effects of trampling and habitat edges on forest understory vegetation: A field experiment. *Journal of Environmental Management* 91: 1811–1820.

Hill, Rachel, and Catherine Pickering. Differences in resistance of three subtropical vegetation types to experimental trampling. *Journal of Environmental Management* 90: 1305–1312.

Hunt, C.B. 1958. *How to Collect Mountains.* San Francisco: W.H. Freeman.

Kim, Min-Kook, and John J. Daigle. 2012. Monitoring of vegetation impact due to trampling on Cadillac Mountain Summit using high spatial resolution remote sensing data sets. *Environmental Management* 50: 956–968.

Korkanc, Selma Yasar. 2014. Impacts of recreational human trampling on selected soil and vegetation properties of Aladag Natural Park, Turkey. *Catena* 113: 219–225.

Kutiel, Pua, and Yelena Zhevelev. 2001. Recreational use impact on soil and vegetation at picnic sites in Aleppo pine forests on Mount Carmel, Israel. *Israel Journal of Plant Sciences* 49: 49–56.

Liddle, M.J. 1997. *Recreation Ecology*. London: Chapman & Hall.

Littlemore, J., and S. Barker. 2001. The ecological response of forest ground flora and soils to experimental trampling in British urban woodlands. *Urban Ecosystems* 5: 257–276.

Lucas-Borja, M.E., F. Bastida, J.L. Moreno, C. Nicolas, M. Andres, F.R. Lopez, and A. Del Cerro. 2011. The effects of human trampling on the microbiological properties of soil and vegetation in Mediterranean mountain areas. *Land Degradation & Development* 22: 383–394.

Malin, L., and A.Z. Parker. 1976. National ecological carrying capacity research: Yosemite National Park. III. Sub- alpine soils and wilderness use. US Department of Commerce, National Technical Information Center PB-27-957.

Mathieu, J. 2011. *The Third Dimension: A Comparative History of Mountains in the Modern Era.* Cambridge, UK: White Horse Press.

Mingyu, Yang, Luc Hens, Ou Xiaokun, and Robert De Wulf. 2009. Impacts of recreational trampling on sub-alpine vegetation and soils in northwest Yunnan, China. *Acta Ecologica Sinica* 29: 171–175.

Monz, C.A. 2002. The response of two Arctic tundra plant communities to human trampling disturbance. *Journal of Environmental Management* 64: 207–217.

Monz, C. A., David N. Cole, Yu-Fai Leung, and Jeffrey L. Marion. 2010. Sustaining visitor use in protected areas: Future opportunities in recreation ecology research based on the USA experience. *Environmental Management* 45(3): 551–562.

Monz, Christopher A., Catherine M. Pickering, and Wade L. Hadwen. 2013. Recent advances in recreation ecology and the implications of different relationships between recreation use and ecological impacts. *Frontiers in Ecology and the Environment* 11(8): 441–446.

Monz, C.A., T. Pokorny, J. Freilich, S. Kehoe, and D. Ayers-Baumeister. 2000. The consequences of trampling disturbance in two vegetation types at the Wyoming Nature Conservancy's Sweetwater River Project Area. *USDA Forest Service Proceedings* 5: 153–159.

Morrocco, Stefan, and Colin K. Ballantyne. 2008. Footpath morphology and terrain sensitivity on high plateaux: The Mamore Mountains, western highlands of Scotland. *Earth Surface Processes and Landforms* 33: 40–54.

Newsome, David, and Claire Davies. 2009. A case study in estimating the area of informal trail development and associated impacts caused by mountain bike activity in John Forrest National Park, Western Australia. *Journal of Ecotourism* 8(3): 237–253.

Ollier, C., and C. Pain. 2000. *The Origin of Mountains.* London: Routledge.

Pickering, Catherine M., and Andrew J. Growcock. 2009. Impacts of experimental trampling on tall alpine herb fields and subalpine grasslands in the Australian Alps. *Journal of Environmental Management* 91: 532–540.

Pickering, Catherine M., Sebastian Rossi, and Agustina Barros. 2011. Assessing the impacts of mountain biking and hiking on subalpine grassland in Australia using an experimental protocol. *Journal of Environmental Management* 92: 3049–3057.

Price, Larry W. 1986. *Mountains and Man: A Study of Process and Environment*. Berkeley and Los Angeles: University of California Press.

Rossi, G., G. Parolo, and T. Ulian. 2009. Human trampling as a threat factor for the conservation of peripheral plant populations. *Plant Biosystems* 143: 104–113.

Rossi, Graziano, Gilberto Parolo, Laura A. Zonta, Julie A. Crawford, and Andrea Leonard. 2006. Salix Herbacea L. fragmented small population in the N-Apennines (Italy): Response to human trampling disturbance. *Biodiversity and Conservation* 15: 3881–3893.

Rusterholz, Hans-Peter, Christine Verhoustraeten, and Bruno Buar. 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: 1024–1032.

Scott, David, Neil G. Bayfield, Alexander Cernusca, and David A. Elston. 2002. Use of a weighing lysimeter system to assess the effects of trampling on evapotranspiration of montane plant communities. *Canadian Journal of Botany* 80: 675–683.

Sun, D., and M.J. Liddle. 1993. A survey of trampling effects on vegetation and soil in eight tropical and subtropical sites. *Environmental Management* 17: 497–510.

Tomczyk, Aleksandra M. 2011. A GIS assessment and modelling of environmental sensitivity of recreational trails: The case of Gorce National Park, Poland. *Applied Geography* 31: 339–351.

Whinam, J., and N. Chilcott. 1999. Impacts of trampling on alpine environments in central Tasmania. *Journal of Environmental Management* 57: 205–220.

Whinam, J., and N.M. Chilcott. 2003. Impacts after four years of experimental trampling on alpine/sub-alpine environments in western Tasmania. *Journal of Environmental Management* 67(4): 339–351.

Willard, Beatrice, David J. Cooper, and Bruce C. Forbes. 2007. Natural regeneration of alpine tundra vegetation after human trampling: A 42-year data set from Rocky Mountain National Park, Colorado, U.S.A. *Arctic, Antarctic, and Alpine Research* 39: 177–183.

Wimpey, Jeremy, and Jeffrey L. Marion. 2011. A spatial exploration of informal trail networks within Great Falls Park, VA. *Journal of Environmental Management* 92(3): 1012–1022.

Yorks, T.J., N.E. West, R.J. Mueller, and S.D. Warren. 1997. Toleration of traffic by vegetation: Life form conclusions and summary extracts from a comprehensive data base. *Environment Management* 21: 121–131.

Ross H. Martin, Texas State University, Department of Geography, 601 University Drive, San Marcos, TX 78666; rhm42@txstate.edu

David R. Butler, Texas State University, Department of Geography, 601 University Drive, San Marcos, TX 78666; db25@txtstate.edu