Take a Walk on the Wild Side

GIS Modeling of Environmental Controls on Trail Degradation in the Maroon Bells–Snowmass Wilderness near Aspen, Colorado

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*"The paradox of Wilderness management is that it's not about managing Wilderness...
It's about managing people."*

Sloan Shoemaker
Executive Director of Wilderness Workshop
28 Jul 2015, Personal Communication

Abstract

This thesis utilizes Geographic Information Systems to model existing trails based on their vulnerability to degradation, as well as the suitability of wilderness landscapes to future trail development, whether that be through re-routes or entirely new tread construction. The introduction contextualizes trail use, impact and degradation in terms of wilderness management and is followed by a literature review uncovers spatial patterns associated with trail degradation from the field of Recreation Ecology. This information is then coded into spatial data and used to interpolate the likelihood of degradation in various areas and along various pre-existing trails in the Maroon Bells–Snowmass Wilderness. Results suggest that the every trail in the wilderness area is vulnerable to degradation and erosion for the majority of their lengths. Resilient segments on trails are few and far between, occurring much more frequently as single points rather than continuous lengths. Maps that model suitability across the entire wilderness area consistently show that valley bottoms and north facing aspects are ill-suited for trail routing, while south facing mid-slopes provide excellent resources for sustainable trail development. Despite some discrepancies between trail-scale interpolations and wilderness-scale models, both stress the importance of proper planning over continuous maintenance. The models could be improved by using feature extraction on National Agricultural Imagery Program (NAIP) data, or using fuzzy overlays to create suitability grids that avoid interdependency. In addition, the models could be broadened to include managerial controls on degradation such as use type and use intensity.

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Abbreviations and Acronyms

ASRD	Aspen–Sopris Ranger District
BMWC	Bob Marshall Wilderness Complex
BRT	Bob Ross Trail
CFI	Colorado Fourteeners Initiative
CPR	Common-Pool Resource
DEM	Digital Elevation Model
GCS	Geographic Coordinate System
GIS	Geographic Information System
GPS	Global Positioning System
GPX	GPS Exchange
LNT	Leave No Trace
MBSW	Maroon Bells–Snowmass Wilderness
NAIP	National Agricultural Imagery Program
NED	National Elevation Dataset
NLCD	National Land Cover Dataset
OID	Object ID
PCS	Projected Coordinate System
RFOV	Roaring Fork Outdoor Volunteers
SWReGAP	Southwest Regional Gap Analysis Program
USGS	United States Geological Survey
USFS	United States Forest Service
VGI	Volunteered Geographic Information
WLC	Weighted Linear Criteria

1 Introduction (*Walk the Line*)

1.1 American Wilderness

Imagine, for a moment, the kind of pristine landscapes in Albert Bierstadt's paintings: misty mountains replete with majestic vistas, hidden wildlife, glossy alpine lakes mirroring towering cliff faces, deep forests with dark, wet foliage, and rays of golden light illuminating waterfalls. These are the exact idyllic landscapes that The Wilderness Act of 1964 (2012) seeks to "secure for the American people of present and future generations". According to the act, wilderness areas are places where "the earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain" (The Wilderness Act of 1964, 2012). So in the eyes of Congress, wilderness areas represent places where the influence of humans is slight and the forces of nature rule; thus, they are places that deserve the highest form of protection and preservation that national lawmakers are capable of giving.

While this thesis assumes that wildernesses are landscapes designated by Congress for their beautiful natural characteristics, it should be noted that considerable work has gone into reconceptualizing wilderness by investigating its underlying form. Most notably, Callicott et al. (2000) and Cronon (1996) have argued that wilderness is a social construction that has no physical or concrete referent and thus functions poorly as a means for spreading a conservation ethic. Also within the emerging field of environmental justice, work from DeLuca and Demo (2001), Finney (2014), and Spence (1996) contends that wilderness areas and other publicly owned natural areas are spaces of minority exclusion and structural racism.

The focus of this work, however, revolves around congressionally designated wilderness areas. These have four general "wilderness character" qualities outlined by The Wilderness Act of 1964 (2012) and elaborated by Landres et al. (2005): they must be untrammeled, natural, undeveloped, and unconfined. Recreation is one of many key drivers of ecological change inside wilderness areas (Leung et al., 2000; Marion et al., 2011; Monz et al., 2010), so each of these criteria—elaborated upon in Table 1—define wilderness as a functional,

Table 1: Interpretations of wilderness characteristics from Landres et al. (2005)

Characteristic	**Interpretation**
Untrammeled	free from human manipulation
Natural	free from the effects of modern civilization
Undeveloped	free from human occupation or permanent improvements
Unconfined	free to enjoy in solitude

recreational, and spiritual resource by creating a framework for protection from human impacts (Landres et al., 2005).

Since recreation is a legitimate and popular use of wilderness resources, the primary challenge among wilderness managers is maintaining its distinctive qualities whilst simultaneously encouraging visitation that engenders more environmental impact (Leung et al., 2000). These challenges are compounding based on growing use intensity and popularity of wilderness areas, so pressures are mounting to manage landscapes based on current and future use (Cole et al., 1996; Wilderness, 2014).

Management avenues that sustainably preserve wilderness characteristics are varied and diverse: conservation biologists can track species movement, disappearance, and introduction; rangers can educate users about Leave No Trace (LNT) ethics and remove improperly buried waste; and scientists may test for bacterial contaminations in water sources to avoid the spread of disease. Managing for human use usually takes precedent because these are more noticeable and visible in landscapes.

Within this broad category of human use there are two more narrowly defined threats to wilderness characteristics: environmental *impacts* and environmental *degradation*. While the difference may feel slight to most, Leung and Marion (1996) insist that the discrepancies between these two terms are what should direct research and management efforts. In this paper, impacts are taken to be the physical, ecological, and aesthetic changes that come about through use of wilderness resources, whereas degradation is the negative result of those changes in wilderness resources. The two are related in that if a user is directed through areas that are more susceptible to impact (e.g. meadows, low cross slope grades, alpine tundra, wetlands, etc.), the quality of those resources will degrade quicker. This thesis focuses on those resources where use impacts are high and degradation is channeled: along foot paths in trail networks.

1.2 Trails as Commons

Let us now move away from the imposing wildernesses of Albert Bierstadt into the more benign landscapes of those depicted in Bob Ross's paintings. This time around, a small footpath—called the Bob Ross Trail—meanders from the foreground to distant peaks and alpine lakes in the background. The trail here is a path where users can experience wilderness resources such as pristine nature, scenery, and solitude from beginning to end and everywhere inbetween. If this trail were meandering through a real landscape in the American West, it would be owned by every tax-paying citizen, maintained (in most cases) by the United States Forest Service (USFS), and open to all with no limits on visitation. Based on these attributes, this trail provides a concrete corollary to the widely recognized allegorical pasture presented by Hardin (1968).

Wilderness trails are public resources that can be categorized based on the classification of goods presented in Table 2. Exclusion and subtractability are two important concepts used to determine how many people benefit from a resource and for how long the resource lasts (Ostrom et al., 1994). According to Table 2, Common–Pool Resources (CPRs) have low exclusion and high subtractability because it is difficult to exclude anyone from enjoying the resource and its quality degrades demonstrably between multiple users and over time. On the other hand, public goods have low exclusion and low subtractability because their quality does not degrade between multiple users or over time.

The pasture in Hardin (1968) represents a CPR because with each additional resource-maximizing herder, the quality of the publicly managed land degrades substantially. In other

Table 2: General classification of goods adapted from Ostrom et al. (1994)

		Subtractability	
		Low	*High*
Exclusion	*Low*	Public Good	CPR
	High	Toll Good	Private Good

words, the value and utility of the public pasture is lessened or *subtracted* with the addition of each new grazer until its environmental quality is irrevocably changed and the tragedy of the commons realizes itself. Public trails differ from the pasture because they demonstrate characteristics of both public goods and CPRs; Figure 1 shows that this is mainly a function of use intensity (e.g. low, medium, and high use patterns) and scale.

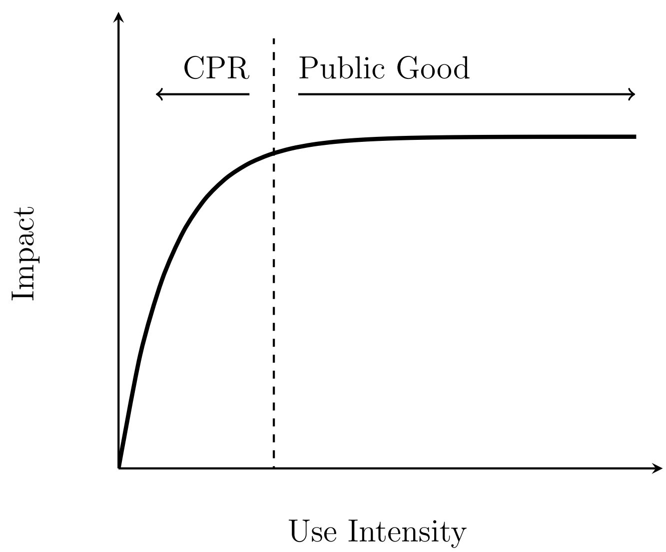

Figure 1: Conceptual use–impact curve for recreational trails

Trails are public goods when it comes to landscape-level wilderness resources because they allow all recreants to experience scenery equally (e.g. the views do not "degrade" between users or over time). Since the focus of this thesis is on trail networks, it is more worthwhile to examine smaller, trail-corridor scales. At these finer scales, trails exhibit CPR characteristics *to a point*. When a path is newly constructed, impacts on the surrounding soil, vegetation, and aesthetics change drastically with small changes in use intensity (Frissell and Duncan, 1965; Leung et al., 2000; Monz et al., 2010). In other words, when a trail is new, small increases in use intensity yield large increases in impact; however, once the trail has been used for a number of years, small changes in intensity yield small changes in impact. The bold curve in Figure 1 illustrates this concept because changes in use intensities closer to the origin result in larger alterations of environmental impact than changes further along the abscissa.

The figure also works for trails that see varying amounts of use from recreants, irrespective of how recently constructed the tread is. If the Bob Ross Trail from the beginning of this section is classified as "low use", but subsequently experiences higher-than-normal hiker traffic over a single summer season, the characteristics of soil and vegetation along the trail will change more than if it were a "high use" corridor with the same increase in traffic. The trail is a CPR until use intensity reaches a point where impact levels off, at which point it becomes a public good.

1.3 Wilderness Management

1.3.1 Conflicts by Definition

Even though impacts on trail corridors level with increases in use intensity and scale, they are still not exempt from experiencing the tragedy of the commons. The tragedy manifests itself as a landscape's failure to emulate the characteristics outlined by the Wilderness Act, and thus as a failure to provide users with a wilderness experience. As a result, federal management agencies are required by law (i.e. the Wilderness Act) to manage for and maintain unfettered landscapes. This may strike readers as counterintuitive, and they would be completely justified: how can wilderness areas be "managed"? In other words, how can an area designated to be natural, unconfined, untrammeled and undeveloped be controlled by people?

The most prominent juxtaposition lies in the idea of wilderness as untouched and pristine and the idea of wilderness as a resource. The Wilderness Act of 1964 (2012) clearly demarcates such areas as a "resource" that can be protected for and utilized by people, but the creation of the act is rooted in the idea that wilderness is untrammeled. Cronon (1996) investigates this wilderness ideology in much more depth, but here we are concerned with the basic premise that recreation is a legitimate use of wilderness despite the fact that it introduces an element of "trammeling".

This irony is a little harder to conceptualize in terms of on-the-ground-management, but the essential takeaway can be distilled in the following way: too many restrictions, closures, and maintenance efforts to preserve wilderness characteristics usually constitute an infringement of one or several other wilderness characteristics. Closures of campsites deemed illegal by knowledgable personnel might be necessary to naturalize an impacted area or keep recreants safe from habituated wildlife, but this action impinges on people's right to unconfined recreation in wilderness. Similarly, building a trail to the top of a high peak may sit well with a user's right to unconfined recreation, but the trail's construction and presence—especially above treeline—promotes erosion and thus degrades the landscape's naturalness.

The general consensus among federal land managers and their increasingly important non-profit partners is that a minimal active management framework in these landscapes is necessary to preserve "the benefits of [the] enduring resource of wilderness" (The Wilderness Act of 1964, 2012), despite the inherent conflicts in wilderness characteristics (Leung et al., 2000). If the Bob Ross Trail from Section 1.2 is significantly widened and rutted from use and erosion; if the corridor has trampled vegetation and muddied surfaces; if user-created trails cut switchbacks and loosen the cross-slope; if trash attracts fauna and changes their behavior; if human waste is visible and causing health concerns; if illegal fire rings are consuming vital organic matter near treeline. . . these are all reasons for responsible stewardship. Figure 1 shows that change in impact lessens in a trail's public good phase, but the impacts themselves can still engender significant degradation and thus warrant appropriate managerial responses.

1.3.2 Scale Specific Management

Large influxes of overnight visitors to the Maroon Bells–Snowmass Wilderness (MBSW) constitute the highest management priority for the Aspen–Sopris Ranger District (ASRD) (Wilderness, 2014). Because of a combination of steady losses in funding, gains in visitation, popular cultural and natural landmarks, and facility closures, the district has been put under enormous stress to manage the wilderness to acceptable standards (Condon, 2015). Under the framework outlined in Table 1, the ASRD is only told to meet certain objectives but not *how* to meet them (Landres et al., 2005). In other words, they are given goals and objectives about desired level of naturalness, but not directives about how to achieve naturalness. This distinction is important at local management scales because wilderness areas like the MBSW attract different user groups and use intensities based on differing cultural landmarks and proximity to large population bases (L. Gerloff, Personal Communication, July 15, 2015).

For example, compare the MBSW to the Bob Marshall Wilderness Complex (BMWC) in Montana. The MBSW is relatively close to metropolitan areas on the Front Range of Colorado, and it contains multiple scenic landmarks in a small area. These two factors engender large hiker–traffic volumes and thus the ASRD focuses on mitigating user impact and preserving a sense of solitude. On the contrary, the BMWC has very few nearby metropolitan areas (compared to Colorado) and it contains multiple landmarks over roughly five times the area of the MBSW. Stock use is more prevalent and dispersed because of the complex's larger expanses, so management efforts there are directed more towards maintaining existing trail corridors or restoring abandoned ones rather than traffic volumes. This example illustrates that every wilderness area has varying management directions based on natural characteristics, landmarks, and use patterns. If the ranger districts from both wilderness areas had to manage based on a singular, overarching national directive, planning and management resources would likely be misallocated to both and neither would do a good job at stewarding the land (L. Gerloff, Personal Communication, July 15, 2015).

The main pitfalls of wilderness character qualities are their vague ambiguity and conflicting objectives. For example: in terms of scale and place-specific geography, what does "unconfined solitude" mean in the context of the two wildernesses above? Is solitude in Montanan wilderness the same as solitude in Coloradan ones? Is solitude measurable, and if so, do those measurements reflect user perceptions of solitude? Can measurements of solitude be good enough to inform management decisions in different wilderness areas? For more on these topics, the reader is encouraged to explore the works of Patterson et al. (1990) and Hollenhorst et al. (2001), among others.

The example above illustrates that while it can be slightly exasperating that "solitude" is an ambiguous term that cannot be globally defined in a clear manner, it also means that the term can be defined and achieved *on regional or local scales* to meet the demands of varying use intensities. In this way, it makes practical sense to develop wilderness-scale methods and models that improve management based on input from the users themselves, as well as different levels of management.

1.3.3 Adaptive Management

The interesting paradox of managing areas that are meant to be unmanaged has led many to reconceptualize the term's meaning into "stewardship"; whereas management might connote control of a resource, stewardship suggests a form of caring supervision (L. Gerloff, Personal Communication, July 15, 2015). So, federal agencies might *steward* wilderness to preserve its natural qualities by *managing* the people that use it as a resource. In this sense, a "steward" responds to environmental problems with dynamic solutions, whereas a "manager" solves problems in order to meet objectives.

The subtle difference between response-based stewardship and solutions-based management is the key to understanding adaptive management, which essentially implements policies as experiments so that they can be continually adjusted and rewritten based on findings (Holling et al., 1978; Walters, 1986). A solutions-based approach to resource management usually treats a given environmental problem narrowly, where a static problem has a static solution. On the other hand, adaptive management acknowledges that humans do not know enough to manage ecosystems and thus treats environmental problems and solutions as dynamic (Lee, 2001).

Ultimately, this conceptual foundation allows managers to actively learn about ecosystem processes and policy successes through experimentation; however, as Lee (2001) notes, this framework functions more as an influential idea rather than a widely implemented means of management. While adaptive management has seen large-scale application at the Glen Canyon Dam (Walkoviak, 2011) and other sites in the Pacific Northwest, experimental learning is quite risky to implement because the benefits might not outweigh the costs (Lee, 2001; Walters, 1986). In other words, adaptive management works well on paper but can be hard to implement in a managerial system that promotes and values completed objectives over incremental learning.

2 Literature Review (*Walk This Way*)

Recreation Ecology is a fairly new field that seeks to identify, understand, and monitor the extent of environmental degradation resulting from recreational endeavors (Leung et al., 2000; Monz et al., 2010). In more general terms, it can be thought of as the adaptive management compliment to the federal government's objective-oriented management. In an ideal world, these two bodies of knowledge would be able to work together to create the best possible management framework available; however, a lack of funding, staff, and researchers in both fields severely limits their ability to conduct research and to communicate their findings to each other (Leung et al., 2000). As a result, neither discipline has been able to conduct large-scale or long-term studies, though there is a clear need for each (Monz et al., 2010).

The gap between the two management schemes outlined above can start being bridged through the implementation of Geographic Information Systems (GIS), mainly because they provide powerful analytic tools for exploring and modeling landscape-level processes with relative ease (Lee, 2001). This thesis utilizes knowledge from both the Recreation Ecology literature and the "gray" literature associated with trail routing to model trail degradation in wilderness areas.

2.1 Environmental Controls on Trail Degradation

Trails within wilderness areas are the transportation networks that both concentrate use along narrow corridors and facilitate access to wilderness resources (Leung and Marion, 1996; Leung et al., 2000; Tomczyk and Ewertowski, 2013). Even though people may be concentrated into small geographic reaches, their impacts may still be felt across geographic boundaries through variations in soil type, vegetation cover, and water quality (Leung et al., 2000; Monz et al., 2010; Tomczyk and Ewertowski, 2013).

Examples of extensive impacts and trail degradation include enhanced erosion, trampled vegetation, braided trails with multiple treads, formation of visitor-created trails, excessive muddiness, exposed tree roots, and invasive species introduction (Leung et al., 2000; Olive and Marion, 2009; Tomczyk and Ewertowski, 2013). Enhanced soil erosion is the most concerning of these impacts because it is irreversible without costly actions that could make the natural settings of wilderness areas feel more artificial (Olive and Marion, 2009), which would go against the "undeveloped" wilderness quality identified in Table 1. Since erosion is the most concerning impact on trails, it will be used interchangeably with "trail degradation" throughout this thesis, though degradation itself means more than just soil erosion.

2.1.1 Soil Type

Soil type plays a large part in trail degradation (Leung and Marion, 1996). Table 3 compares soil types across many different categories, including particle size and erosive potential. Clays and silts have small pore spaces and particle sizes that make them highly erodible, whereas coarse soils have large pore spaces that drain water rather than encourage runoff.

Table 3: Comparisons in soil type from Basch et al. (2007).

	Coarse Soils	**Silts**	**Clays**
Relative Particle Size	Large	Medium–Small	Small
Draining Capability	Excellent	Poor–Moderate	Poor
Erosive Potential	Low–Moderate	Moderate–High	High
Restoration Potential	Difficult	Good	Good

Soil moisture also plays a role in erosion: Willard and Marr (1970) found that soil moisture bore a positive relationship with soil erosion. Additionally, Leung and Marion (1996) reported that soils with high organic matter content retain water for longer than other soils, though findings from Marion and Merriam (1985) showed that well drained soils with well developed organic horizons on flat slopes are best at tolerating foot traffic. The difference in these findings might have to do with a lack of experimental controls on slope, soil type, or use intensity.

2.1.2 Tread Surface

Table 3 shows that soil type has a large bearing on the processes of compaction and erosion on tread surfaces, primarily through water drainage. Compaction is the process by which soils lose pore space to become hardened surfaces as a result of increased traffic and use (Ferguson, 1998; Monz et al., 2010). While trails get compacted along their entire lengths, areas with moist soils, low organic matter content, and a range of small-to-medium particle sizes are particularly vulnerable (Leung et al., 2000). An important point to note is that compaction is not necessarily a harbinger of degradation: in fact, it is necessary to harden a trail's tread to make it more resilient to increased use intensity, differing use types like pack animals, and future trampling (see Figure 1). For example, if a relatively flat trail is hardened, precipitation runs off more easily and prevents muddiness and trail braiding. If, however, this same trail becomes steeper, the ability of the trail to shed water becomes concerning because water and gravity can incur considerable damage to the trail surface through rutted erosion and visual scarring (Ferguson, 1998; Leung et al., 2000).

The implicit assumption with tread surface erodibility and compaction is that the paths are made of dirt. There is not much discussion about treads that utilize talus or bedrock, essentially because there is nothing to discuss: rock is the most durable surface for trail routing (Basch et al., 2007). It erodes on time scales beyond human lifetimes, and if placed correctly within the surrounding soil or talus slopes, a rock step can last a very long time (D. Hamilton, Personal Communication, August 6, 2015). The only difficulty with utilizing rocks are their weight and bulk: building trails through talus fields—while sustainable—is difficult without a strong, skilled work force.

2.1.3 Vegetation Type

Studies on vegetation—especially in the context of trampling—make up one of the largest research areas in Recreation Ecology (Leung et al., 2000). Despite this frequency in the literature, the relationship between vegetation and trail degradation is complex and poorly understood. Hammitt et al. (2015) contend that this is because it is difficult to generalize the effects of vegetation given the amount and variety of interactions it has with other influential environmental factors like soil type and topography. Nonetheless, Monz et al. (2010) maintain that certain preliminary findings can be reported.

Cole (1995a,b) found that grasses and sedges have the greatest tolerance to foot traffic, while leafed forbs have the least resistance. This corroborated findings from Cole (1993), where sedges were 25-30 times more resistant to trampling than ferns. Leung et al. (2000) hypothesize that this is the result of more flexible stems in short grasses and sedges, as opposed to the brittle stems of tall grasses. Liddle et al. (1997) found that alpine meadows have extremely slow resource recovery rates due to trampling of brittle-stemmed grasses.

Woody plants are more fragile to trampling and trail routing, especially in alpine wetland environments where soil moisture is higher (Leung et al., 2000). Other areas with moist soil, such as some areas of tundra and mesic forests, also showed a higher susceptibility to erosion

Table 4: Tolerance to impact from various vegetation types

Tolerance to Impact	Veg Type	Source
Low	Woody plants (willows)	Leung et al. (2000)
	Forbes (ferns, broad leafed plants)	Cole (1995a,b)
	Brittle stemmed plants (tall grasses)	Liddle et al. (1997)
	Alpine wetlands	Leung et al. (2000)
	Tundra (w/ moist soils)	Monz et al. (1996)
	Mesic forests	Bratton et al. (1979)
High	Grasses & Sedges	Cole (1995a,b)
	Xeric, open forests	Leung et al. (2000)
	Dense forests (w/ little understory)	Leung et al. (2000)

(Bratton et al., 1979; Burde et al., 1986; Monz et al., 1996). Otherwise, dry, open forests or dense forests with minimal understory are more suited to trail routing than grasslands because they confine users to the tread—at least in areas of high use (Bright, 1986; Dale and Weaver, 1974; Leung et al., 2000).

2.2 Topographic Controls on Trail Degradation

While soil type, tread surface, and vegetation all influence erosion rates on trails, their effects are either difficult to isolate from each other, difficult to obtain spatial data on, or difficult to extrapolate to larger scales (Monz et al., 2010). Cole et al. (1988) also maintain that vegetation takes a back seat in affecting trail degradation when use intensities are high, mostly due to the curvilinear relationship presented in Figure 1. Basch et al. (2007) implicitly suggest that vegetation cover could serve as a proxy for soil type, but this would be an imprecise comparison that could lead to substantial errors in model making.

Topographic variables, on the other hand, are easy to work with at large scales, easy to obtain data for, and are easily isolated. They are also the largest contributors to soil erosion of any of those previously mentioned (Bratton et al., 1979; Leung and Marion, 1999, 1996; Olive and Marion, 2009; Price et al., 1983). Section 2.2 overviews both what is known about topographical factors contributing to degradation and what design considerations are implemented to reduce that degradation.

2.2.1 Slope and Trail Alignment

There are two types of slope that factor into trail sustainability. The first is the slope of the trail itself—the *trail gradient* (TG)—and the second is slope of the landscape at any given point—the *cross slope* (XS). As cross slope increases, degradation increases in the form of erosion (Bratton et al., 1979). In addition, if the trail gradient is nearly equivalent to the cross slope (e.g. if the slope alignment angle is small), a trail can become eroded and gullied because it acts as a conduit for water flowing downhill (Bratton et al., 1979).

Table 5 shows a scheme of possible rating classifications for cross slopes cross tabulated with trail grade. Optimal trail gradients are always one quarter of cross slopes between 20% and 48%. This means that if a cross slope is 40%, 36%, or 24%, the trail gradient cannot exceed 10%, 9%, or 6% in that respective location; however, if the cross slope is greater than 48%, trail gradient is capped at 12% regardless of how large cross slope becomes. In these areas, trail gradients that are greater than 12% are deemed vulnerable because they provide a steep pathway for water to flow over and erode despite an otherwise acceptable cross slope.

Cross slopes less than 10% are considered vulnerable to degradation because water cannot easily drain from the tread, resulting in widened trails, multiple treads, and muddy surfaces (Basch et al., 2007; Leung et al., 2000; Olive and Marion, 2009). Even with restorative efforts such as implementation of drainage dips and water bars, no significant reduction in degradation occurs on these flatter cross slopes (Leung and Marion, 1999). Cross slopes greater than 70% are also considered vulnerable because trails on steep slopes require more soil excavation and rock armaments in order to withstand the erosive forces of water and gravity (Doucette and Kimball, 1990).

Table 5: Slope classifications for trails adapted from Basch et al. (2007).

Rating	XS Criteria	TG Criteria
Vulnerable	XS $<$ 10%	All
	XS $>$ 70%	All
	20% $\leq$ XS $\leq$ 48%	$> \frac{1}{4}$ XS
	48% $<$ XS $\leq$ 70%	$>$ 12%
Acceptable	10% $\leq$ XS $<$ 20%	All
	48% $<$ XS $\leq$ 70%	$\leq$ 12%
Resilient	20% $\leq$ XS $\leq$ 48%	$\leq \frac{1}{4}$ XS

According to the distribution of criteria in Table 5, it is clear that few parts of the landscape are considered "Resilient" to trail routing in terms of cross slope and trail gradient. The topographic controls described in Section 2.2.2 make a more complete model of resilience and sensitivity.

2.2.2 Aspect, Slope, and Elevation

Aspect engenders substantial degradation on trails because it determines how fast a soil can dry after snowmelt or rain storms (Basch et al., 2007). The ability of the soil to dry quickly has immediate effects on the trail corridor through potential muddiness, widening, and braided trails with multiple treads (see Section 2.1.1). North facing aspects are especially problematic for trail networks at high elevations because they retain snow well into the summer recreational season (Basch et al., 2007; Duffy, 1991).

While aspect is important in determining a landscape's suitability for trail routing, it is not very useful on its own; Basch et al. (2007) cross tabulated it with other important variables for trail sustainability in settings specific to Colorado ecosystems. Their on-the-ground management experience acknowledges that aspect has varying effects on trail sustainability—and by extension, degradation potential—depending on the prevailing cross slope and elevation. Their guidelines can be seen in Tables 6 and 7.

Table 6: Aspect and Slope classifications for trails from Basch et al. (2007), where higher values represent a stronger suitability for trail development

	Aspect							
Prevailing Cross Slope	**W**	**SW**	**S**	**SE**	**E**	**NE**	**N**	**NW**
0–20 %	1	1	1	1	1	0	0	0
20–40%	3	3	3	3	3	0	0	0
40–60%	2	2	2	2	2	0	0	0
60–70%	1	1	1	1	1	0	0	0
70% +	0	0	0	0	0	0	0	0

Table 7: Aspect and Elevation classifications for trails from Basch et al. (2007), where higher values represent a stronger suitability for trail development

	Aspect							
Elevation (ft)	**W**	**SW**	**S**	**SE**	**E**	**NE**	**N**	**NW**
3,300–7000	3	3	3	3	3	1	1	1
7,000–9,000	2	3	3	3	2	1	1	1
9,000–10,000	1	2	2	2	1	0	0	0
10,000–11,500	0	1	1	1	0	0	0	0
11,500+	0	0	0	0	0	0	0	0

Higher values in Table 6 represent sustainable places to build a trail. All north facing aspects are poor places to build a trail. The same is true for slopes greater than 70% regardless of aspect, which is consistent with the information in Section 2.2.1. The key take-away from this table is that there is a non-linear relationship between increasing cross slope and trail sustainability, which is somewhat at odds with the findings of Bratton et al. (1979). Despite this discrepancy, Cole (1991) showed that steeper slopes are most prone to erosion while intermediate slopes experience about equal amounts of erosion and deposition.

Higher values in Table 7 represent areas with higher suitability. North facing aspects at high elevations are not suitable because of the potential for summer snowpack. Low elevations are the most ideal for trail placement regardless of aspect; however, a southerly aspect becomes more important in maintaining trail sustainability as elevation increases. Indeed, elevations above 11,500 ft.—about the elevation of treeline in Colorado—are unsuitable regardless of aspect because there are few physical barriers to prevent short-cutting the trail, which can lead to sediment redistribution in ecosystems that are not used to these disturbances (Basch et al., 2007).

2.3 Suitability vs. Sustainability

When it comes to modeling trail quality in the final output maps of this thesis, suitability is a more accurate way of conceptualizing trail routing over sustainability. This is mainly because the latter term—despite frequent use in the literature—is too nebulous to describe the quality of a trail at any given point. If a sustainability rating is used for a landscape, stakeholders are likely to interpret scores as measures in polarity, where lower numbers of a rating spectrum represent bad places to put a trail and higher numbers represent excellent places to put a trail. While this is not by any means an erroneous assumption, it can lead the stakeholder to believe that if a trail is in an excellent part of the landscape, it will not degrade; however, the opposite is true. Trails degrade no matter where they are placed, as argued in Sections 1.2–1.3 and 2.1–2.2. Consequently, suitability ratings can help stakeholders better conceptualize the landscape in terms of an ability to withstand degradation. In this scheme, degradation is implicit, so lower ratings represent more sensitive areas and higher ratings represent more resilient areas. The model created in this work rate existing trails in terms of suitability and resilience.

2.4 Incorporating Adaptive Management

Despite the suitability of GIS in making adaptive management attainable, Lee (2001) cautions that analyses are prone to at least three shortcomings, the first being that information is fickle and relevant geo-referenced data is hard attain. This point is a little less relevant 14 years after that article's original publication—since remotely sensed data has been made increasingly available and uncertainties have been significantly reduced—but it is still worth discussing because the data utilized in this thesis are free and widely available to the general public through wearable tech such as GPS watches. The other cautions deal more with the problems of maps more generally and are expanded upon in Section 5.

With the proliferation of mobile fitness apps such as Strava and Movescount, as well as navigational apps like GaiaGPS and AvenzaPDF, people are beginning to log their workouts and trips with GPS-enabled devices, which feeds a continuously growing dataset of trail locations across the country, if not the world. This widely available dataset can be viewed, downloaded, and manipulated by anyone with the gumption. In other words, this democratized data can be a great asset for federal agencies and nonprofits alike who are struggling with funding.

3 Methods (*These Boots Are Made For Walking*)

3.1 Study Area Characteristics

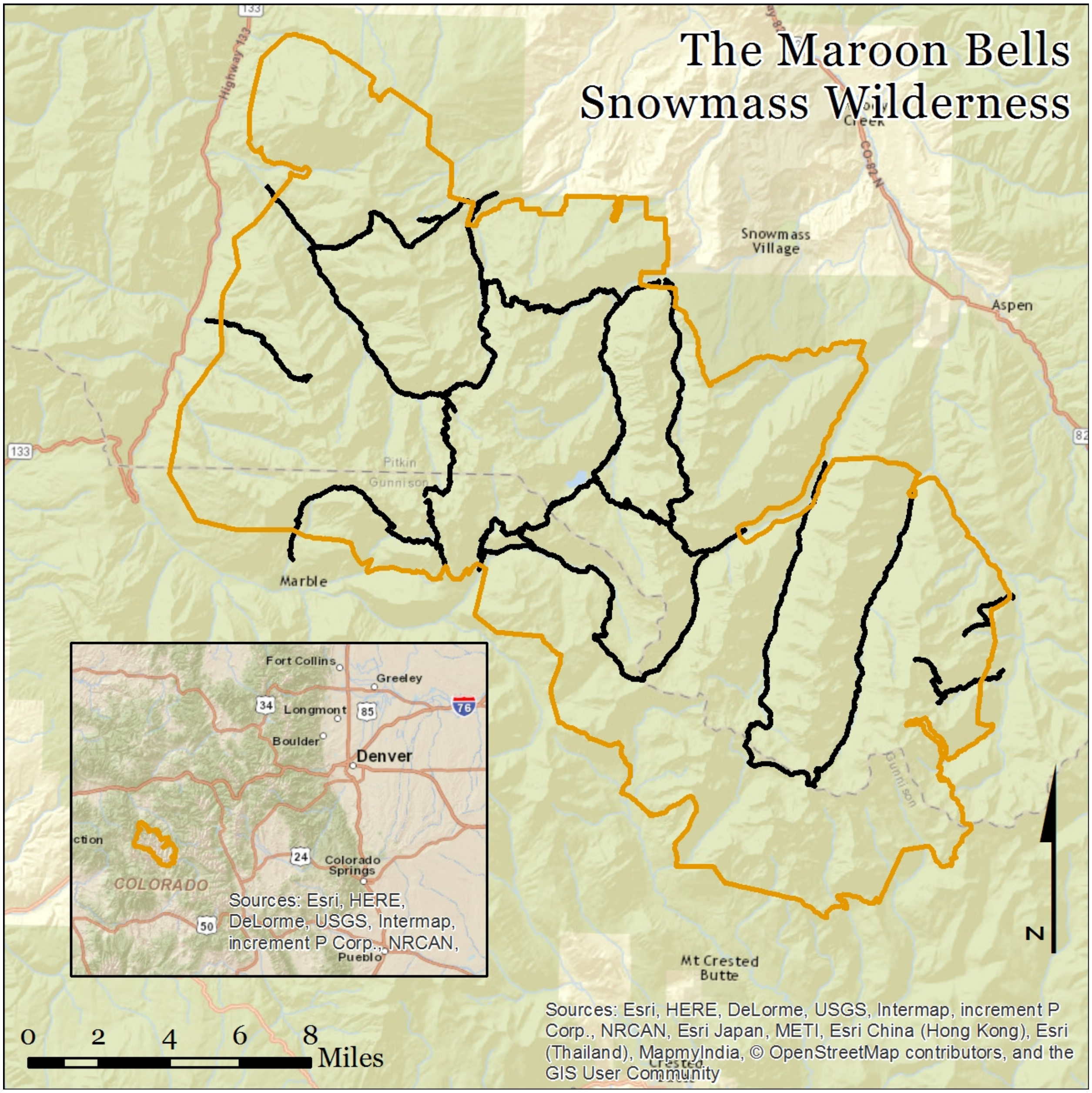

Figure 2: The Maroon Bells–Snowmass Wilderness near Aspen, CO

3.1.1 Physical Geography

All field research and data collection was conducted in the Maroon Bells–Snowmass Wilderness located between Aspen, Carbondale, and Marble in the Elk Mountains of Colorado at 39° N and 107° W. The MBSW ranges in elevation from roughly 1980 m to 4360 m and consists of montane forests, subalpine, and alpine zones over an area of roughly 182,000 acres (wilderness.net, 1996). Forests generally extend to maximum elevations around 3550 m and are predominantly composed of Aspen, Spruce, and Fir trees. Most areas above treeline are either exposed rock and soil or sparse, high alpine vegetation. High elevation wetlands also exist in the wilderness, giving rise to woody areas with willows and herbaceous wet meadows of sedges and grasses.

Out of the roughly 160 km network of trails in the study area, most are easiest to access from Aspen and see the highest impact from visitor use as a result. The trail network is centralized around the Four Pass Loop as well as seven prominent fourteeners (peaks that rise above 14,000 ft.) including the Maroon Bells, Capitol Peak, and Snowmass Mountain. Popular day hikes such as Conundrum Hot Springs, American Lake, and Electric Pass are located near the eastern edge of the wilderness, while another trail ascends to the peaks of Mount Sopris in the northeastern-most corner. Most trails are classed as "high use" by the ASRD, which determines these rankings based on information from self-registered overnight use permits. No data are available on day use intensities, but the majority of hotspots are near Aspen.

3.1.2 Management Objectives

In 2009, a focus group of 13 wilderness professionals put together by the USFS found that the MBSW ranked as the most visited and used wilderness areas among the 35 inside Colorado (WildernessWorkshop, 2015). Over the course of five years since that study, there has been a 40% increase in overnight visitation to the MBSW, amounting to 15,000 overnight occupants between Memorial Day and Labor Day weekends in 2014 (Schroyer and Fancomb, 2015; Wilderness, 2014). Significant proportions of total overnight users have historically been concentrated on just two trails in the entire network: the Four Pass Loop and the Conundrum Creek Trail, though trails that provide access to fourteeners also see significant visitation (Wilderness, 2014). This phenomenon can be attributed to the significant natural beauty surrounding the trails, their destinations and/or physical challenge, and advertising from popular outdoor magazines (WildernessWorkshop, 2015). These realities pose significant challenges to the ASRD as they try to manage based on the wilderness characteristics outlined in Table 1, especially with regards to solitude and unconfined recreation.

To keep consistent with the natural wilderness characteristic, restrictions on food storage within the entire study area were implemented through an emergency special order on 14 July 2015 due to increased human/bear interactions (Kight and Nyland, 2015). The popular designated camping area near Crater Lake was also closed in a separate directive for similar reasons (Kight and Nyland, 2015). An overly aggressive bear was identified roaming the Capitol Creek drainage and it slashed multiple overnight campers' tents throughout the summer. Due to these conditions, all overnight visitors were required to carry a bear resistant container for the duration of their trips inside the MBSW.

3.2 Data Collection

There were two phases to data collection for this project. *Field collection* consisted of recording GPS tracks of all relevant trails in the MBSW, and *ancillary data collection* involved the collection, creation, and processing of supplemental data such as Digital Elevation Models (DEMs) and land cover datasets. Due to time constraints, a small portion of existing trails could not be recorded, so some tracks were downloaded from internet-based fitness/navigational app clouds like Strava, Suunto Movescount, and GaiaGPS.

3.2.1 Field Collection

While the USFS is beginning to implement a database for trails across the country, most features in this collection only exist for public lands in the Pacific Northwest and parts of northern Utah's Wasatch Mountains. As a result, I had to hike the majority of marked trails in the MBSW and record every one with a GPS-enabled Suunto Ambit 3 wristwatch from July 2015 through August, 2015. In order to ensure no data loss from the watch, trail markers were recorded concurrently on a mobile phone with an application called GaiaGPS. These devices were used because of their low costs compared to dedicated GPS units, as well as their prolific use throughout the outdoor community. When either of the devices were low on battery, I would recharge them with an Anker Astro 6400 mAh external battery. This battery was chosen based on weight savings against energy storage capacity, since multi-day trips required carrying all necessary materials for data collection and mountain safety.

All field collection trips lasted four days or less, and trails that were disconnected from the central network could usually be done in a single day. Multi-day trips were planned according to the following guidelines, listed in order of importance:

1) *"Summiting is optional; descending is mandatory."* Retrieving accurate GPS logs was the primary goal of these trips, but not at the cost of personal safety. If afternoon thunderstorms unexpectedly blew in while climbing to high points, I would descend immediately despite data redundancy.

2) *Respect all forest mandates and LNT ethics.* I carried a bear canister at all times and strictly followed LNT principles to lighten the load on the landscape.

3) *Avoid off-trail travel.* Trips were recorded in late summer to avoid spring snowpack at high elevations. If I had to leave the trail for any reason, my backpack and GPS devices were left on the trailside to avoid improper logging. At times, trails would disappear intermittently and scouting was warranted.

4) *Contiguous logging.* Once GPS devices were turned on, they would not be turned off until trail destinations were reached. This measure avoided data gaps in GPS logs.

5) *Avoid redundancy.* Most trails were only hiked once to avoid recording the same trail length multiple times. However, If trails were out-and-back, GPS devices logged data in both directions.

6) *Avoid busy weekends* Crowding is a serious problem on popular trails over the weekends, so planning trips that avoided crowds helped minimize impact in camping areas.

7) *Avoid wildlife.* Based on the surge in human/bear interactions mentioned in Section 3.1.2, I completely avoided habituated bear domains when setting up camp.

GPS data could be stored offline on both devices until a network connection could be made, at which point they could automatically sync to two separate online clouds: GaiaGPS and Suunto Movescount. From these platforms, GPS logs could be copied and saved to an external Google Drive folder, which ensured data security and accessibility from any device.

3.2.2 Ancillary Sources

The boundaries of the MBSW were defined with a polygon shapefile downloaded from wilderness.net; otherwise, the model utilizes two rasters from the United States Geological Survey (USGS) as environmental predictors of trail degradation: one DEM and one land cover dataset.

Topography comes from the USGS National Elevation Dataset (NED) at 1/3 arc-second ($\sim$10m) resolution. The DEM and derivatives such as slope and aspect were used as topographical predictors of trail degradation.

Land Cover comes from the Southwest Region Gap Analysis Program (SWReGAP) aggregated at 30m resolution. The layer was reclassified based on vegetation characteristics outlined in Table 4.

SWReGAP was chosen over the National Land Cover Dataset (NLCD) because it was designed as an aid to modeling themes in landscape ecology such as biodiversity and wildlife habitat (Lowry et al., 2005). As a result, it has richer vegetation attribution at higher elevations in remote areas where NLCD tends to provide lackluster data. While the SWReGAP was originally designed for scales on the order of thousands of kilometers, it was the best option short of aerial photo interpretation using the National Agricultural Imagery Program (NAIP). This was a technique suggested for smaller regions by Lowry et al. (2005), but one which was beyond the scope of this thesis. Questions of scale aside, the dataset's fine attribution comes from ground-truthing, decision tree classifiers, and fuzzy sets implemented by the University of Utah, so it is fairly accurate despite a lack of precision in resolution (Lowry et al., 2005).

3.3 Pre-processing

Pre-processing was required for data from GPS devices as well as ancillary sources because neither produced files that were ready for analysis. The following sections detail the steps taken in order to make all data more manageable.

3.3.1 Field Data

Python and the arcpy module helped immensely when pre-processing all 21 trails in this study. Since all trails were recorded in GPS Exchange (GPX) format on both devices, the first step involved conversion of the waypoints into vector data points as shapefiles. The next step required defining a projection so that all shapefiles were in like coordinates. Every file was projected into Universal Transverse Mercator (UTM) Zone 13N coordinates based off of the WGS 1984 datum, because working with the data in a Projected Coordinate System (PCS) allowed for easier distance and slope calculations as compared to a Geographic Coordinate System (GCS).

Once the shapefiles were projected correctly, features in the attribute table were reordered based on their date/time stamp. This step was necessary because the Object IDs (OIDs) of each entry somehow became disorganized during the conversion from GPX to shapefiles. When the OIDs were reordered, redundancies on trail sections that were hiked more than once were manually trimmed. Some paths—such as the Silver Creek Trail stretching between Avalanche Lake and Lead King Basin Road—had to have entire sections deleted because the trail tread was essentially nonexistent. This produced a gap in the trail's shapefile, but these manual trimmings also ensured that only "certain" trail segments were being displayed.

3.3.2 Ancillary Data

The boundaries of the wilderness area were the first piece of ancillary data that needed to be processed. Once the file was projected into UTM coordinates, the polygon was visually inspected to make sure that there weren't any holes: three were identified and consequently filled using Arc's Overlay tools—specifically, Intersect followed by a Union. Lastly, the polygon was buffered by a distance of three miles. This step defined an extent that was larger than the wilderness area, which avoided edge effects in analysis with raster grids.

The extent also helped greatly when downloading the Colorado SWReGAP dataset, which was ready for analysis once reprojected. Downloading DEMs for the study area, however, proved to be a very involved process. This was mainly because they come as tiles with fixed extents from the NED. The MBSW happens to lie in a region where four tiles intersect each other, so each had to be downloaded separately and mosaiced into a new raster; once assembled, the new raster had to be reprojected. While reprojecting, ArcMap would automatically build pyramids by Nearest Neighbor, which caused a striping artifact that was not immediately evident in the DEM but was plainly seen in hillshading and other DEM derivatives like slope and aspect. Specifying Bilinear Interpolation or Cubic Convolution in the Project Raster tool did not solve this problem because the map document was set to automatically rebuild pyramids of all input grids using Nearest Neighbor. Once this option was unchecked and the Project Raster tool was rerun, the DEM had no artifacts and was ready for use!

3.4 Data Analysis

The data described above were classified based on factors presented in Section 2. These factors were then used to create a spatial model that both classifies existing trails based on their resilience to degradation and models the suitability of the entire landscape to future trails. Since no spatial data were available for soil type or tread surface, they were excluded from the model. Cross slope and trail gradient are the two main controls of degradation on existing trails; thus, they were used as the primary predictors of degradation of established trails in the MBSW. Landscape level models, on the other hand, were created using various combinations of the ancillary sources described in Section 3.2.2.

3.4.1 Slope Suitability

Despite the fact that both the Suunto Ambit 3 wristwatch and GaiaGPS mobile application recorded elevations along trails, they often deviated from each other. These deviations tended to occur more frequently on steep or secluded terrain, where measuring elevation with GPS is notoriously inaccurate, but they also happened along entire lengths of trails in most cases. These measured values would not have produced accurate calculations for trail gradient in the model because they could have potentially exceeded maximum cross slopes at some locations, which is physically impossible. Thus, elevations were interpolated from a DEM in order to make consistent calculations on trails across the landscape.

Trail gradients were calculated using Equation 1 below. The coordinates of each point are represented by x, y, and z, while i refers to the point whose slope is being calculated and $(i-1)$ refers to the point that came before. In this way, trail gradient was recursively calculated as a percentage based on differences in elevation from the previous location.

$$TG(\%) = 100 * \left. \frac{z_i - z_{i-1}}{\sqrt{(x_i - x_{i-1})^2 + (y_i - y_{i-1})^2}} \right|_{i\,=\,1}^{n} \tag{1}$$

Sometimes, two track points would be recorded at exactly the same location, which would make the equation attempt division by zero; under these circumstances, the slope of the point would be forced to a value of zero.

Once trail gradients were calculated, values from a slope percent raster—derived from the original DEM—were extracted to points via bilinear interpolation, since slope is a continuous variable across space. This allowed for direct comparisons between trail gradients and cross slopes based on the ordinal classification scheme presented in Table 5.

3.4.2 Multi Criteria Models

The Multi Criteria Models were carried out through a series of grid reclassifications. Figure 3 shows the workflow of reclassifications and raster calculations necessary to create rasterized versions of Tables 8 and 9. Blue ovals represent input data and results are represented by green ovals, whereas yellow boxes indicate a tool/process used to transform data.

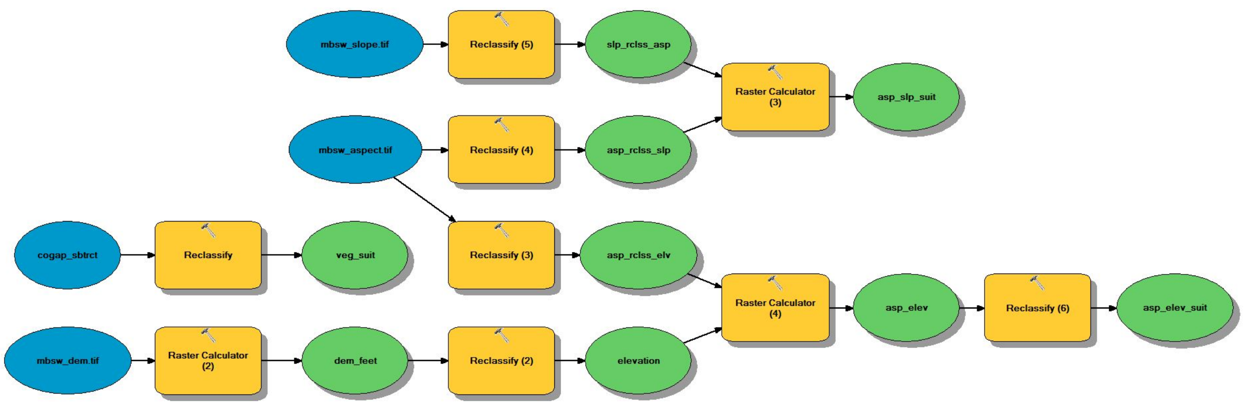

Figure 3: Workflow used to process ancillary data sources into usable raster grids

Aspect and slope rasters were derived from the USGS 1/3 arc-second DEM. Since the suitability scores for slope in Table 6 do not change across aspect, a simple reclassification scheme could be devised, demonstrated in Table 8. Red numbers in parentheses represent how each field was classified and the black numbers inside the table represent the product of the reclassified cross slope and aspect layers. Note that the prevailing cross slope classification ranges here are slightly different than those presented in Table 6. This was done in order to stay consistent with the slope classifications between trail grade and cross slope in Table 5.

Reclassifying elevation and aspect was more complicated, as seen in Table 9: the reclassified rasters were added together, and if the red numbers in parenthesis did not match the desired black numbers within the table, further reclassifying was required. This table set a higher elevation for treeline ($11,500ft. \longrightarrow 11,800ft.$) in order to reflect the elevation of

Table 8: Reclassification scheme for aspect and slope rasters

	Aspect							
Prevailing Cross Slope	**W**(1)	**SW**(1)	**S**(1)	**SE**(1)	**E**(1)	**NE**(0)	**N**(0)	**NW**(0)
0–10 % (0)	0	0	0	0	0	0	0	0
10–20% (1)	1	1	1	1	1	0	0	0
20–48% (3)	3	3	3	3	3	0	0	0
48–70% (2)	2	2	2	2	2	0	0	0
70% + (0)	0	0	0	0	0	0	0	0

treeline within the MBSW.

Table 9: Reclassification scheme for aspect and elevation rasters

	Aspect							
Elevation (ft)	**W**(0)	**SW**(1)	**S**(1)	**SE**(1)	**E**(0)	**NE**(6)	**N**(6)	**NW**(6)
3,300–7000 (3)	3	3 (4)	3 (4)	3 (4)	3	1 (9)	1 (9)	1 (9)
7,000–9,000 (2)	2	3	3	3	2	1 (8)	1 (8)	1 (8)
9,000–10,000 (1)	1	2	2	2	1	0 (7)	0 (7)	0 (7)
10,000–11,800 (0)	0	1	1	1	0	0 (6)	0 (6)	0 (6)
11,800+ (-1)	0 (-1)	0	0	0	0 (-1)	0 (5)	0 (5)	0 (5)

Reclassifying vegetation data was slightly more straightforward, but only because there was not a lot of sensitivity in ordinal classification schemes. The literature does not definitively rank certain vegetation types above others in terms of tolerance to impact; all that can be reported is relative tolerance. The reclassified vegetation in Table 10 follow this framework, where a "1" means "High Relative Tolerance" and a "0" means "Low Relative Tolerance".

Once all of these grids were created, the DEM derivatives were re-aggregated to 30m and snapped to the reclassified vegetation grid to avoid misaligned pixels, and to make sure that

Table 10: Vegetation reclassification implemented into the WLC workflow

SWReGAP Class	**Reclassification**	**Justification**
Mixed Forest	1	Dense Forest
Aspen Forest	1	Open compared to pine forests
Dry Evergreen Forests	1	Dry microclimate
Mesic Evergreen Forests	0	Wet microclimate
Subalpine Grassland	0	Brittle stemmed grasses
Gamble Oak Shrubland	1	Dry Microclimate
Alpine Wet Meadow	0	Wet microclimate
Riparian Shrubland	0	Wet microclimate
Rocky Mountain Fell Field	0	Sensitive vegetation
Scree and Bedrock	1	Durable tread surface
Subalpine Mesic Meadow	0	Wet microclimate

analysis was performed at the same resolution. The grids were consequently incorporated into final models through various linear combinations such that each had a weight towards suitability for trails. For example, one iteration had slope account for 60% of a final trail suitability rating while elevation and vegetation would divide the remaining 40% between them in increments of 10. So in this iteration, there were three final weighting schemes for <slope/aspect, vegetation, elevation/aspect>: <60%, 10%, 30%>, <60%, 20%, 20%>, and <60%, 30%, 10%>. All environmental factors have some stake in determining trail suitability, so no grids had zero weight in any of the final WLC models, resulting in 36 possible models for trail suitability.

4 Results (*Walkin' On Sunshine*)

4.1 Slope Classifications

Maps that classify trails based on their slope characteristics can be found in Appendix A. These maps classify lengths of trails based on their current ability to withstand degradation; in this scheme, resilient segments stand better chances of resisting degradation and erosion than vulnerable segments. Acceptable segments are also prone to degradation, but their locations and gradients make them a lower priority in identifying segments that need reroutes compared with vulnerable segments. This does not mean that these segments do not require monitoring, just that they have lower priority than other lengths.

All maps represent ordinal rankings, and each trail has four map tiles: one showing every classification together, and three others displaying locations of each ranking separately. This was done to avoid confusion with displaying scores on trails that span larger areas, since distinguishing between classes can be more difficult at smaller scales. For trails where this does happen, inset maps were added to each tile in order to highlight one specific area that seemed particularly interesting or substantive.

4.1.1 Vulnerable Characteristics

Visual assessment of 21 trails inside the MBSW shows that the majority are vulnerable to degradation. While every trail has varying degrees of "Resilient", "Acceptable", and "Vulnerable" slope characteristics, the key take away from most trails is that vulnerable points occur more frequently and in longer, more continuous sections as compared to resilient and acceptable classifications. The map tiles in Appendix A illustrate this trend quite robustly for most trails. Particularly notable cases include the Capitol Creek Trail in Figure A.5, the Cathedral Lake Trail in Figure A.6, the Electric Pass Trail in Figure A.11 and the Haystack Mountain Trail in Figure A.15.

The inset map in Figure 15(d) shows that a specific section of the Haystack Mountain

Trail is almost entirely made up of vulnerable points, despite being part of a switchback that should theoretically keep degradation in check. Any points that might have resilient or acceptable characteristics are literally few and far between in this inset. This pattern holds at smaller scales as well: a visual comparison of the component maps making up Figure 15(a) reveals that vulnerable segments have the highest counts and longest stretches compared to the spotty inconsistency of other classifications along the trail's entire length.

4.1.2 Acceptable Characteristics

While a large proportion of trails tend to be vulnerable to degradation, there are certainly many points that have acceptable routing characteristics. The Willow Pass Trail in Figure A.21 provides a representative example of locations and variability of this classification seen on many other trails in the MBSW. Longer, more continuous stretches of acceptable routing tend to occur in areas where cross slope is low—more specifically, where $10\% \leq \text{XS} < 20\%$, as defined in Table 5. On the Willow Pass Trail, these segments are near the northeastern terminus or in the cirque south of the pass itself, which is highlighted in all of the inset maps. Isolated points of acceptable rating, on the other hand, tend to happen on steeper cross slopes between 48% and 70%, where the trail grades dip below the 12% threshold identified in Section 2.2.1. Segments with longer stretches of acceptable rating occurring on steeper terrain are largely the result of exaggerated switchbacks, such as those seen in the inset map for the Silver Creek Trail in Figure 17(b).

4.1.3 Resilient Characteristics

Resilient characteristics along a given trail occur predominantly as singular points or small extents that are generally shorter than their vulnerable or acceptable counterparts. There are very few long stretches of unbroken, continuous resilient trail segments. Another interesting attribute of most resilient points is that they are usually surrounded by vulnerable points. In other words, there are few instances where resilient points or segments neighbor acceptable points or segments, as seen on the American Lake Trail in Figure A.1.

4.2 Landscape Suitability

Maps that classify the landscape based on the WLC models can be found in Appendix B. Since every model had its own unique weighting scheme, each had different minimum and maximum absolute suitabilities across the same landscape. In order to control for these discrepancies in absolute ratings, each map was normalized to a range between zero and one, where a value of one represents high suitability for trail corridors.

The first three maps in this appendix show what the MBSW looks like in terms of each individual suitability grid; subsequent maps show the wilderness in terms of normalized WLC models. These maps depict the entirety of the MBSW in order to show the full range in values as well as where those values change compared to each other. The literature on trail sustainability maintains that vegetation does not play as significant a role in predicting degradation compared to topographic variables; thus, weighting schemes where vegetation exceeds 20% of the overall landscape suitability are not included in the results and discussion of this thesis. Lastly, in order to get a sense for how landscape suitability compares to ratings based on the slope characteristics of existing trails, 15 maps highlight a section of the Four Pass Loop Trail in Appendix C.

As expected, when each individual suitability grid gains more weight, it becomes more resolved compared to the other grids. In other words, final WLC maps look very similar to their component maps if those underlying component maps compose a majority of the weighted criteria. Therefore, it makes more sense to unpack the meaning of each component map rather than delving into each WLC model individually.

4.2.1 Slope/Aspect Component Map

The component map for slope and aspect in Figure B.1 is the most spatially heterogeneous out of all three criteria analyzed in this thesis. It appears that low suitability ratings are the most connected, whereas higher suitability ratings tend to happen in patches. These patches do not necessarily have small areal extents, but they are usually more disconnected compared to lower suitabilities. This means that north facing aspects paired with steep and shallow slopes make for more continuous features of the landscape as compared to south facing aspects and mid-range slopes. In addition to these findings, valley floors are typically poor places to route trails, whereas mid-slopes on more southerly aspects of the same valleys tend to be significantly more hospitable for trail development. The same goes for ridgelines, where crests tend to be fairly accommodating places to put a trail as long as they don't deviate too much to either side.

4.2.2 Elevation/Aspect Component Map

The component map dealing with elevation and aspect can be found in Figure B.2. The wilderness area performs very poorly in terms of elevation because most of the wilderness is high in elevation. Below treeline, aspect plays a rather subdued role in determining landscape suitability for trail routing. This is because there are very few low-elevation valleys in the wilderness area that have an E-W alignment. Notable exceptions are the Avalanche Creek Valley in the northwest corner and the valley leading up to Haystack Mountain in the north-central portion of the wilderness.

4.2.3 Vegetation Component Map

The vegetation grid in Figure B.3 is the easiest to analyze because it is a simple binary map: either there are places which are suitable for trail routing, or there are places which are not. The majority of the MBSW consists of high tolerance vegetation, and low tolerance vegetation tends to occur in small patches with rough edges. Visual inspection yields an interesting result: high tolerance landcover tends to occur at higher elevations, along ridgelines, or on south facing aspects irrespective of elevation. In this sense, it is in direct conflict with the elevation-based component map in Figure B.2.

4.3 Comparison of WLC Maps and Slope Classifications

While the WLC maps characterize the landscape best at the wilderness scale, it is beneficial to investigate how they change at the trail-corridor scale; after all, these are the scales in which these maps could become useful for re-routing purposes. Appendix C focuses on a northern length of the Four Pass Loop Trail from Trail Rider Pass in the East to Buckskin Pass in the West. Each map is made up of four subsets, similar to the maps in Appendix A: the top map shows the trail in terms of all slope classifications, and the bottom three subdivide the trail based on each individual class. Only visual comparisons are possible between the two suitability classification methods because they consist of different resolutions; whereas one rates trails with three coarse classes, the other rates the landscape on a spectrum of many classes.

As the slope/aspect criteria in Figure B.1 becomes more visible in the WLC models, predictions between classification schemes coincide. In this situation, resilient trail segments only occur in more suitable parts of the landscape. Vulnerable and acceptable segments are more fluid under these circumstances because they can be present on multiple slope angles, meaning that they have a far bigger range of locations in which they can occur. As slope and aspect become less of a control on degradation, the WLC models suggest that the landscape becomes less hospitable to trail corridors, despite slope classifications on existing trails suggesting otherwise.

5 Discussion (*Walk On*)

5.1 Slope Classifications

The significant absence of continuous resilient trail segments was initially unexpected, considering the amount of time and energy that gets put into these trails from organizations like the Roaring Fork Outdoor Volunteers (RFOV) or the USFS. However, these organizations often focus their energy on fortifying existing tread, so while the model identified vulnerable segments, they could potentially have already been addressed. Because this is a possibility, these maps cannot be read as if they identify restoration priority. These maps interpolate vulnerability/resiliency to degradation based on the characteristics of the surrounding environment. This does not mean that there is extensive degradation on an extent of vulnerable trail, just that there exist extents where degradation is more likely to happen based upon slope characteristics.

This interpretation holds for all three ordinal classes. Take, for example, a length of the Electric Pass Trail in Figure A.11. While a majority of the trail is vulnerable to degradation, there are lengths which have acceptable characteristics. If the map in Figure 11(b) was read incorrectly, a decision maker might see a long section where the trail should have acceptable slope characteristics and thus low prioritization. However, this is not the case! Figure 4 shows what the trail looks like in exactly this segment: it has multiple treads—one which is more eroded and incised than the other—and a small slope alignment angle. This is why it is important to reiterate the meaning of these maps: they identify where erosion and degradation are most or least likely to occur, not where erosion or degradation actually are or are not. The model suggests that this length of the Electric Pass Trail is routed acceptably, but the real world begs to differ.

An interesting result from these maps persists: rather than being designed with gradients under one fourth of the cross slope with occasional steepening, most trails have slopes that exceed of 12% in the critical resilience zone—between 20% and 48%—with occasional flattening. The conclusion that can be drawn from this specific trend is that many of these trails did not have proper planning or initial design, or they did but field crews made too many simplifications in building or updating them. Because this trend isn't flipped, far more of the trails in the MBSW are vulnerable to degradation and erosion.

Figure 4: A view of the Electric Pass Trail

5.2 WLC Models

In order to evaluate the usefulness of the WLC models created in this thesis, it is worth delving into their underlying assumptions through the procedure put forth by Malczewski (2000). This investigation is done in list form in the following section.

5.2.1 Overview of Methods

Defining a set of attributes. The objective of this modeling is to minimize the likelihood of degradation on trails or identify areas where trails are more sustainable. Attributes associated with this objective are topographic characteristics like aspect, slope, and elevation, as well as land cover. These attributes are *measurable* in that ordinal ratings exist based on management experience, they are *operational*, and *minimal*. Some attributes are *redundant* because aspect is double counted in both slope and elevation calculations.

Defining a set of alternatives. Feasible alternatives are achieved by hierarchically targeted constraints within each attribute: slope ranges are identified and ranked based on their suitability for trail routing, and vegetation is classified based on Boolean constraints.

Generating attribute maps. Linear transformations are performed to rank attributes within maps.

Assigning weights. Weights are assigned iteratively so that more than one possible outcome can be achieved.

Based on the framework above, WLC models seem like reasonable ways to model suitability of the landscape. There are only two problems, one smaller than the other. The major problem with the way these models were carried out has to do with interdependency. As noted, aspect turned up multiple times in the model: both with slope and elevation, but also with land cover to the extent that some vegetation types—like evergreen forests—are fairly well correlated with aspect. The value of a resultant pixel of a WLC model is only "true" if it is independent from the surrounding pixels, and because aspect introduces an interaction phenomenon, some areas of these maps may be interdependent. Visual inspection of the component maps did show that aspect plays a part in all three, though its effects were less prolific in the elevation and vegetation grids. This makes it tempting to say that the effects of aspect are not serious, but Malczewski (2000) alludes to the need for parameterized region-growing programming to solve issues like these, which are beyond the scope of this thesis and my own skill set. A potential solution to this interdependency problem could be in the development of fuzzy overlays.

The other less pressing, still relevant problem with WLC maps in this paper is that issues with scale tend to arise when grids need to be reaggragated to different resolutions. Higher resolution data are less biased when it comes to WLCs because the larger the aggregation, the larger the correlation between two variables of interest. Topography had to be resampled to a lower resolution in order to create the final suitability maps; however, while it is not explicitly stated in the article, this problem with aggregation only seems relevant when the resolution of the grid cells is comparable to the size of the study area. In this case, reaggregation to 30m probably has little effect on the outcome of the final maps. This is discussed more in Section 5.3.4.

5.2.2 Usefulness of Elevation

It was fairly obvious from first glance that the elevation component map in Figure B.2 was not particularly useful to the overall WLC models, mainly because most of the MBSW was rated "Poorly". While it is indeed true that higher elevations are typically more prone to degradation because of wind/solar exposure and a lack of deeply rooted vegetation, so much of the draw to this wilderness area has to do with its high elevations and vertical relief above treeline. For example, the Four Pass Loop is popular specifically because it has four passes that go above 12,000 ft in altitude. This is where a balanced management scheme discussed in Section 1.3 is necessary. The job of agencies like the USFS is not solely to protect landscapes like the MBSW, but also to provide meaningful access for recreants; if that access involves travel above treeline, a balanced perspective must be achieved with regards to trail routing. The component map associated with elevation should be used in the formulation of that perspective, but it should not dominate.

5.2.3 Usefulness of Vegetation

Including the vegetation grid into the final WLC models essentially meant sacrificing spatial accuracy for the benefit of a more realistic model. In the end, the benefits did not particularly outweigh the costs. The vegetation suitability grid does not have much fine distinction between areas of high impact tolerance and areas of low impact tolerance: it is just a binary grid that does not provide much resolution. Even after going through the trouble of including this grid into the WLC models, none of the final maps display vegetation taking up more than 20% of the total weight for trail suitability. This was done because the literature specifically mentioned that vegetation has little effect on trail sustainability compared to topographic variables, but it came with the cost of downplaying the effect of exposed rock and talus, which are actually crucial in deciding the resilience of trails to degradation.

In another iteration of this project—if it were to come about—a different approach would seem prudent for dealing with the effects of vegetation and land cover. Table 10 provided justifications for the classification of certain vegetation types, and most of them revolved around the presence of water; thus, topographic indices for soil moisture could be used to interpolate a part of landscape suitability. This would not only serve as a close proxy to wet microclimates, but it could also produce grids at the same spatial resolution as the DEM, which could improve the overall accuracy of the models. Otherwise, a finer distinction of land cover could be taken from NAIP imagery given enough time and accurate extraction algorithms. From this layer, a finer understanding of exposed rock, talus, and scree fields could be extracted to all current trails, at which point any trails that pass through those areas would be termed "Resilient" regardless of slope characteristics.

5.2.4 Combination of WLC Maps and Slope Classifications

The essential take-away from the comparisons between the slope classification and WLC maps in Appendix C is that acceptable and vulnerable lengths of trail are unconstrained by the topography of the landscape. Despite being routed through highly suitable areas, trails can still have characteristics which make them vulnerable to degradation. This is not a novel finding, as a close inspection of Table 5 could have yielded the same conclusion, but the maps demonstrate this pattern in a very compelling manner (GO MAPS!).

Perhaps a less intuitive finding with these maps is that if the landscape is modeled in a way where more areas become less hospitable for trails (e.g. as elevation dominates the suitability rating), they can still maintain resiliency—if only in terms of slope. This unveils an important point about routing trails more generally: if a segment of trail needs to be re-routed, or an entirely new trail needs to be built, it can still have some measure of resilience despite a corridor that is less-than-suitable. This arrangement only works, however, when the trails are designed with forethought. Thoughtful design can have far-reaching consequences for the resilience of a trail in the long term, both in terms of ecological integrity and maintenance needs.

5.3 General Considerations

No model is perfect, but some models are useful. The ones in this paper are certainly useful, but none are completely representative because of issues with accuracy, precision, implicit assumptions, and data limitations.

5.3.1 Absence of Use-Related Variables

While the premise of the landscape models in this thesis involves the role of environmental controls on trail degradation, it could have been valuable to incorporate use-related controls such as intensity (high, med, low) and type (day, overnight, hiking, stock, etc.). The USFS does keep a record of overnight visitation through voluntary backcountry permits, but there are no public records for day-use, which make up the majority of use type for trails like American Lake and Electric Pass. Despite a lack of data to map and model use type and intensity in the MBSW, perhaps a framework could be implemented to predict these variables throughout a summer season. For example, day users typically hike to landmarks such as lakes, passes, and peaks, whereas overnight users connect those landmarks on more ambitious treks. Devising a way to model these behaviors based on topography, land cover, and economic data on tourism would easily fill a dissertation.

5.3.2 Interpolation

The model in this thesis uses a $\sim$10m DEM to interpolate elevations and slopes at particular points in the landscape; the use of this Digital Elevation *Model* comes with the implicit assumption that it is relatively accurate and precise. If all the data are correctly georeferenced and projected in a consistent manner, this is not a wrong assumption to make, but it is an assumption that must be acknowledged and reconciled nonetheless.

Slope and elevation values were interpolated to each point on each trail using bilinear interpolation. This method was used because both of these landscape attributes are continuous across space. If vegetation and land cover had been interpolated to each point, on the other hand, the value would be done by nearest neighbor because the 30m land cover grid does not symbolize transition zones between vegetation types very well. Regardless, the accuracy of bilinear interpolation tends to stray if the surfaces being interpolated have significant amounts of curvature or roughness. This is especially true for cubic convolution, which applies the same distance weighting concept as bilinear interpolation but with the nearest 16 cells (Bolstad, 2012). Since many of the trails in the MBSW are routed through rough topography that might not be accurately represented at a 10m resolution, there could be a concentration in errors on trails that follow ridgelines or traverse passes. These locations would be ideal places to "ground-truth" interpolations.

5.3.3 Temporal Resolution and Spatial Autocorrelation

For all the errors that might occur, interpolation is generally considered a better fate than direct value extraction from the raster. To illustrate: the temporal resolution of the GPS units in this study were very fine. Consider the pins dropped by GPS devices as systematic sampling points: as a given unit moves up a trail, it does its best to sample x, y, and z coordinates at constant time increments. The Suunto Ambit 3 sampled trail locations *every second*; the Four Pass Loop alone—a trail spanning 26 miles—had around 11,000 sample points in total!

On the surface (pun intended), this might seem like a terrific sampling rate to use... Not so. If the unit is moving at an average rate of 2 mph—roughly 0.9 meters per second—then eleven points would be dropped in the span of 10 meters. Despite the fact that this is an amazing feat of technology, this means that the average pixel in a 10m raster would have *at least* eleven sample points inside it. If interpolation was not used in this situation, that would mean eleven points with the same exact values for both elevation and slope. Even with interpolation, this leads to eleven points with extremely similar values. Multiply the number of points per pixel by the number of pixels the trail passes through, and this effect has the potential to mushroom.

This phenomenon is known as spatial autocorrelation, and it is a big reason why this thesis does not *predict* vulnerable trail segments, but rather *interpolates* them. The distinction might seem rather tenuous to some, but Bolstad (2012) begs to differ: whereas spatially predictive models might incorporate spatial autocorrelation and cross correlation in their underlying statistical assumptions, interpolation is often at their mercy. In other words, interpolation unquestioningly applies Tobler's First Law of Geography that "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970), whereas prediction internalizes systematic conflicts inherent in that law. None of the analysis in this thesis utilizes statistical models to predict resilience or vulnerability; rather, it incorporates managerial knowledge to discern how Tobler's First Law fits into the context of trail routing.

5.3.4 Resampling

Depending on the scope of geographic analysis being performed compared with the resolution and quality of data in use, the premise of Tobler's Law can become muddled and indistinguishable. This was the case when making the WLC models. In order to make valid comparisons with the land cover grid, all topographic rasters had to be resampled to larger resolutions and snapped to avoid misaligned pixels and inaccurate results. Interpolation with the grids was performed at their finest resolution in order to avoid more pronounced autocorrelation effects, but otherwise the resampling process was unavoidable, though thoroughly necessary.

If a manager were to make re-routing decisions based on the maps presented in Appendix B, they would have to make gross generalizations about trail corridors rather than fine distinctions because new trail corridors would be decided using pixels that are close to 100 feet. Let us return to the Bob Ross Trail (BRT) discussed in Section 1.2. It seems more beneficial to provide maps that suggest tighter corridors based on smaller pixel sizes for re-routes of this trail. This way, a manager trying to re-route a vulnerable section of the BRT could make more substantive on-the-ground decisions rather than get pigeon-holed into decisions simply because a model popped out a broad suggestion. A smaller pixel size might give a manager a sense that boundaries can be pushed and the new segment does not have to fit exactly within the specified corridor, whereas larger pixels might suggest that the new trail must be within the boundaries set by the map.

5.3.5 Cartographic Representation

The fine temporal resolution of the sample points from the GPS units was too much in terms of cartographic design. The points are so close together that distinguishing them could only be done with small point sizes or large scales. The only problem is that small point sizes do not contrast with their backgrounds very well in larger areal extents. A process of rating generalization with trail points could help a lot in this respect because there were many linear extents where singular resilient ratings were tucked into otherwise continuous vulnerable segments. The chances that the one resilient rating among a sea of vulnerable ratings is correct—let alone useful—seems doubtful, so generalization would help declutter the final maps without too much loss in accuracy.

After generalization, converting continuous lengths of similarly classed points into multi-part polylines would be the next step; after all, a series of points does not show connectivity very well compared to polylines. This would have the added benefit of helping define what is exactly meant by "continuous lengths" of the same rating, a term which has been otherwise nebulous until this point. Some statistics could be performed through a Python script in order to determine quantities like average or median length and variation in that length. Statistics like these would be highly useful for organizations like RFOV or Colorado Fourteeners Initiative (CFI) because the bulk of their field work funding is justified by linear extents of degradation potential.

6 Conclusion (*Long Walk Home*)

While it is true that a good manager should exercise proper judgement despite the output of a model, it is all too certain that a map could be taken too literally. This is where maps tend to have problems when it comes to policy action and decision making. Despite the fact that maps are often static representations of dynamic processes and imperfect visualizations of the real world, they can still be "the gospel" in terms of decision justification. The maps that came out of this thesis were from an iterative process in weighting, so while each individual map does portray a singular static representation of the landscape, the fact that multiple outcomes can exist from a single model indicate that trail degradation in a landscape is neither statically defined nor perfectly representational.

The shear number of possibilities associated with modeling trail degradation justifies the need for more on-the-ground management; whether this management comes from knowledgeable personnel and/or motivated citizens is to be seen. With a trend in funding that does not look promising, ranger districts like the ASRD must transfer a portion of their responsibilities to local nonprofits and users themselves. This thesis shows that there is a clear opening for user-generated content and Volunteered Geographic Information (VGI). Imagine the impact that a geographic citizen science program could have! The ASRD could maintain an up-to-date database on trail locations and conditions; users could geotag photos of trails that stewards could use to direct restorative efforts; more ground-level data could pave the way for robust statistical models of degradation... The possibilities are endless.

With the exception of Tomczyk (2011) and Tomczyk and Ewertowski (2013), very little work has explored the role of GIS in questions associated with public land management. The use of widely disseminated digital data provides insights into simple trail characteristics such as slope that would be utterly time consuming and tedious to sample in the real world, but there is still room to grow. More modeling can be done that incorporates managerial controls on degradation such as predominant use type and use intensity. Statistically robust models could also be used to predict degradation based on sampling-based or census-based monitoring techniques overviewed by Marion et al. (2006).

While the use of GIS in this paper has undoubtedly given the spatial questions in Recreation Ecology a new dimension, it is my personal belief that GIS cannot grow the field and keep it afloat on its own. There is a significant hole in this literature that can be filled with research in cultural geography and political ecology. For example, a study investigating how scale influences funding decisions at all levels of government could shed light on the growing interdependence between non-profit organizations and federal managers. My personal view is that this literature lacks a deep understanding that wilderness—and any publicly owned space more generally—is political in nature. The health of wilderness landscapes is tied to more than just ecological processes: it depends on user behavior, public perception, ethnic representation, economic drivers, government involvement, and activism at all scales.

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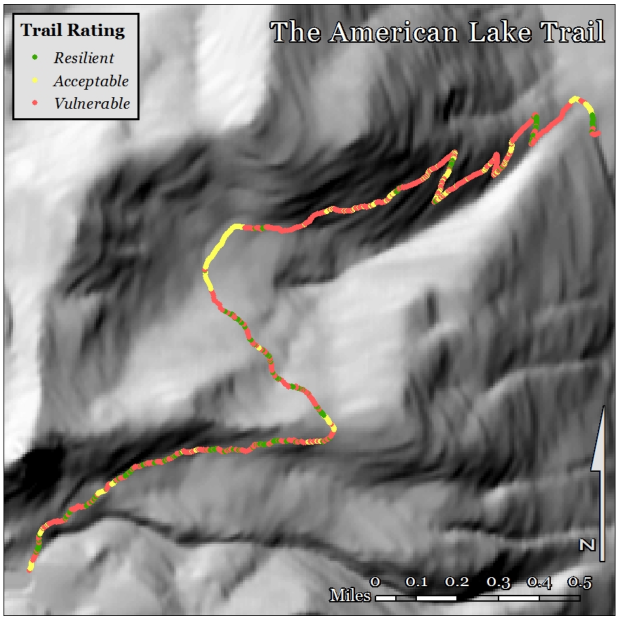
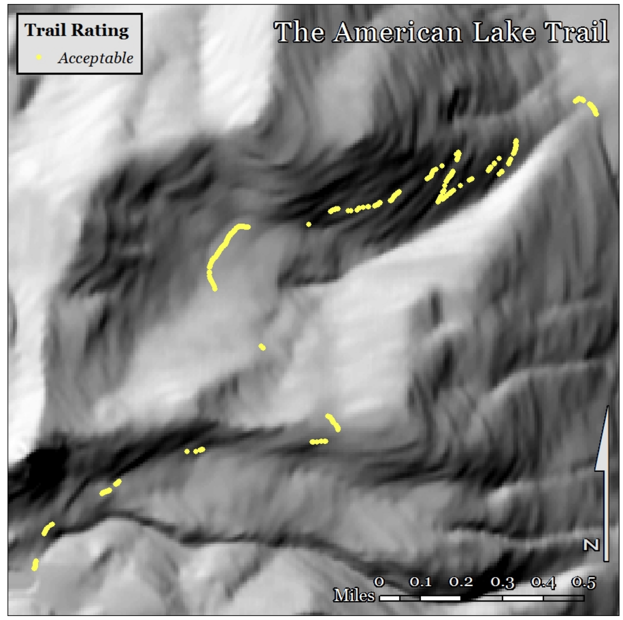
A Degradation Classification Maps

American Lake



(a) All classifications



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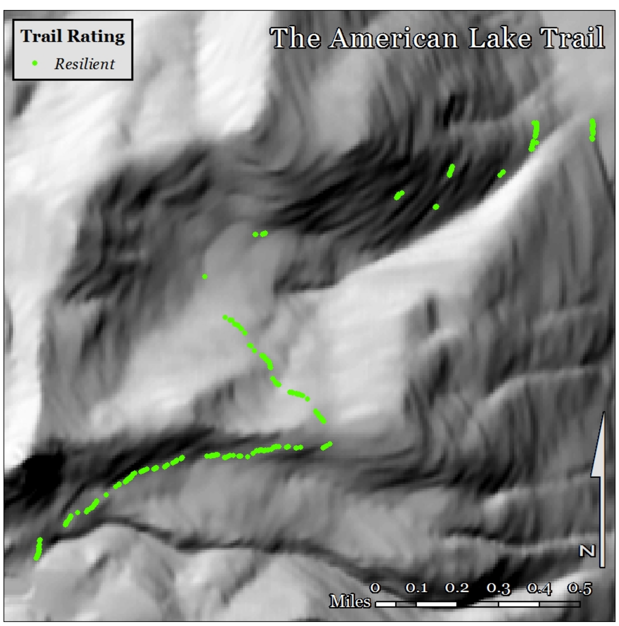
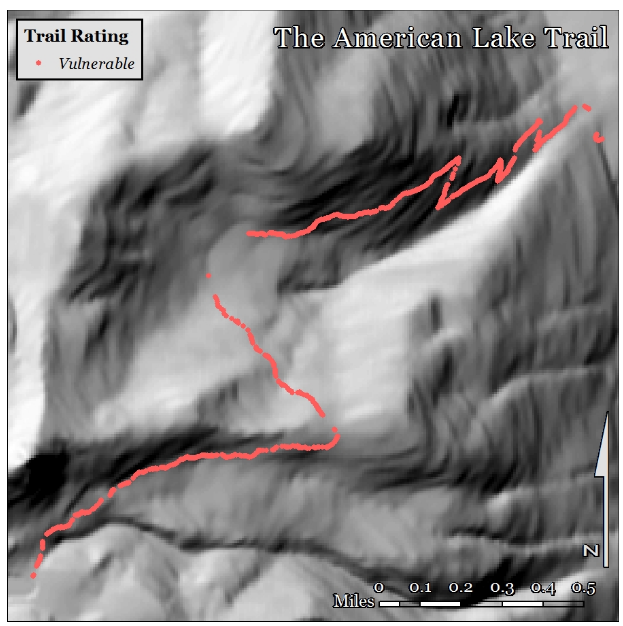


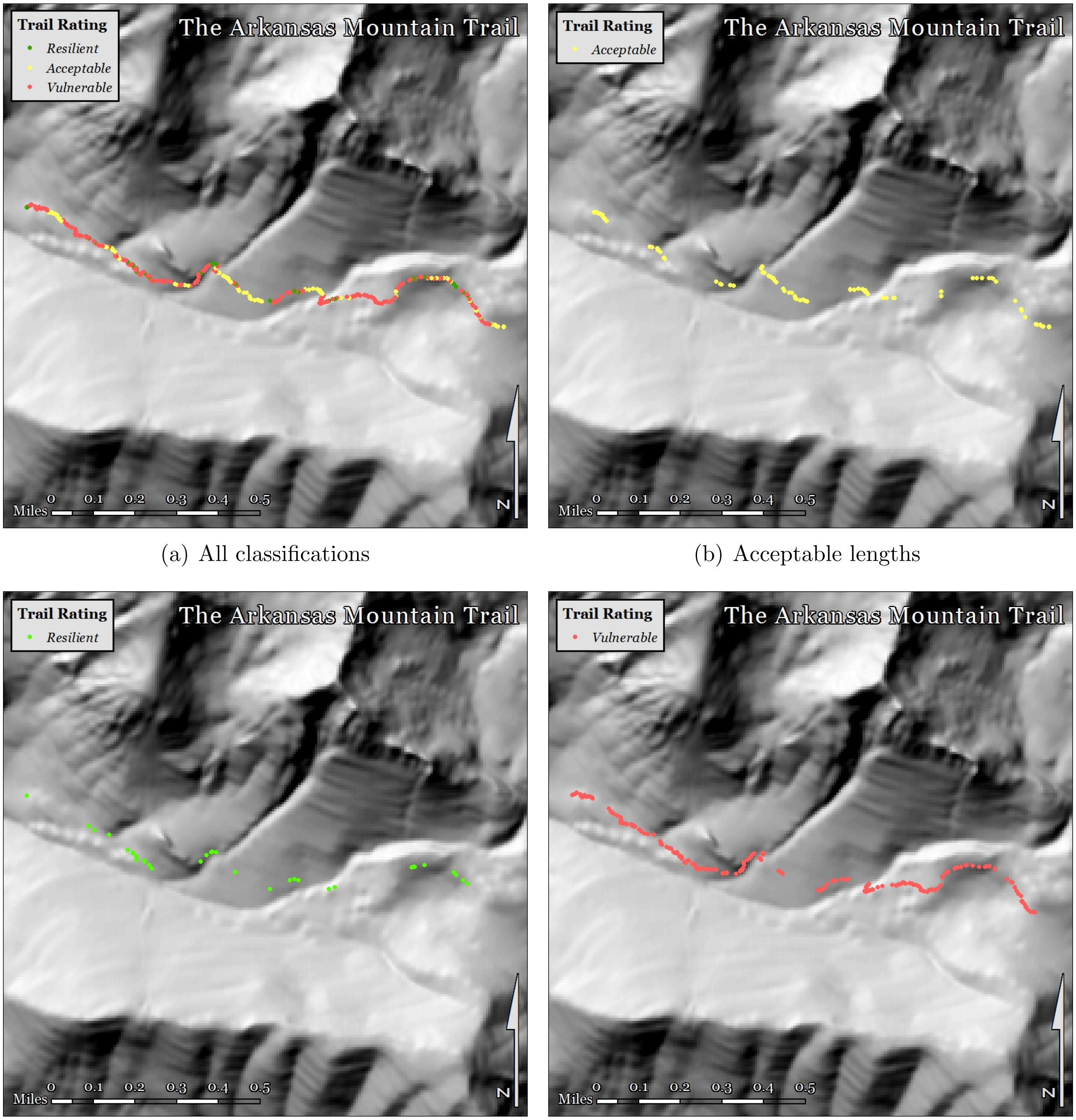
(c) Resilient lengths



(d) Vulnerable lengths

Figure A.1: Degradation classifications for American Lake

Arkansas Mountain



(a) All classifications

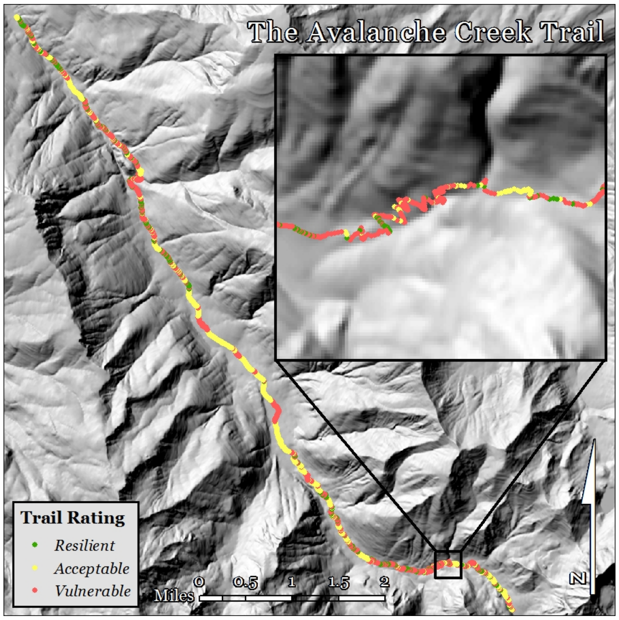
(b) Acceptable lengths

(c) Resilient lengths

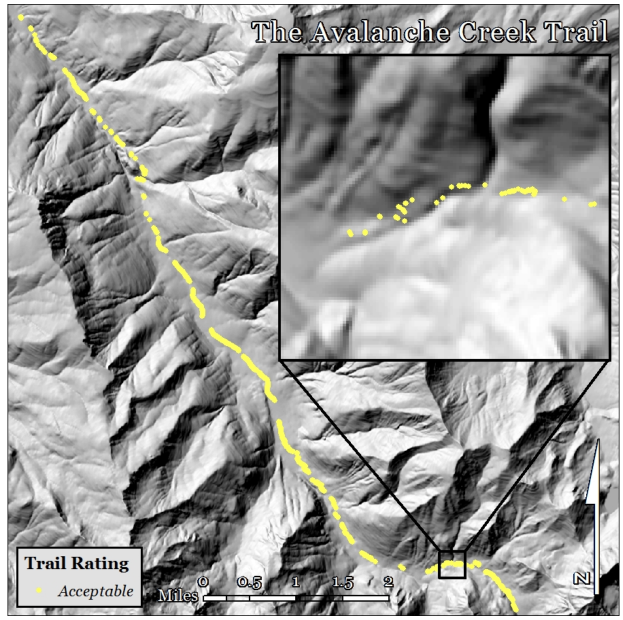
(d) Vulnerable lengths

Figure A.2: Degradation classifications for Arkansas Mountain

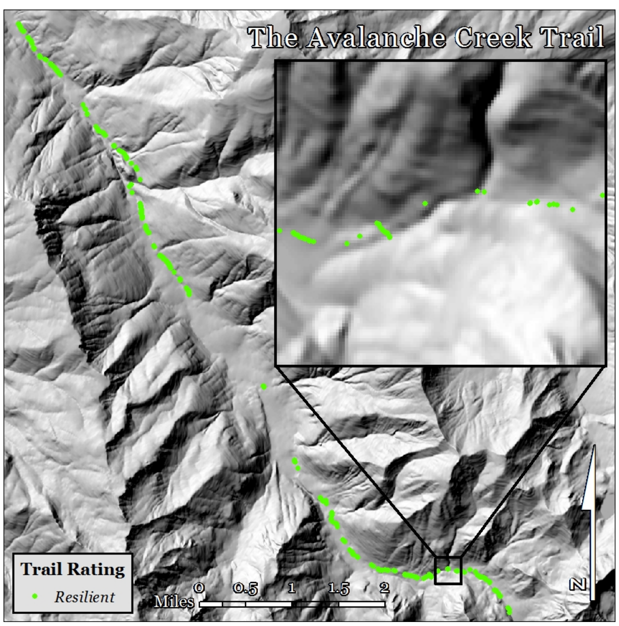
Avalanche Creek



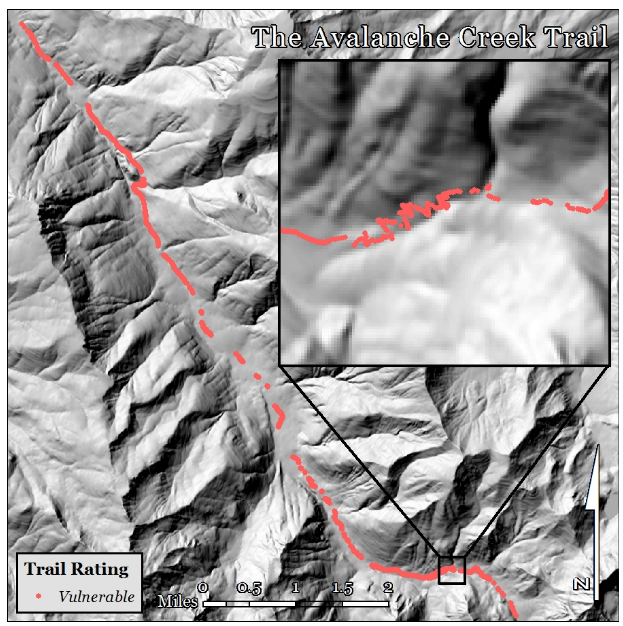
(a) All classifications



(b) Acceptable lengths



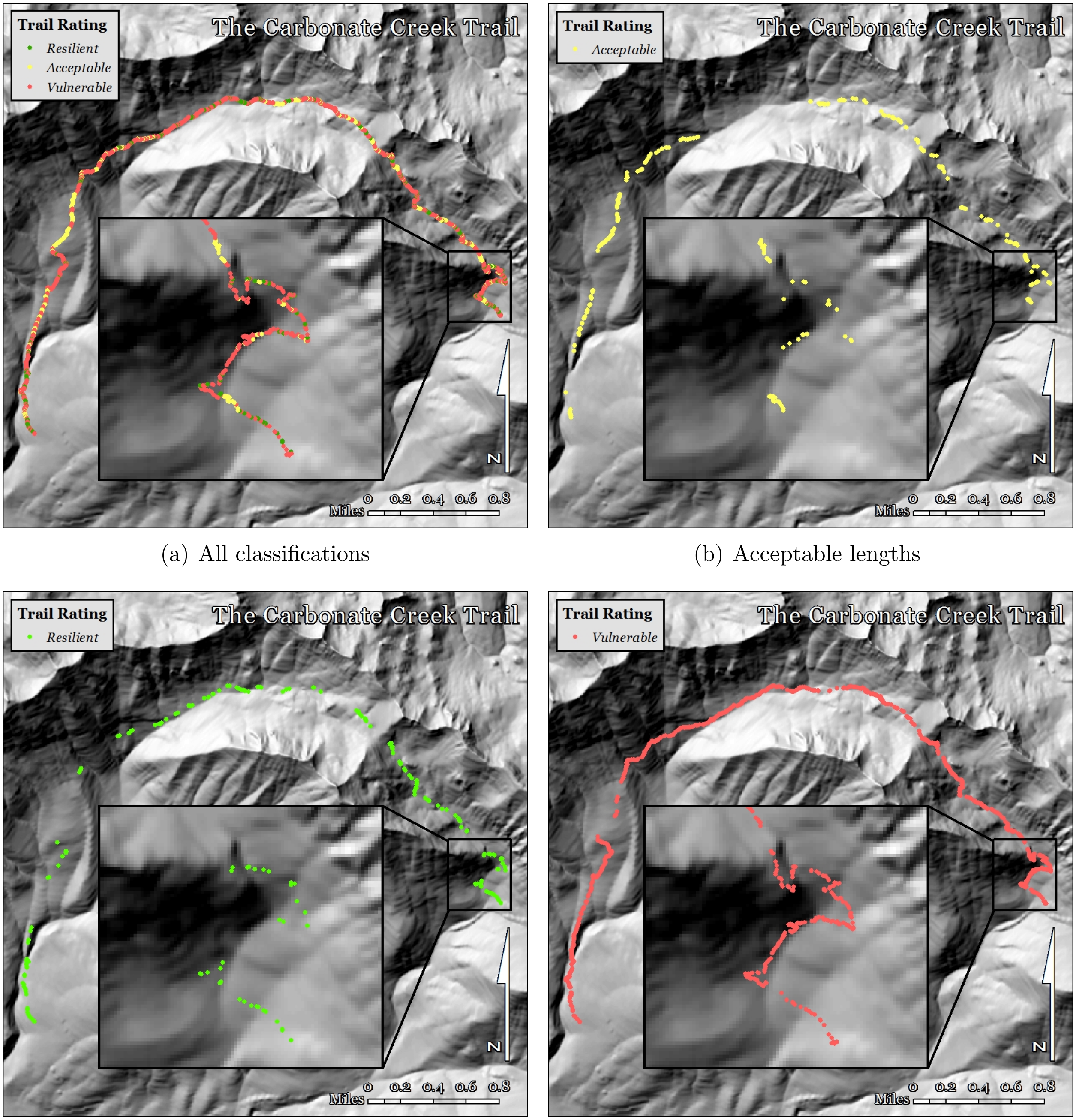
(c) Resilient lengths



(d) Vulnerable lengths

Figure A.3: Degradation classifications for Avalanche Creek

Carbonate Creek



(a) All classifications

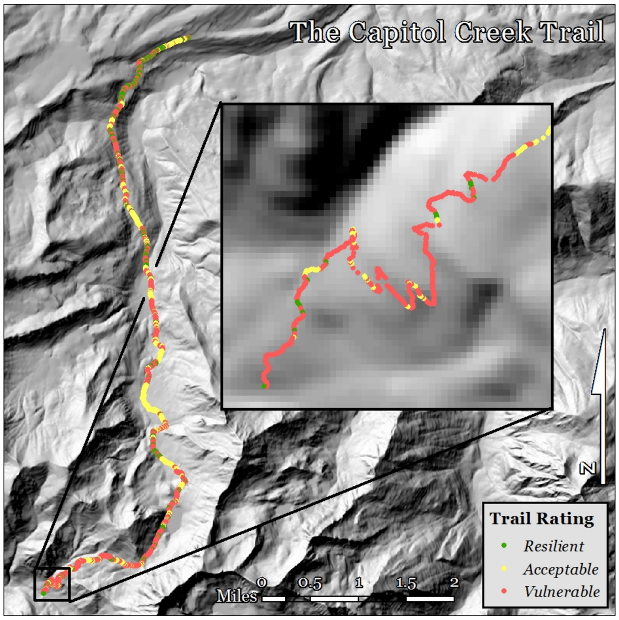
(b) Acceptable lengths

(c) Resilient lengths

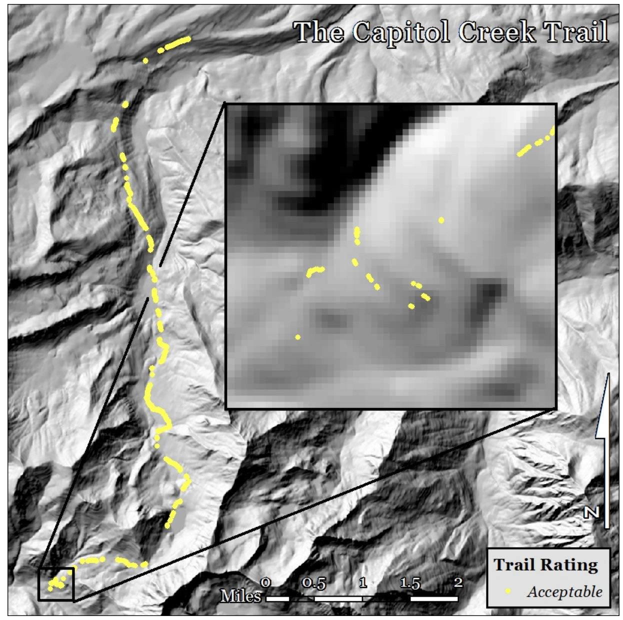
(d) Vulnerable lengths

Figure A.4: Degradation classifications for Carbonate Creek

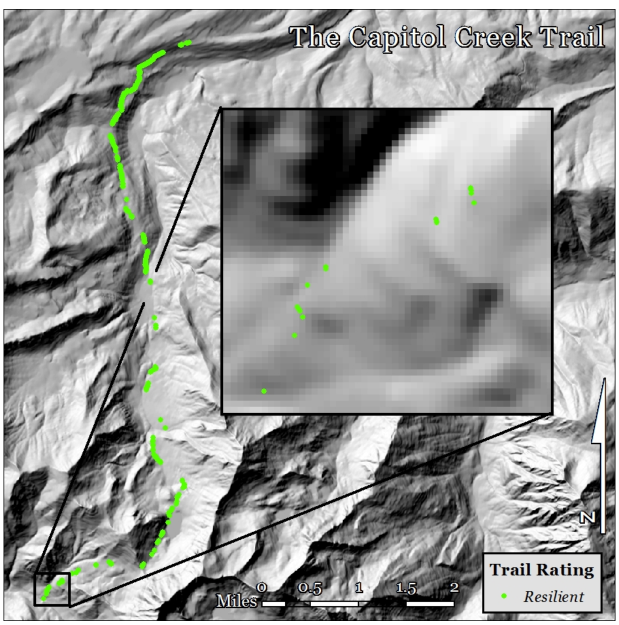
Capitol Creek



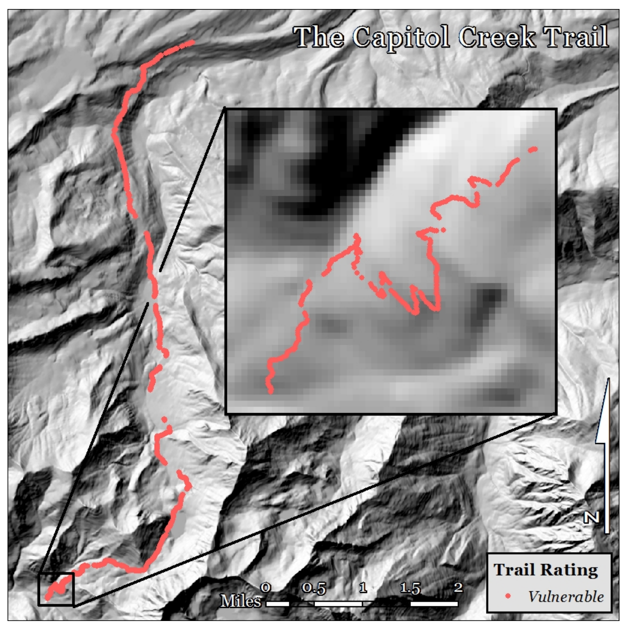
(a) All classifications



(b) Acceptable lengths



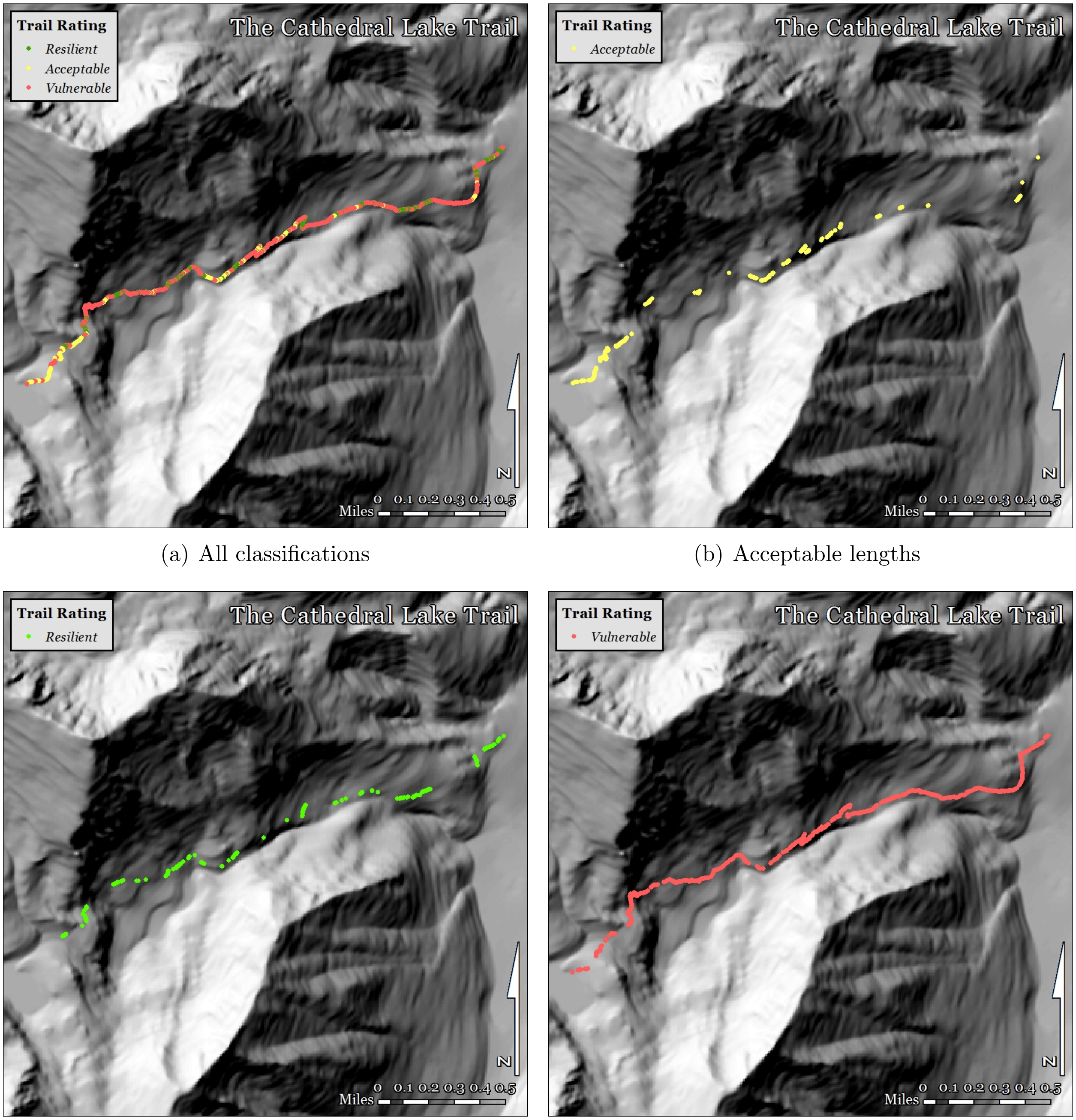
(c) Resilient lengths



(d) Vulnerable lengths

Figure A.5: Degradation classifications for Capitol Creek

Cathedral Lake



(a) All classifications

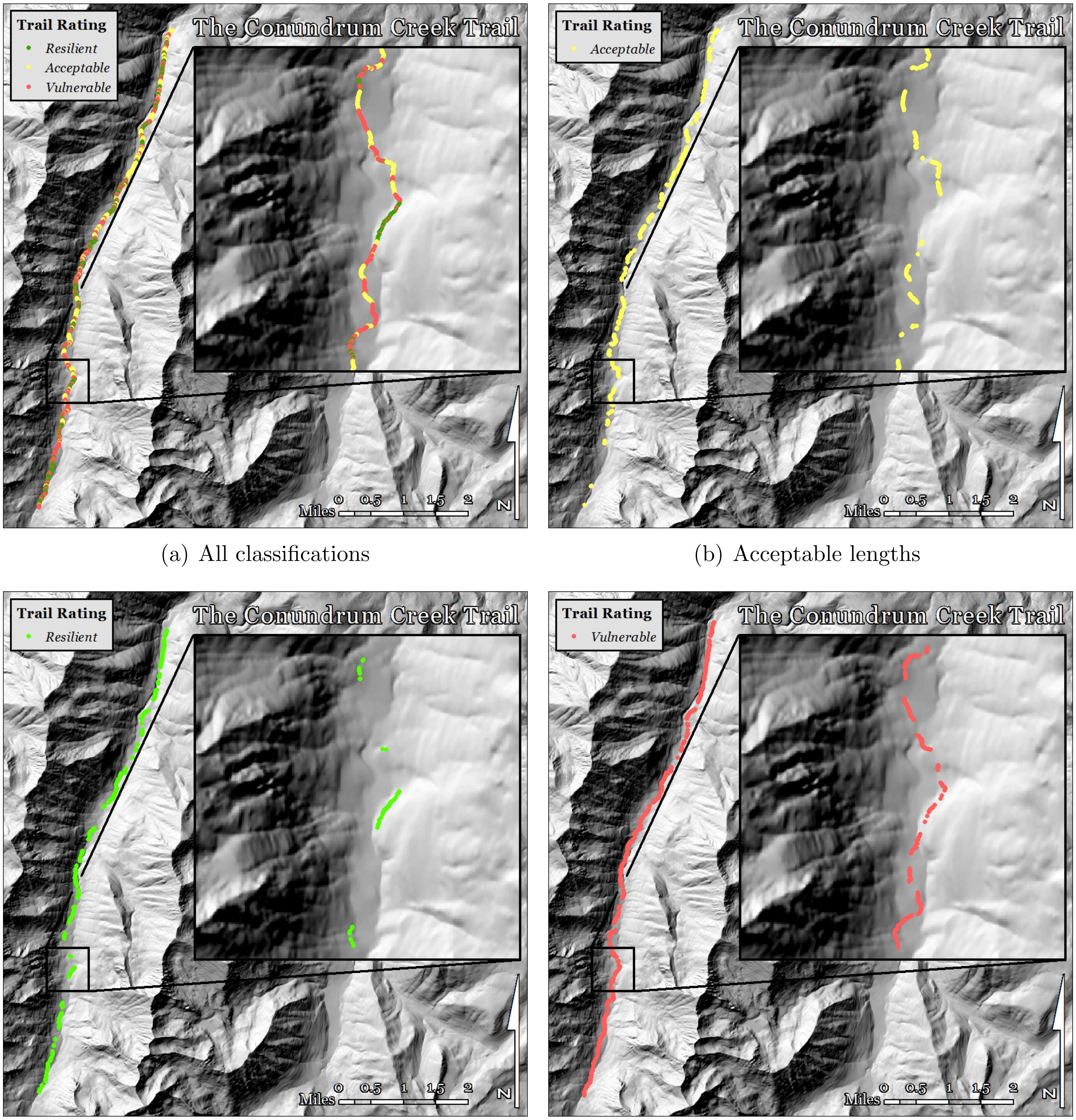
(b) Acceptable lengths

(c) Resilient lengths

(d) Vulnerable lengths

Figure A.6: Degradation classifications for Cathedral Lake

Conundrum Creek



(a) All classifications

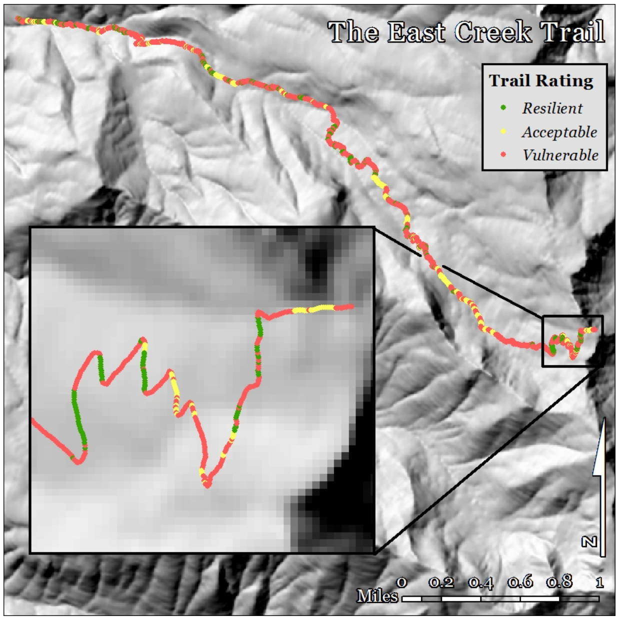
(b) Acceptable lengths

(c) Resilient lengths

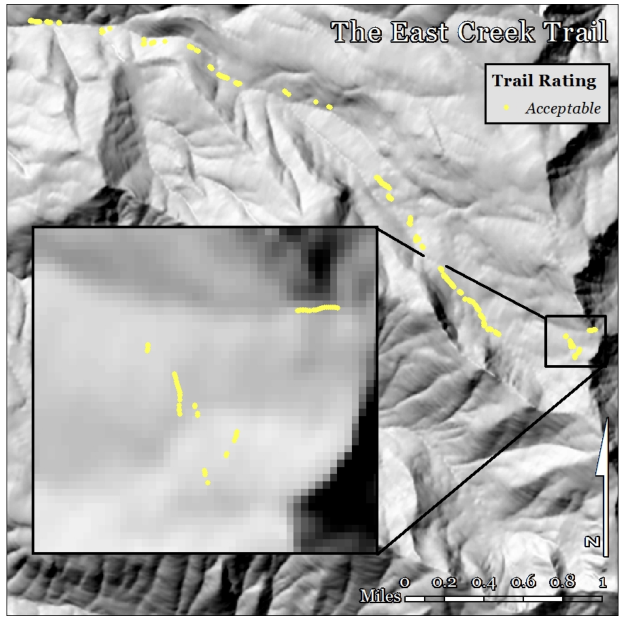
(d) Vulnerable lengths

Figure A.7: Degradation classifications for Conundrum Creek

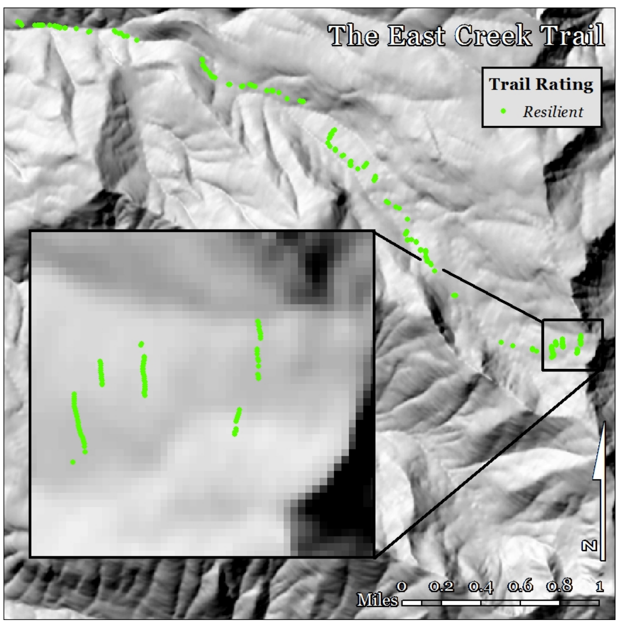
East Creek



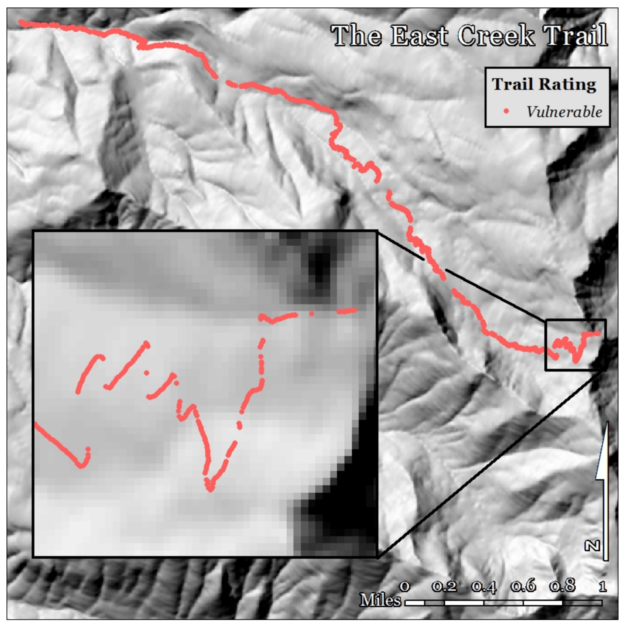
(a) All classifications



(b) Acceptable lengths



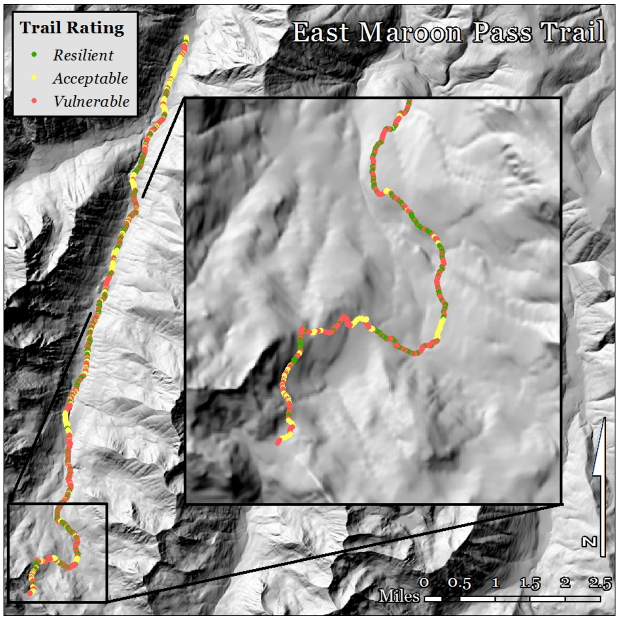
(c) Resilient lengths



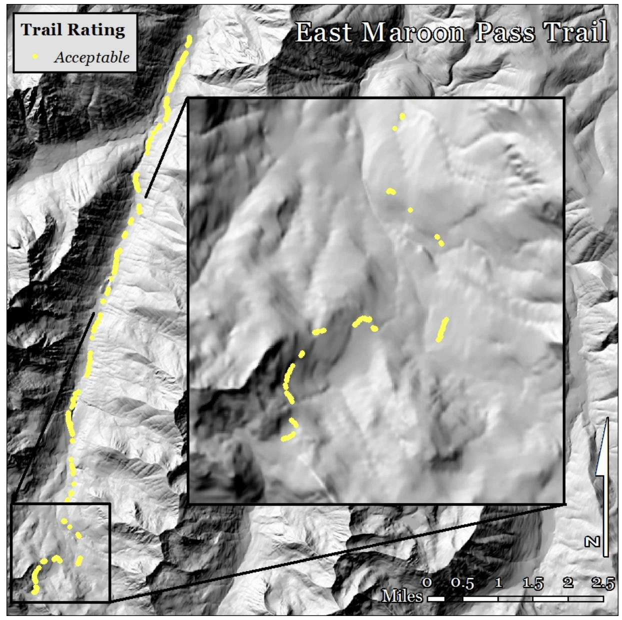
(d) Vulnerable lengths

Figure A.8: Degradation classifications for East Creek

East Maroon Pass



(a) All classifications



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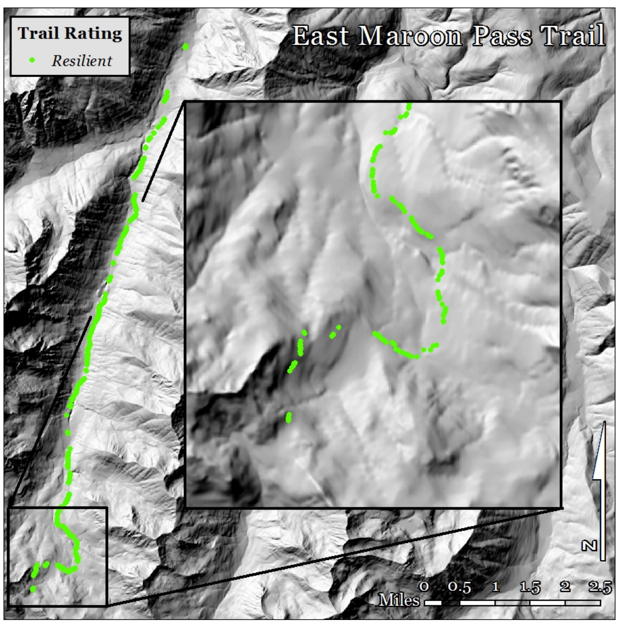
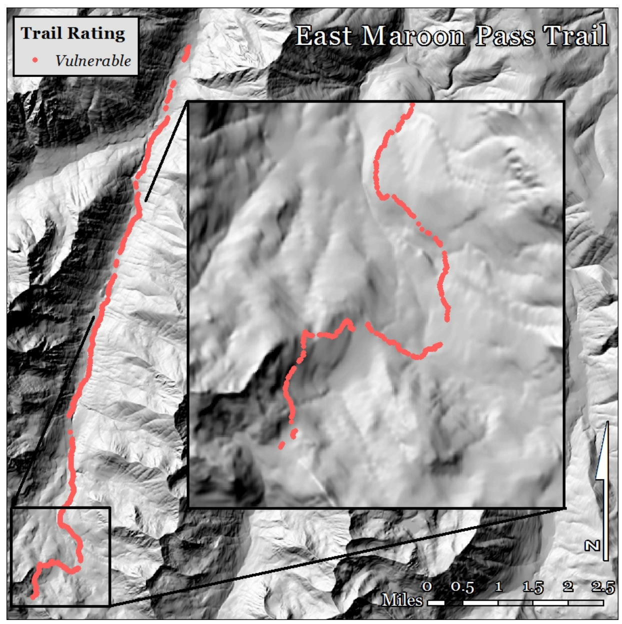


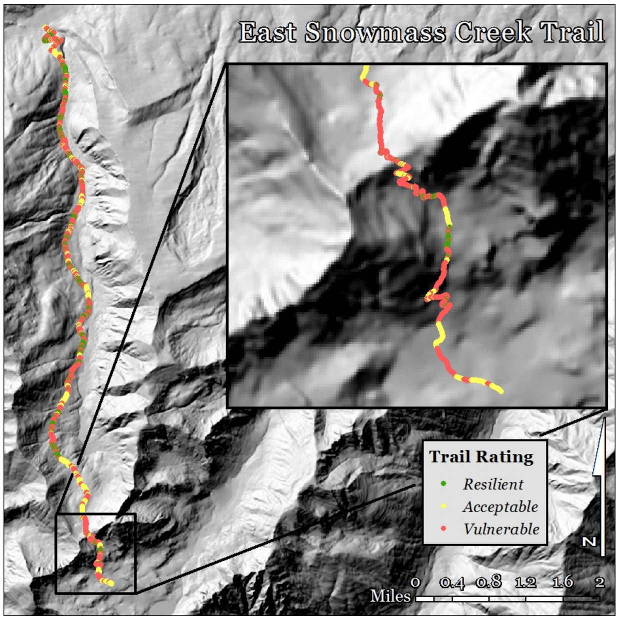
(c) Resilient lengths



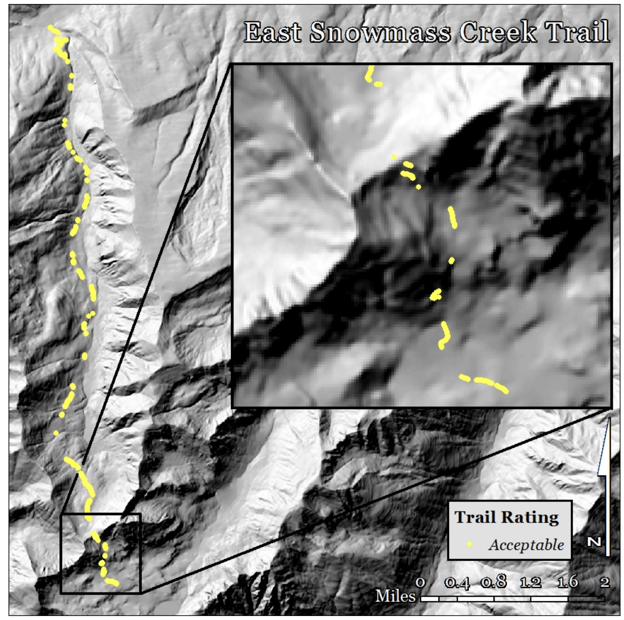
(d) Vulnerable lengths

Figure A.9: Degradation classifications for East Maroon Pass

East Snowmass Creek



(a) All classifications



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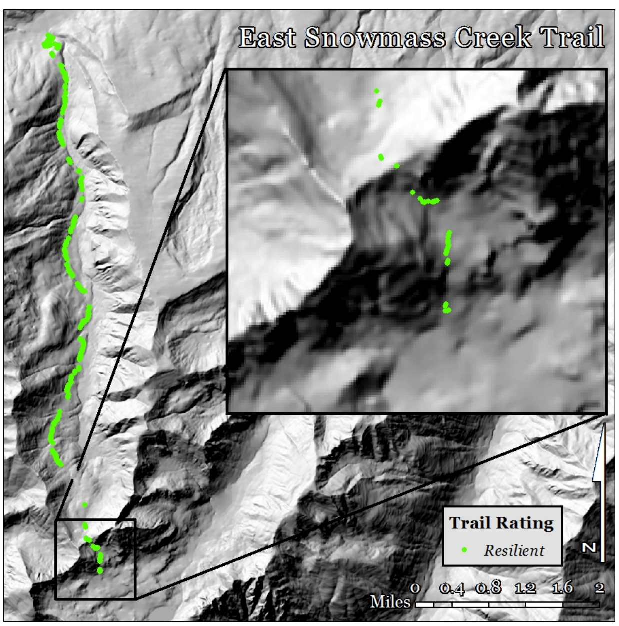
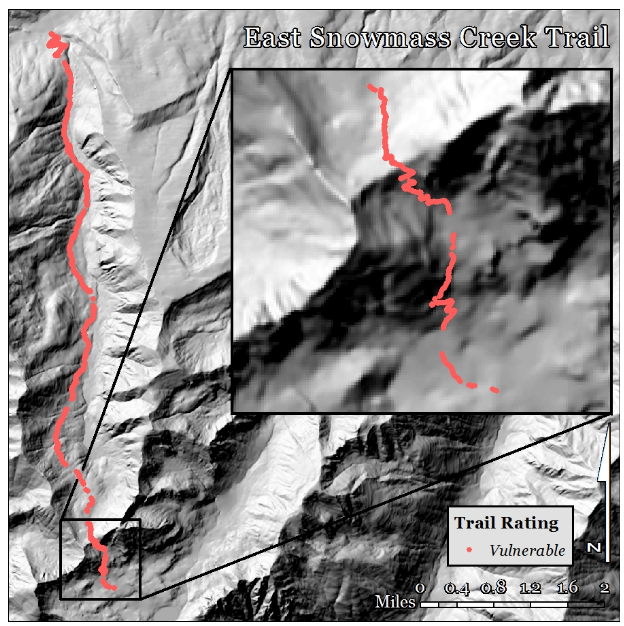


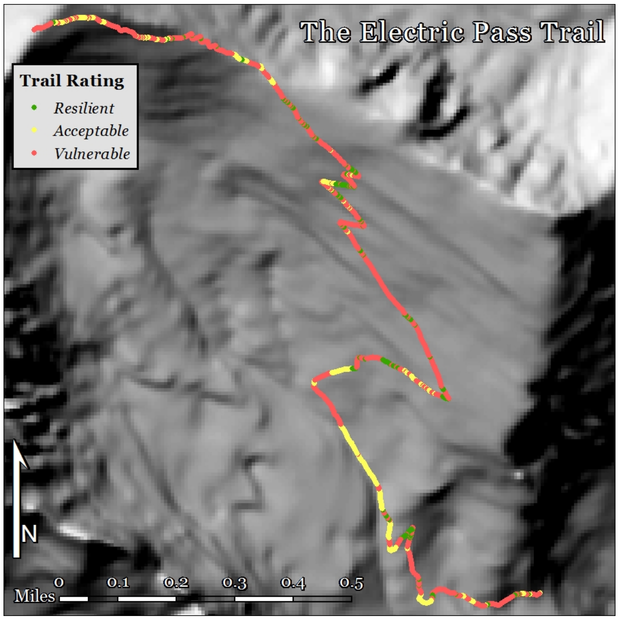
(c) Resilient lengths



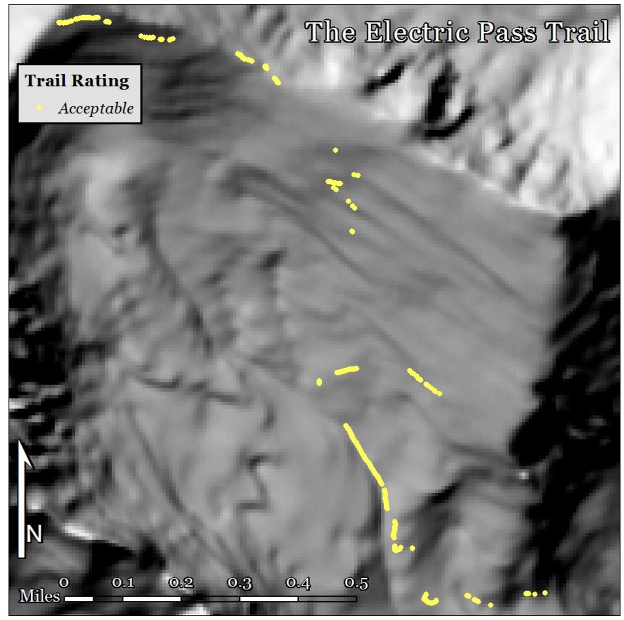
(d) Vulnerable lengths

Figure A.10: Degradation classifications for East Snowmass Creek

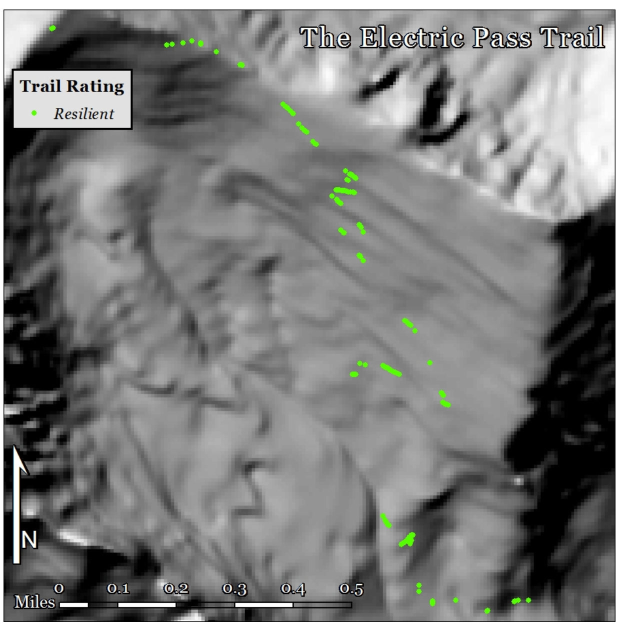
Electric Pass



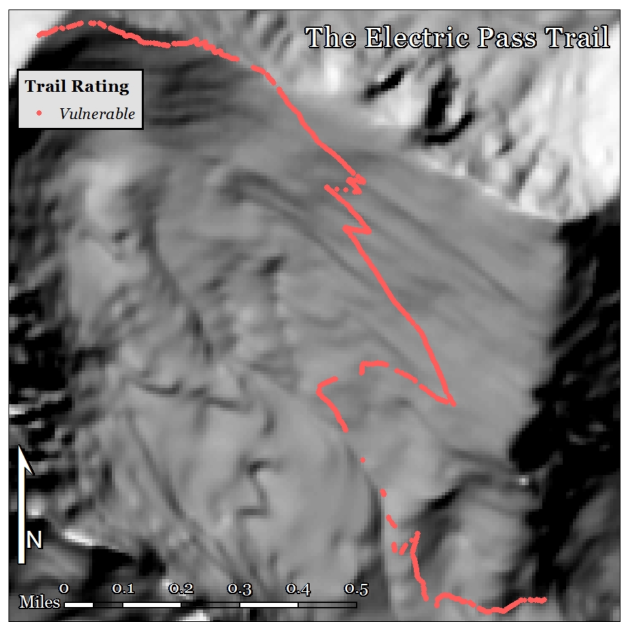
(a) All classifications



(b) Acceptable lengths



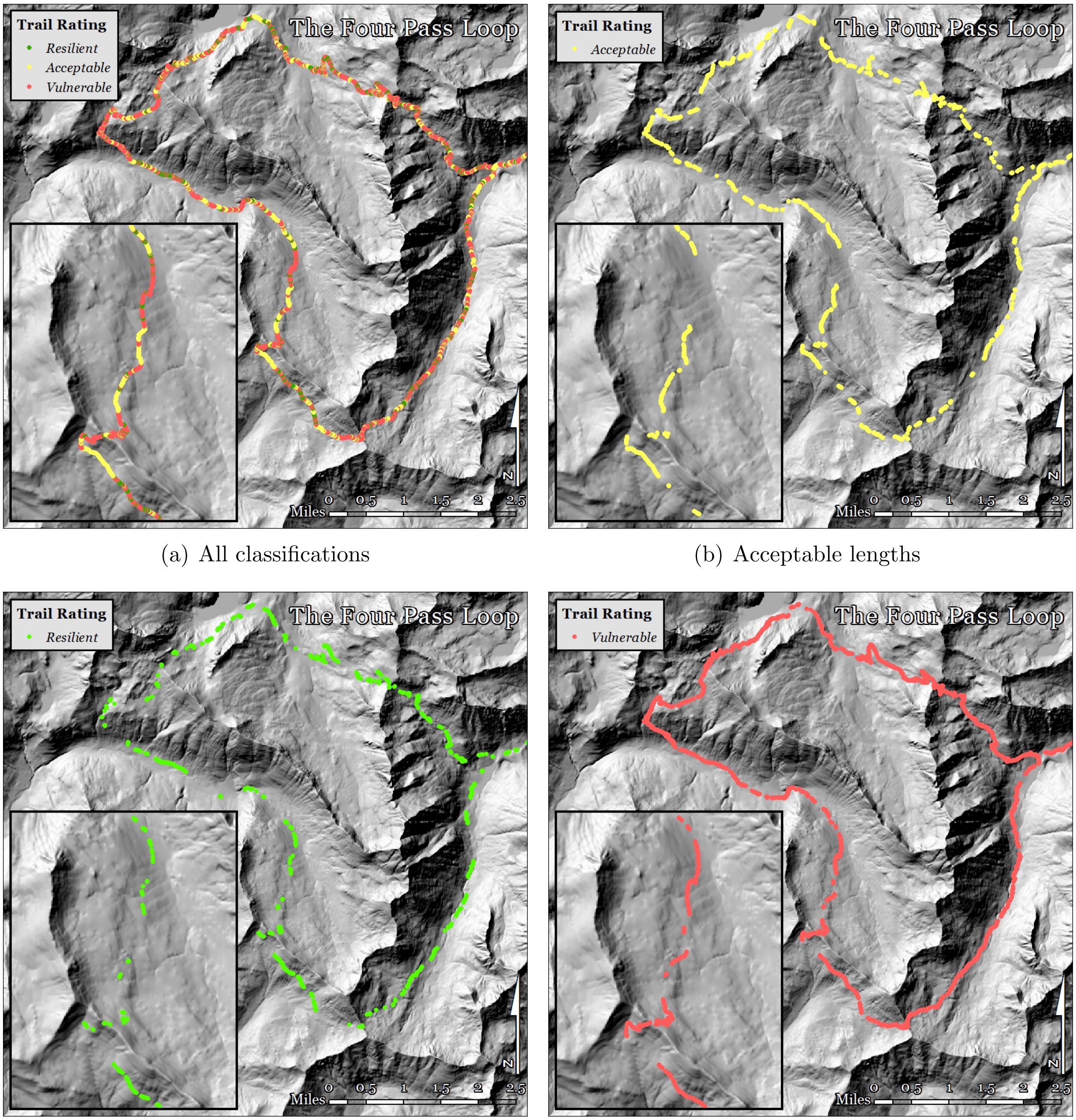
(c) Resilient lengths



(d) Vulnerable lengths

Figure A.11: Degradation classifications for Electric Pass

Four Pass Loop



(a) All classifications

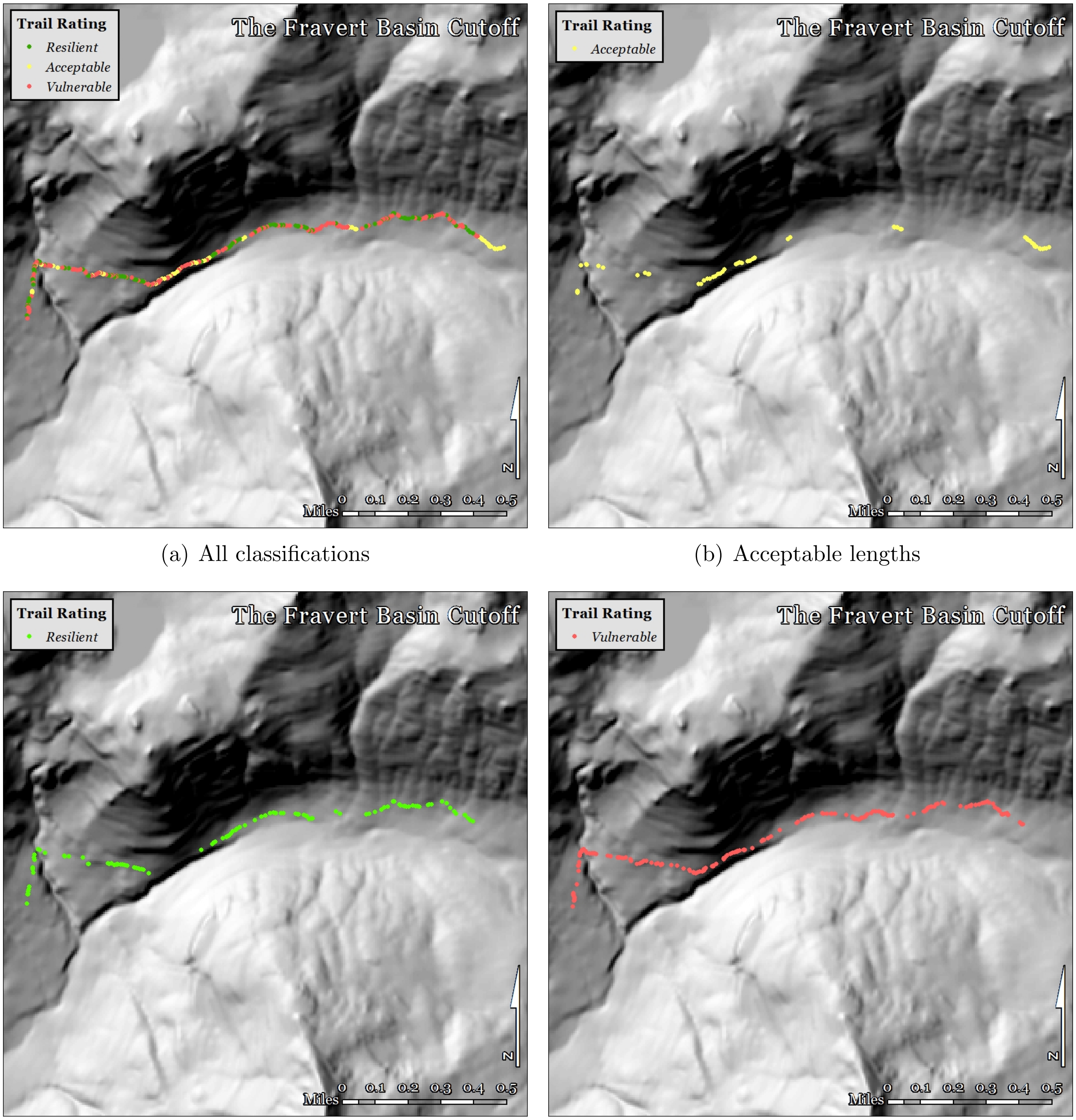
(b) Acceptable lengths

(c) Resilient lengths

(d) Vulnerable lengths

Figure A.12: Degradation classifications for the Four Pass Loop

Fravert Basin



(a) All classifications

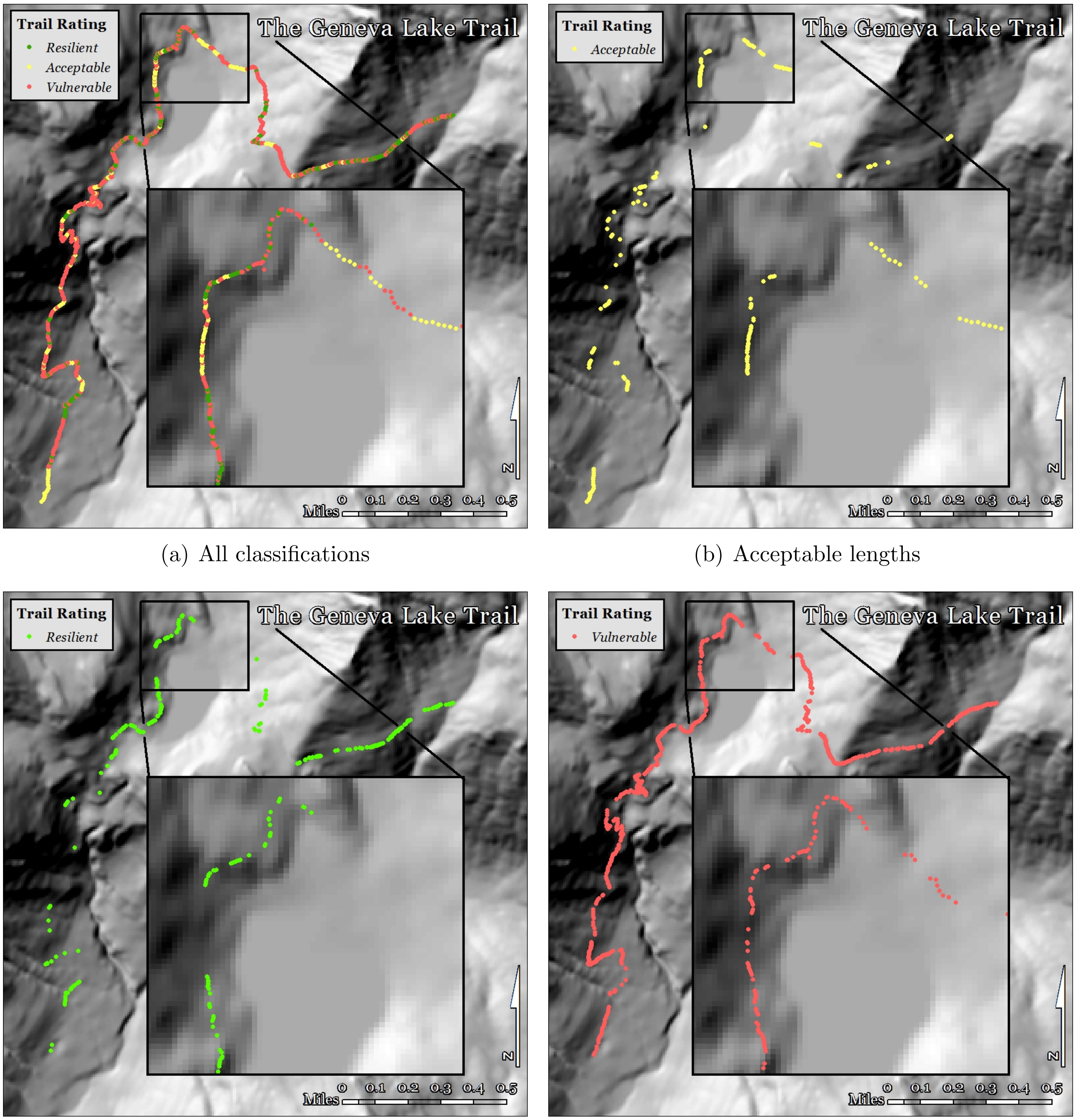
(b) Acceptable lengths

(c) Resilient lengths

(d) Vulnerable lengths

Figure A.13: Degradation classifications for Fravert Basin

Geneva Lake



(a) All classifications

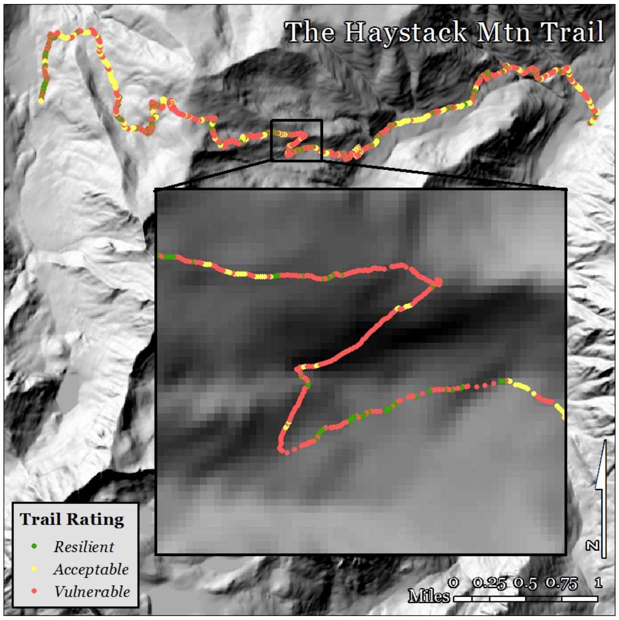
(b) Acceptable lengths

(c) Resilient lengths

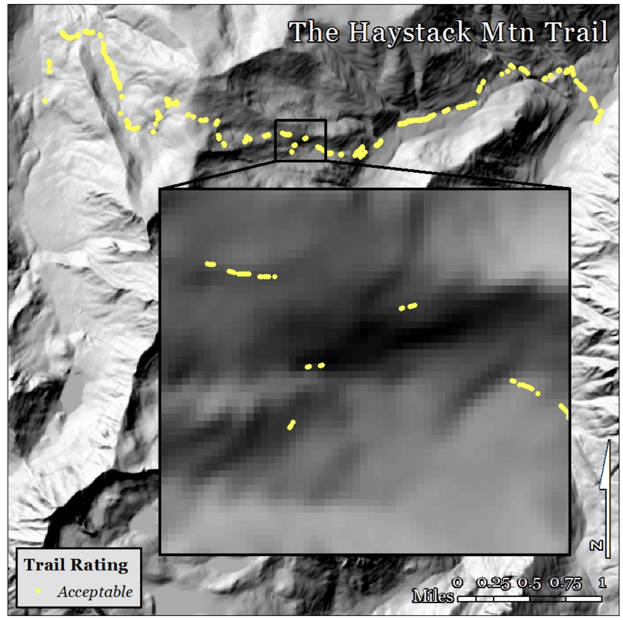
(d) Vulnerable lengths

Figure A.14: Degradation classifications for Geneva Lake

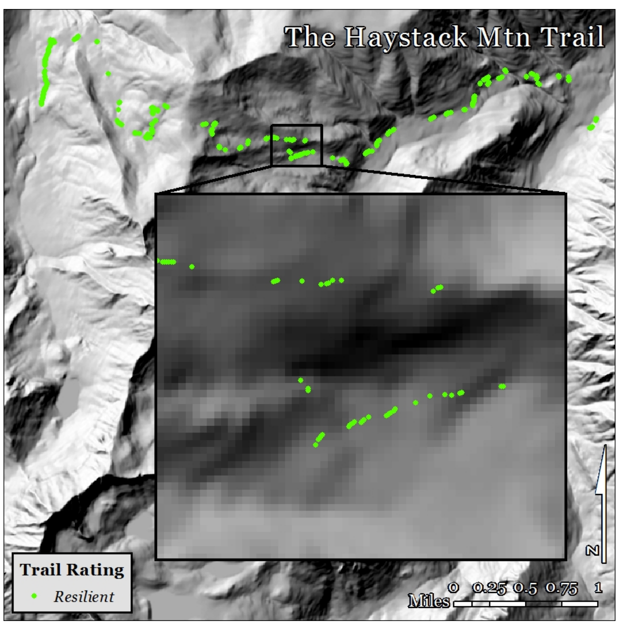
Haystack Mountain



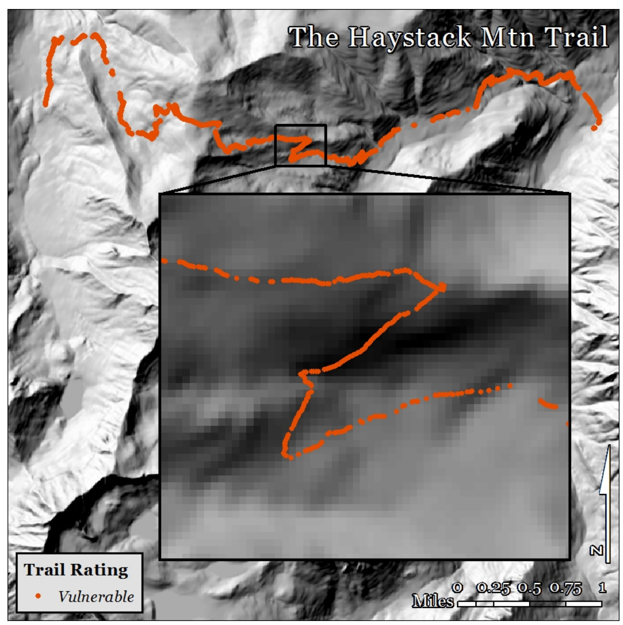
(a) All classifications



(b) Acceptable lengths



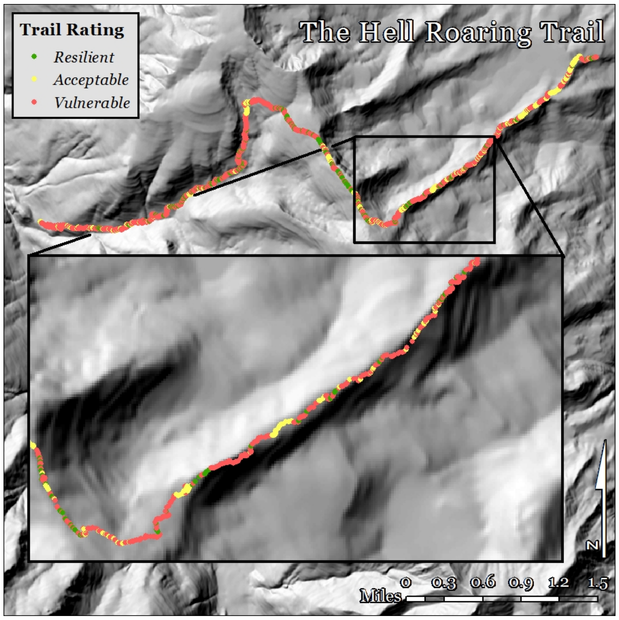
(c) Resilient lengths



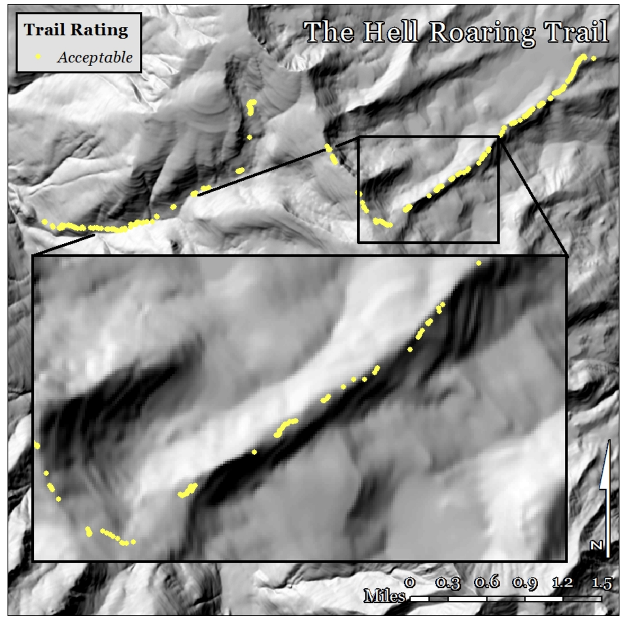
(d) Vulnerable lengths

Figure A.15: Degradation classifications for Haystack Mountain

Hell Roaring Creek



(a) All classifications



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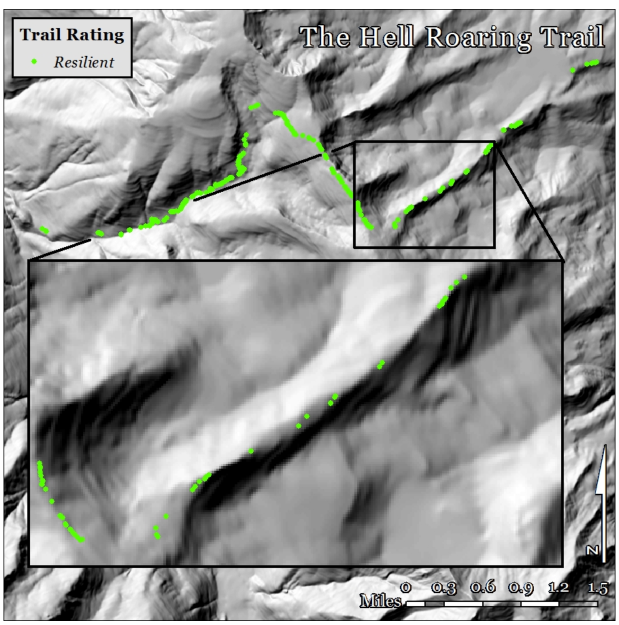
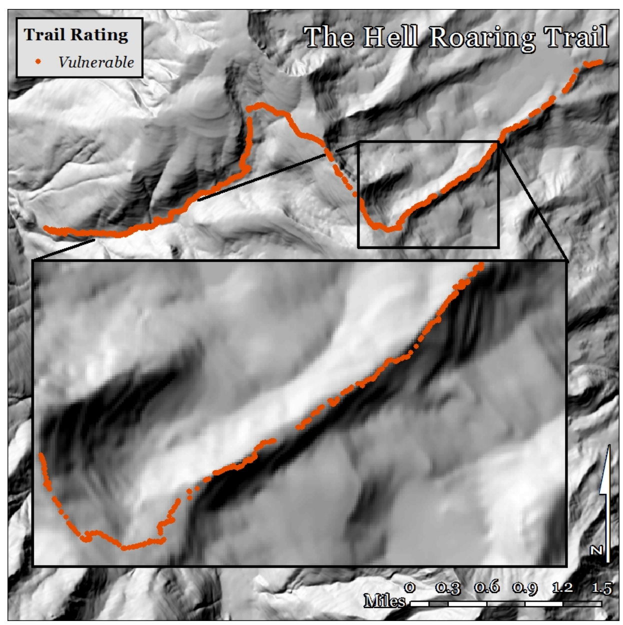


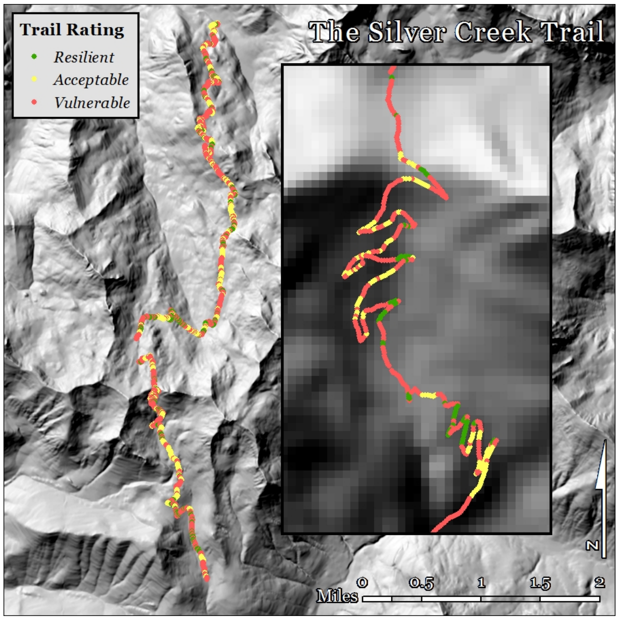
(c) Resilient lengths



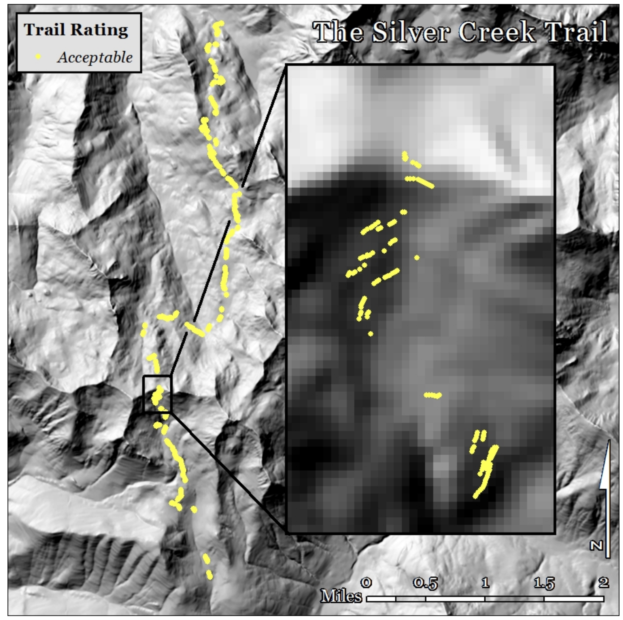
(d) Vulnerable lengths

Figure A.16: Degradation classifications for Hell Roaring Creek

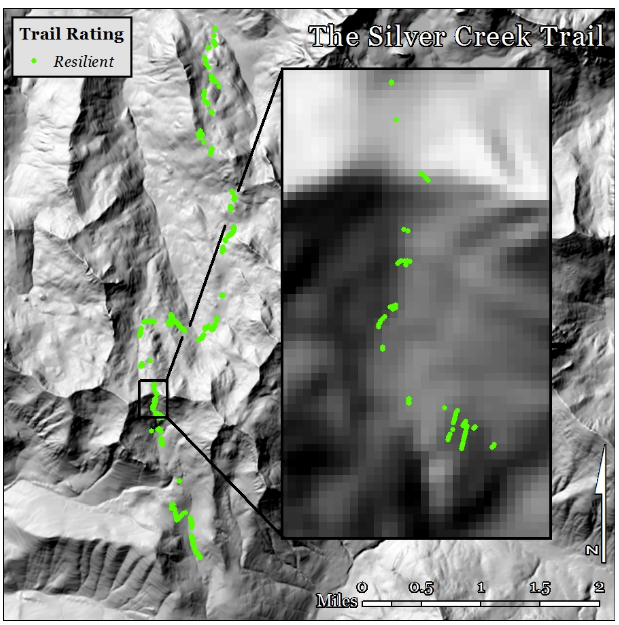
Silver Creek



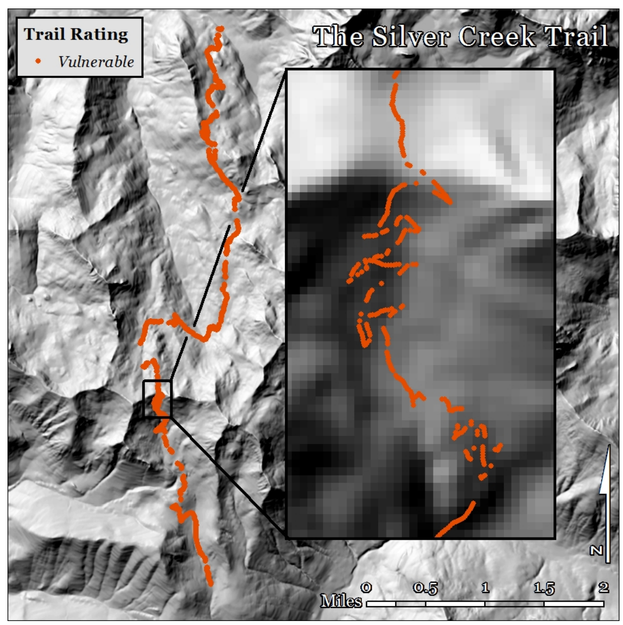
(a) All classifications



(b) Acceptable lengths



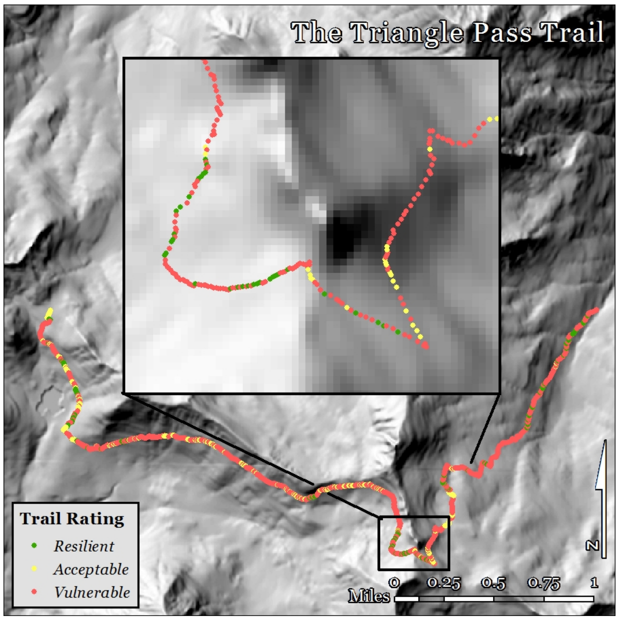
(c) Resilient lengths



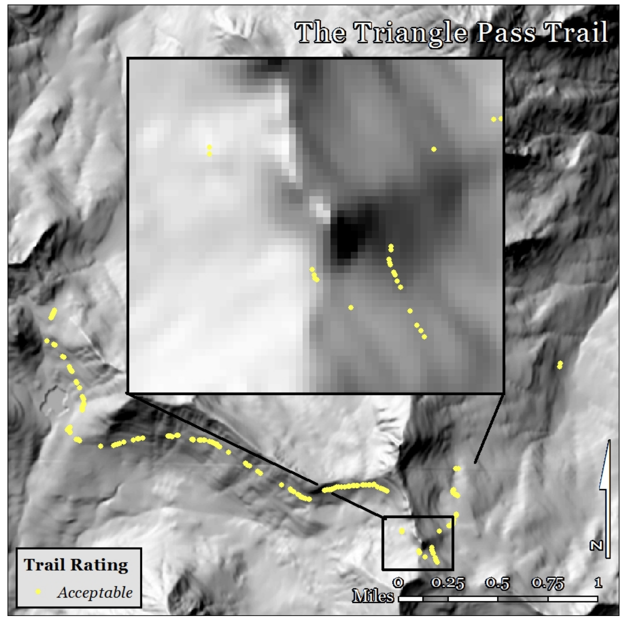
(d) Vulnerable lengths

Figure A.17: Degradation classifications for Silver Creek

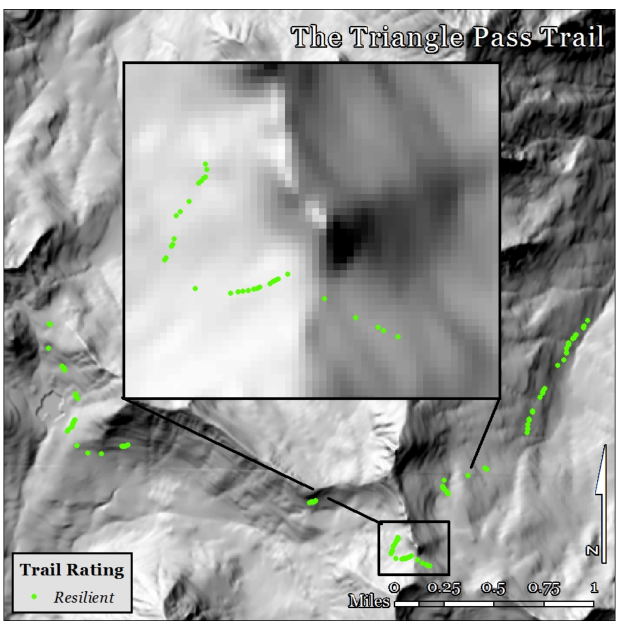
Triangle Pass



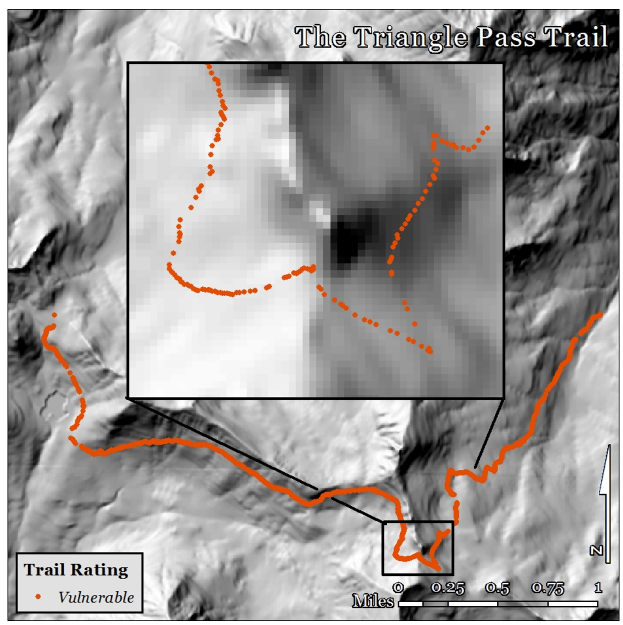
(a) All classifications



(b) Acceptable lengths



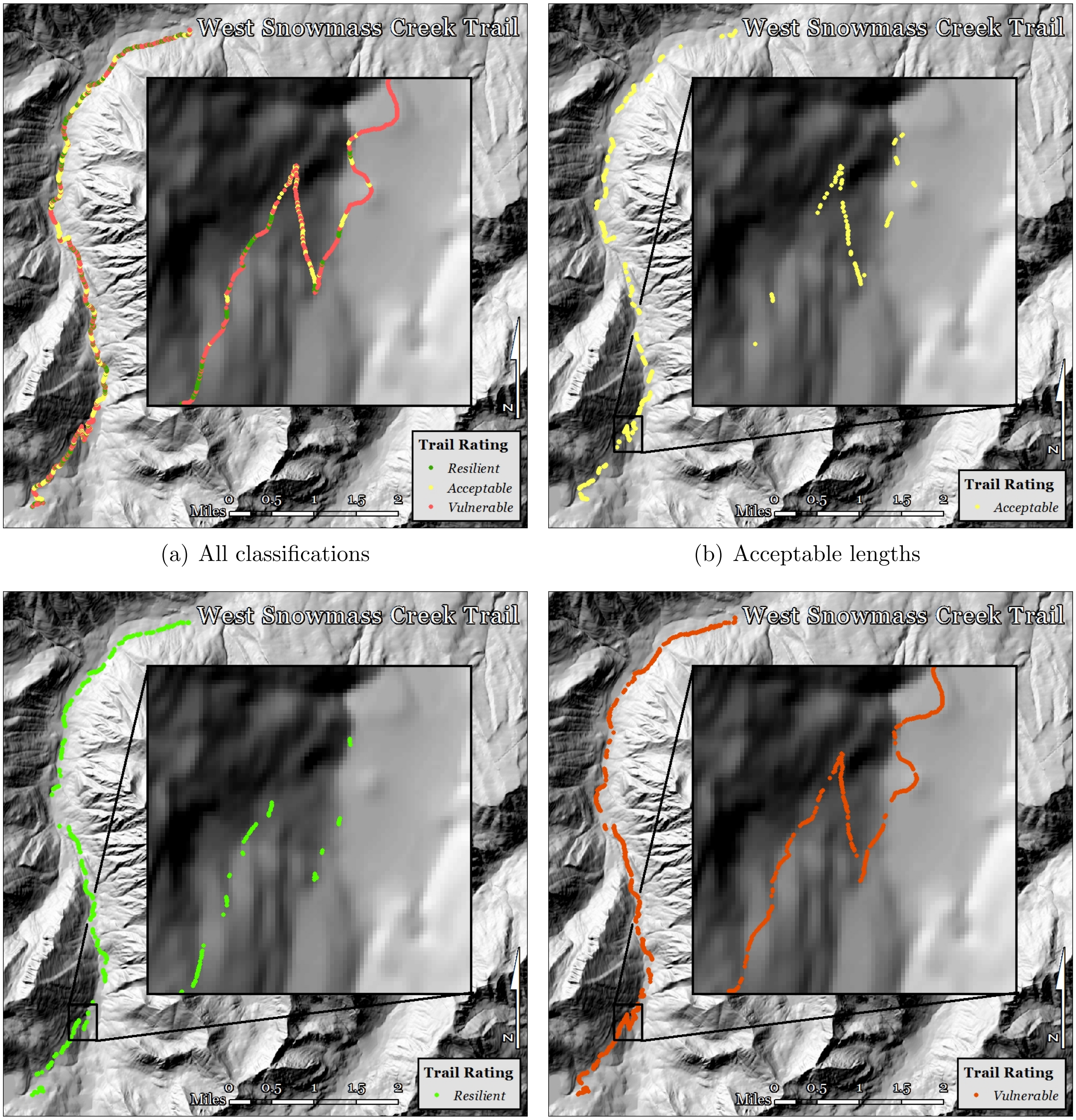
(c) Resilient lengths



(d) Vulnerable lengths

Figure A.18: Degradation classifications for Triangle Pass

West Snowmass Creek



(a) All classifications

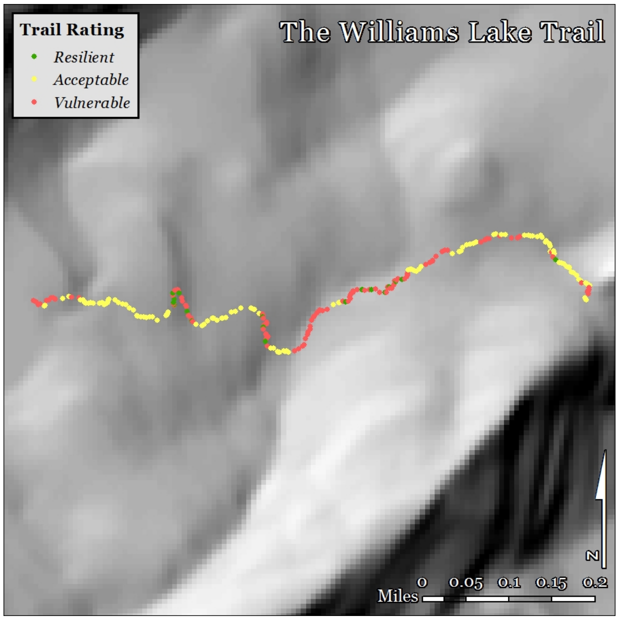
(b) Acceptable lengths

(c) Resilient lengths

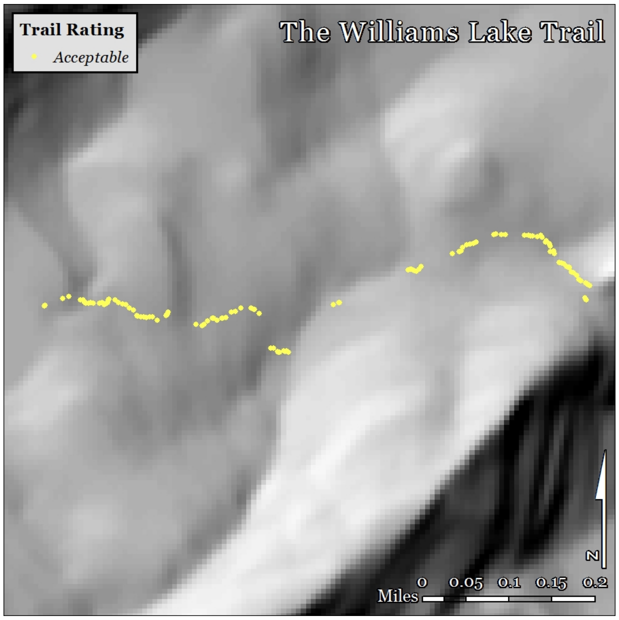
(d) Vulnerable lengths

Figure A.19: Degradation classifications for West Snowmass Creek

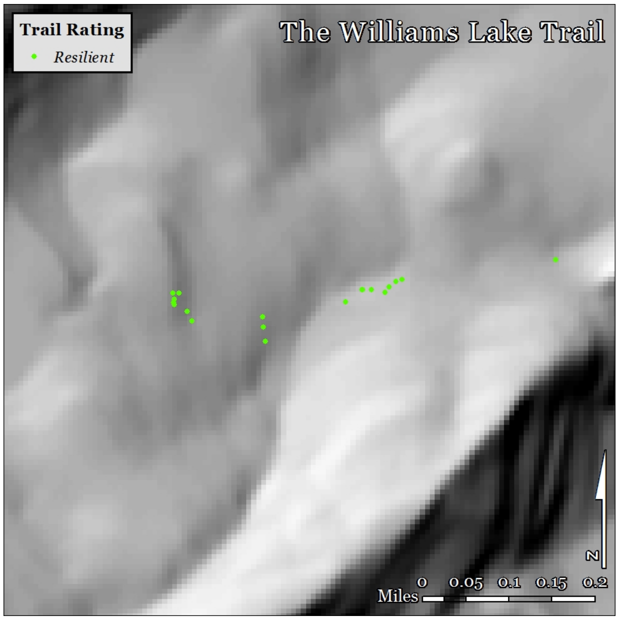
Williams Lake



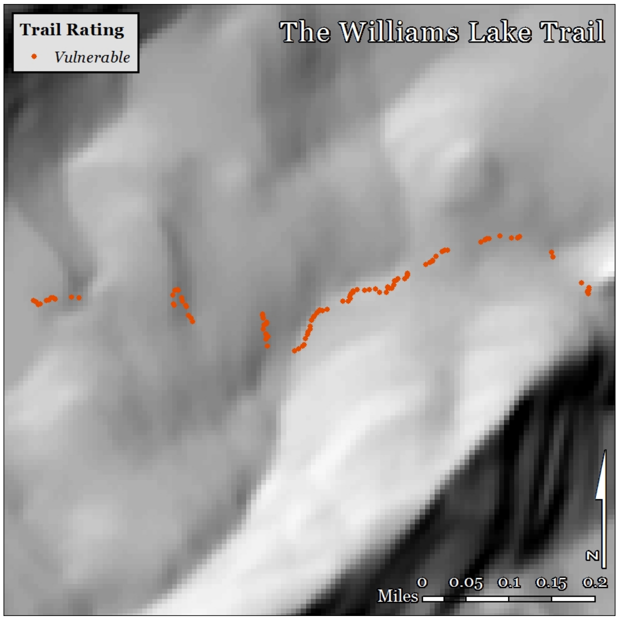
(a) All classifications



(b) Acceptable lengths



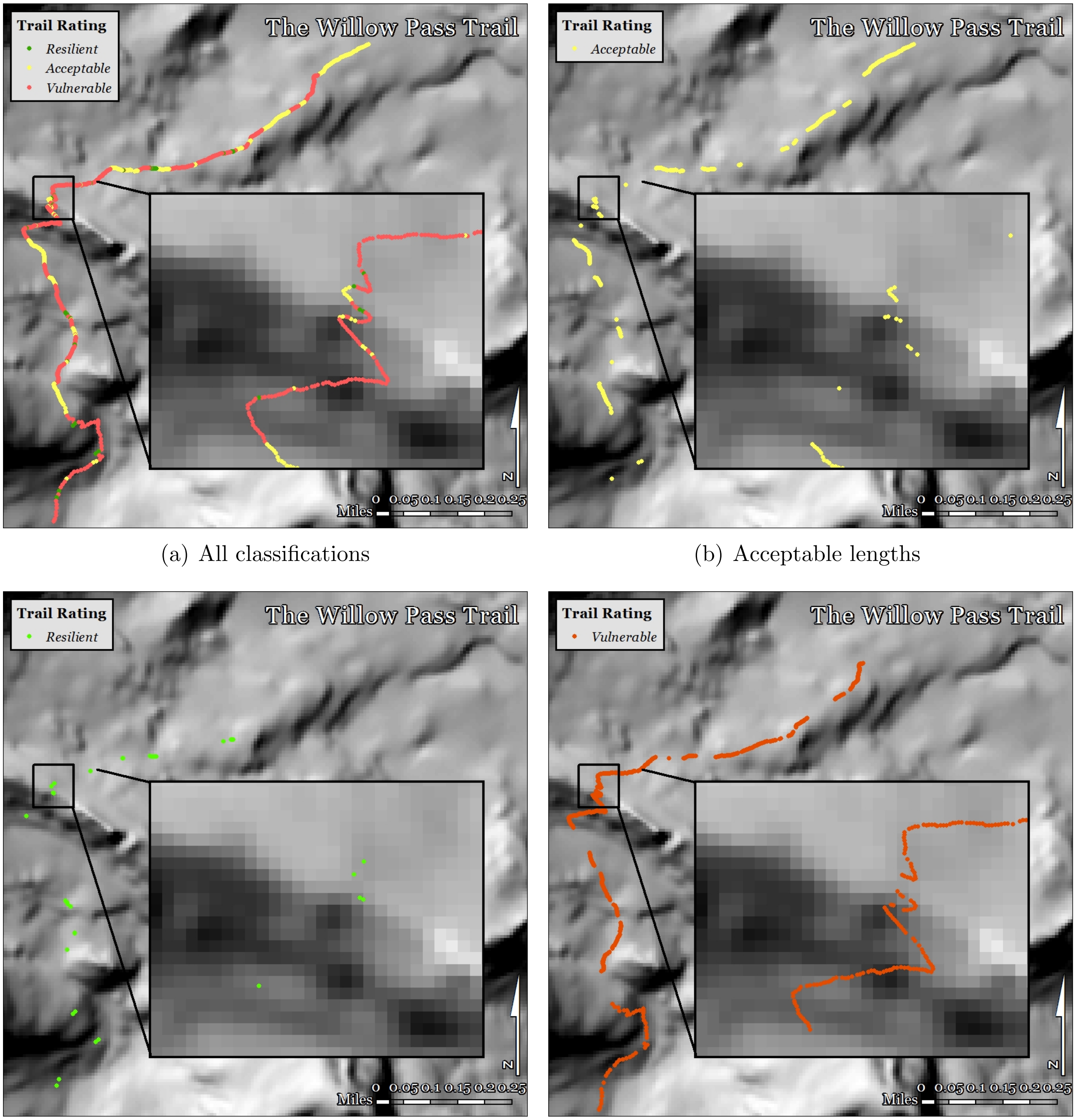
(c) Resilient lengths



(d) Vulnerable lengths

Figure A.20: Degradation classifications for Williams Lake

Willow Pass



(a) All classifications (b) Acceptable lengths

(c) Resilient lengths (d) Vulnerable lengths

Figure A.21: Degradation classifications for Willow Pass

B WLC Suitability Maps

Component Maps of the WLC Maps

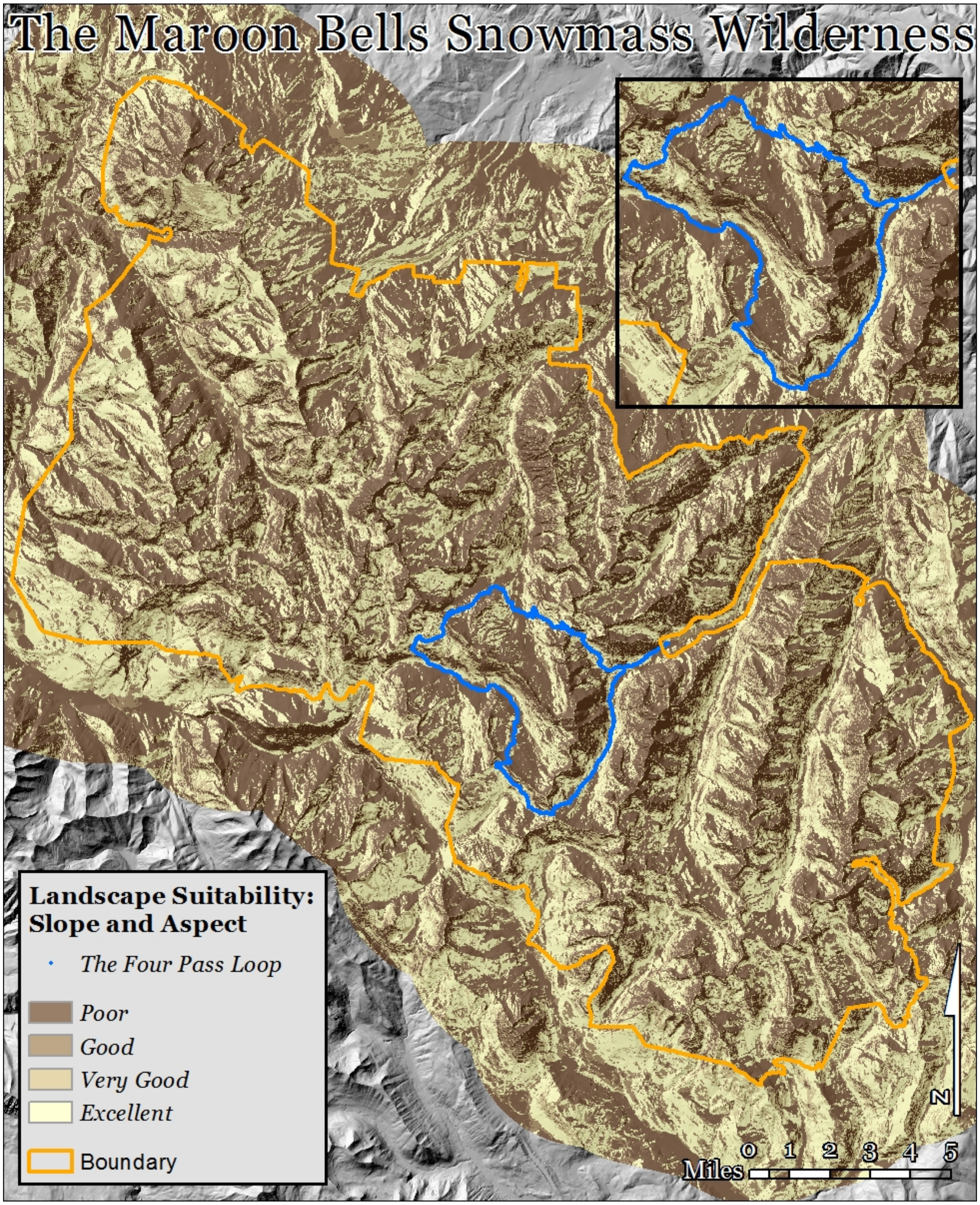


Figure B.1: Suitability of the MBSW to trail routing in terms of slope and aspect

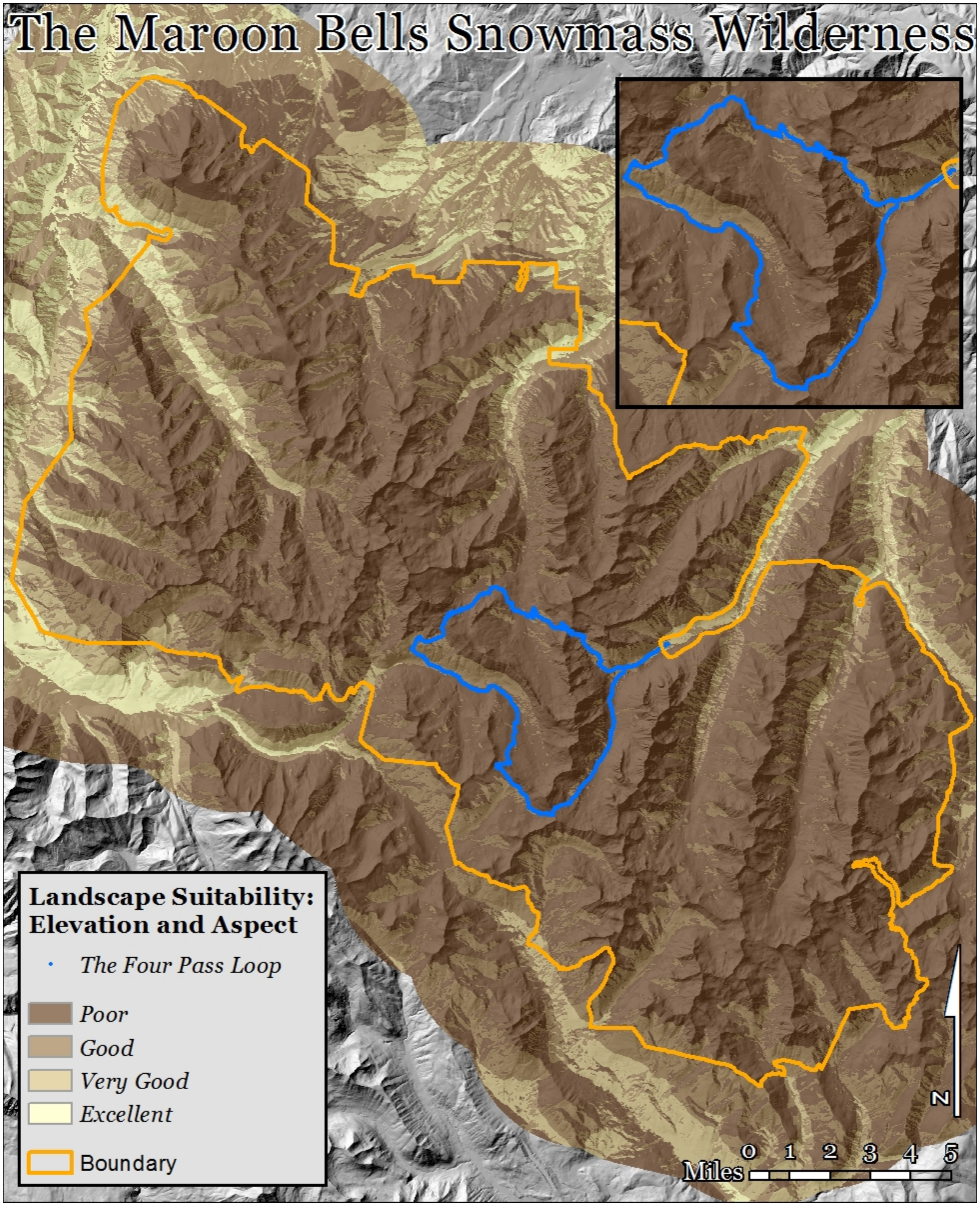


Figure B.2: Suitability of the MBSW to trail routing in terms of elevation and aspect

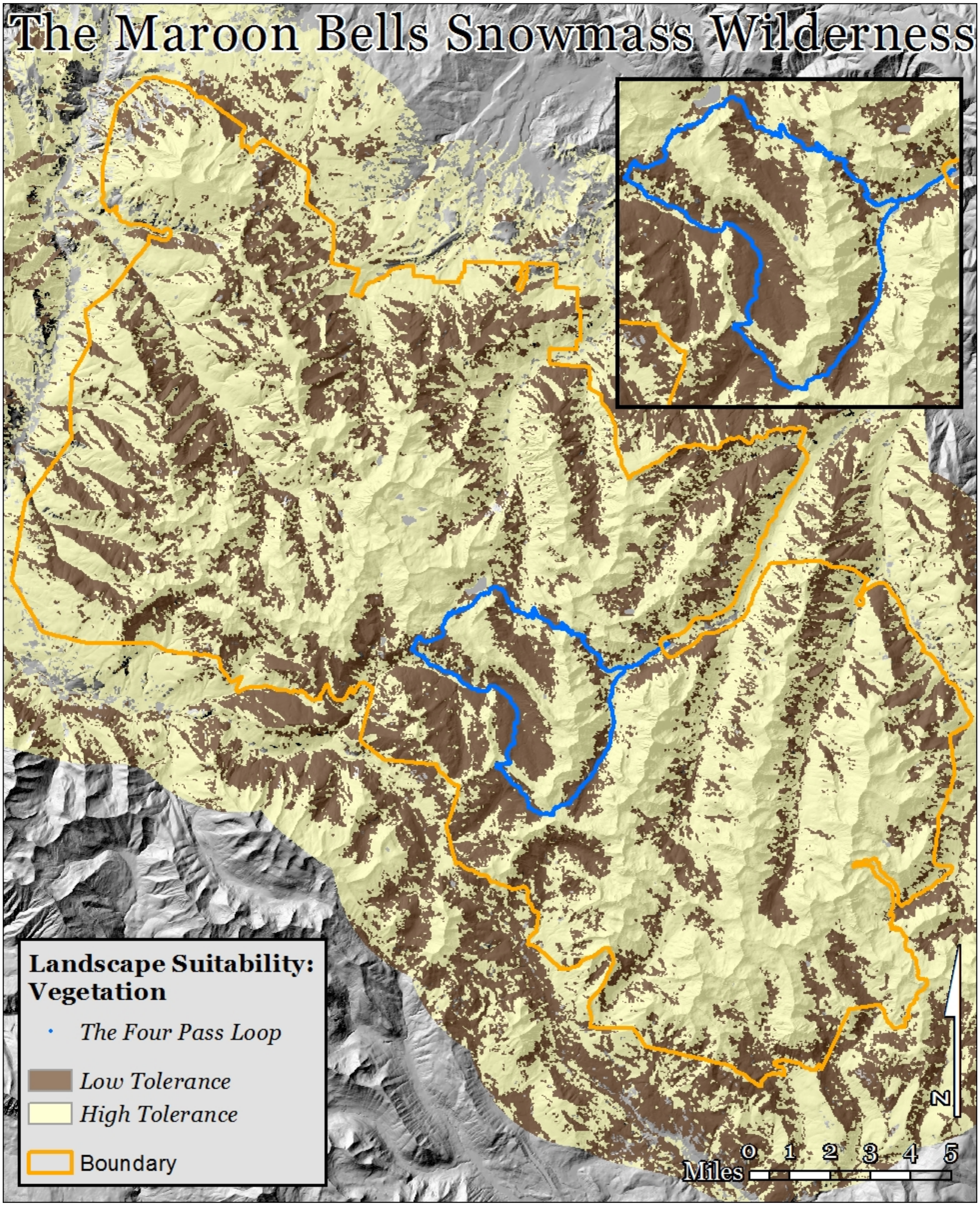


Figure B.3: Suitability of the MBSW to trail routing in terms of vegetation

WLC Maps

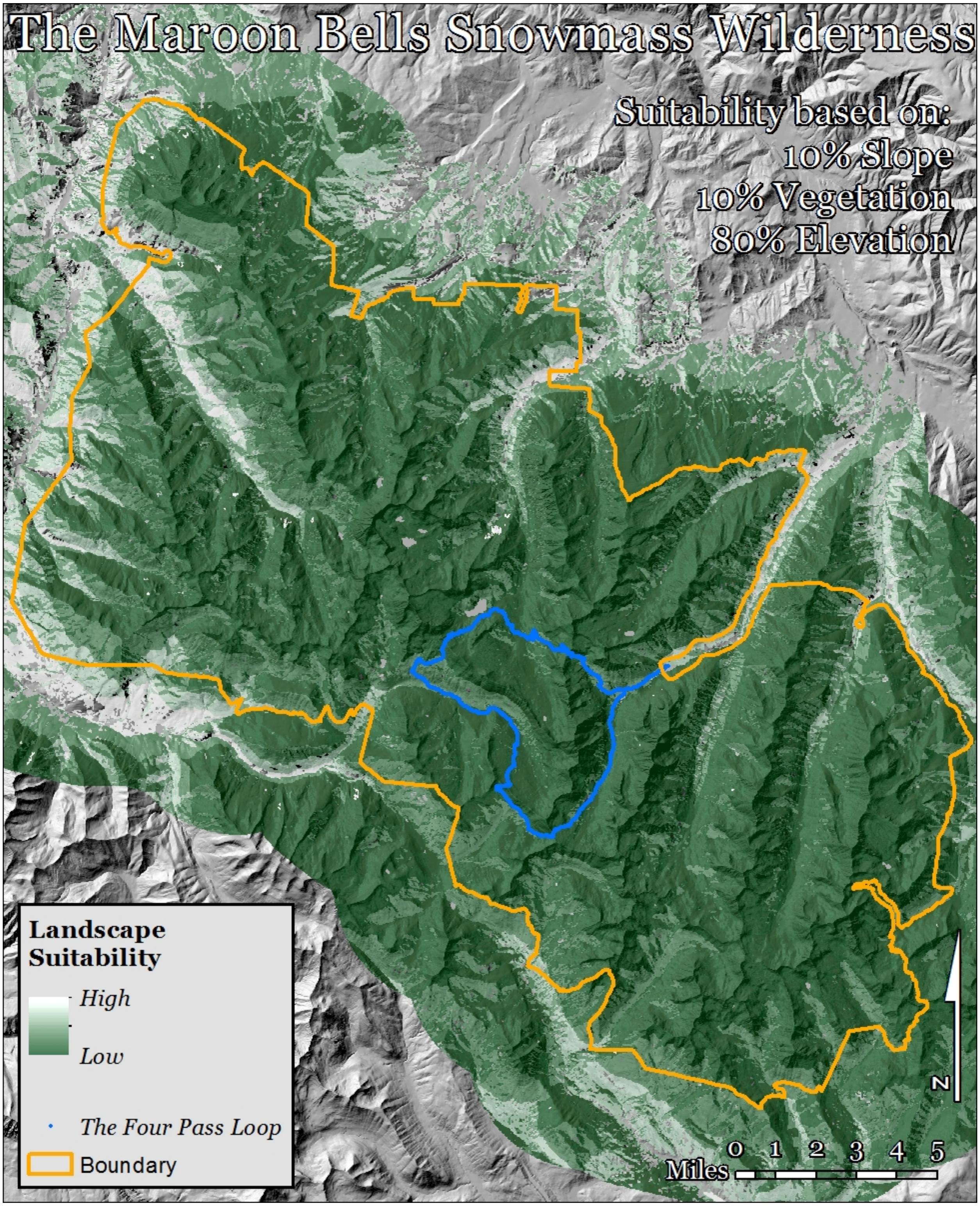


Figure B.4: Suitability of the MBSW: 10% Slope, 10% Vegetation, and 80% Elevation

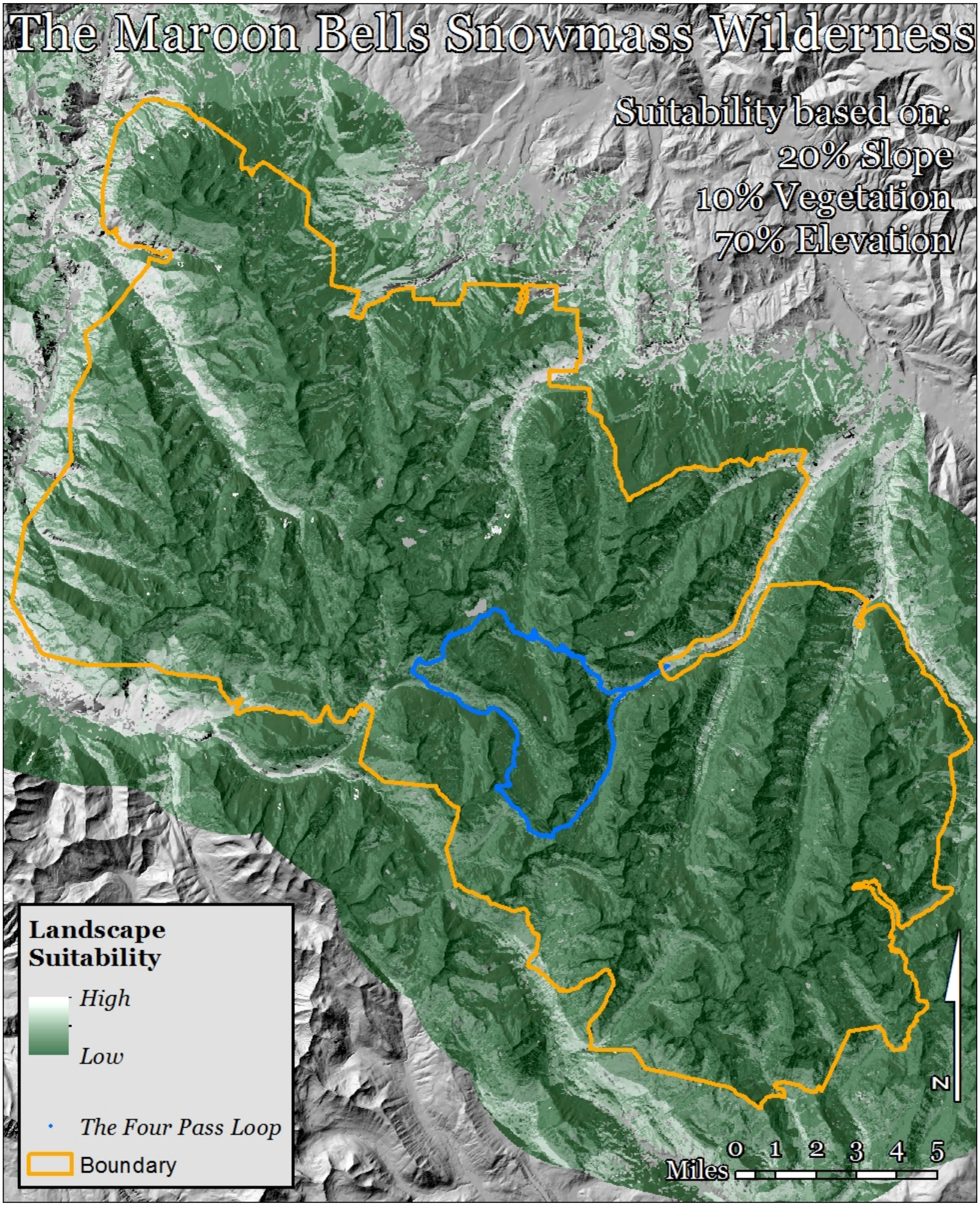


Figure B.5: Suitability of the MBSW: 20% Slope, 10% Vegetation, and 70% Elevation

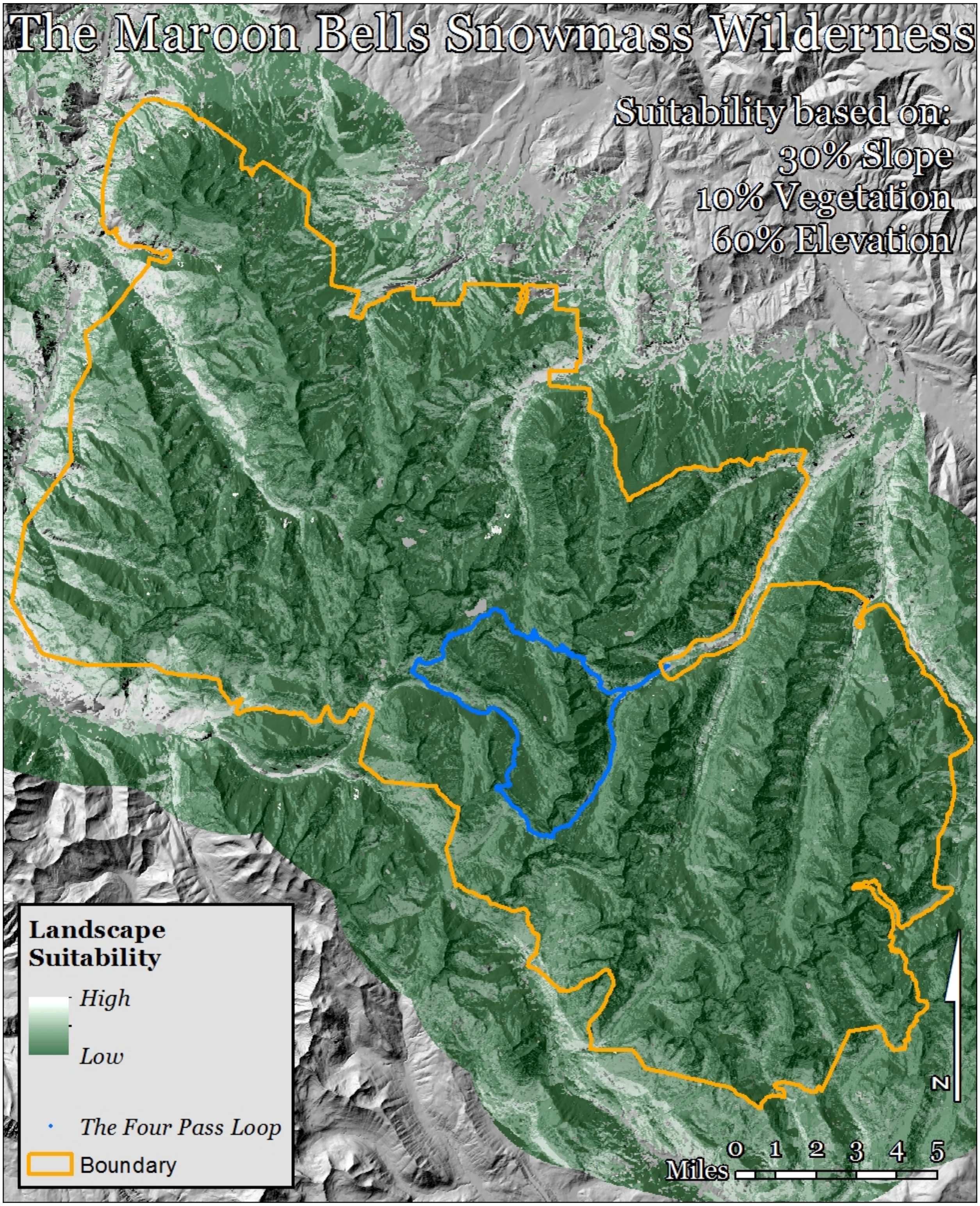


Figure B.6: Suitability of the MBSW: 30% Slope, 10% Vegetation, and 60% Elevation

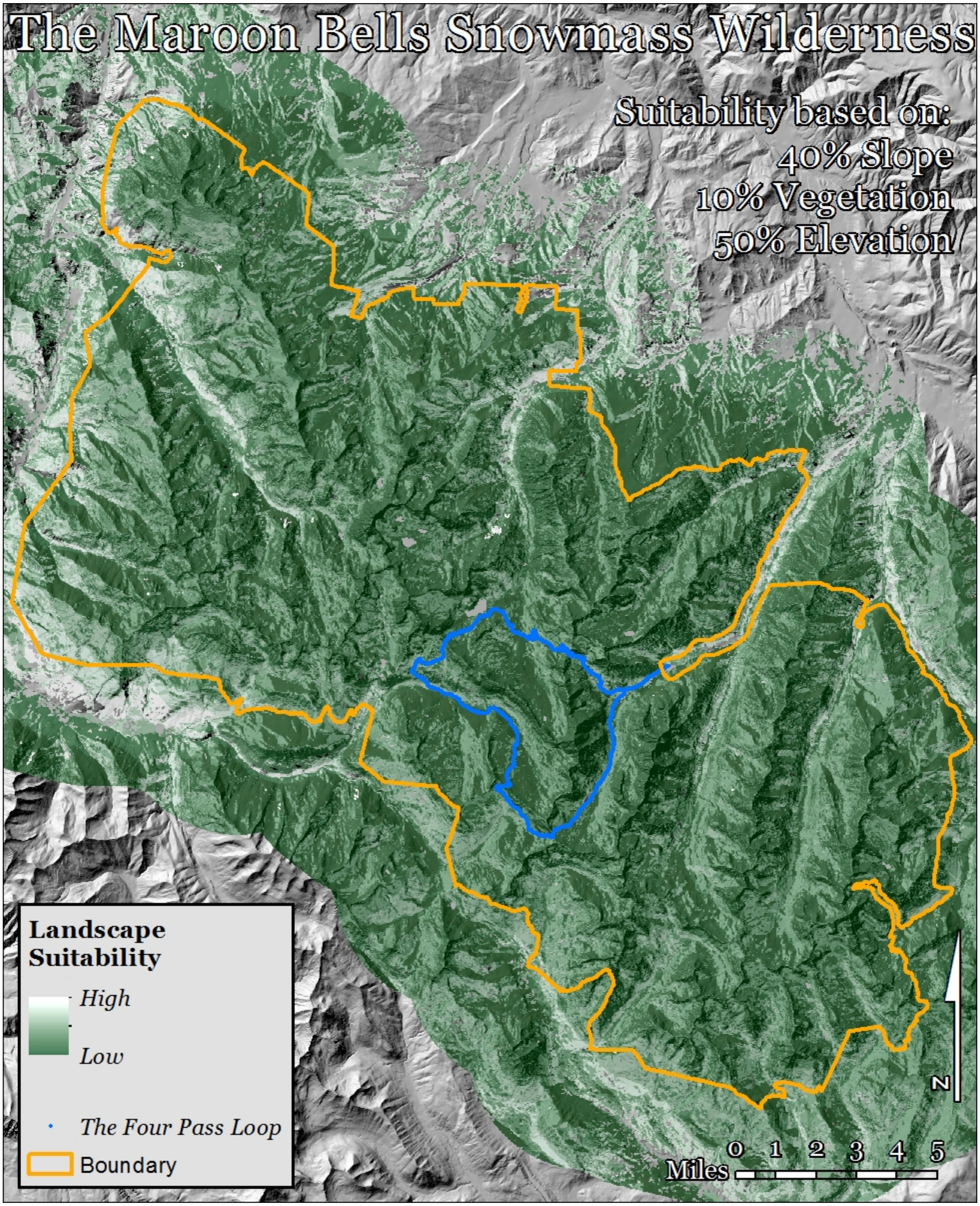


Figure B.7: Suitability of the MBSW: 40% Slope, 10% Vegetation, and 50% Elevation

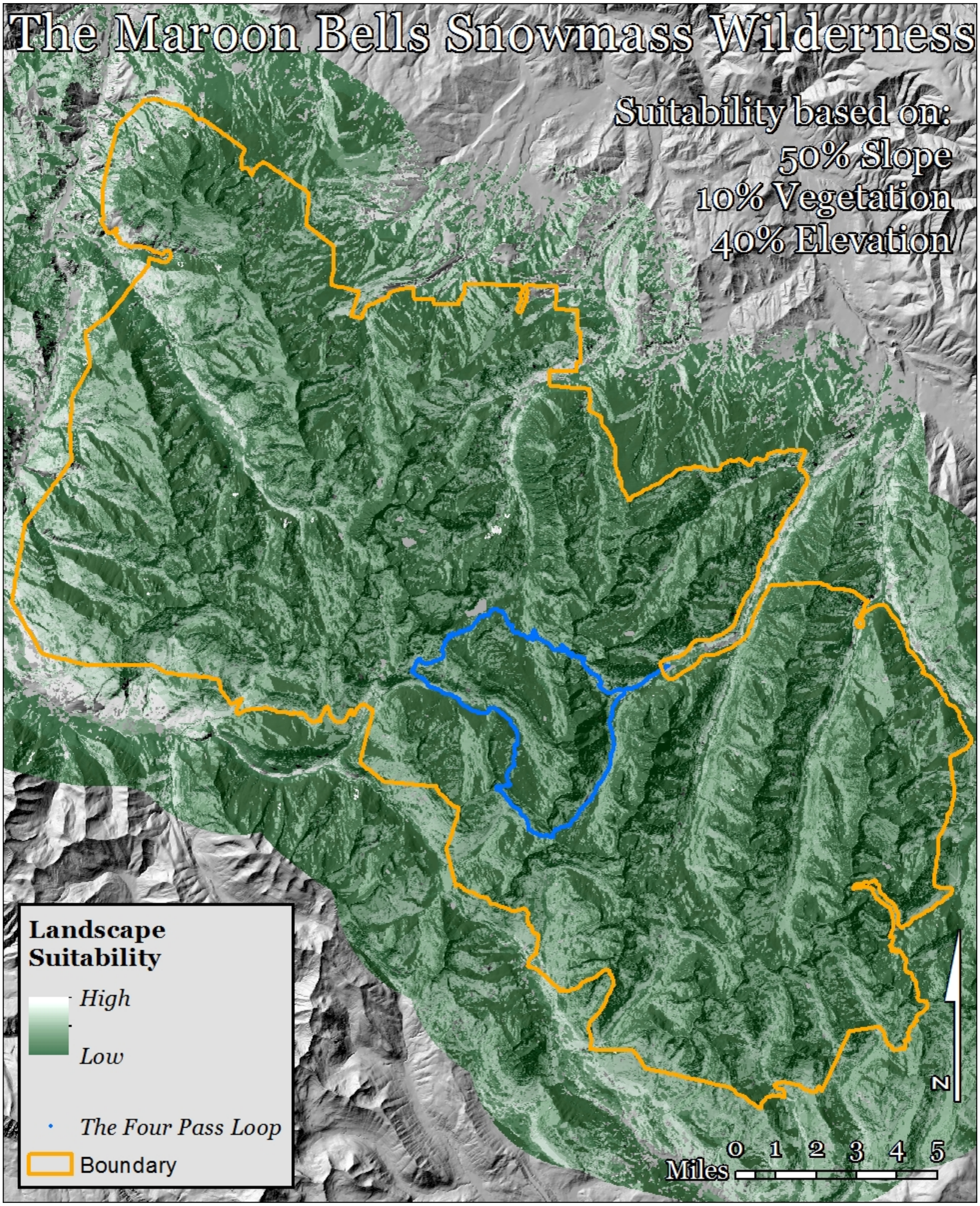


Figure B.8: Suitability of the MBSW: 50% Slope, 10% Vegetation, and 40% Elevation

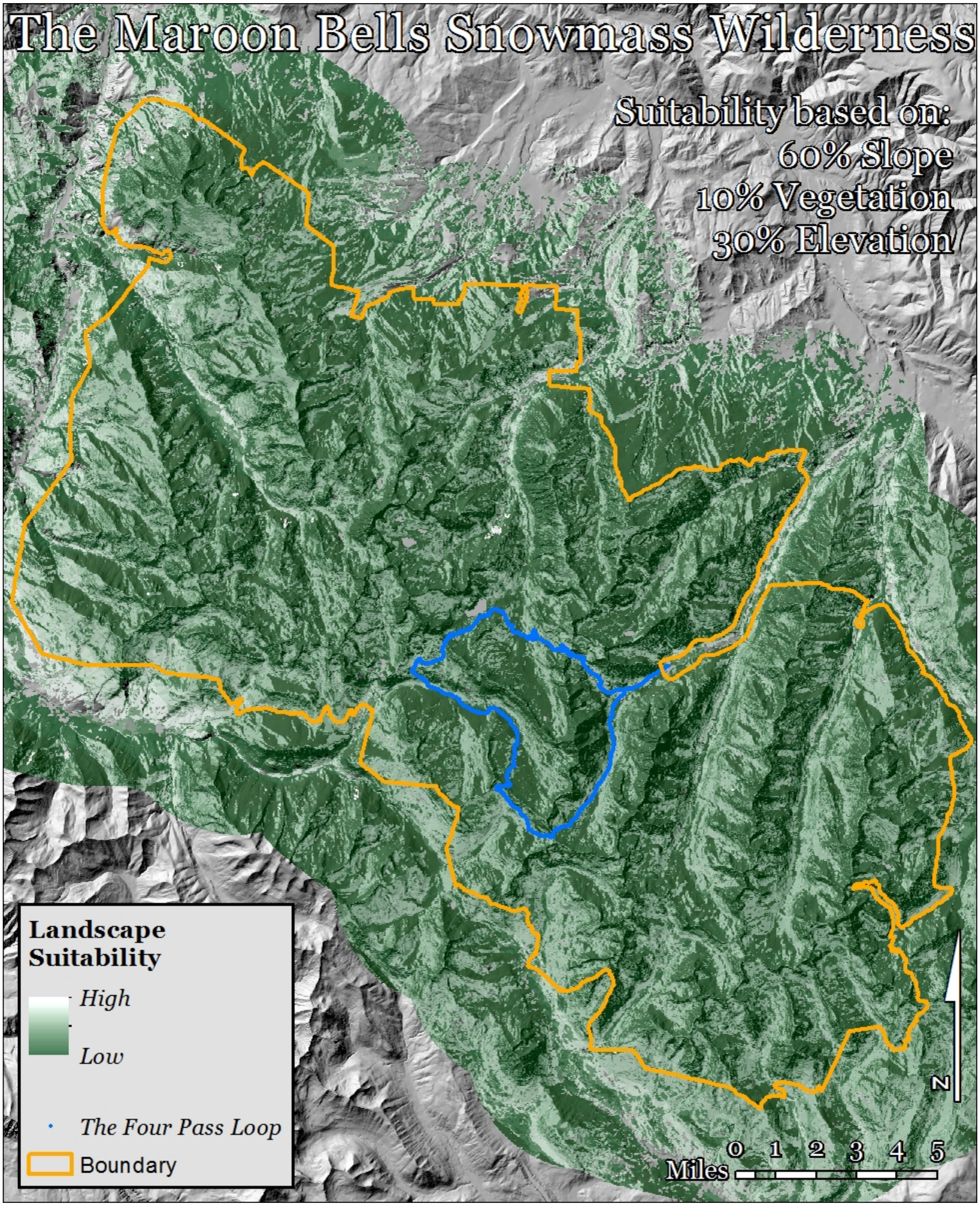


Figure B.9: Suitability of the MBSW: 60% Slope, 10% Vegetation, and 30% Elevation

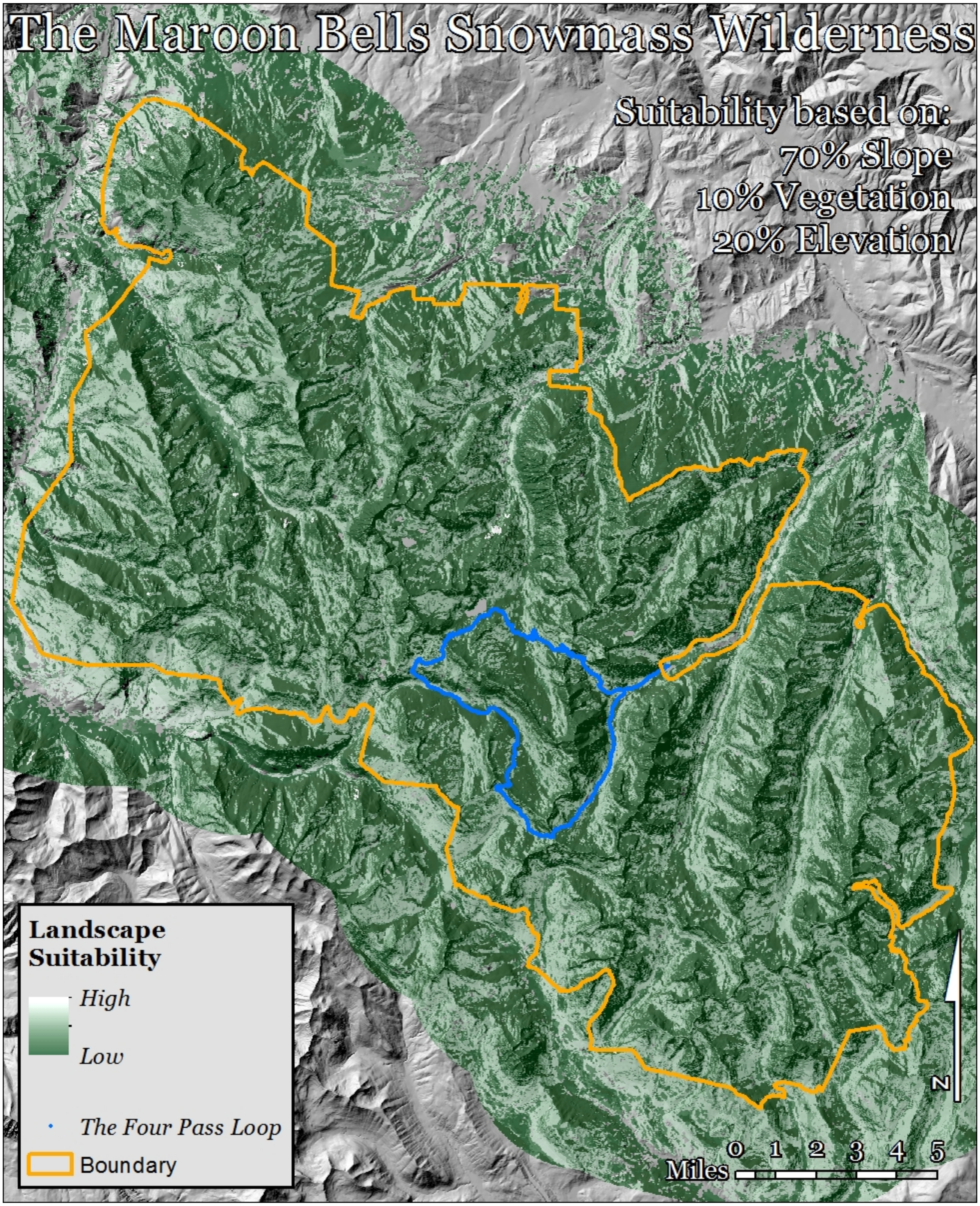


Figure B.10: Suitability of the MBSW: 70% Slope, 10% Vegetation, and 20% Elevation

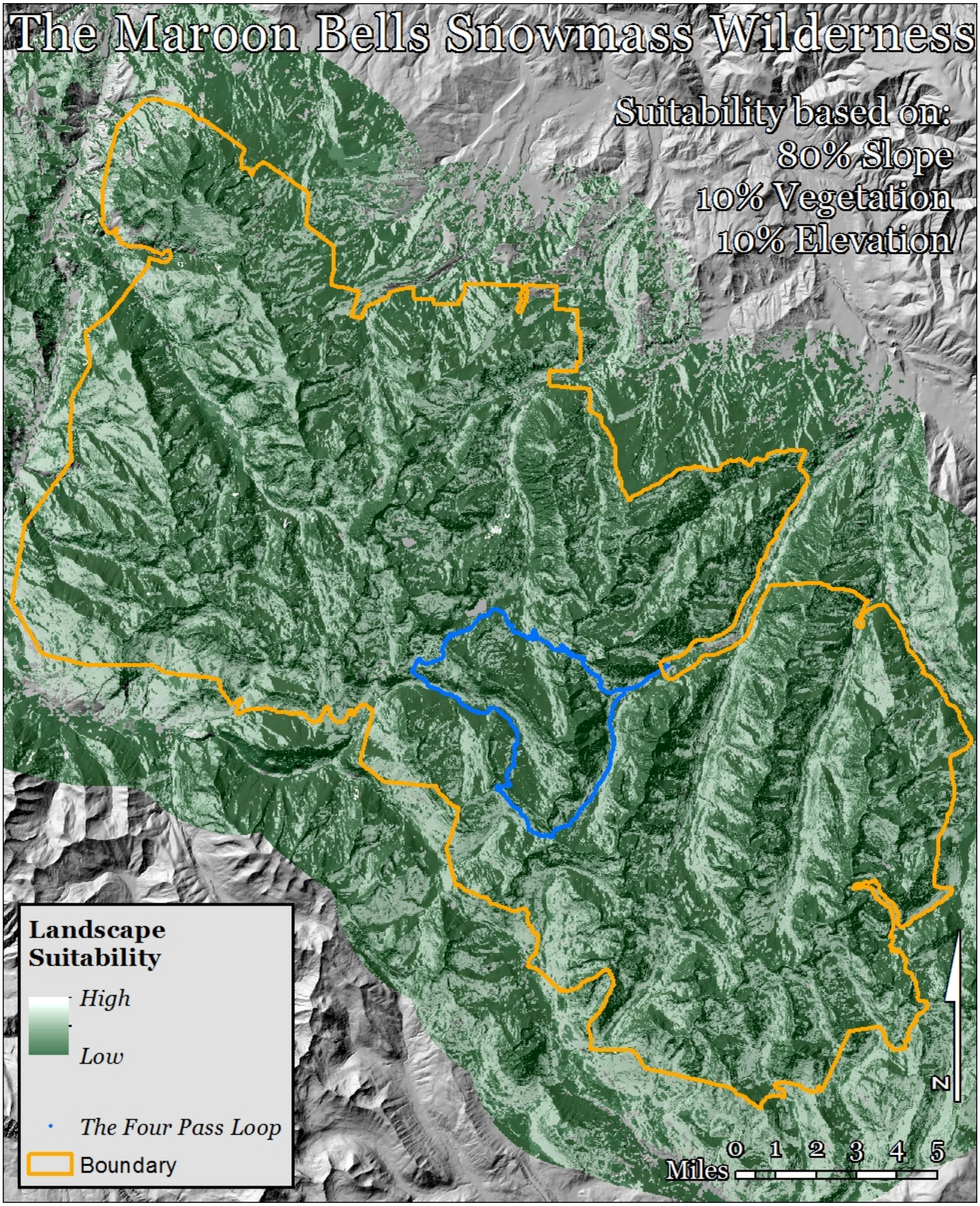


Figure B.11: Suitability of the MBSW: 80% Slope, 10% Vegetation, and 10% Elevation

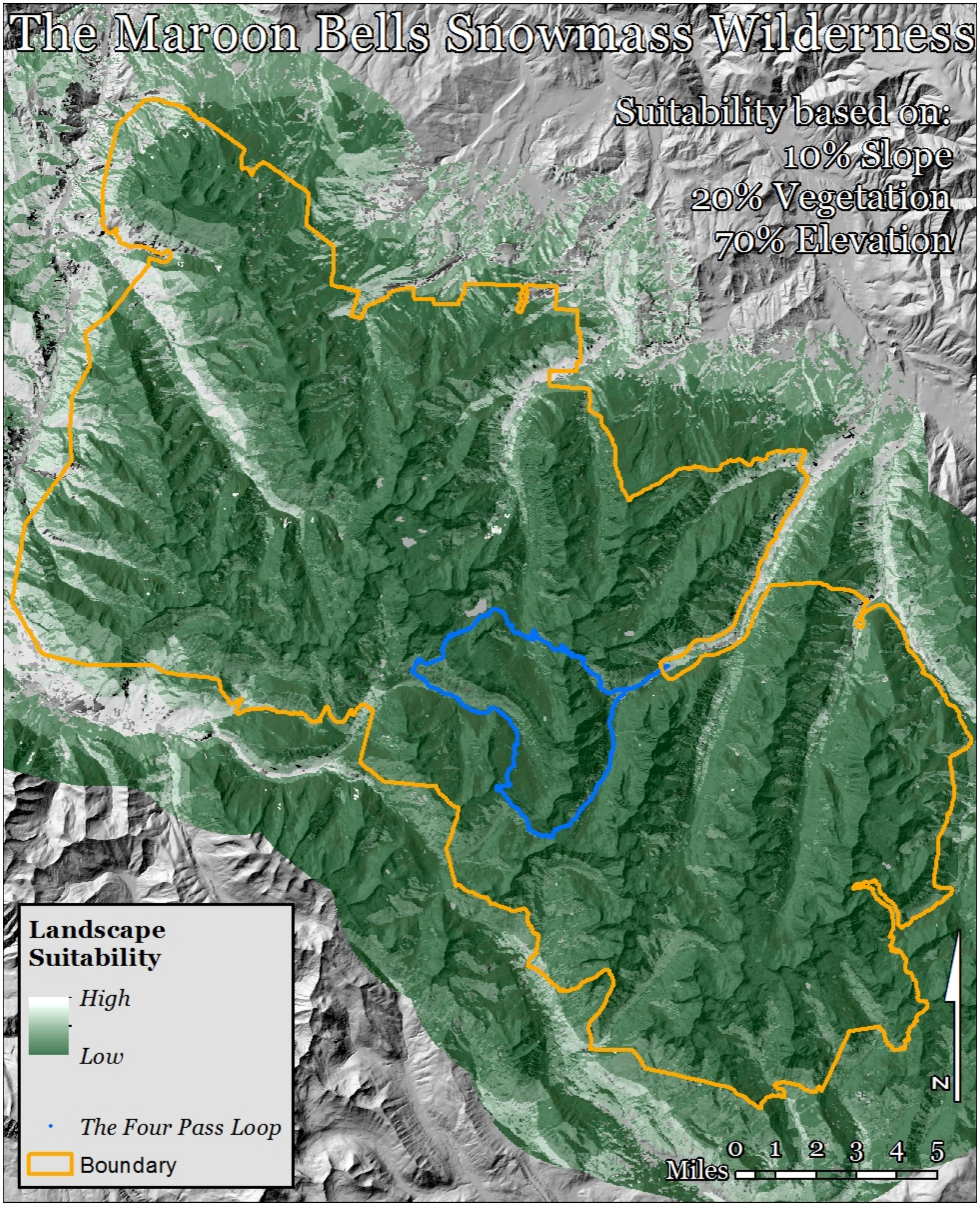


Figure B.12: Suitability of the MBSW: 10% Slope, 20% Vegetation, and 70% Elevation

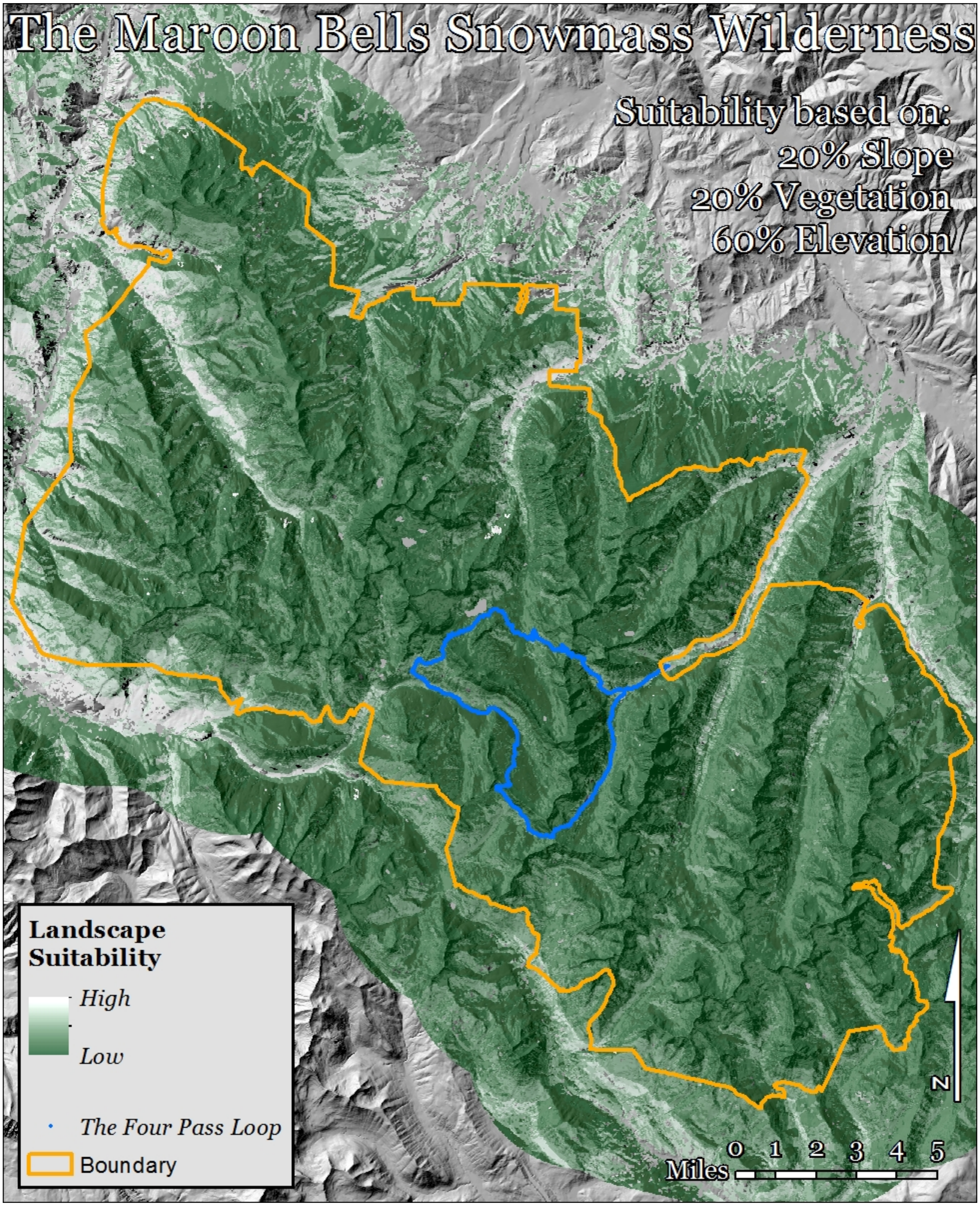


Figure B.13: Suitability of the MBSW: 20% Slope, 20% Vegetation, and 40% Elevation

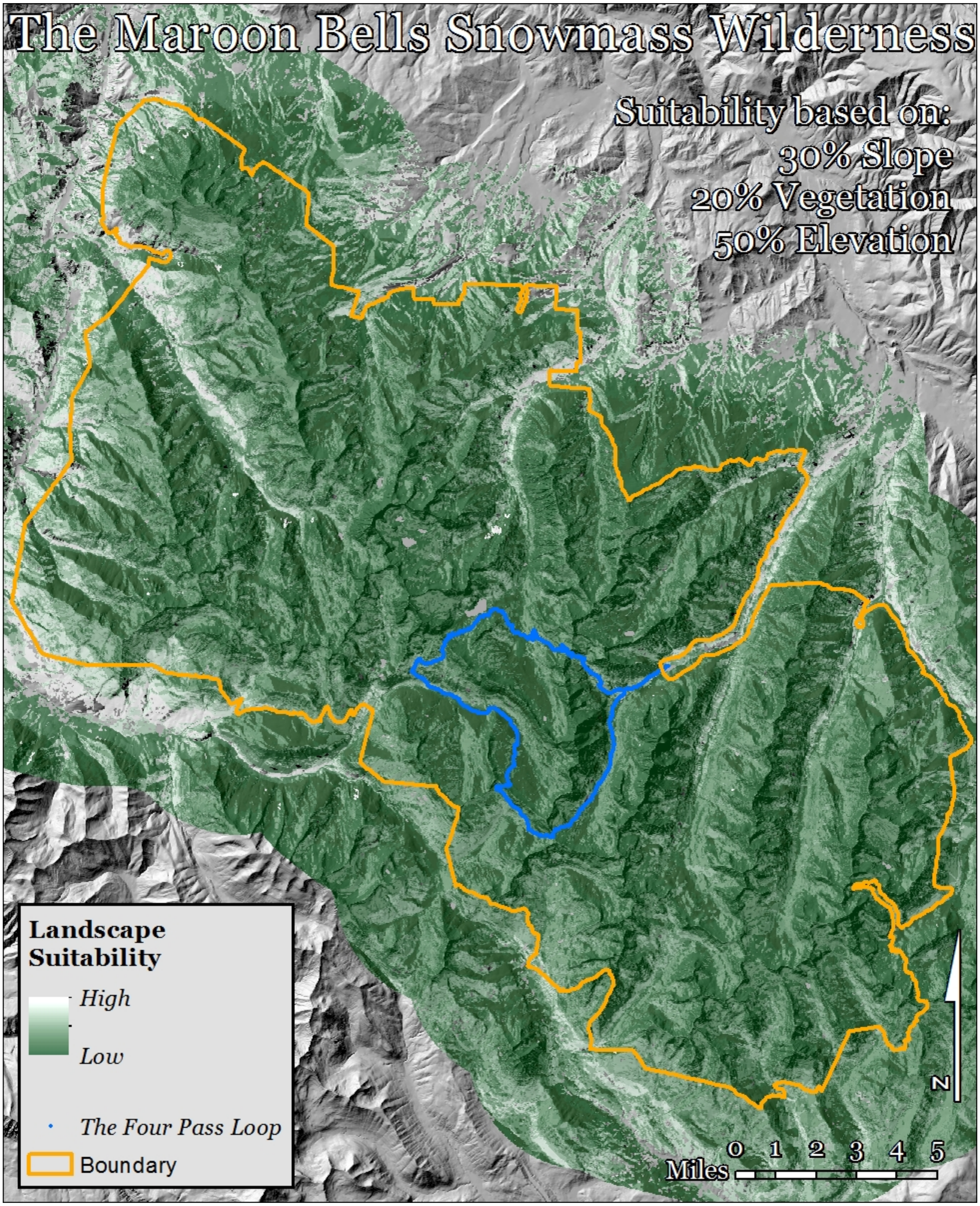


Figure B.14: Suitability of the MBSW: 30% Slope, 20% Vegetation, and 50% Elevation

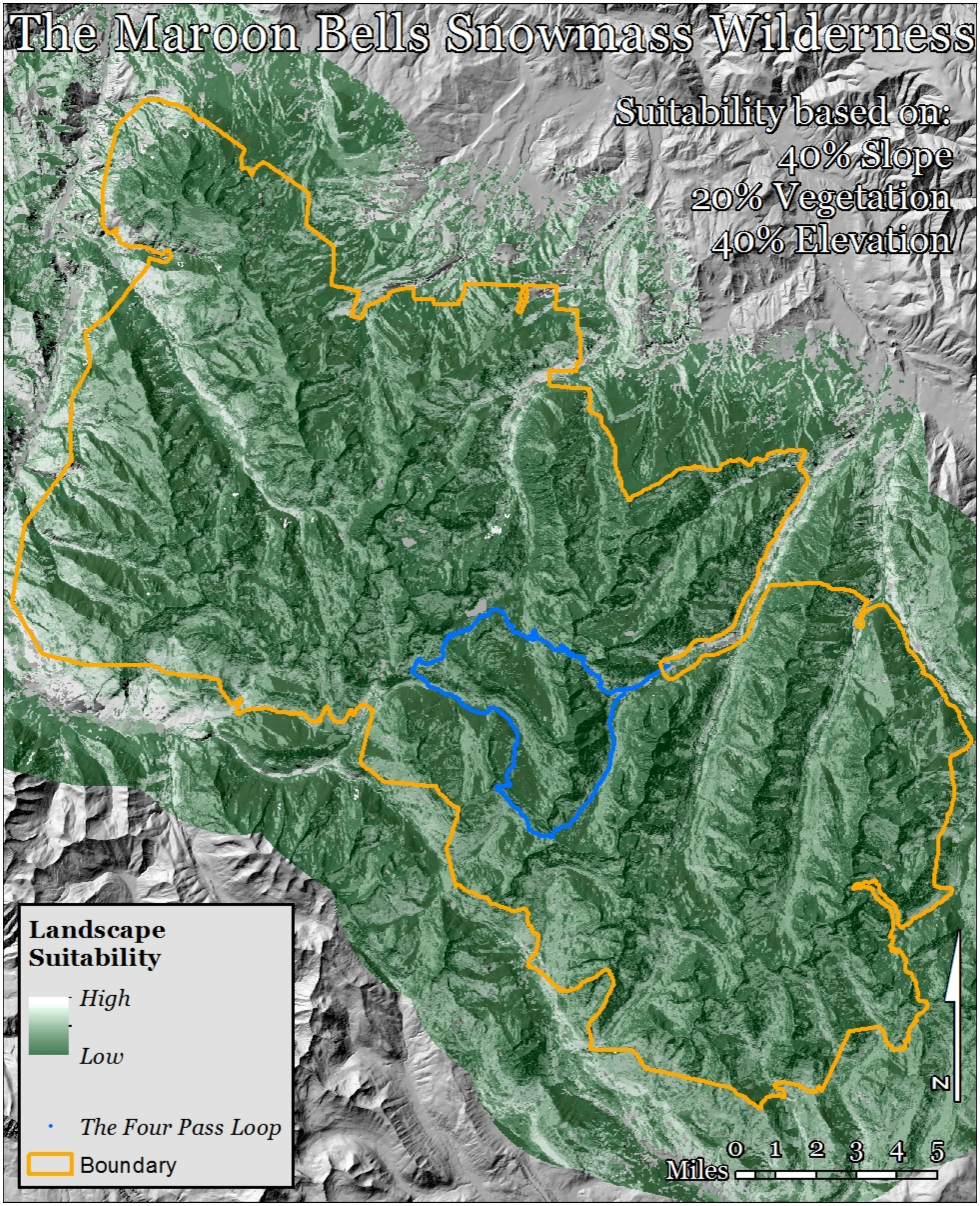


Figure B.15: Suitability of the MBSW: 40% Slope, 20% Vegetation, and 40% Elevation

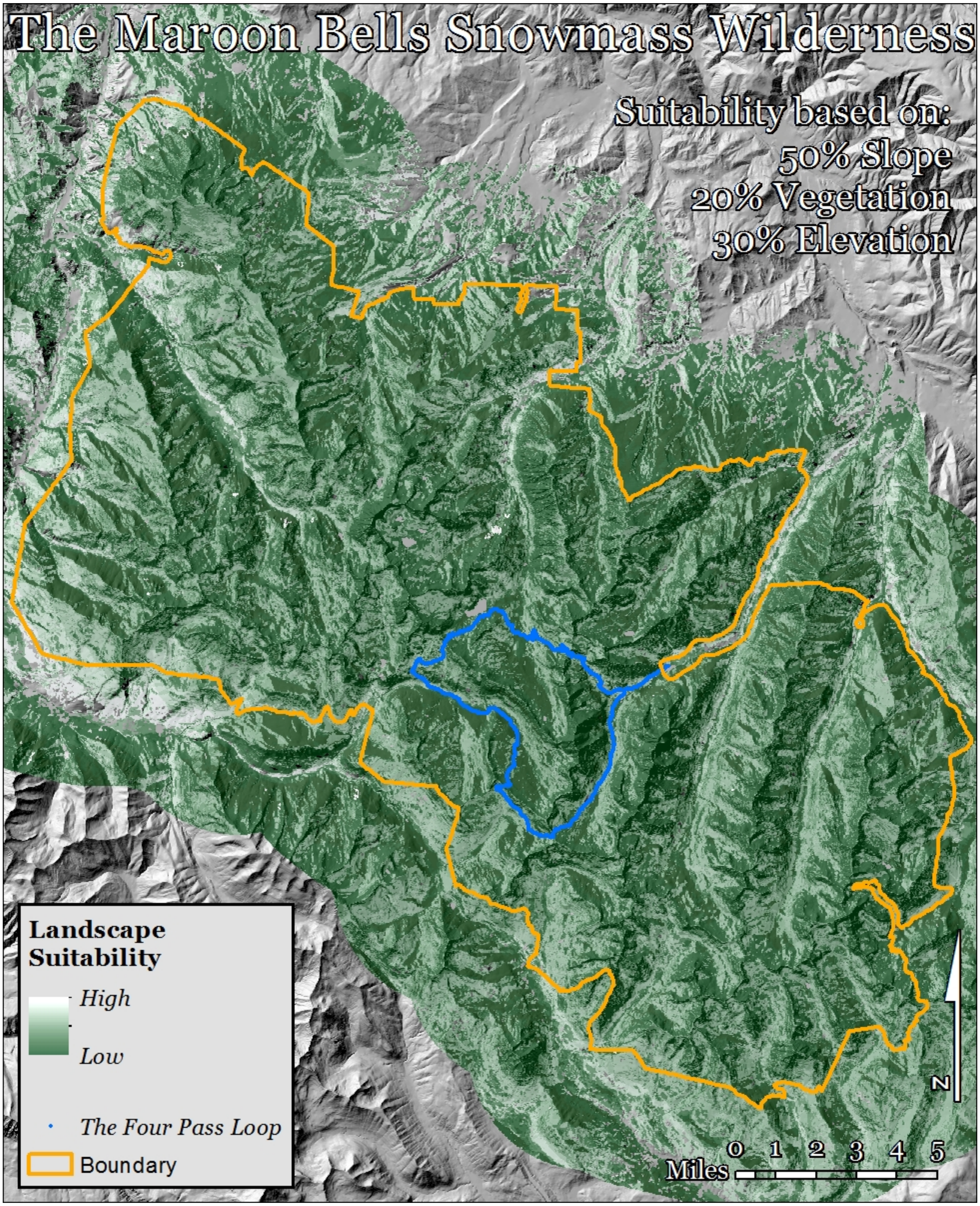


Figure B.16: Suitability of the MBSW: 50% Slope, 20% Vegetation, and 30% Elevation

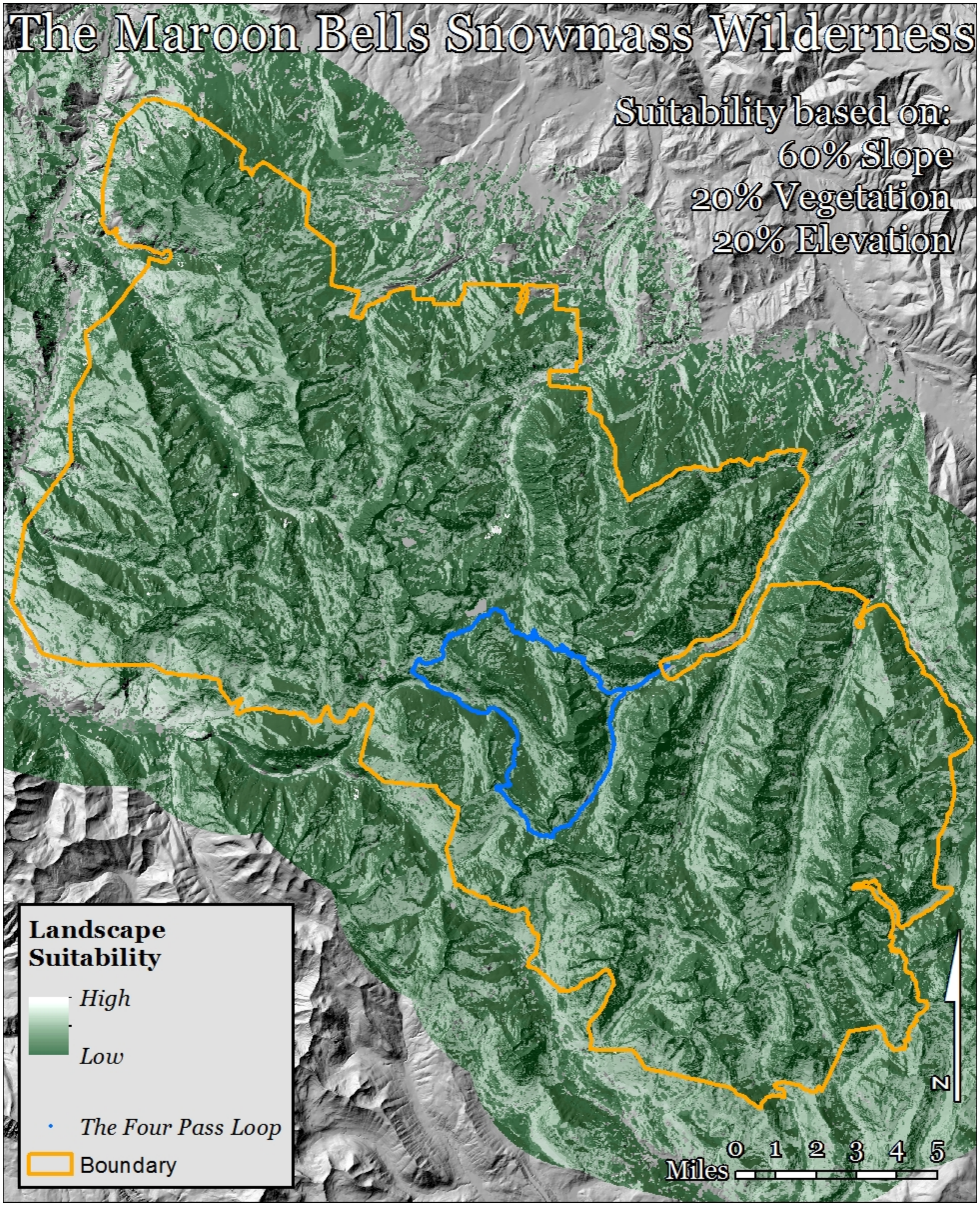


Figure B.17: Suitability of the MBSW: 60% Slope, 20% Vegetation, and 20% Elevation

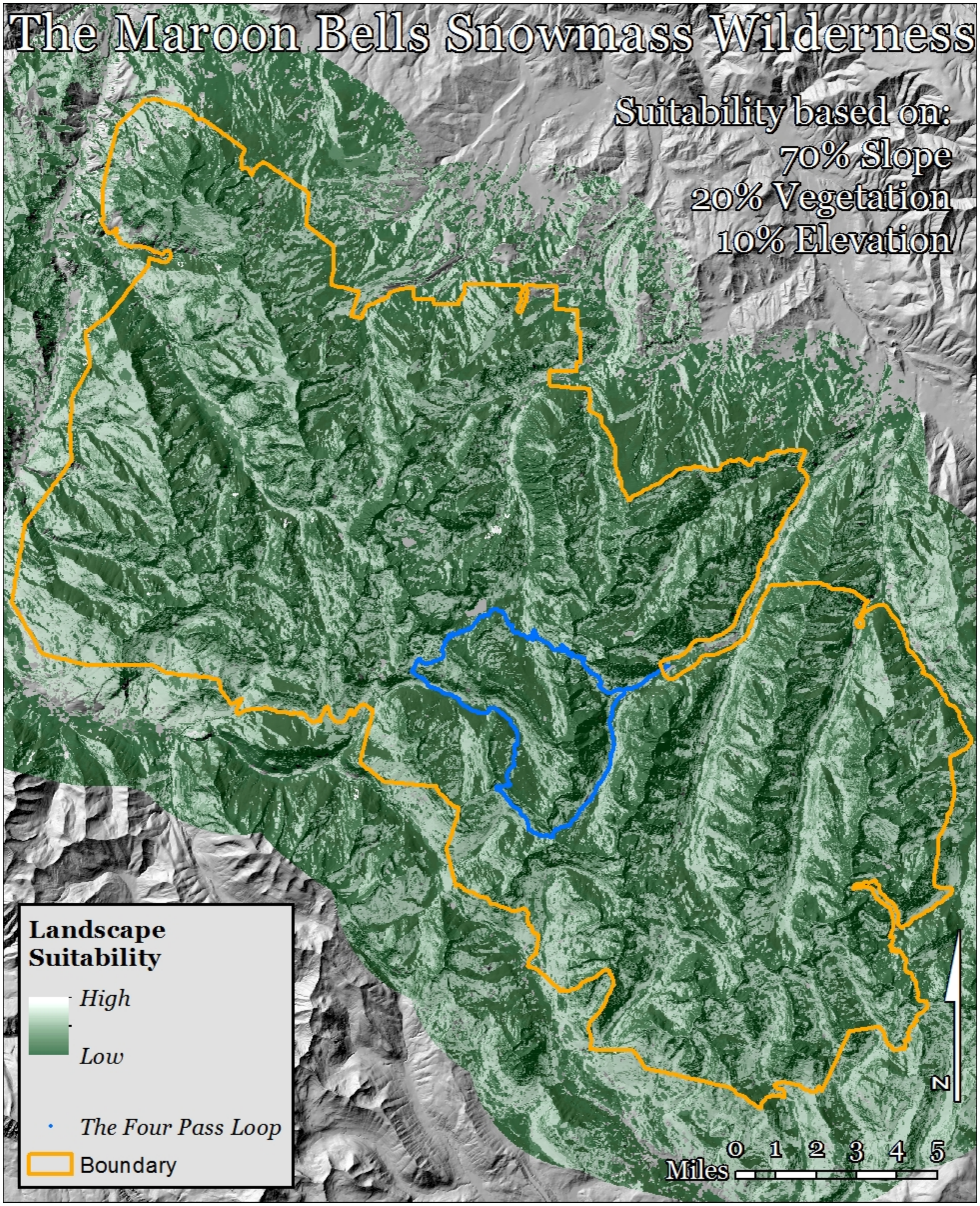


Figure B.18: Suitability of the MBSW: 70% Slope, 20% Vegetation, and 10% Elevation

C Suitability near the Four Pass Loop

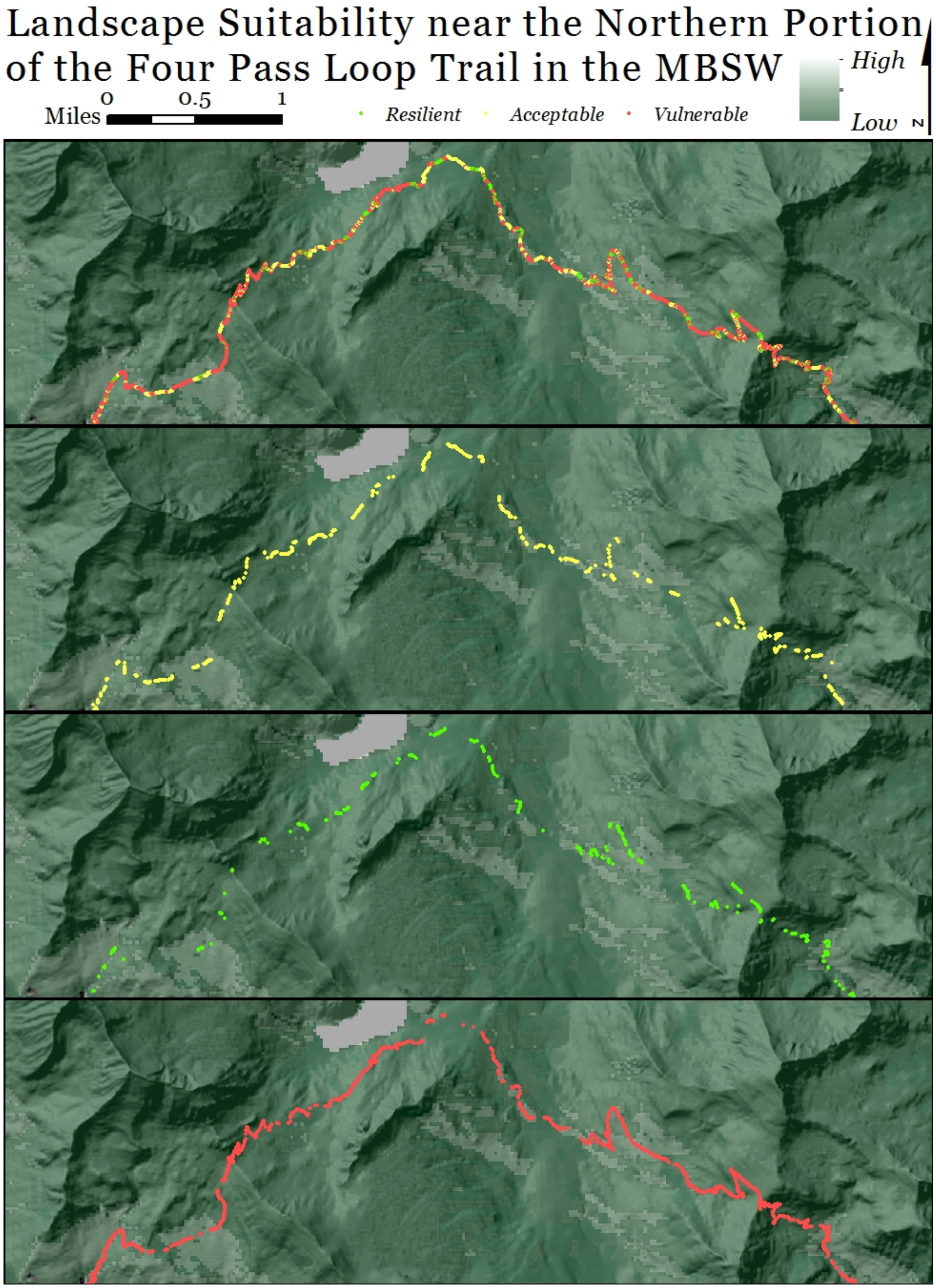


Figure C.1: The Four Pass Loop: 10% Slope, 10% Vegetation, and 80% Elevation

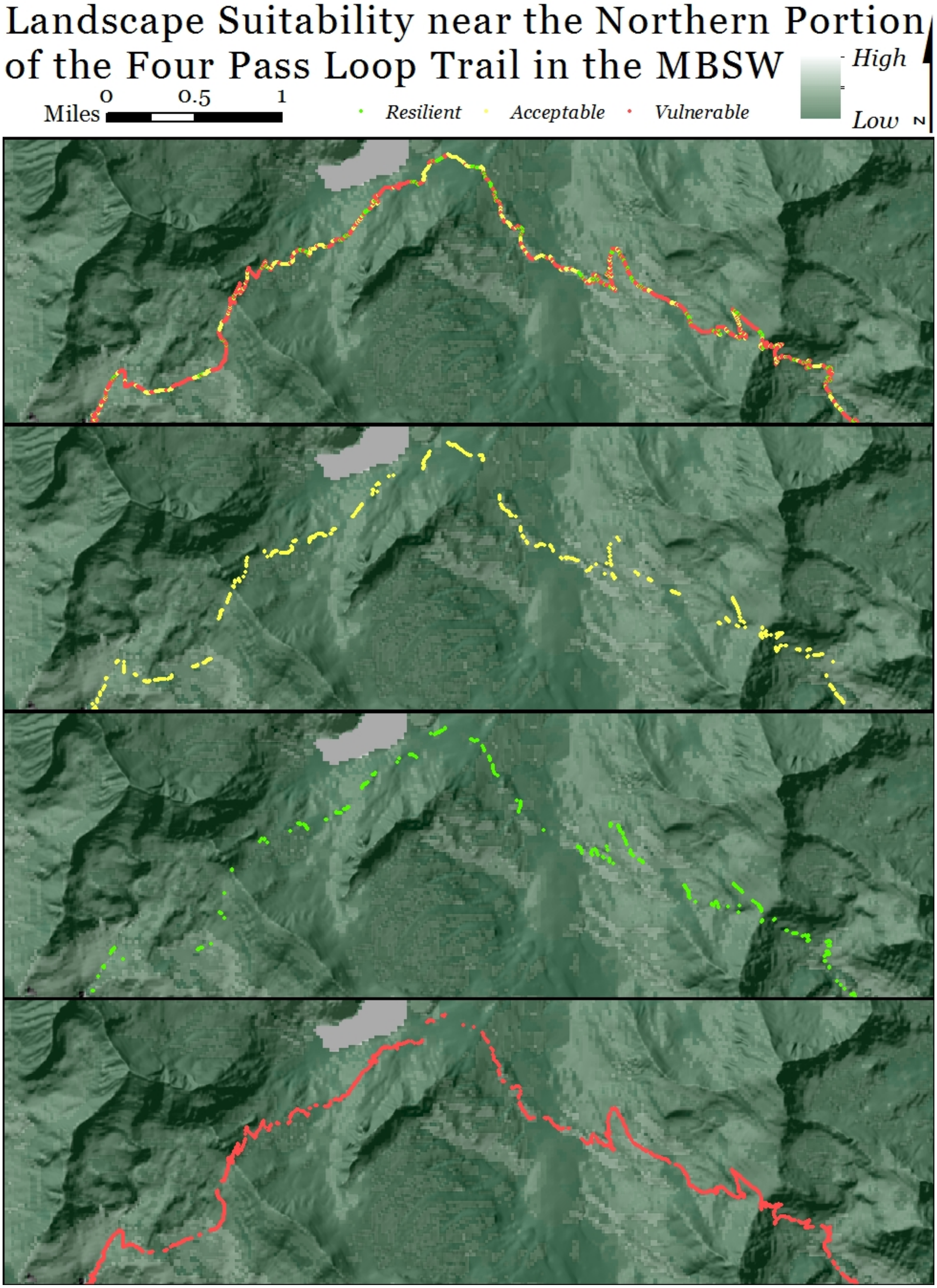


Figure C.2: The Four Pass Loop: 20% Slope, 10% Vegetation, and 70% Elevation

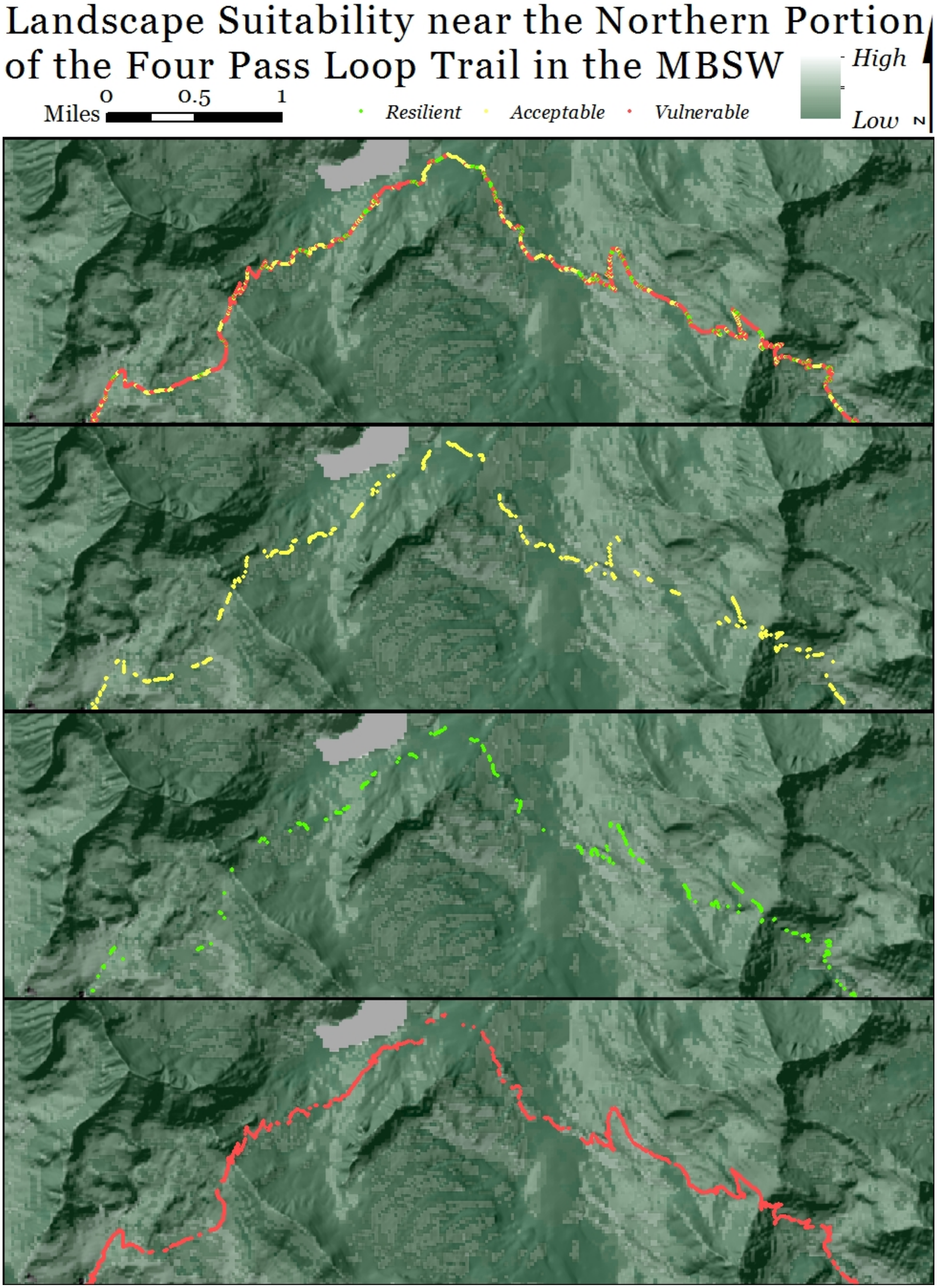


Figure C.3: The Four Pass Loop: 30% Slope, 10% Vegetation, and 60% Elevation

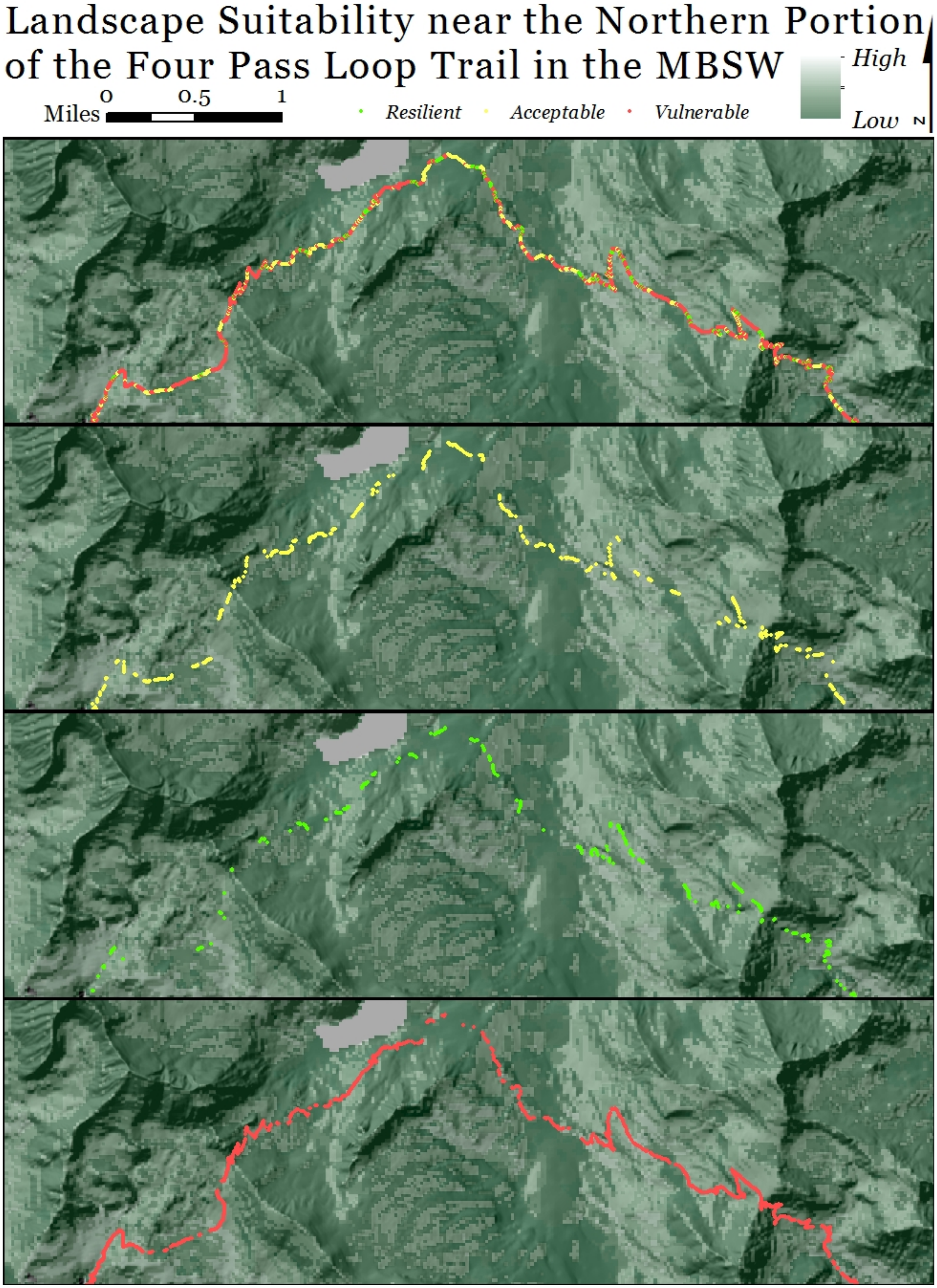


Figure C.4: The Four Pass Loop: 40% Slope, 10% Vegetation, and 50% Elevation

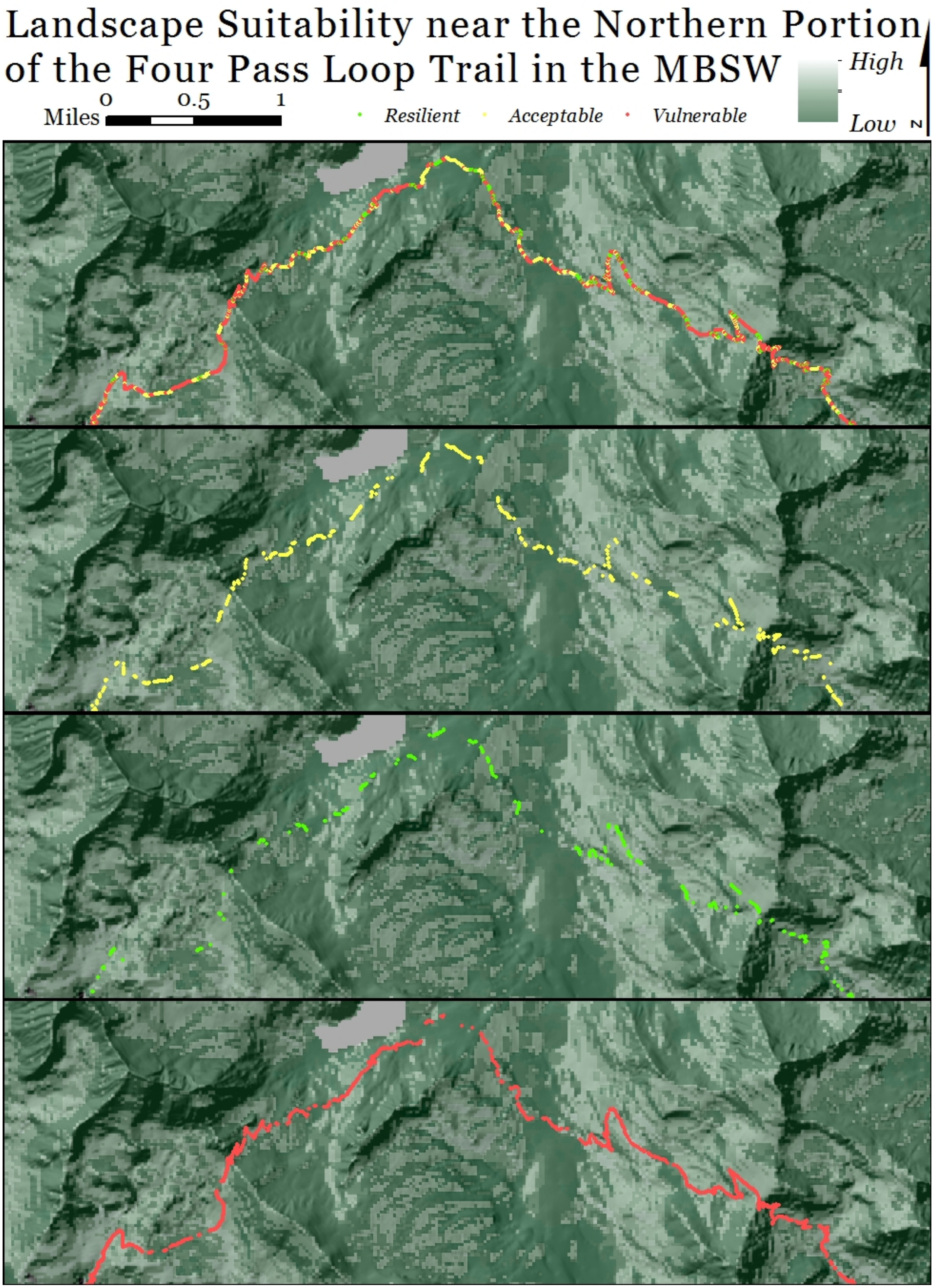


Figure C.5: The Four Pass Loop: 50% Slope, 10% Vegetation, and 40% Elevation

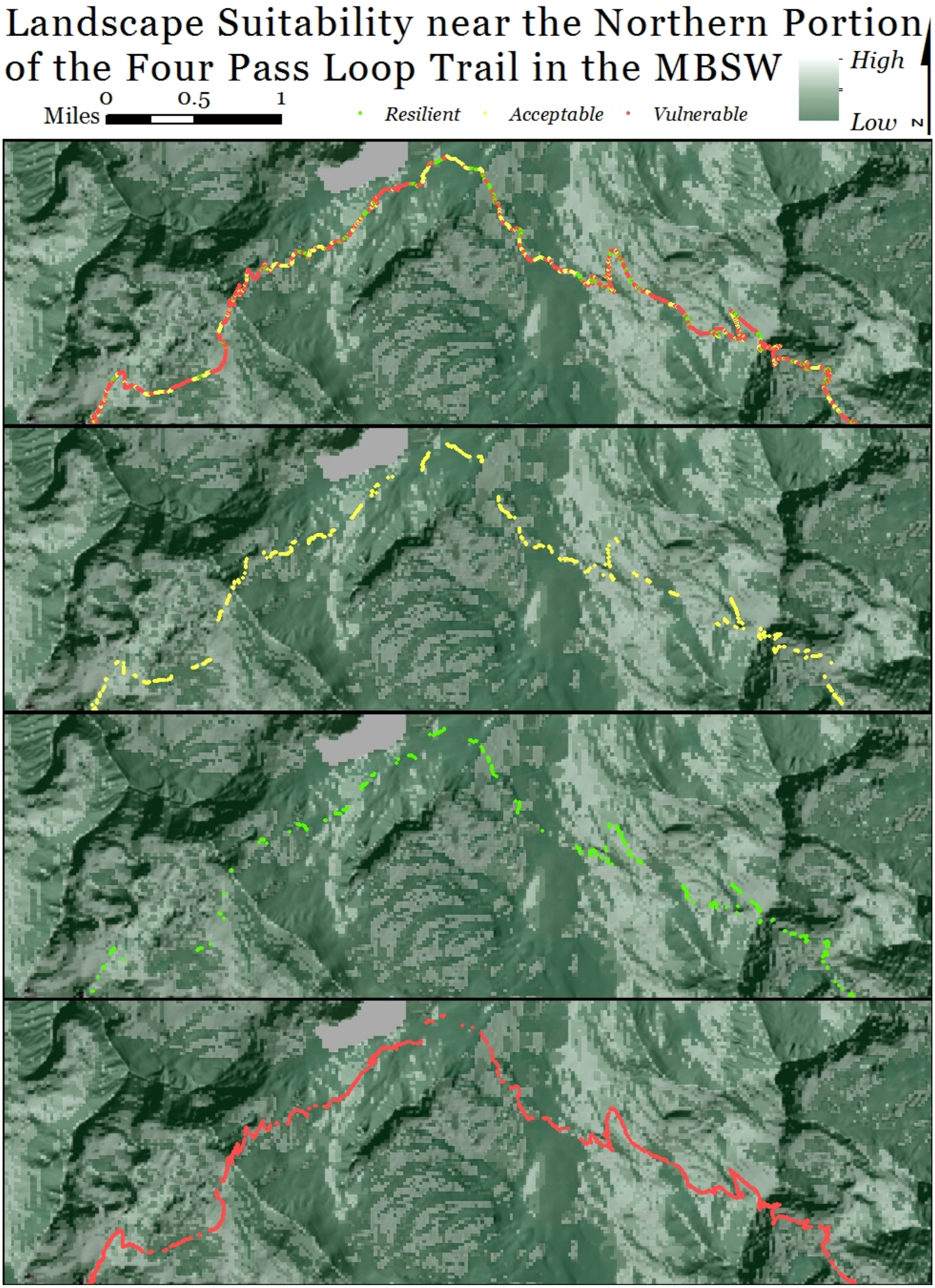


Figure C.6: The Four Pass Loop: 60% Slope, 10% Vegetation, and 30% Elevation

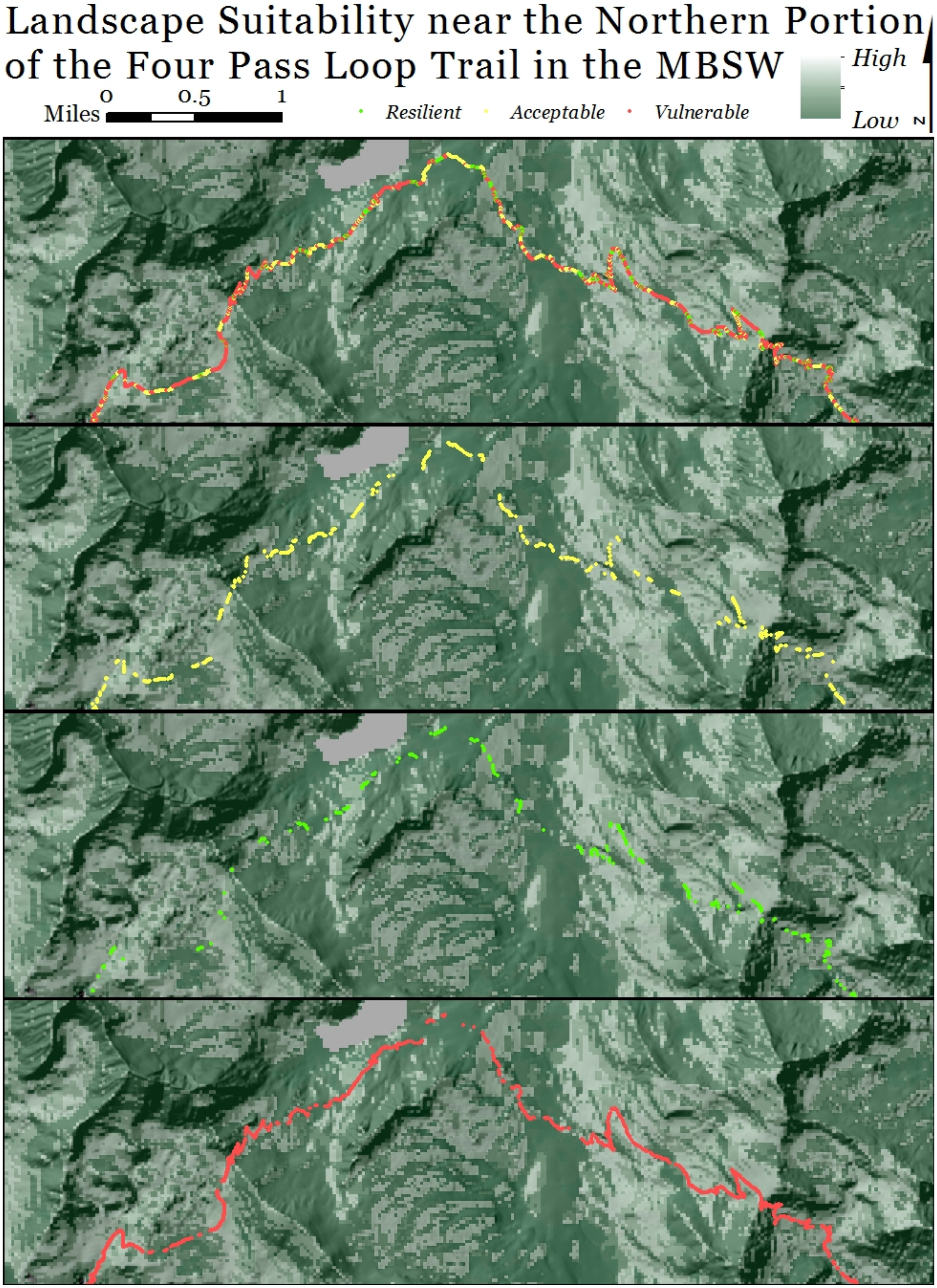


Figure C.7: The Four Pass Loop: 70% Slope, 10% Vegetation, and 20% Elevation

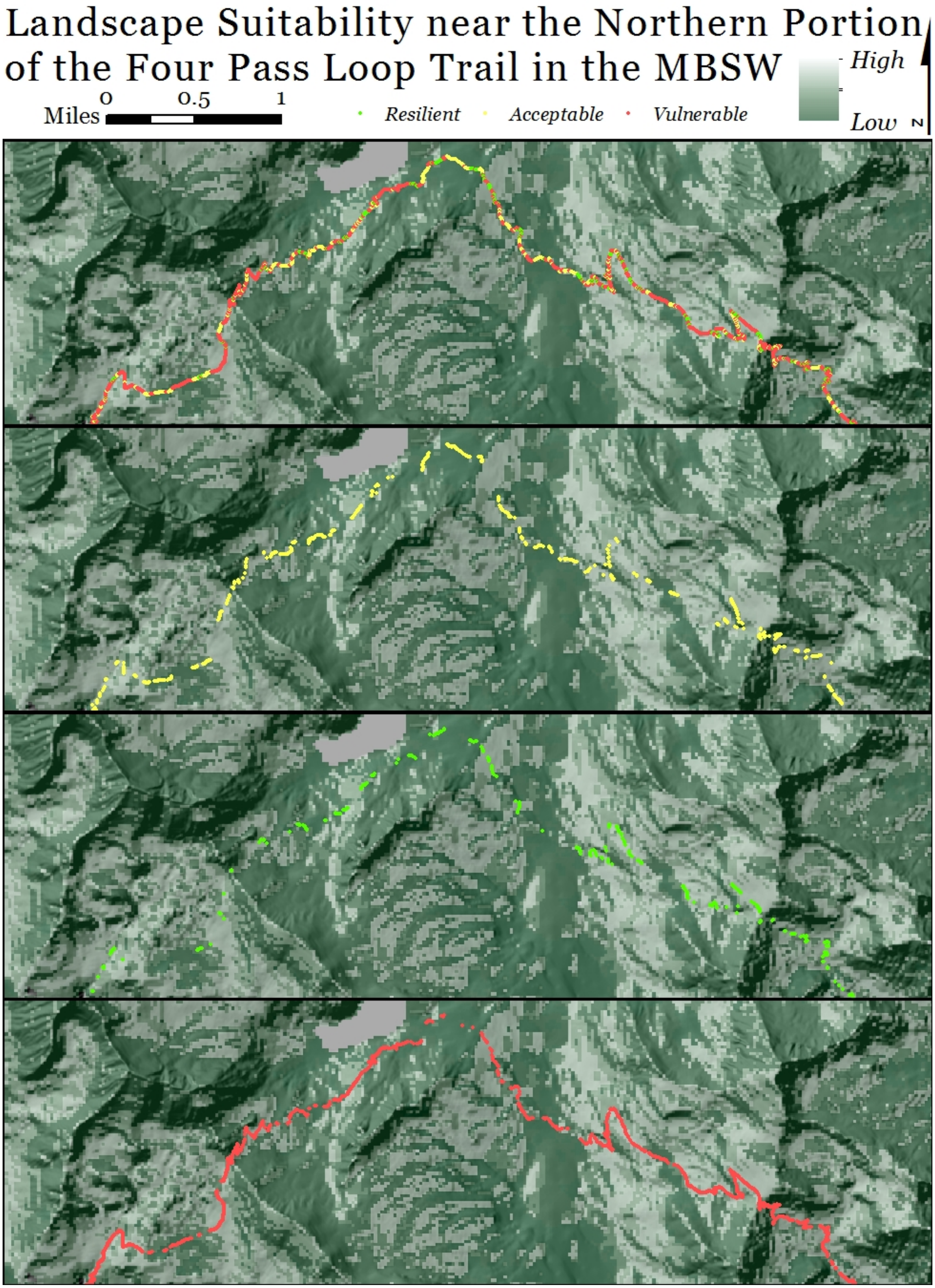


Figure C.8: The Four Pass Loop: 80% Slope, 10% Vegetation, and 10% Elevation

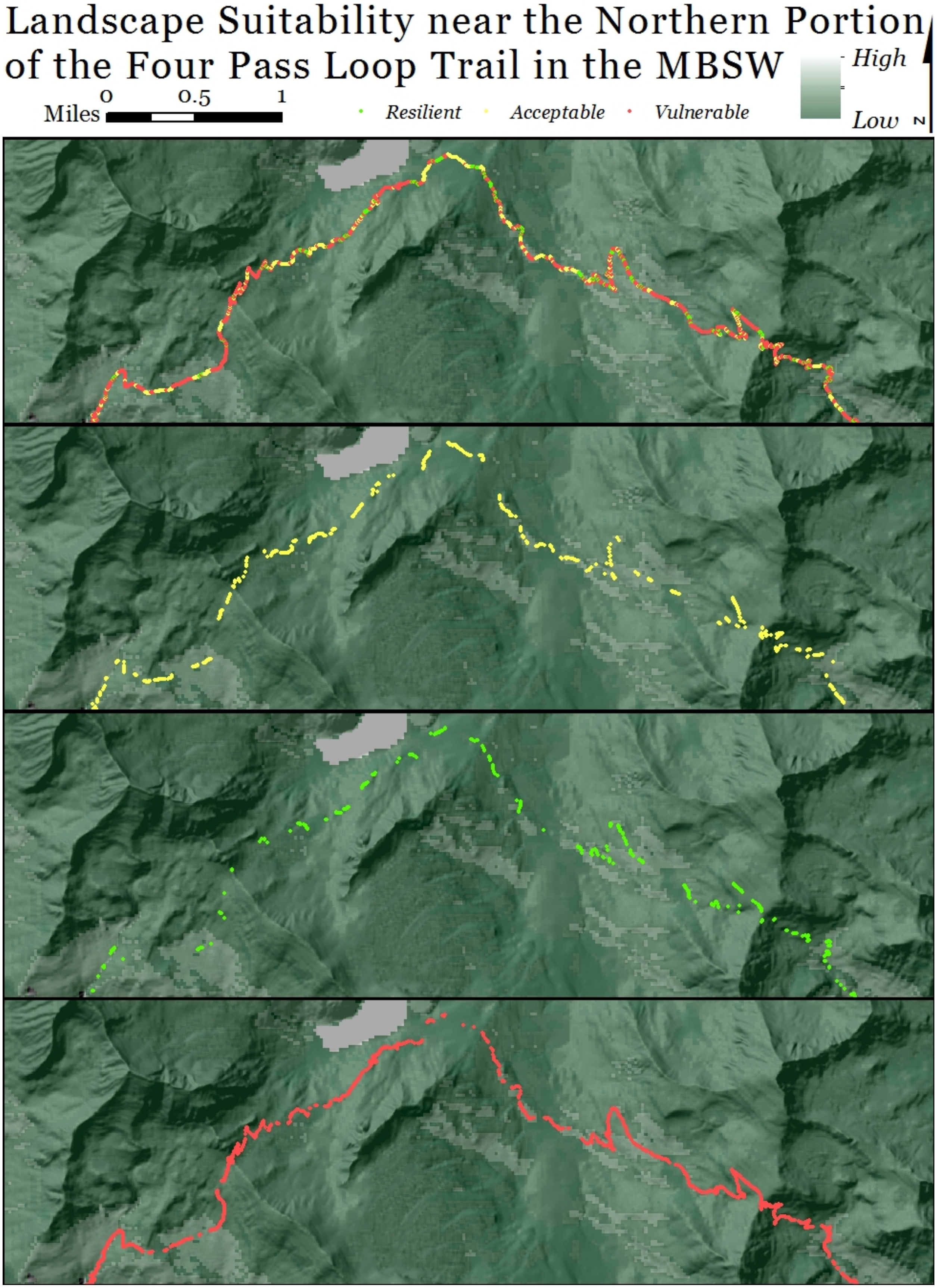


Figure C.9: The Four Pass Loop: 10% Slope, 20% Vegetation, and 70% Elevation

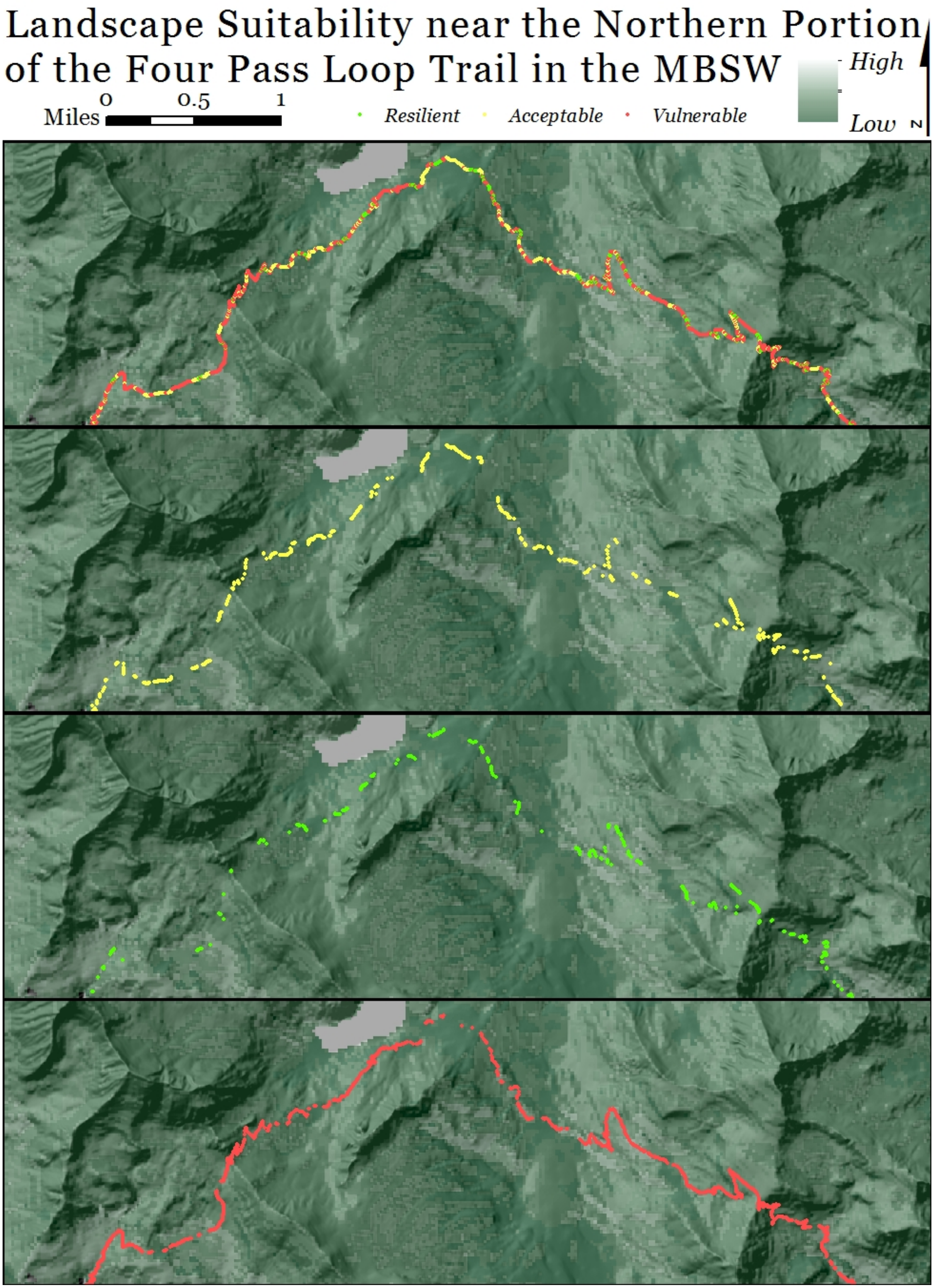


Figure C.10: The Four Pass Loop: 20% Slope, 20% Vegetation, and 40% Elevation

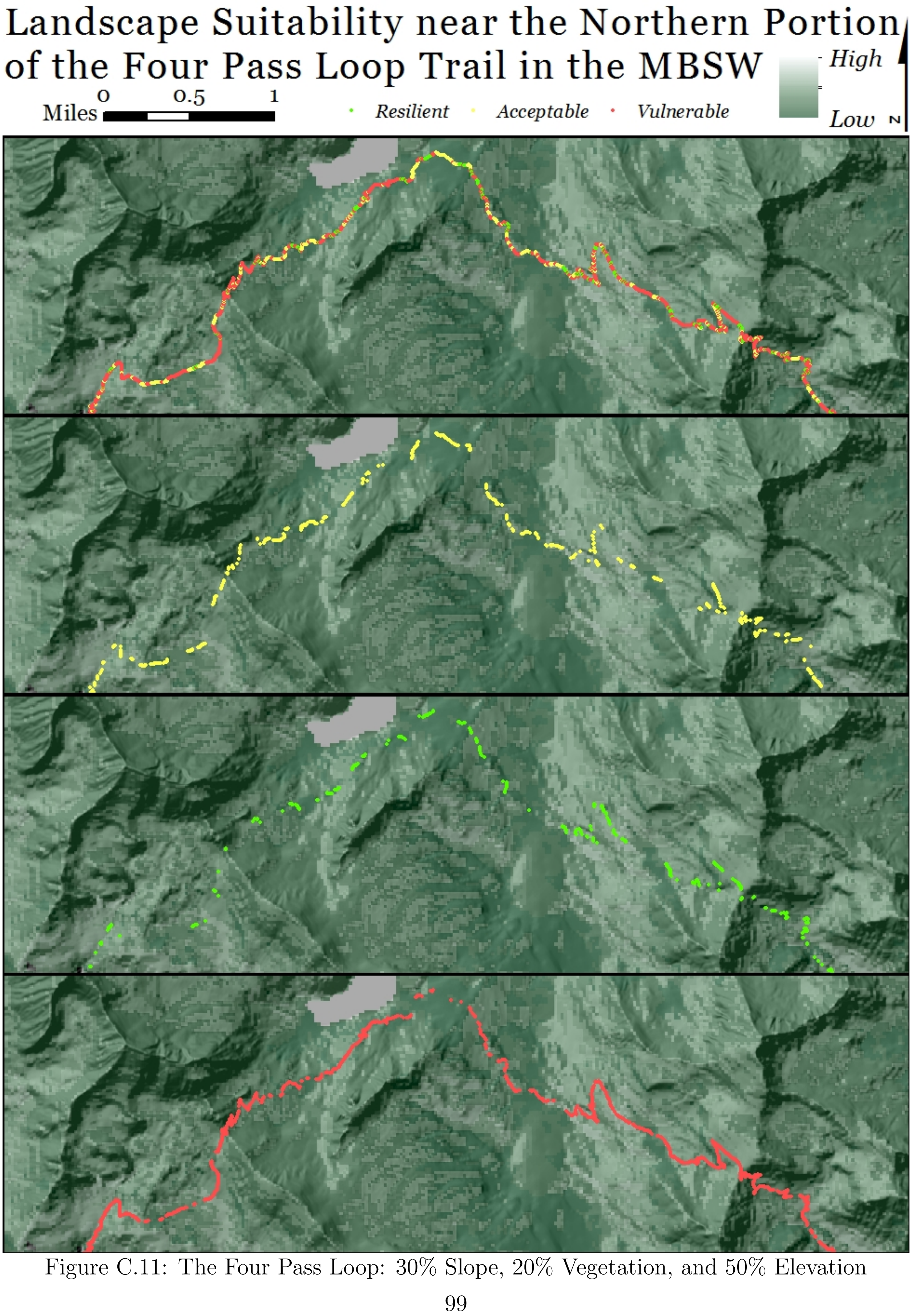


Figure C.11: The Four Pass Loop: 30% Slope, 20% Vegetation, and 50% Elevation

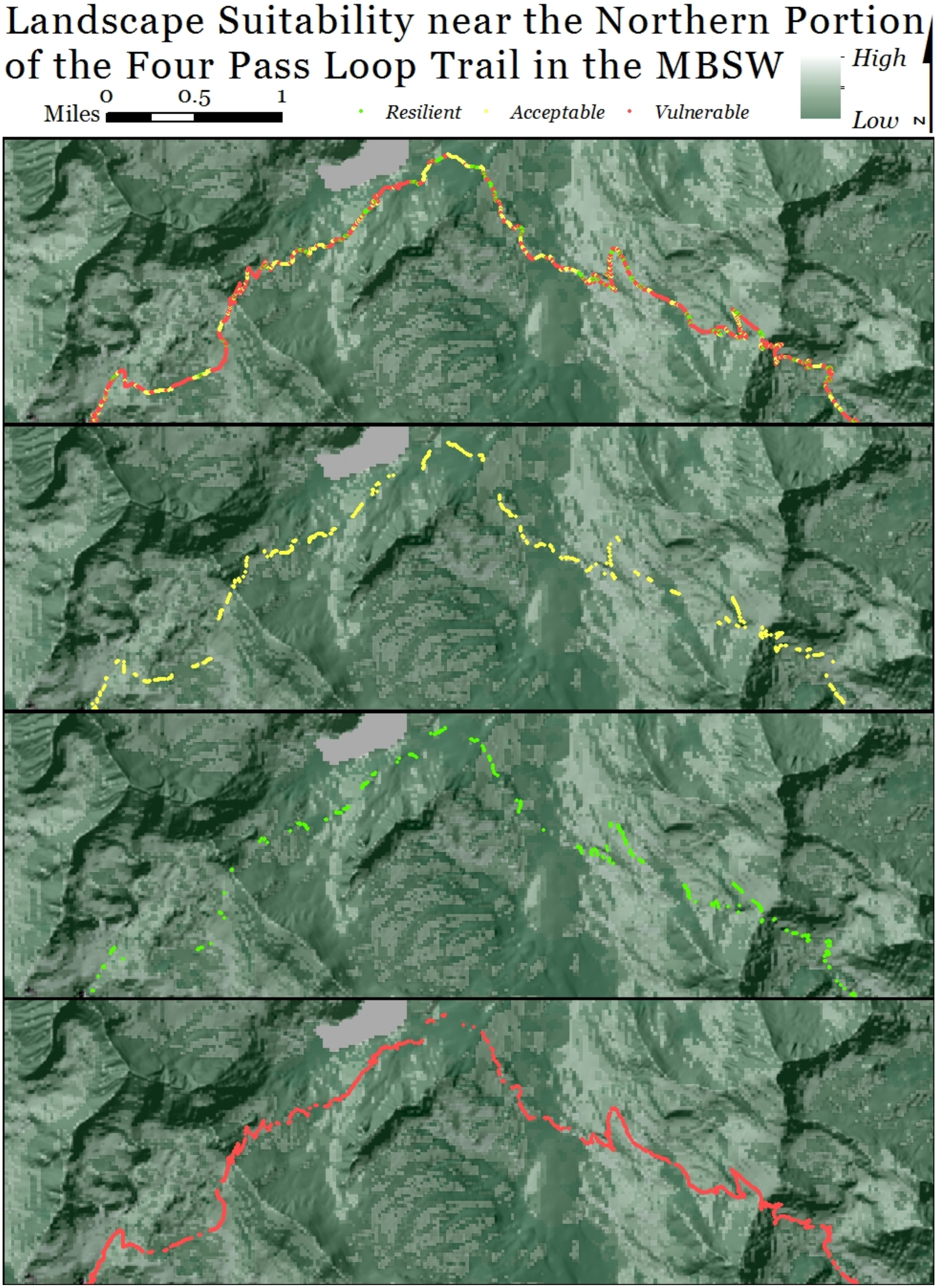


Figure C.12: The Four Pass Loop: 40% Slope, 20% Vegetation, and 40% Elevation

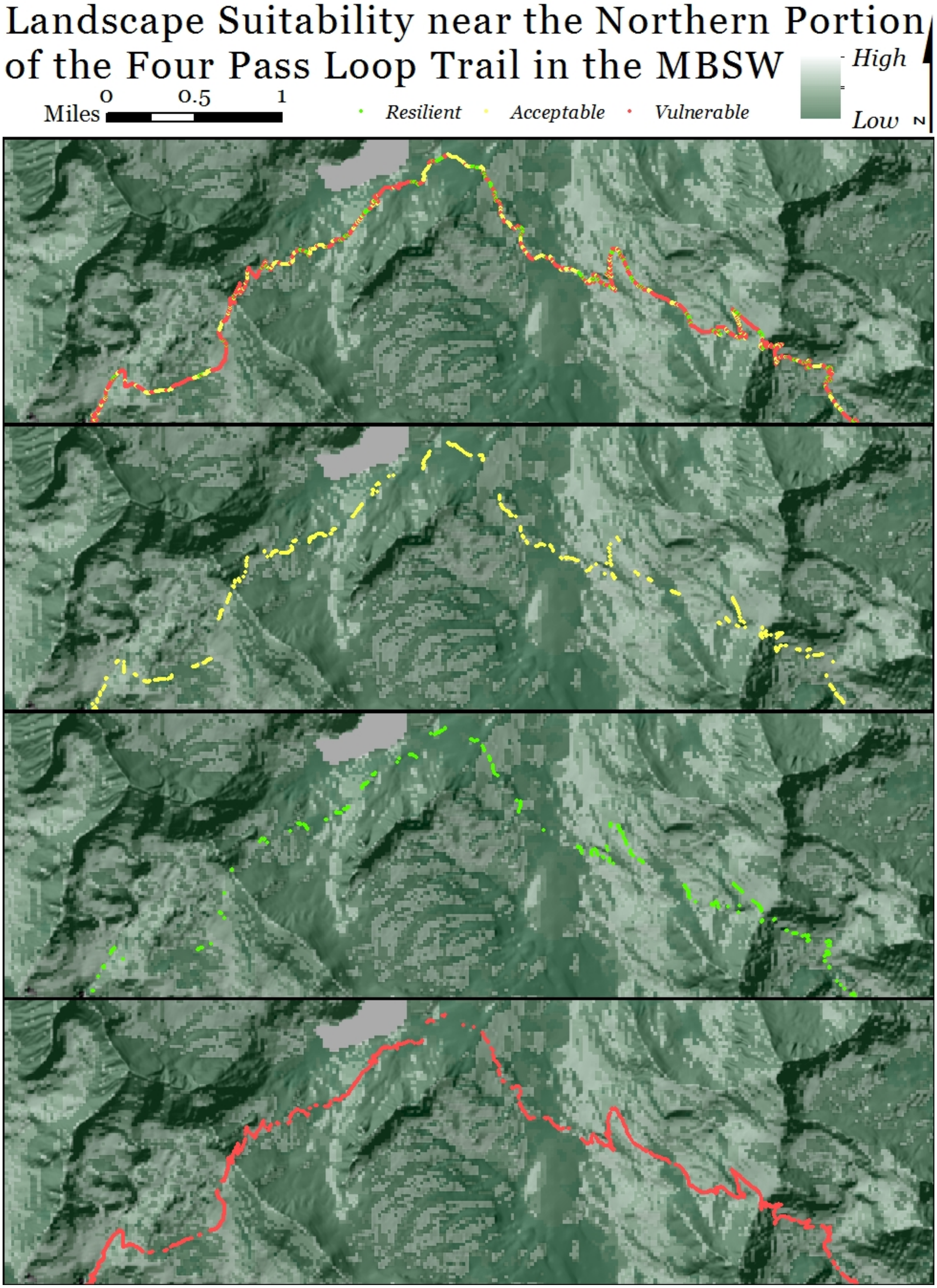


Figure C.13: The Four Pass Loop: 50% Slope, 20% Vegetation, and 30% Elevation

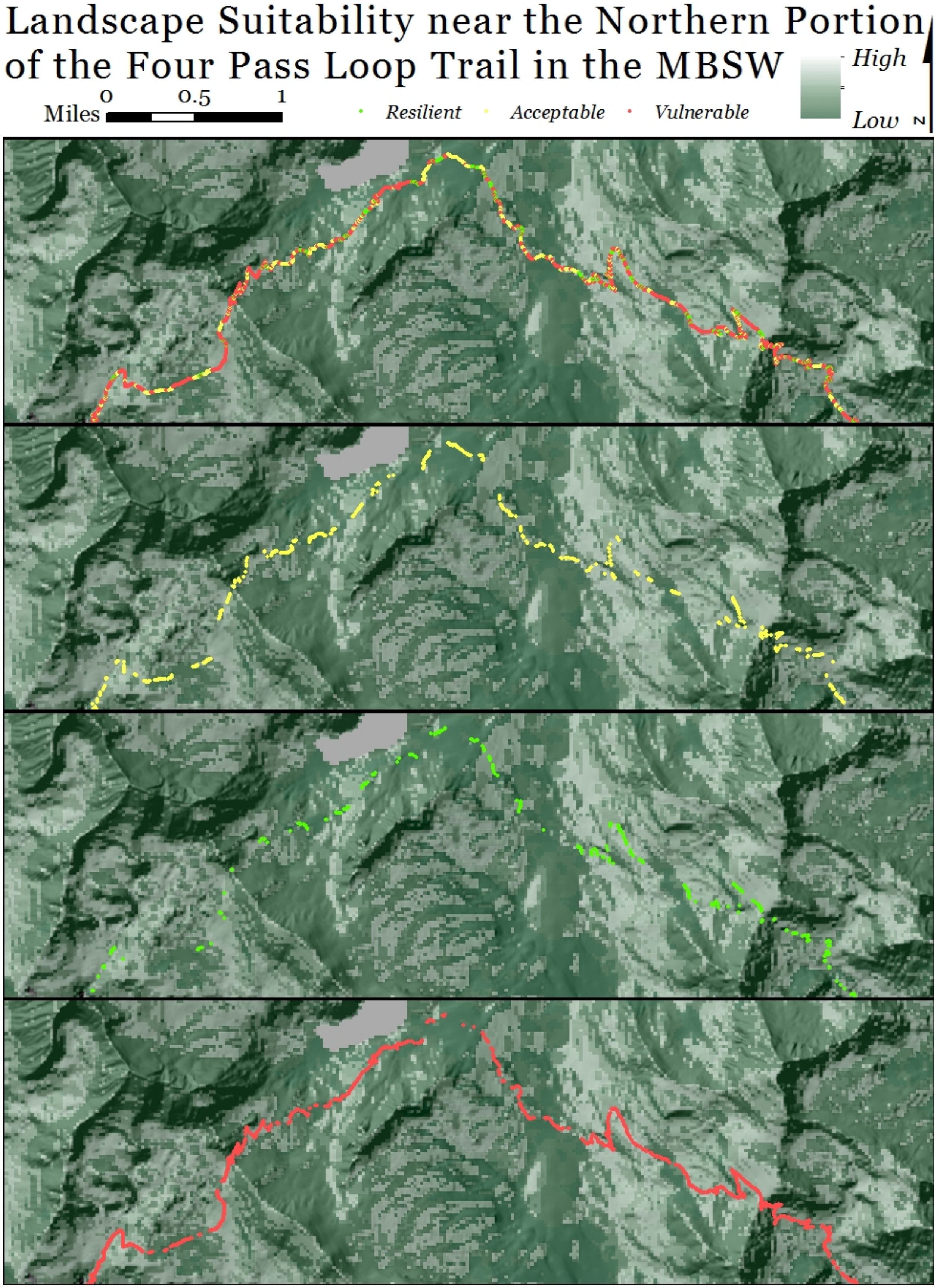


Figure C.14: The Four Pass Loop: 60% Slope, 20% Vegetation, and 20% Elevation

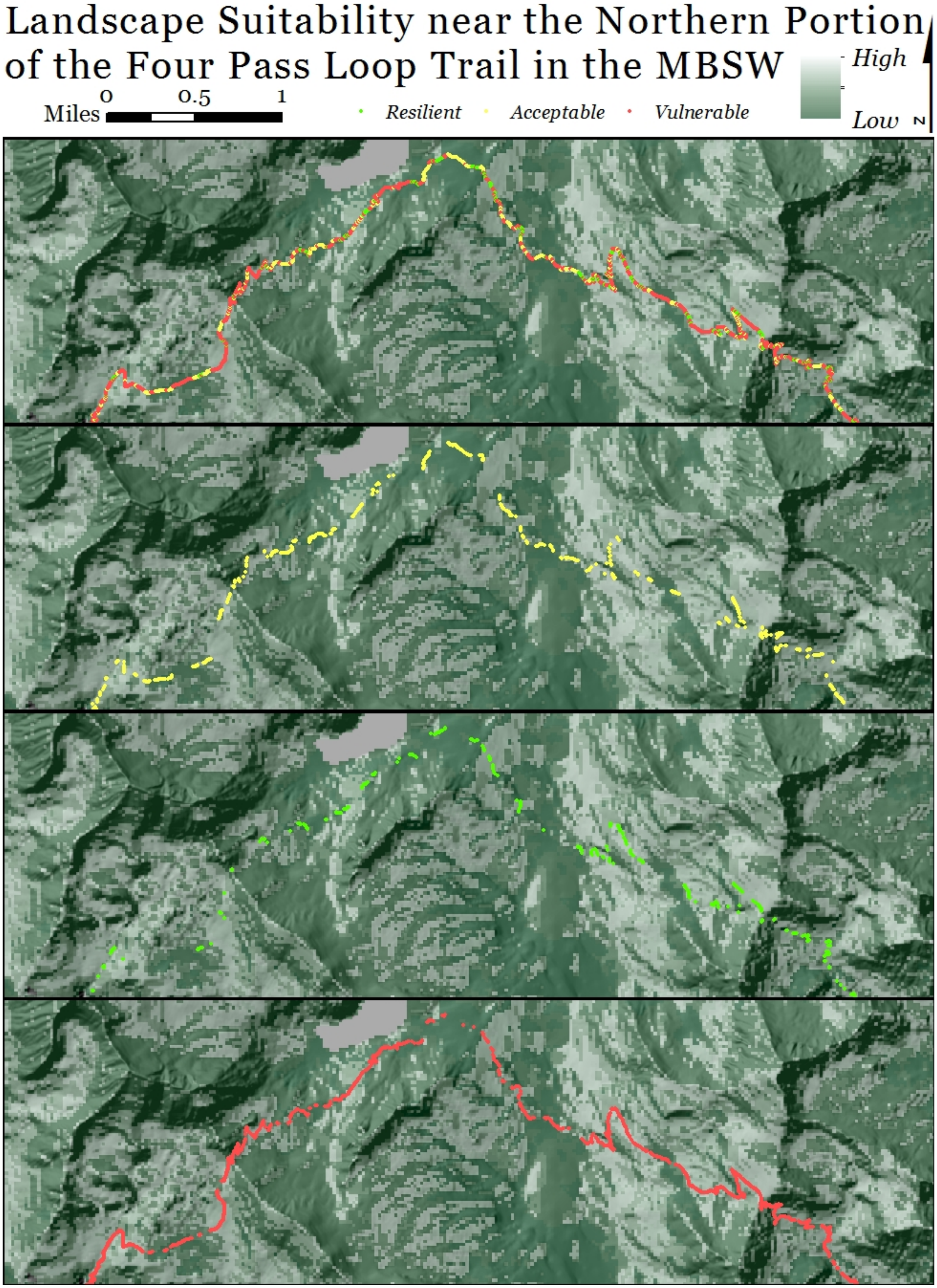


Figure C.15: The Four Pass Loop: 70% Slope, 20% Vegetation, and 10% Elevation