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FINAL RESEARCH REPORT

Assessing the Condition and Sustainability of the Trail System at Tallgrass Prairie National Preserve

Final Research Report, June 2022

Virginia Tech, College of Natural Resources & Environment

Department of Forest Resources & Environmental Conservation

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EXECUTIVE SUMMARY

This research assessed the condition and sustainability of the trail system at Tallgrass Prairie National Preserve, a National Park Service unit that partners with The Nature Conservancy (TNC) in the management of this unit. The Preserve was created through a 10,862-acre TNC land purchase in 2005 which included a "legacy" system of primitive unsurfaced ranching roads. The objectives of this study included assessing the sustainability of the trail system (including trail grades and alignments relative to the topography), its current resource conditions, an inventory of trail system features (stream crossings, gates, signs, culverts), and suggestions to improve trail system sustainability and ability to accommodate increasing use and additional uses such as horses and mountain bikes.

Fieldwork was performed in May 2022, with three field staff driving or walking all system trails to collect georeferenced data and photographs. The field assessment manual (Appendix 1) describes data collection protocols, and all collected data were recorded using a cell phone app (Fulcrum), with data transferred to Excel and ArcGIS Pro for analyses. Additional GIS analyses were conducted using accurate LiDAR Digital Elevation Model (1x1m resolution) topography data to analyze trail grades and landform alignment angles for the entire trail system in 10 ft cells. All georeferenced project data in GIS formats with metadata are a product of this research, in addition to this final report.

Field staff surveyed eighteen trails with an aggregate length of 31.75 miles, predominantly with native prairie vegetation and soils; the only graveled trails are the Bottomland Nature Trail (1.5 mi) and the Scenic Overlook Trail (3.2 mi). Trail grade is an important element of sustainability, with flat grades susceptible to rutting and soil displacement that contribute to excessive trail widening and muddiness. Unfortunately, 51.3% of the Preserve's trails (16.3 mi) are relatively flat (0-2% grade) (Table 6). While some of these trail segments are in flat terrain (6.3 mi, 19.8%), others are in more sloping terrain with nearly flat "side-hill" alignments (10 mi, 31.6%) (Table 3). While 44.0% of the trail system has more optimal trail grades ranging from 2-10%, 3.5% have steeper grades (10-15%) that are more susceptible to soil erosion, and 1.3% have exceptionally steep grades that are not recommended for recreational trails or unsurfaced roads (Table 3).

Trail sustainability is also a function of a trail's alignment to the prevailing landform grade, with sustainable "side-hill" trails aligned closer to contour lines, where steeper side-slopes center traffic on a narrow, easily drained tread, vs. unsustainable "fall-line" trails aligned closer to 90° from contour lines, making them highly susceptible to soil loss and widening when trail grades are steep. Approximately 37.6% (11.9 mi) of the Preserve's trails have a strong fall-line alignment, while 24.9% (7.9 mi) have a strong side-hill alignment (Table 7). A sustainability rating system was developed to provide approximate rankings applied to the Preserve's trails (Table 4). Based on this, only 15.6% of the Preserve's trails were rated as sustainably aligned, 52.0% were rated as slightly unsustainable (mostly trails with flatter trail grades), and 32.2% were rated as unsustainable. We emphasize that these ratings are based on locational or trail alignment attributes which the literature reveals as important elements of trail sustainability. We also present and discuss additional non-locational elements of trail sustainability, including attributes like the composition of tread substrates, vegetation type, soil moisture and tread drainage, and the type, amount, and behavior of trail users.

Data are presented for the entire trail system and for individual trails. An inventory of trail system features is presented, and more comprehensive data and photos are provided in a geospatial database accessible with GIS. While fieldwork was conducted during a very rainy period and documented muddy tread conditions, we note that this was atypical, and results describe the Preserve's trails as being in predominantly in good condition. This is somewhat surprising given the poor sustainability ratings, and is attributed to the following: relatively low trail system use, particularly during wet periods, wide use of very low ground pressure vehicles (e.g., 6-wheel Gator UTVs), prairie vegetation in full sunlight that has very high trampling resistance and resilience (ability to quickly recover), and graveling in higher traffic areas.

Preserve staff have inherited a largely unsustainable system of former ranching roads so guidance is also provided for making decisions about potential relocations to avoid future impacts as visitation and park/ranching use of the trail system increases over time. The most non-sustainable locations where active erosion is currently occurring includes short segments where trail grades exceed 15% (1.3% of the system, 0.4 mi), particularly locations that are proximate to streams. An additional 3.5% (0.3 mi) of Preserve trails with trail grades in the 10-15% range may also be experiencing soil loss in areas where treads receive sufficient use to remove protective vegetation cover and where alignments are either fall-line or treads are not well-drained. Of particular concern are 32 trail stream crossings (fords), which in some instances include steep embankments with obvious tread soil erosion into waterways. Observations indicate that greater soil erosion into the streams is associated with the cattle than visitor use. Upstream watershed sizes were calculated for each stream crossing (Table 22), and guidance to improve the sustainability of these crossings is provided. However, additional assessment of these crossings is recommended by qualified soil conservation specialists to resolve/abate further soil erosion.

A wide range of additional sustainable trail management practices are described. In flat terrain where drainage is problematic, solutions include keeping use minimized during wet periods, use of gravel in chronically wet swales or ruts, and relocating trails to side-hill alignments when possible. In more sloping terrain additional options include improving tread drainage by maintaining out-sloped treads or installing/cleaning ditching along the uphill side and passing the water through culverts or rock-armored swales. Any new/relocated trail segments should incorporate tread grade reversals to prevent water accumulation. Non-vegetated trail segments with grades above 10% require persistent attention to tread drainage to prevent soil erosion and fall-line segments are most optimally relocated to side-hill alignments. Gravelling with larger angular aggregate may be somewhat effective but only if not displaced or eroded downhill. Regardless, it is best to address locational deficiencies prior to using more permanent graveling or landform-altering tread drainage actions. Fortunately, many existing trails would recover to fully natural conditions in several years if simply abandoned, with use relocated to more sustainable side-hill alignments.

Finally, the literature review included an examination of horse and biking impacts, and the Preserve's trail system was considered to evaluate the potential addition of these two uses. Many of the Preserve's trails could likely accommodate bike use, but horses exert substantially greater ground pressures that require very dry soils, and/or treads with substantial rock content. Mixing angular crushed gravel with native mineral soil is often an optimal sustainable practice for horse trails and could also be used for bike trails that receive high use. The potential for social conflicts between different types of trail users must also be considered. Three options are presented for the accommodation of these potential new uses.

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INTRODUCTION

The National Park Service Act (1916) provides a mandate to the National Park Service "*to promote and regulate the use of the Federal areas known as national parks, monuments, and reservations…by such means and measures as conform to the fundamental purpose to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."* This guidance provides park managers with a "dual mandate," directing them to: 1) make parks available for public visitation and enjoyment, and 2) preserve the natural and cultural resources within parks. This challenge becomes increasingly difficult as more people visit parks. The NPS manages 418 park units and more than 84 million acres of protected lands, accommodating over 300 million visitors annually.

The Nature Conservancy (TNC) is a global environmental nonprofit organization whose mission is to "conserve the lands and waters on which all life depends," and a vision of "a world where the diversity of life thrives, and people act to conserve nature for its own sake and its ability to fulfill our needs and enrich our lives" (TNC 2022).

An increasing number of protected area visitors inevitably contribute negative effects to fragile natural and cultural resources. Such visitation-related resource impacts can degrade natural conditions and processes and the quality of recreation experiences. According to the NPS *Management Policies*: The fundamental purpose of the national park system, established by the Organic Act and reaffirmed by the General Authorities Act, as amended, is to conserve park resources and values (NPS 2006, Section 1.4.3). The NPS *Management Policies* acknowledge that some resource degradation is an inevitable consequence of visitation but directs managers to "ensure that any adverse impacts are the minimum necessary, unavoidable, cannot be further mitigated, and do not constitute impairment or derogation of park resources and values" (NPS 2006).

Responding to these concerns, TNC and NPS managers at Tallgrass Prairie National Preserve requested and the TNC funded this research investigating the sustainability of their inherited "legacy" network of predominantly unsurfaced ranching roads and trails. The information provided by this study was developed to inform Preserve planning and decision-making related to the design and management of a sustainable infrastructure of primitive roads and trails. This trails system is needed to accommodate access to the Preserve's lands for ranching, TNC, and NPS staff and Preserve visitors and volunteers. Both administrative and recreational activities have the potential to negatively impact the Preserve's natural and cultural resources and natural processes – a sustainable trail system can avoid some forms of impact while minimizing those that are unavoidable.

This research was designed to inform Preserve managers about sustainable trail design principles and Best Management Practices (BMPs), the types, severity, and spatial distribution of trail-related resource impacts, and an inventory of trail-related management attributes (e.g., gates, stream crossings, signs, culverts), including high-resolution photographs. Results from assessing the sustainability of the existing trails system are presented, including suggestions for their improved design and management. Finally, protocols that can be applied in the future to track and monitor trail conditions as part of a future Visitor Use Management planning and decision-making process are also included. All collected data, including photographs, were georeferenced and will be provided in a format suitable for use in Geographic Information Systems (GIS).

LITERATURE REVIEW

Visitors participating in various types of recreational activities, including day-hiking, mountain biking and horseback riding, contribute to a diverse array of direct and indirect impacts on protected area resources, including vegetation, soils, water, and wildlife (Table 1). The term *impact* is commonly used to denote any undesirable visitor-related change in these resources. Marion et al. (2016) provide a comprehensive review of these trampling-related impacts, which are summarized here. Even light recreational traffic can reduce ground vegetation height, cover, and biomass (Cole 1995a,b, Cole 2004, Leung & Marion 1996). Trampling disturbance can alter the appearance and composition of vegetation by reducing plant height and favoring trampling resistant species. Plant resistance is the intrinsic capacity of vegetation to withstand the direct effect of trampling by feet, hooves, and tires (Liddle 1997).

Under light recreational traffic, most plants respond with a reduction in plant height. Even light trampling will break rigid stems, which can halt flower and seed development and reduce plant vigor (Barros & Pickering 2015, Cole 1987). Plant morphological characteristics influence the response of vegetation to trampling disturbance. The taller rigid stems of many forest forbs (herbs) are highly susceptible to trampling damage, with stem breakage eliminating the growing tips, flowers, and seed production (Cole & Monz 2002). In contrast, grasses and sedges have flexible stems and leaves that are considerably more resistant to traffic and research has shown them to be significantly more resilient, i.e., they recover relatively quickly. Studies reveal that these differences in morphology and trampling resistance/resilience are positively correlated with the amount of sunlight that reaches ground vegetation (Cole & Monz 2003, Liddle 1997), i.e., shade-tolerant forest plants lack the resistance and resilience of shade-intolerant (sun-loving) plants.

Table 1. Direct and indirect effects of recreational trampling on soils and vegetation.

Effects	Vegetation	Soil
Direct	Reduced height/vigor Loss of ground vegetation, shrubs and trees Introduction of non-native vegetation	Loss of organic litter Soil exposure and compaction Soil erosion
Indirect	Altered composition – shift to trampling resistant or non-native species Altered microclimate	Reduced soil pore space and moisture, increased soil temperature Increased water runoff Reduced soil fauna

Higher levels of trampling cause more complete ground vegetation loss and compositional change (Cole 1995b; Marion & Cole 1996). Concentrated traffic also pulverizes soil leaf litter and humus layers, which are either lost through erosional processes or intermixed with underlying mineral soils (Marion et al. 2016). These soils then become exposed and vulnerable to displacement, wind or water erosion, and compaction (Monti & Mackintosh 1979). The compaction of soils decreases soil pore space and water infiltration, which in turn increases water runoff, muddiness, and soil erosion (Liddle 1997).

Severe trampling impacts, such as erosion and muddiness, often cause additional avoidable impact to water resources or to vegetation and soils in the form of trail widening and formation of parallel secondary trails. Trail widening can substantially expand the cumulative spatial extent of disturbance (Leung & Marion 1996, Marion et al. 1993). Trails can also alter natural patterns of water runoff (Sutherland et al. 2001), resulting in irreversible soil erosion and subsequent turbidity and deposition in streams and other water bodies (Fritz 1993, Leung & Marion 2000). Trails that are close to water resources require special consideration in their design and management to prevent the introduction of suspended sediments into bodies of water. Eroded soil that enters water bodies increase water turbidity and cause sedimentation that can affect aquatic organisms (Fritz and others 1993). Trout and other fish lay their eggs in gravels on the bottom of streams and lakes, and sediments can smother those eggs, reducing reproductive success. Sedimentation can also hurt invertebrate organisms, which serve as food for fish and other creatures. In addition, some sediment may contain nutrients that can contribute to algal blooms that deplete the dissolved oxygen in water bodies when they die off.

Recreational activities can also directly degrade and fragment wildlife habitats, and the presence of visitors may disrupt essential wildlife activities such as feeding, reproduction and the raising of young (Knight & Cole 1995, Marion et al. 2016). For example, Miller and others (1998) found decreased presence of nesting birds near trails in grassland ecosystems. Trails can fragment the landscape with barriers to flora and some small fauna (Leung *et al.* 2002, 2011, Leung & Louie 2008). Finally, visitors and recreational stock can also introduce and transport non-native plant species along trails, some of which may out-compete undisturbed native vegetation and migrate into adjacent undisturbed areas (Adkison & Jackson 1996, Benninger-Truax *et al.* 1992, Bhuju & Ohsawa 1998, Eagleston & Marion 2018, Hill & Pickering 2006, Potito & Beatty 2005).

Formal Trail Impacts

In this section we review the four "common" forms of trail impact: 1) soil loss – from the compaction, displacement, or wind/water erosion of tread soils, 2) muddiness – from poorly drained treads that retain mud and water, 3) widening – from visitor trampling to avoid tread erosion/ruts, muddiness, rockiness, or other trail users, and 4) informal (visitor-created) trail creation/proliferation – when visitors travel off formal trails for various reasons (e.g., to take short-cuts, avoid tread impacts, or access desired locations away from formal trails).

Trail Soil Loss

Soil loss as measured in trail studies is largely caused by water erosion, though wind can remove tread soils in dry climates, and soil can be compacted or displaced downhill or laterally (Marion & Wimpey 2017). The rate and severity of soil loss is influenced by trail alignment relative to topography and environmental attributes, tread substrates, climate, tread maintenance actions, and use-related factors including amounts and types of use (Leung & Marion 1996, Olive & Marion 2009).

Many trail studies have revealed a strong positive relationship between soil erosion and high trail gradients, with soil loss increasing substantially with grade (Bratton et al. 1979, Dissmeyer & Foster 1980, Fox & Bryan 2000, Marion & Wimpey 2017, Nepal 2003, Olive & Marion 2009). This trend is explained by the increased erosive force of water and increased soil displacement by boots, wheels, and hooves on steeper trail treads (Fox & Bryan 2000, Leung & Marion 1996). Flat trail grades (0-2%) are problematic as treads can be easily compacted or soils displaced so that water is retained and can't be drained away. Problems with trail muddiness and widening are common, with no easy remedies. Trails with lower grades (2-5%) are optimal. Intermediate grades (5-10%) are also acceptable and soil loss can be minimized with adequate water drainage from treads. More steeply graded trails (10-15%) often require rock in tread substrates and/or enhanced water drainage design and sustained maintenance work to prevent soil loss. Exceptionally steep trail grades (>15%) are rarely recommended and require treads to be armored with rock pitching or steps to prevent substantial soil loss.

Studies have also consistently linked trail soil loss to trails that are aligned with the fall line, which is perpendicular to contour lines (side-hill trails) (Figure 1). Such trails become incised quickly and water drains directly down their treads, with erosional rates correlated with tread grade. Two metrics have been developed to describe a trail's alignment to landform topography. Trail practitioners use Slope Ratio (SR), which is calculated by dividing the trail grade by the landform grade and ranges from 0.0 to 1.0 (IMBA 2004). Fall line trails are nearly as steep as their surrounding terrain and have high SR values close to 1, whereas side-hill trails have low SR values closer to 0. The International Mountain Biking Association developed guidance known as the "Half Rule" stating that trail grades should be no more than half the landform (side-slope) grade to prevent trail alignments close to the fall-line. Alternately, some trail researchers use Trail Slope Alignment (TSA), a measure of the smallest angle between the azimuth of the trail and the azimuth of the prevailing fall line, expressed in angular degrees ranging from 0° to 90° (Marion & Wimpey 2017) (Figure 1).

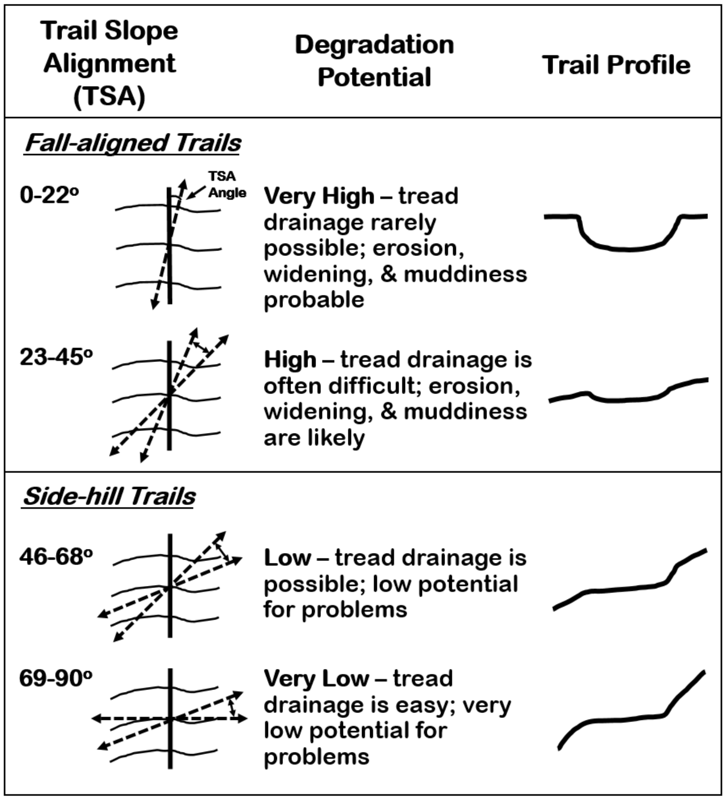


Figure 1. Trail Slope Alignment (TSA). Expected trail degradation potential and trail cross-section profiles for four categories of trail slope alignments ranging from fall-line trails (0-22°) to contour-aligned side-hill trails (69-90°). Dashed lines depict trail alignments and solid vertical lines depict the prevailing landform grade or aspect. Curved lines are contour lines.

Direct ascent fall-line trails with SR values >.75 and/or TSA values lower than 22° are particularly prone to soil loss due to the difficulty of draining water from incised treads – both side-slopes are often higher than the tread surface (Marion & Wimpey 2017). For example, predictive equations from a study in Big South Fork National River and Recreation Area in Kentucky and Tennessee suggest that every degree that TSA alignments shift from 90° (side-hill) to 0° (fall-line) contributes 6cm^2 of additional soil loss (Olive & Marion 2009). Several studies report that the significance of TSA increases as trail grade increases (Bratton et al. 1979, Leung & Marion 1996, Marion & Wimpey 2017, Olive & Marion 2009).

In additional to trail grade and trail alignment to landforms there are several additional attributes that influence trail sustainability, including soil type, particularly the amount of rock in tread substrates, density and efficacy of tread drainage features, and vegetation types. Additionally, note that the SR and TSA indices reflecting trail alignments to prevailing landform grades also have some important deficiencies. They do not account for the following variable and unique situations:

1) Flat trail grades generally become concave or rutted due to soil compaction and displacement in flat terrain, and/or develop higher berms along the lower trail edge of side-hill alignments in sloping terrain - in either situation the treads can retain water that contribute to muddiness and trail widening (Meadema et al 2019). Avoiding flat terrain is preferable when possible, or durable treads can be developed by applying gravel and soil mixtures (Aust et al. 2005). In sloping terrain, side-hill treads should not be aligned close to the contour line (e.g., with trail grades <2%) to facilitate tread drainage (Marion & Wimpey 2017). When trails need to be aligned close to the contour line, they should be routed sinuously with a rolling design above and below the contour line to maintain trail grades above 2%. Trails with steeper grades (>2%) can also retain water or erode soil when treads are incised or berms develop, highlighting the importance of installing and maintaining good tread drainage on all trail systems.

2) While fall-line trails in flatter terrain (e.g., <5% grade) may have limited susceptibility to soil erosion, they are still vulnerable to muddiness and trail widening. Fall-line trails become increasingly unsustainable as trail/landform grades increase (Eagleston & Marion 2020, Marion & Wimpey 2017). Soil erosion on fall-line trails increases exponentially for most soils that lack rock as trail grades exceed about 15% (Dissmeyer & Foster 1984,

Figure 2. Sustainable tread grade-reversals (top) are 100% effective in draining water and rarely require maintenance. Drainage ditches (middle) are easily installed, with excavated soil mounded just downhill, but require annual cleaning to maintain their efficacy. Water bars constructed of rock (bottom) or wood are longer lasting but also require cleaning and are generally not tire friendly.

Meadema et al. 2019). Fall-line trails also become more susceptible to trail widening as trail grades increase (Wimpey & Marion 2010). Soil loss can be minimized by applying large angular gravel at lower grades (5-10%), and large tread-armoring stonework, rock steps, or pavement at steeper grades, though closure and rerouting to side-hill alignments is the most optimal solution.

3) Side-hill trails in flatter terrain (e.g., <5%) offer very limited advantages as drainage remains challenging and side-slopes are insufficiently steep to compel tread-centering behaviors (Meadema et al. 2019). As landform grades increase from about 5-20%, sidehill trails become increasingly more sustainable as they are easier to drain, and steeper side-slopes inherently constrain tread widening behaviors. However, tread construction costs often increase as landform grades increase beyond 30%, and steeper terrains increase tread vulnerability to slumping.

Soil texture, reflecting the relative amounts of different substrate particle sizes, influences the ability of soils to withstand wind and water erosion, displacement, and compaction. When dry, uniformly fine-grained soils are highly compactible and resistant to erosion; coarse-textured soils drain easily but are displaced with little force (Hammitt et al. 2015). An ideal tread substrate has a mixture of grain sizes, including sand to improve drainage, fine silts for cohesion, and rock or gravel to harden the tread to increase weight-bearing capacity and deter soil displacement (Leung & Marion 1996, Marion et al. 2016). A gravel/rock/soil mixture provides an optimal tread substrate to sustain heavier or intensive traffic with little impact, even when soils are damp or wet (Aust et al., 2004).

Since rainfall and snowmelt can increase soil erosion and displacement, the amount and intensity of precipitation influences the severity of soil loss (Bratton et al. 1979, Leung & Marion 1996, Tomczyk et al. 2016). High elevation trails with limited rock in tread substrates can be more vulnerable to erosion due to the combined effects of high precipitation, strong winds, and numerous freeze-thaw cycles (Nepal 2003). Trailside vegetation can limit erosion by protecting exposed soil from splash, slowing and filtering runoff, and increasing soil porosity with roots (Bratton et al. 1979). More rarely, soil loss can be prevented by the growth of trampling-resistant grasses, sedges, or short herbs on treads, generally only on low use trails in sunny settings (Dixon et al. 2004, Marion et al. 2016).

One objective of sustainable trail design is for trails to be “hydrologically invisible;” to not intercept and divert water along their treads. However, trails constructed with out-sloped treads to shed water rarely retain out-sloping very long after being opened. This is due to soil compaction and displacement from initial trail traffic, and over time to tread substrate erosion and the development of a raised berm along the lower trail border (Parker 2004). In the absence of effective maintenance, trails will intercept and divert erosive water along their treads. Trails require a permanent program of tread drainage and maintenance to avoid or minimize soil loss, with amount and frequency of maintenance inversely correlated with the sustainability of a trail's alignment. Removing water from fall-line trails is difficult or impossible when treads become deeply incised (IMBA 2004, Parker 2004). Constructing out-sloped treads on side-hill trails to drain water is rarely effective over time as treads become concave and lower trailside berms form to prevent drainage. Maintainers can periodically excavate berms and restore out-sloping but this is a strenuous task over long distances (Hesselbarth et al. 1996, Marion & Wimpey 2017).

The most sustainable option for diverting water from treads is to periodically reverse the grade of the trail, forcing all water off the trail and lessening the need for maintenance (Marion & Wimpey 2017, Parker 2004) (Figure 2). Tread grade reversals are optimally designed during a trail's layout, though these can be retrofitted on side-hill trails with low to intermediate grades (Hesselbarth et al. 2007, IMBA 2004, 2007). More commonly maintainers install unarmored drainage dips (Figure 2), or rock and wooden water bars to minimize erosion by diverting flowing water from treads (Birchard & Proudman 2000, Hesselbarth et al. 1996). Research reveals greater soil loss with increasing distances between drainage features, that feature density must increase with increasing trail grade, and that drainage features become ineffective when not maintained (Marion & Wimpey 2017, Mende & Newsome 2006). Drainage features become ineffective when filled with leaves and sediment, and armored water bars are sometimes circumvented by hikers, widening the trail (Hesselbarth et al. 2007).

Maintainers can also avoid or minimize soil loss by armoring treads with rock or wood. The addition of stonework, imported gravel or crushed native stone may seem unnatural but can be an effective practice to create highly resistant treads, particularly when both fine and coarse particles are combined (Marion 2016). Mixing gravel with native soil is an effective practice to create highly resistant substrates that remain natural in appearance. Coarse gravel applied to steep trail grades (>10-15%) is not a sustainable practice as the gravel will displace or erode down-slope, requiring labor intensive re-application and maintenance (Marion & Wimpey 2017, Olive & Marion 2009). Steeper trail grades generally require the construction of well-anchored rock steps or armoring to prevent erosion but no available research has examined their long-term efficacy (Marion 2016). A variety of geosynthetics are also available, including geotextiles, sheet drains, and geo-cells, and while most are installed in flat terrain to address muddiness, some have been applied to prevent erosion (Hesselbarth et al. 2007, Marion 2016). Research on the efficacy of geosynthetics in sloping terrain is also rare, and the high cost and artificial nature of these materials discourage their use, particularly in backcountry and wilderness settings (Marion & Leung 2004). Generally in sloping terrain they become exposed to the sun and break down relatively rapidly.

Type, amount, and season of trail use have also been shown to influence soil loss, though most studies report their effects are less influential than trail alignment and substrate factors (Cole 1991, Marion & Wimpey 2017). Most tread impacts occur with low to moderate use, with diminishing per-capita impact occurring at higher use levels, particularly on well-maintained sustainably designed trails. However, intensive use during wet periods can accelerate tread soil displacement and loss (Farrell & Marion 2001, Nepal 2003). Several studies have also observed significantly more soil displacement, loss, muddiness and widening on equestrian trails relative to hiking and mountain biking trails (Bratton et al. 1979, Leung & Marion 1999, Olive & Marion 2009).

Trail Muddiness

While studies suggest that soil loss is primarily caused by moving water, trail muddiness is caused by poor drainage and water retention. Although a common problem in many trail systems during wet seasons (Cole 1983, Leung & Marion 1999, Nepal 2003), little research has been focused on modeling the factors that influence trail muddiness. Trails routed through flat areas are prone to muddiness because it is difficult or impossible to drain water from their incised treads (Cole 1983, Tomczyk et al. 2017). Trails in areas with high water tables or on soil types with substantial organic content that retain water often become muddy quagmires (Bratton et al. 1979, Cole 1991, Leung & Marion 1999).

Mud-holes form most often in flatter valley bottoms in areas of poor drainage or near seeps and springs (Bratton et al. 1979, Leung & Marion 1999, Nepal 2003). Water retention and muddiness can also occur on incised sections of nearly level side-hill trails and ridge-tops when insufficient maintenance allows berms to form and/or drainage features to clog (Bratton et al. 1979, Hesselbarth et al. 2007, Leung & Marion 1999). The most sustainable solution is to relocate persistently muddy trail segments to side-hill alignments with sloping trail grades (e.g., >5%) (Hesselbarth et al. 2007, Steinholtz & Vachowski 2001). When relocations are not possible, trail maintainers can harden muddy sections with rock, puncheon, geosynthetics, or elevated bog bridging (Birchard & Proudman 2000, Hesselbarth et al. 2007). For side-hill trails the enhancement and maintenance of drainage is an effective solution to muddiness.

Trail Widening

Unlike soil loss and muddiness, which are primarily driven by water, trail widening is rooted in visitor behaviors, most frequently related to visitors selecting the smoothest and easiest route of travel (Cole 1991, Wimpey & Marion 2010). Unmitigated degradation on poorly routed trails can prompt visitor behaviors that contribute to trail widening; hikers meandering laterally over eroded rocky and root-covered treads in search of the best footing often pioneer smoother areas adjacent to the degraded treads (Leung & Marion 1999, Tomczyk et al. 2016, Wimpey & Marion 2010). Similarly, trail users frequently sidestep wet and muddy trail sections, creating multiple treads and wide mud-holes (Bayfield 1973, Leung & Marion 1999, Tomczyk et al. 2017). Additional trail widening behaviors identified by Wimpey and Marion (2010) include visitors moving laterally to pass or allow passing, and side-by-side travel; trail widening associated with these behaviors is generally related to variations in visitor travel patterns and numbers.

Some motorized vehicles and equestrians have a functional need for wider trails but these trail uses can also have greater speeds, travel distances, ground pressures, and soil displacement from churning hooves and tires that collectively contribute to greater trail widening (Marion & Olive 2006, Svajda et al., 2016, Tomczyk et al. 2017).

Despite the strong behavioral linkages associated with trail widening, research reveals that trail routing relative to topography and trail maintenance actions can significantly influence trail width. Trails in flat terrain are prone to widening due to the ease of off-trail travel, while the steeper side-slopes of side-hill trails effectively center and concentrate traffic to inhibit tread widening (Bayfield 1973, Wimpey & Marion 2010). In forested areas maintainers can manipulate the density of trailside woody vegetation and the width of the trail corridor through trimming and forest management practices (Bayfield 1973, Bright 1986, Hesselbarth et al. 1996, Tomczyk et al. 2017). In non-forested areas, the substantial trampling resistance and resilience of grasses and sedges can effectively resist trail widening pressures, though sloping terrain is required to prevent the formation of parallel secondary treads and muddiness (Tomczyk & Ewertowski 2011, Tomczyk et al. 2017).

When available, both natural and intentionally placed trailside rocks, logs, and woody debris can effectively center traffic (Bayfield, 1973). Constructed trailside barriers including stone or wooden borders, scree walls, and fencing, can physically obstruct traffic or serve as visual cues to center and concentrate traffic (Park et al. 2008, Svajda et al. 2016, Tomczyk et al. 2017, Wimpey & Marion 2010). Finally, preventing or mitigating degraded trail conditions, particularly muddiness and rugosity (exposed roots or rocks caused by erosion), can motivate visitors to remain on the intended tread.

Informal Trails

When formal trail networks fail to provide visitors the access and experiences they desire, visitors frequently "vote with their feet" by venturing off-trail to reach locations not accessible by formal trails. Even relatively low levels of recreational traffic can wear down vegetation and organic litter to create long-lasting *informal* (visitor-created) trails (ITs) and recreation sites (Thurston & Reader 2001, Wimpey & Marion 2011). The establishment of ITs and recreation sites is commonplace in protected natural areas, especially in heavily visited areas. The creation and proliferation of ITs and sites can directly impact sensitive plant communities, rare or endangered flora and fauna, and wildlife habitats (Leung et al. 2002, Wimpey & Marion 2011). For example, a small population of rare plants may be eliminated by trampling or habitat changes from visitor use or through competition from introduced non-native species. Off-trail and off-site traffic may also contribute to the further introduction and spread of non-native and invasive plant species.

Resource degradation on ITs can be severe due to their lack of professional design, siting/layout, construction, and maintenance. Such unplanned recreation infrastructure generally receives no environmental reviews, yet they sometimes accommodate considerable use. Furthermore, some park managers have formalized trails that were originally created by visitors (Marion & Leung 2004). Resource impacts to such trails are often linked to their unsustainable alignments and proximity to fragile vegetation, soils, and sensitive wildlife habitats, or their disturbance to rare flora, fauna, or archaeological sites (Wimpey & Marion 2011). These attributes make them substantially more susceptible to resource impact.

In summary, most recreation resource impacts are limited to the immediate vicinity of formal trails, though impacts like the creation of ITs, altered surface water flow, invasive plants, and wildlife disturbance, can extend considerably further into natural landscapes (Kasworm & Monley 1990, Tyser & Worley 1992). However, even localized disturbance can harm rare or endangered species or damage sensitive plant communities, particularly in environments with slow recovery rates.

Impacts from Horseback Riding

Many studies demonstrate that trampling by a horse is more destructive to vegetation than trampling by foot (Nagy & Scotter 1974, Weaver & Dale 1978, Whittaker & Bratton 1978). Whittaker and Bratton (1978) found vegetation on horse trails to be churned up and often cut off at the roots, instead of flattened, as on hiking trails. An experimental trampling study by Nagy and Scotter (1974) found vegetation loss to be four to eight times greater from horse trampling than hiker trampling. The greater vegetation loss from horse use tends to widen horse trails, which are often two to three times the width of hiker trails (Weaver & Dale 1978). The greater width of exposed soil and inherent characteristics of horses also contribute to greater erosion on horse trails.

Soil erosion resulting from horse use is a product of the trampling and eventual loss of vegetative cover, subsurface soil compaction leading to lowered water infiltration rates, and the increased roughness and detachment of surface soil particles. A horse carries a heavy weight on a small, usually shod, hoof. This weight exerts approximately 18 lbs/in^2 ground pressure for unshod horses to 62 lbs/in^2 for shod horses, compared to 2.9 lbs/in^2 for a hiker in boots (Liddle 1997). Thus, horse traffic causes significant compaction to the underlying soil layers, reducing water infiltration and increasing surface runoff. In addition, the action of a horse hoof tends to puncture and dig up the soil surface (McQuaid-Cook 1978). An evaluation by Deluca *et al.* (1998) of the mechanisms by which trail traffic leads to accelerated erosion suggested that soil loosening and detachment of soil particles by horses contributed to the higher erosional rates. Soil compaction and decreased infiltration were not considered as important, a finding supported by the work of Wilson and Seney (1994).

Heavy horse traffic in areas with wet soils can result in the formation of muddy quagmires and excessive trail widening. Whittaker and Bratton (1978) found loosening of the soil to be a precursor to muddy trail sections. Loose soil is more apt to form mud than compacted soil and the highly compacted subsurface soils prohibit water infiltration. The resulting impermeable basins retain water and mud long after rainfall. Marion (1994) noted that deep hoof prints collect and retain water, providing greater surface contact between water and soil and accelerating the formation of mud. Trail muddiness can be a temporary or seasonal problem, making travel difficult and often resulting in significant trail widening when trail users seek to circumvent muddy sections.

Other trail problems attributed to horse use include the proliferation of informal trails, manure on trails, tree damage, and the introduction and spread of exotic vegetation. Trail braiding is especially troublesome in meadows, where stock users tend to spread out rather than ride in single file (Hammitt et al. 2015). The creation of side trails to access water, features of interest, or short cuts to other trails are also considered a significant form of trail impact. Informal trails are often poorly routed and not maintained, resulting in an increased potential for degradation. Manure on trails is both an ecological and social problem. Manure can contain the seeds of exotic plants, although seeds may also be introduced from horse feed, equipment, and mud stuck to horse hooves. Large numbers of weed seeds can pass through the gut of horses and germinate in their manure (St John-Sweeting & Morris 1991). However, Whinam *et al.* (1994) found that weed seeds were limited to the manure, and Whinam and Comfort (1996) revealed no indication of introduced weeds from monitoring. Large amounts of manure may also pose a threat to water quality (Hammitt et al. 2015).

Impacts from horse use can also be social: impacts to the experiences of other visitors. For example, many studies have revealed conflicts between hikers and horseback riders. Watson *et al.* (1993) found that 36% of wilderness hikers did not like encounters with horses on trails but only 4% of horse riders disapproved of meeting hikers. In another wilderness study, 75% of managers reported they received complaints about horses, including excessive trail impacts, manure on trails, and damage to meadows and riparian areas (Shew *et al.* 1986). There is not space for a complete review of the social impacts of horse use here; additional pertinent references include Hammitt et al. (2015), Jacob and Schreyer (1980), McClaran (1989), and Newsome *et al.* (2002).

Impacts from Biking

Thurston and Reader (2001) conducted an experimental trampling study involving mountain bikers and hikers in Boyne Valley Provincial Park of Ontario, Canada. The researchers measured plant density (number of stems/area), diversity (number of species present), and soil exposure (area of mineral soil exposed) before and after 500 one-way passes by bikers and hikers. Data analysis and statistical testing revealed that the impacts of hiking and biking were not significantly different for the three indicators measured. Wilson and Seney (1994) evaluated tread erosion from horses, hikers, mountain bikes, and motorcycles on two trails in the Gallatin National Forest, Montana. They applied one hundred passes of each use-type on four sets of 12 trail segments, followed by simulated rainfalls and collection of water runoff to assess sediment yield at the base of each segment. Control sites that received no passes were also assessed for comparison. Results indicated that horses made significantly more sediment available for erosion than the other uses, which did not significantly vary from the control sites. Traffic on prewetted soils generated significantly greater amounts of soil runoff than on dry soils for all uses.

Marion and Olive (2006) studied 78 miles of trail in the Big South Fork National River and Recreation Area, examining the relative contribution of different use types, including horse, hiking, mountain biking, and ATV. Trails predominantly used for mountain biking had the least erosion of the use types investigated. Computed estimates of soil loss per mile of trail also revealed the mountain biking trails to have the lowest soil loss. White and others (2006) also examined trails predominantly used for mountain biking in five ecological regions of the Southwest along 163 miles of trail. Two trail condition indicators, tread width and maximum incision, were assessed at each sample point. Results show that erosion and tread width on these trails differed little in comparison to other shared-use trails that receive little or no mountain biking.

Goeft and Alder (2001) evaluated the resource impacts of mountain biking on a recreational trail and racing track in Australia over a 12-month period. A variety of trail condition indicators were assessed on new and older trail segments with uphill, downhill, and flat trail sections. Results found that trail slope, age, and time were significant erosion factors, and that downhill slopes and curves were the most susceptible to erosion. New trails experienced greater amounts of soil compaction, but all trails exhibited both compaction and loosening of soils over time. The width of the recreational trail varied over time, with no consistent trend, while the width of the racing trail grew following events but exhibited net recovery over time. Impacts were confined to the trail tread, with minimal disturbance of trailside vegetation.

Cessford (1995) provides a comprehensive, though dated, summary of trail impacts with a focus on mountain biking. Of particular interest is his summary of the two types of forces exerted by bike tires on soil surfaces: The downward compaction force from the weight of the rider and bike, and the rotational shearing force from the turning rear wheel. Mountain bikers generate the greatest torque, with potential tread abrasion due to slippage, during uphill travel. However, the torque possible from muscle power is far less than that from a motorcycle, so wheel slippage and abrasion occur only on wet or loose surfaces. Tread impact associated with downhill travel is generally minimal due to the lack of torque and lower ground pressures. Exceptions include when riders brake hard enough to cause skidding, which displaces soil downslope, or bank at higher speeds around turns, which displaces soil to the outside of the turn. Impacts in flatter terrain are also generally minimal, except when soils are wet or uncompacted and rutting occurs.

White and others (2006) and Hendricks (1997) note that the majority of mountain biking research has focused on social issues, such as conflicts between trail users. These studies report increased conflict between hikers and mountain bikers primarily related to safety, given the greater speed of mountain bikers, particularly in forested settings with blind curves.

Tread Hardening

A number of tread hardening techniques may also be employed during original trail construction or during subsequent reconstruction and maintenance. Wet soils can be capped with crushed stone or excavated and replaced with crushed stone or other suitable fill material (Meyer 2002). Large stones are often used to form a stable base in wet soils, often capped with crushed stone and “crusher fines” or “whin dust” (screened material less than ¼ in) to provide a smoother tread surface that can be periodically hand or machine graded (Scottish Natural Heritage 2000). In Scotland, aggregate placed on top of geosynthetics has been used to effectively “float” trails over deep peat substrates (Bayfield & Aitken 1992, Footpath Trust 1999).

Even soils that are not seasonally wet may require capping with crushed stone to create a tread surface capable of sustaining heavy horse or motorized traffic. Trail surfacing provides two basic functions: it can enhance the trafficability and/or it can reduce erosion. Surfacing such as gravel is commonly used to enhance the trafficability of wet areas. Unfortunately, applications of gravel to trafficked wet areas can be lost as the gravel in churned to lower horizons. Use of larger stone or geotextile underneath the stone can deter this problem and greatly enhance the longevity of the trail. As previously mentioned, gravel can be used to protect bare soil from the erosive forces of water. In general, larger sizes of stone withstand traffic better, but smaller stones provide a smoother walking or traveling surface. Honeycomb geotextiles can also be used to retain gravel in flatter terrain. This method will retain the stone better but when used in sloping terrain it becomes exposed to and deteriorates in sunlight or is broken by hoofed traffic. When wet soils do need to be traversed, constructing parallel drainage ditches can be effective by draining water away from tread soils. More expensive options include turnpike and puncheon construction, which elevate the trail above wet ground (Steinholtz & Vachowski 2001).

Gravel use is common and effective for erosion control is more sloping terrain, but steeper sections tend to lose gravel rapidly, particularly as traffic moves loose stones downhill. Crushed stone (aggregate) will migrate downslope at unacceptable rates when applied to trail grades over 8% (Footpath Trust 1999). Trail segments with steeper grades should be rerouted wherever possible, particularly those receiving moderate to heavy use. When topographic features prohibit relocation more extensive tread work involving drainage and armoring with larger rock (stone pitching) are essential to prevent excessive erosion. Using larger stone in combination with a "sheepfoot" roller packer can pack the stone so that it is less likely to erode.

Other options for steep slopes include aggregate with rock anchors positioned flush with the path surface to prevent the downward migration of gravel (Footpath Trust 1999). Rounded (natural) gravel has little cohesion, requiring closely spaced anchors and limiting its application on steeper grades. Angular crushed stone with crusher fines included contains a mix of particle sizes that pack tightly to form a hard durable surface when dry. With a sufficient number of stone anchors and adequate drainage, crushed stone can be applied to slopes up to 16% (Bayfield & Aitken 1992, Footpath Trust 1999). Stone pitched paths, consisting of well-anchored rockwork across the entire tread surface, are another alternative for steep slopes. Trails with low slope alignment angles must have extensive rockwork armoring with little exposed soil or severe erosion is inevitable. Overall, the best solution is to locate and construct trails of less than 10% grade so that standard gravel applications will suffice.

Kochenderfer and Helvey (1987) evaluated 11 sections of forest road that were used for both timber harvesting and recreation. Some sections were graveled, and other sections had bare soil. They monitored erosion for 4 years and concluded that road sections having bare soil averaged almost 50 ton/acre/year of erosion and that graveled sections eroded at 6 tons/acre/year.

The Use Impact Relationship

Research indicates that visitor activities occurring on native vegetation can cause fairly rapid impacts. Most forest plant communities have herbaceous ground vegetation that is neither resistant nor resilient to trampling. Even open meadow vegetation with resistant grasses and sedges cannot sustain substantial or intensive levels of persistent or long-term traffic (Marion 2016, Marion et al. 2016). A large body of recreation ecology research reveals that the relationship between amount of visitor traffic and amount of impact to vegetation and soils is asymptotic (Cole 1995a, Marion 2016, Monz et al. 2013). This relationship is examined in greater depth in this section as it has significant implications for the management of visitor use within protected areas.

Above a relatively low threshold of trampling pressure, impacts occur rapidly as plants and organic litter are trampled and lost (Marion et al. 2016). This is followed by the exposure and loss of organic soil and compaction of underlying mineral soil. Once the majority of vegetation and litter cover have been lost, soil compaction occurs quickly and further increases in visitation result in diminishing amounts of vegetation and soil impact. At this point a fundamental management challenge is to constrain the aggregate areal extent of impact by limiting the width of formal trails and creation of informal trails.

Trail and experimental trampling studies have consistently documented this nonlinear asymptotic use-impact relationship between amount of recreational trampling and most types of vegetation and soil impacts (Cole 1995a,b, Hammitt et al. 2015, Monz et al. 2010). This asymptotic use-impact relationship has also been consistently documented in other countries with diverse vegetation and soil types (Barros & Pickering 2015, Hill & Pickering 2009, Littlemore & Barker 2001, Newsome et al. 2013).

The implications of this asymptotic use-impact relationship are that reducing use on well-established moderate-to high-use trails is unlikely to appreciably diminish vegetation and soil impacts; it is an ineffective strategy unless *very* substantial reductions in use occur (Marion 2016). In contrast, limiting use within low use areas, where impacts occur rapidly, can lead to substantial reductions in vegetation and soil impact. More specifically, it is effective only at relatively low levels of traffic, generally between 50 to 250 passes per year along a trail (Leung & Marion 2000, Cole 1995a,b,c).

There are a few important caveats to these general findings. The timing and location of use influence the amount of impact that the same number of visitors can have. For example, visitors have substantially greater impact on wet soils compared to dry soils, or on growing plants than on the senesced fall/winter plant remnants. Visitors can also travel or recreate on durable non-vegetated substrates such as gravel, rock, and snow, or artificial substrates like wood and rockwork on trails that support substantial traffic with very limited impact. Finally, Monz et al. (2013) notes the possibility of alternative use-impact response curves for other types of impact, including wildlife responses and aquatic systems that may have differing management implications.

Carrying Capacity Decision-Making

As reviewed in Marion (2016), the traditional body of knowledge developed by managers and scientists to address the negative impacts of visitation to resource and social conditions was termed “carrying capacity.” While the early management activity and literature focused on defining a numeric limit on visitor numbers below which resource and social conditions would be protected, several decades of management and research experience have exemplified the curvilinear use-impact relationship, demonstrating that amount of use is strongly correlated with the magnitude of resource impact only at low levels of use. Thus, limiting use is often an ineffective means for achieving resource protection objectives on moderate to high use trails and recreation sites, prompting the need to consider a diverse array of alternative considerations and actions (Leung & Marion 2000, Manning 2007, 2011, Wagar 1964). This is widely accepted in the context of minimizing resource impacts, though court challenges based on dated laws specifying the role that numerical limits should play in carrying capacity planning continue to focus management attention on visitor numbers (Capacity Work Group 2010, Graefe et al. 2011, Whittaker et al. 2011).

Instead of an emphasis on amount of use, research increasingly points to strong influence of a diverse array of use-related, managerial, and environmental factors affecting resource and social/experiential impacts (Marion & Leung 2004, Marion 2016, Marion et al. 2016):

- Use-related factors include attributes like the number visitors, the types of activities they are engaged in, the locations where activities occur, and the extent to which visitors know and apply low impact behaviors.
- Managerial factors include the presence and physical size/capacities of facilities (e.g., formal trails and their widths), the types of facilities and level of containment (e.g., trails in flat vs. sloping terrain, presence of containment borders), durability of substrates (e.g., vegetation, soil, wood, gravel, rock), regulations and enforcement, existence/efficacy of low impact education efforts.
- Environmental factors include the resistance and resiliency (ability to recover) of soils and vegetation, weather (vegetation and soil impacts increase with increasing soil moisture), topography, and to the presence of water resources and wildlife, and their sensitivity to human impact.

Particularly influential factors that minimize resource impacts demonstrated in scientific studies include:

1) sustainable siting and designs for trails relative to topography and soil/vegetation type,
2) actions that spatially concentrate activity to a limited “footprint” of disturbance, and
3) regulations and persuasive communication that promote low impact behaviors and reduce the number of People At One Time (PAOT) within single locations or small areas (Cole 1989, Hammitt et al. 2015, Leung and Marion 2000, Marion 2014).

Similar findings have been identified for social impacts like crowding and conflict, such as the significant influence of visitor motives, use type, user behavior, and the density of use and location or timing of encounters (Manning 2007, 2011).

NPS *Management Policies* (2006) defines carrying capacity as, “the type and level of visitor use that can be accommodated while sustaining the desired resource and visitor experience conditions in the park. By identifying and staying within carrying capacities, superintendents can prevent park uses that may unacceptably impact the resources and values for which the parks were established.” These policies additionally state that:

> *“When making decisions about carrying capacity, superintendents must utilize the best available natural and social science and other information, and maintain a comprehensive administrative record relating*

to their decisions. The decision-making process should be based on desired resource conditions and visitor experiences for the area; quality indicators and standards that define the desired resource conditions and visitor experiences; and other factors that will lead to logical conclusions and the protection of park resources and values.

The general management planning process will determine the desired resource and visitor experience conditions that are the foundation for carrying capacity analysis and decision-making. If a general management plan is not current or complete, or if more detailed decision-making is required, a carrying capacity planning process … should be applied in an implementation plan or an amendment to an existing plan.

As use changes over time, superintendents must continue to decide if management actions are needed to keep use at acceptable and sustainable levels. If indicators and standards have been prescribed for an impact, the acceptable level is the prescribed standard. If indicators and standards do not exist, the superintendent must determine how much impact can be tolerated before management intervention is required. (Section 8.2.1).”

Many managers will already have considered or made carrying capacity decisions in a general management plan. The 1978 National Parks and Recreation Act (P.L. 95-625) requires the NPS to determine carrying capacities for each park as part of the process of developing management plans. Specifically, amendments to Public Law 91-383 (84 Stat. 824, 1970) require relevant NPS management plans to include “identification of and implementation commitments for visitor carrying capacities for all areas of the unit” and determination of whether park visitation patterns are consistent with social and ecological carrying capacities.

Carrying capacity has long provided the predominant framework for planning and management decision-making that addresses the protection of natural resource and social conditions (Manning 2011). Over time, managers have shifted from a narrow focus on numeric carrying capacity to a broader decision-making framework that incorporates a more comprehensive array of management strategies and actions (Graefe et al. 2011). As directed by the NPS *Management Policies*, carrying capacity determination and management should be developed through an adaptive management process. In its simplest form adaptive management means learning by doing and adapting based on what’s learned (Williams and Brown 2012). A more formal definition is “… flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process” (National Research Council 2004).

Visitor Use Management

Recently, six U.S. federal agencies – the Bureau of Land Management, Forest Service, National Oceanic and Atmospheric Administration, NPS, U.S. Army Corps of Engineers, and U.S. Fish and Wildlife Service – formed an Interagency Visitor Use Management Council (IVUMC; http://visitorusemanagement.nps.gov/) to “increase awareness of and commitment to proactive, professional, and science-based visitor use management on federally-managed lands and waters.” They have developed a new Visitor Use Management (VUM) framework focused on managing visitor use to protect resources and provide high quality experiences, with numeric carrying capacity determinations included as an option when needed or required by law. Its attributes include prescriptive management objectives that define desired resource and social conditions, selection of indicators and thresholds (standards) specifying the limits of acceptable change, monitoring to compare current conditions to standards, and implementation and evaluation of corrective management actions.

Comprehensive guidance for implementing VUM is available at the IVUMC website, including several publications. They define VUM as the “proactive and adaptive process for managing characteristics of visitor use and the natural and managerial setting using a variety of strategies and tools to achieve and maintain desired resource conditions and visitor experiences." They emphasize that managing visitor access and use for recreational benefits and resource protection is inherently complex, requiring consideration of natural and social science studies, management experience, and professional judgment. Guidance for implementing VUM, depicted in Figure 3 was released in 2016 for use by all federal land management agencies for managing visitor use and carrying capacity. It is expected to be widely adopted across U.S. federally protected natural areas.

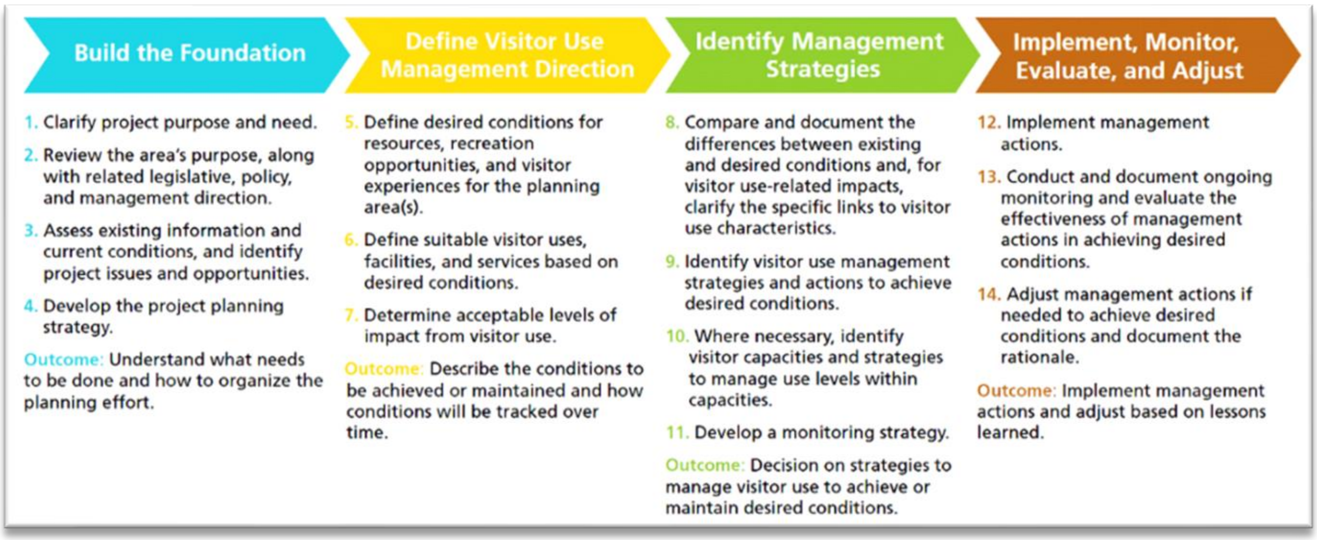


Figure 3. The Visitor Use Management (VUM) framework recommended by the IVUMC for adaptively managing visitor use and carrying capacities in protected natural areas.

VUM incorporates lessons learned from agency experience to address past planning and legal challenges (Graefe et al. 2011, Whittaker et al. 2011). VUM incorporates additional guidance for carrying capacity decision-making when needed, but its primary focus is on visitor use management topics. Because VUM provides a defensible and adaptive management decision-making framework, it offers an effective and efficient process for evaluating and managing all aspects of visitor use, including determinations of carrying capacities.

The *Visitor Use Management Framework: A Guide to Providing Sustainable Outdoor Recreation* (IVUMC 2016) describes the VUM framework in more detail:

> *"This framework will enhance consistency in visitor use management on federally managed lands and waters, since it will be used by all agencies. The elements of this framework are broadly applicable to all visitor use management issues and opportunities. The framework is applicable across a wide spectrum of situations that vary in spatial extent and complexity, from site-specific decisions to large-scale comprehensive management plans. This framework may also be used across multiple, tiered projects and may be applied to internally driven activities (e.g., analyzing a management action), as well as externally driven activities (e.g., a permit request or an action by another agency)."*

The strengths of this framework are that it is "iterative, adaptable and flexible" to a variety of environmental settings and scales (IVUMC 2016), and that it embraces a "sliding scale" concept to optimize the efficiency of the framework's application:

> *"Applying different levels of analysis can be likened to using a sliding scale in which one end of the scale requires a low level of analysis and the other a high level of analysis. In either case, the analysis still must satisfy all framework requirements. It is the investment of time and resources that varies along the sliding*

scale, not the elements in the framework; the same fundamental elements are used regardless of the placement on the scale.

This sliding scale approach is consistent with direction given in the Council on Environmental Quality's interpretation of NEPA. This approach implements the instruction that agency NEPA documents shall "focus on significant environmental issues and alternatives" (40 CFR 1502.1) and shall discuss impacts "in proportion to their significance" (40 CFR 1502.2(b)). (Note: Under the Council on Environmental Quality's regulations and judicial rulings, the degree to which environmental effects are likely to be controversial with respect to technical issues is a factor in determining significance.)"

Applying this "sliding scale of analysis" seeks to match the investment made in analysis with the level of complexity and risk associated with the issues being addressed. For this reason, the VUM framework can provide structure to trail-wide or location-specific resource and social impacts, or to the management of temporal problems like the thru-hiker bubble or special events.

IVUMC places substantial emphasis on "proactive, professional, and science-based visitor use management on federally-managed lands and waters." Managers who make proactive decisions should be prepared to prove the viability of their strategies, or risk public disapproval or even legal action against the agency. Resource and visitor use monitoring programs provide the means for such demonstrations. Current legislation and agency documents establish mandates for monitoring, which is reviewed in the following section (Marion 1991). Recent legislative mandates allow managers more latitude to make proactive decisions that can be defended in the court of law or public opinion, when necessary.

Monitoring Visitor Impacts

This section reviews relevant NPS laws and management policies pertaining to resource monitoring. Formal or informal monitoring is generally conducted to evaluate the occurrence and acceptability of resource impacts associated with visitor use and is generally an essential component of decision-making frameworks like VUM.

The National Parks Omnibus Management Act of 1998 established a framework for fully integrating natural resource monitoring and other science activities into the management processes of the National Park System. The Act charges the Secretary of the Interior to:

"develop a program of inventory and monitoring of National Park System resources to establish baseline information and to provide information on the long-term trends in the condition of National Park System resources."

Congress reinforced the message of the National Parks Omnibus Management Act of 1998 in its text of the FY 2000 Appropriations bill:

"A major part of protecting [park] resources is knowing what they are, where they are, how they interact with their environment and what condition they are in. This involves a serious commitment from the leadership of the National Park Service to insist that the superintendents carry out a systematic, consistent, professional inventory and monitoring program, along with other scientific activities, that is regularly updated to ensure that the Service makes sound resource decisions based on sound scientific data."

Relative to the need for balancing visitor use and resource impacts, the NPS *Management Policies* (2006) state that:

"The "fundamental purpose" of the national park system, established by the Organic Act and reaffirmed by the General Authorities Act, as amended, begins with a mandate to conserve park resources and values. This mandate is independent of the separate prohibition on impairment, and so applies all the time, with respect to all park resources and values, even when there is no risk that any park resources or values may be impaired. NPS managers must always seek ways to avoid, or to minimize to the greatest degree practicable, adverse impacts on park resources and values.

Monitoring programs are also explicitly authorized in Section 4.1 of the *Management Policies*:

"Natural systems in the national park system, and the human influences upon them, will be monitored to detect change. The Service will use the results of monitoring and research to understand the detected change and to develop appropriate management actions". (*Section 4.1*)

"Further, The Service will:

- *Identify, acquire, and interpret needed inventory, monitoring, and research, including applicable traditional knowledge, to obtain information and data that will help park managers accomplish park management objectives provided for in law and planning documents.*
- *Define, assemble, and synthesize comprehensive baseline inventory data describing the natural resources under its stewardship, and identify the processes that influence those resources.*
- *Use qualitative and quantitative techniques to monitor key aspects of resources and processes at regular intervals.*
- *Analyze the resulting information to detect or predict changes, including interrelationships with visitor carrying capacities, that may require management intervention, and to provide reference points for comparison with other environments and time frames.*
- *Use the resulting information to maintain-and, where necessary, restore-the integrity of natural systems" (Section 4.2.1).*

Thus, relative to visitor use management, park managers must evaluate the types and extent of resource impacts associated with visitor activities and determine to what extent they are unacceptable and constitute impairment. Further, managers must seek to avoid or limit any form of resource impact, including those judged to fall short of impairment. Visitor impact monitoring programs can assist managers in making objective evaluations of impact acceptability and impairment and in selecting effective impact management practices by providing quantitative documentation of the types and extent of specific impacts to natural resources.

NPS has directives for carrying capacity decision-making, adaptive management, and monitoring as a tool to accomplish management goals. If managers are to avoid unacceptable visitor impacts to the park resources and experiences it is clear they should be focused, purposeful and proactive in their decisions. The application of the VUM framework offers an efficient structured process that can guide decisions. Again, the sliding scale of analysis offered by VUM means managers can provide any level of structure needed for evaluating and managing visitor impacts on a scale appropriate to the problem.

Visitor impact monitoring protocols are often developed by scientists to provide accurate and precise data on physical attributes (e.g., trail width), vegetation cover, and soil exposure, loss, or muddiness (Marion 1991, Cole 2006). Thorough reviews of the visitor impact monitoring literature, assessment methods, and examples of monitoring indicators can be found in publications for formal trails (Dixon et al. 2004, Hawes et al. 2006, Hill and Pickering 2009, Marion and Carr 2009, Marion and Leung 2011, Marion et al. 2006, 2011a) and informal (visitor-created) trails (Leung and Louie 2008, Leung et al. 2011, Marion and Wimpey 2011, Marion et al. 2011a, b). Many of the cited publications are reports that contain full sets of field assessment protocols that can be applied or adapted into visitor impact monitoring programs. We note that monitoring data can provide beneficial information needed for adaptive management decision-making.

STUDY AREA

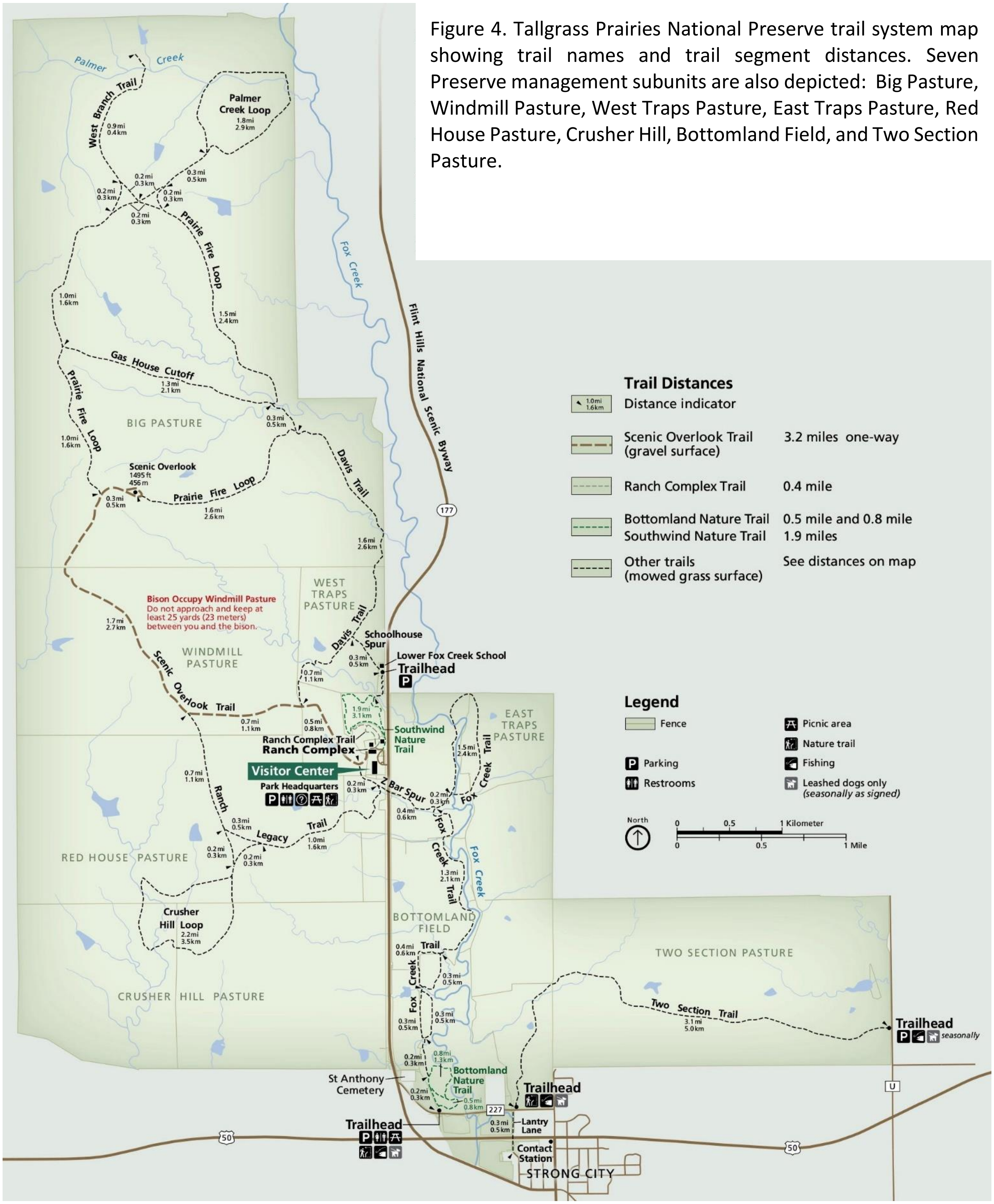
Tallgrass Prairie National Preserve (TPNP), located in the Flint Hills region of east-central Kansas, was created in 1996 to preserve 10,894 acres of a nationally significant example of the once vast tallgrass ecosystem. This unit is managed by the National Park Service (NPS), though the land was purchased in 1994 by the National Park Trust, which sold 10,862 acres to The Nature Conservancy (TNC) in 2005. TNC is a global environmental non-profit organization that specializes in the protection and management of unique, irreplaceable landscapes and biological resources. TNC retains and collaboratively manages the Preserve's lands with the NPS, including interpretation and public visitation of the Preserve, the story of its ranching legacy, historic ranch buildings, American Indian history, diverse tallgrass prairie ecosystem, cattle grazing, and a small herd of bison introduced in 2009. TPNP has over 30 miles of maintained hiking trails (Figure 4), most of which are old grassy ranching roads open to the public, though overnight camping is not available. The park offers a visitor center, bus tours, self-guided tours, and access to several historic structures.

The Flint Hills region consists of alternating layers of shale and limestone, including concentrations of chert (flint) that often accumulate at the surface. The erosion-resistant limestone and flint form flatter benches on the hillsides and cap the hilltops, intermixed with thin gravelly soils of decomposed shale. The rocky exposures, steeper slopes, and thin gravelly soils are what prevented much of the Flint Hills region from being plowed for intensive crop cultivation and preserved a diverse array of native tallgrass prairie plants. While some bottomland prairie areas have thicker river-deposited soils that were cultivated, most of the land has a long history of cattle grazing.

As with most protected natural areas, TPNP's current trail and primitive road system consists of a collection of "legacy" routes, including trails and old dirt roads of varying origins. Most of the existing road and trail infrastructure was developed to support ranching objectives and was not laid out by a professional with knowledge of sustainable trail design or in support of current recreational or administrative objectives. This proposed research project is designed to address current trail system planning and management deficiencies.

Recreational uses include exploring the visitor center to learn about the Preserve's prairie ecosystem and related geology, soils, and vegetation, or taking a self-guided tour of the central ranch buildings and historic home. The primary recreational activities away from the developed areas is hiking through the pastures on the Preserve's trail system. Bicycling and horseback riding are not currently permitted. Dog walking on leash is permitted. Some visitors walk or jog on the Bottomland Trails, some of which are accessible. There are also two nature trails with interpretive signs. Hiking out the Scenic Overlook Trail to see prairie vistas and buffalo is one of the more popular hikes, or when running, taking a bus on this graveled road through the buffalo pasture to the Scenic Overlook. Fishing in three of the Preserve's ponds and Fox Creek are also permitted (catch-and-release).

Figure 4. Tallgrass Prairies National Preserve trail system map showing trail names and trail segment distances. Seven Preserve management subunits are also depicted: Big Pasture, Windmill Pasture, West Traps Pasture, East Traps Pasture, Red House Pasture, Crusher Hill, Bottomland Field, and Two Section Pasture.



STUDY METHODS

Field staff visited the park to conduct fieldwork from May 18-25, 2021. Kristen Hase, Natural Resource Program Manager for the Preserve, was our principal contact and partner on this project. Prior to initiating fieldwork, we met with park staff to describe the project, our protocols, and tour a sample of the Preserve trail system. We were also provided with a six-wheel drive Ranger for negotiating the muddy Preserve roads/trails as our survey work occurred during an unusually rainy period and the trail system was exceptionally muddy.

A fieldwork trail assessment manual was developed and modified both prior to and as field work was conducted (Appendix 1). Data were collected with four separate forms:

General Comments Form: Used to collect descriptive information about each trail's environmental and social/experiential sustainability, current and potential trail uses, and general conditions or needs. A section on accessibility also assessed information about the tread surface, typical trail width, slope, resting spots, passing spaces, and barriers.

Transect Form: Used to assess both "typical" and "problem" trail segments. Representative "typical" transects are designed to characterize general trail segment conditions, with additional records added to characterize the trail if conditions change (e.g., a section of tread with natural soil substrates to a section where ruts have been filled with gravel). When significant tread degradation occurs the "problem" transects are also added to identify the type of degradation, frequency, locations, lineal length, and corrective suggestions so that management can efficiently plan and execute corrective solutions and evaluate their efficacy over time. Three core types of trail impacts will be evaluated: excessive soil loss, muddiness, and widening, each with a recorded begin and end point and comment field. Problem transects are only assessed when one of the three problems affects more than ten lineal feet of the tread. This form also collected information about each trail's design characteristics, including trail grade, landform grade, trail slope alignment angle (e.g., trail alignment relative to the contour line (90^{o}) vs. the fall line (0^{o}), secondary treads, tread width, maximum incision, tread drainage features and types of features, tread condition characteristics (the percentages of nine types), and transect photos.

Trail Feature Inventory Form: Used to assess seven types of features: stream crossings, culverts, signs, gates, trail markers, drainage features, and benches. Photos were taken of each feature and comments on their condition, sustainability, and suggestions were recorded.

Informal Trail Form: Used to assess informal (visitor-created) trails, including mapping them with a Garmin GPS unit, and assessing their typical width, condition class in five descriptive categories, and comments.

A Fulcrum smartphone app was developed for recording these data using the four forms (Figure 5). Multiple records could be collected within the phone app and every time a record was opened the phone app automatically collected a date, time, and GPS location using the phone's GPS (locational accuracy about 20 ft). Thus, all data records and photos are georeferenced and can be examined within a GIS database, which will be provided to Preserve staff. Some of the fieldwork was conducted by driving surveys using the Ranger but we found it more efficient after the first few days to split up and assess trails with walking surveys to cover all the terrain more efficiently.

Data were exported to Excel files and imported into GIS software for creating tables, maps, figures, and other geospatial calculations, such as mean trail grades, trail slope ratios, and watershed sizes for each stream crossing. Data presented on trail and landform grades were developed from GIS calculations by overlaying the park trail layer with an accurate LiDAR-derived Digital Elevation Model (1x1m resolution). Some editing of the trail alignments was needed to edit/move the trail centerlines to match the visible LiDAR trail alignments. For trail grades we used the density tool to add vertices to the trail centerline every 10 ft and obtained elevation "z" values for the vertices. These were used to calculate trail grades for each 10 ft trail segment. For landform grades we used the Surface Parameters Tool in ArcGIS Pro to get the interpolated landform slope using a "neighborhood" distance of 15 ft from the center of each 10 ft trail segment. Thus, our trail grade and landform grade calculations included in all report tables are derived from these accurate GIS calculations (not from fieldwork), averaged from an exceptionally large number of 10 ft trail segment values.

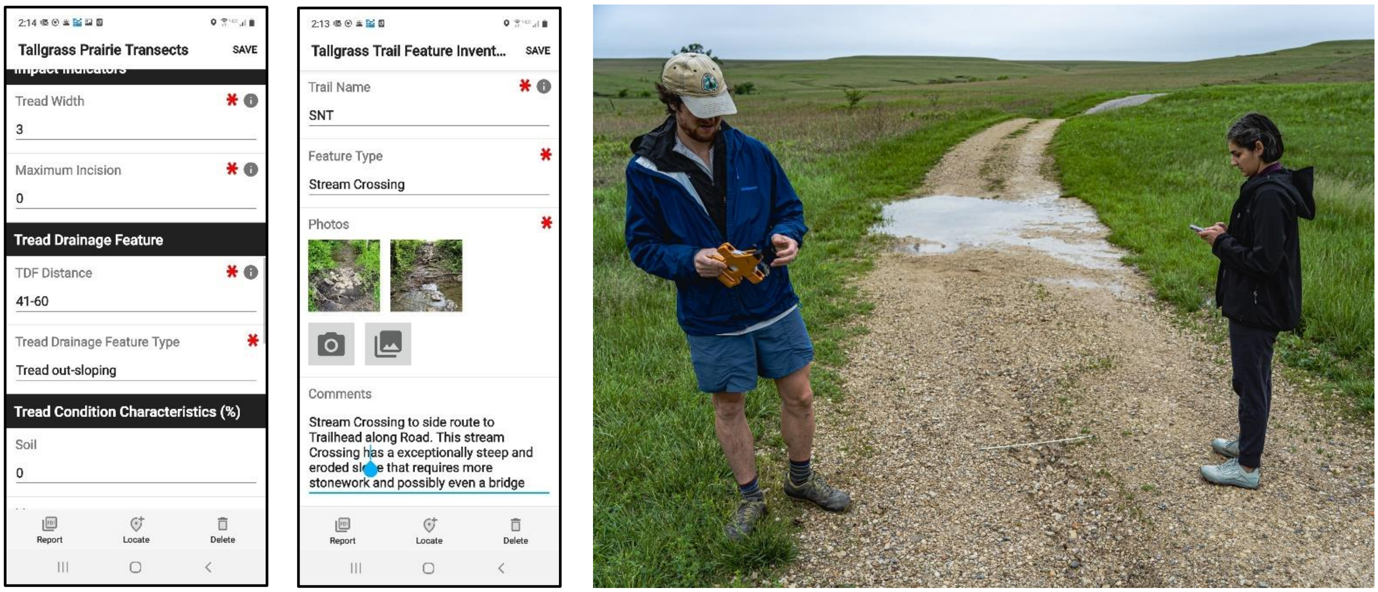


Figure 5. Examples of the Fulcrum phone app data entry forms developed for recording field data. Forms allow for the input of categorical data, metric counts or measures, text comments, and photographs.

RESULTS

All Trails Combined

Trail Grade

Field staff surveyed eighteen trails with an aggregate length of 31.75 miles (Table 2). The trail system consists primarily of undeveloped "legacy" ranch roads (the Southwind, Bottomland, and Fox Creek Trails are the exceptions), most with treads on native prairie soil. Graveled trails include only the Bottomland Nature Trail (1.5 mi) and the Scenic Overlook Trail (3.2 mi). As noted in the Literature Review, trail grade is an important determinant of trail sustainability. Fully 51% of the Preserve's trail system has "flat" trail grades (Table 2), which are considered somewhat unsustainable because trail uses compact, displace, or erode soils to create ruts in tread substrates, which then collect and retain water to create muddiness during wet seasons. Additionally, trail users seeking to avoid mud can easily "move over" to expand trail boundaries in flat terrain, which can substantially increase the aggregate area of trail impact.

Some of the Preserve is indeed flat and it is not always possible to avoid traversing these areas. Graveling rutted treads is an effective management practice in these areas. However, sloping terrain is available in many areas but was historically rarely used within the Preserve to develop more sustainable side-hill trail alignments. It is important to note that serious resource impacts have *not* occurred along many Preserve trails with somewhat unsustainable alignments due to their relatively low use, particularly during wet periods, and to the high trampling resistance and resilience of the abundant prairie grasses (these and other factors are discussed later).

Slightly sloped trail grades (2-5%) are optimal and 31.2% of the trail system falls in this category; even trail grades of 5-10% (13.0% of the trail system) are acceptable if trails are side-hill aligned and maintained to keep water off tread substrates. Fortunately, a relatively small percentage of the trail system has steep trail grades (10-15%, 3.6% of the trail system), or very steep grades (>15%, 1.3% of the trail system). However, even short steep trail segments can be highly detrimental if they erode substantial amounts of soil into waterways.

Table 2. All trails combined: trail grade categories (miles and percent).

<table>
<tr><th>Trail Grade (%)</th><th>Miles</th><th>Percent</th><td rowspan="7">Sustainability: Flat trail grades (0-2%) are problematic as incised treads retain water that can't be drained. Problems with trail muddiness and widening are common, with no easy remedies. Trails with lower grades (2-5%) are optimal. Intermediate grades (5-10%) are also acceptable and soil loss can be minimized with side-hill alignments and adequate water drainage from treads. More steeply graded trails (10-15%) must have side-hill alignments and often require rock in tread substrates and/or enhanced water drainage design and sustained maintenance work to prevent soil loss. Exceptionally steep trail grades (>15%) are rarely recommended and require treads to be armored with rock pitching or steps to prevent substantial soil loss.</td></tr>
<tr><td>0-2</td><td>16.3</td><td>51.0</td></tr>
<tr><td>2.1 - 5</td><td>9.9</td><td>31.2</td></tr>
<tr><td>5.1 - 10</td><td>4.1</td><td>13.0</td></tr>
<tr><td>10.1 - 15</td><td>1.1</td><td>3.6</td></tr>
<tr><td>15+</td><td>0.4</td><td>1.3</td></tr>
<tr><td>All</td><td>31.8</td><td>100</td></tr>
</table>

Trail Alignment with Landform Grade

A trail's alignment relative to the prevailing landform grade is also a critical sustainability attribute. As illustrated in Figure 1, side-hill trails are highly sustainable because their steeper side-slopes actively "center" traffic on the tread and allow easy tread drainage to lower slopes. Sustainably designed side-hill trails have a superior ease of drainage allowing them to be more "hydrologically invisible" in shedding rather than capturing and transporting surface water flow along their treads. In sharp contrast, as trail alignments approach the fall-line (perpendicular to the contour line) they become increasingly unsustainable because water captured by their concave or rutted treads cannot be removed, gravity carries it down treads and erodes soil at rates commensurate with the steepness of the trail grade (Figure 1).

As explained in the Literature Review, slope ratio (SR) can inform PA managers about a trail's alignment relative to landform grades (IMBA 2004). Sustainable side-hill trails aligned close to the contour line have SR values close to 0, while unsustainable fall-line trails have SR values closer to 1. An improved approach is to visually examine how the Preserve's trail system mileage and proportions array across a "triangle table" of trail grade and landform grade categories, presented in Table 3. The diagonal cells in this table include those closest to the fall-line with high SR values close to 1, while the increasingly distant cells to the upper right reflect side-hill trails closer to the contour line with low SR values close to 0.

We have developed and applied a color-coding scheme (Table 4) ranging from 1 (highly sustainable) to 6 (highly unsustainable) to Table 3 cells to further illustrate "approximate" levels of sustainability as an aid in understanding these fundamental trail alignment relationships with trail and landform grades. Since we have already described the influence of trail grade, we will discuss this table with a focus on landform grade, along with salient interactions. The first cell in Table 3 reveals that 19.8% of the trail system lies in flat terrain (trail and landform grades of 0-2%), where trails will retain water during wet periods that can't be drained (rated level 5 for sustainability). Flat terrain allows rutting from soil compaction and displacement to retain water, creating muddiness and trail widening due to the lack of topographic barriers to traveling off-trail. A Preserve photo in Figure 6B illustrates these flat terrain trails and types of impacts. If seasonal muddiness is deemed environmentally or experientially unacceptable, potential solutions include tread armoring, seasonal closure, or relocation to sloping terrain.

In the landform grade of 2-5%, both cells were rated a low level 4 for sustainability because trail alignments are close to the fall-line (difficult to drain) or trail grades are too flat (high potential for rutted treads to retain water). Unfortunately, 40.8% of the Preserve's trail system occurs in these two cells. Again, when possible, the best solution is to shift trails to steeper landform grades that allow greater opportunities for intermediate side-hill alignments between the contour and fall-lines.

Landform grades of 5-10% finally begin to offer limited opportunities for gently sloping trail grades with side-hill designs that allow water to be drained downhill from treads. Side-hill cut-and-fill "bench" constructed treads are necessary, as opposed to simply creating the trail with traffic. Water drainage is most sustainably achieved by constructing an appropriate density of tread grade-reversals to drain all water from the tread with little need for continuing maintenance (Figure 2). About a quarter (27.7%) of the Preserve's trails are in this landscape slope category, with 10.2% rated level 3 for sustainability. A Preserve photo of a fall-line trail up a 5-10% grade (Figure 6C, sustainability rating 5, illustrates the potential for erosion if this type of alignment received sufficiently heavy use to remove vegetation cover, particularly during wet periods. Also note that this trail swings right to a sustainable side-hill alignment (sustainability rating 3) higher on the slope.

Landform grades of 10-15% are more optimal as they allow two categories of sustainable side-hill trails. Unfortunately, only 1.5% of the Preserve's current trails fall into the cell with optimal trail grades (2-5%) and steeper side-slope grades (10-15%), sufficiently steep to keep most traffic centered on the trail. In contrast, 2.4% of Preserve trails are in the unsustainable (rating 5) category of fall-line trails with 10-15% landform and trail grades. In the final landform grade column of 15+% there are also two categories of sustainable side-hill trails, though they account for only 1.1% of the Preserve's trails. As noted, trail grades above 10% are less sustainable and this column includes fall-aligned trails with trail/landform grades that exceed 15% (the least sustainable category, with 1.3% of Preserve trails). A photo illustrating this "worst" possible alignment is included as Figure 6D, with a sustainability rating of 6.

A summary table for the sustainability rating scheme is included as Table 4, presenting the percentage of the Preserve's trail system within each "approximate" sustainability level. This suggests that only 15.6% of the Preserve system is sustainably aligned, a somewhat surprising finding given that the conditions of the Preserve trails are generally quite good. Coincidentally, 84.2% of the trail system is rated as unsustainable, though fully 52% is in the lowest unsustainable category 4 (Table 4), and only 1.3% is in the most concerning top category rated 6. Recognize that these sustainability ratings are focused only on trail attributes related to trail alignments, including trail grade and alignment to landform grades, with these ratings generated from GIS analyses. Maps showing the sustainability ratings applied to each trail are included in the Individual Trail Summaries section of this report. As noted in the Literature Review, tread substrates, drainage, vegetation type, and use-related factors are also influential and may either offset or worsen topographic settings and trail alignments. Graveling remains an option on more of the Preserve's trail system, prairie vegetation is highly resistant and resilient to impact, tread drainage could be further improved, and current administrative and visitor trail use is relatively low and could be curtailed during wet seasons.

Based on the current situation, we suggest a focus on mitigating the 1.3% of the Preserve trail system that is in the most concerning highly unsustainable category rated 6, the steepest and most fall-aligned trail segments, particularly those near stream crossings. Further evaluations and armoring of the less steep approaches to stream crossings is also suggested to prevent degrading water quality. Finally, we also note that it should be relatively easy to relocate additional non-sustainable trails in category 5 because those that are not graveled or in eroded condition would quickly recover to natural conditions. Doing so would prevent more substantial future impacts when trail system use increases.

Table 3. All trails combined: trail grade by landform grade categories (sum of miles and percent of total).

Trail Grade Categories (%)	Landform Grade Categories (%)											
	0 - 2		2.1 - 5		5.1 - 10		10.1 - 15		15+		All	
	Sum (mi)	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*	*Sum (mi)*	*% of Total*
0-2	6.3	19.8	7.1	22.5	2.7	8.5	0.4	1.3	0.1	0.3	16.3	51.3
2.1 - 5			5.9	18.3	3.2	10.2	0.5	1.5	0.1	0.4	9.9	31.1
5.1 - 10					2.8	8.9	0.9	2.8	0.2	0.7	4.1	12.9
10.1 - 15							0.7	2.4	0.3	1.1	1.1	3.5
15+									0.4	1.3	0.4	1.3
All	6.3	19.8	13.0	40.8	8.8	27.7	2.5	7.9	1.2	3.7	31.8	100
Color Coding	Sustainable:			*Low*	*3*	*2*	*1*	*High*				
	Unsustainable:			*Low*	*4*	*5*	*6*	*High*				

Table 4. The color-coded sustainability scale (1-6) with percentages of the entire trail system, including rating descriptions and rationales.

1 (0.4%)	**High Sustainability.** Side-hill trail alignments with a gentle grade (2-5%) in steep (>15%) landform grades with steep off-trail side-slopes that compel trail users to remain on the trail while facilitating tread drainage.
2 (2.2%)	**Moderate Sustainability**. Includes segments with gentle trail grades in moderately steep landform grades or moderate trail grades in very steep landform grades.
3 (13.0%)	**Low sustainability.** Side-hill alignments have optimal trail grades (2-10%) located in landform grades that are one category steeper. These alignments ascend the landform more steeply making tread drainage somewhat more challenging and less-steep side-slopes may allow some tread widening.
4 (52.0%)	**Unsustainable.** Fall-line trails with 5-15% trail and landform grades that inhibit drainage and allow tread widening, and steep trail grades in steep terrain (10-15%).
5 (32.2%)	**Moderately Unsustainable.** Trails in flat terrain (0-2%) due to poor drainage and susceptibility to tread widening, and fall-line trails in somewhat steeper 5-10% grade terrain where erosion easily occurs.
6 (1.3%)	**Highly Unsustainable.** Fall-line trails in very steep terrain (>15%) grades that will develop substantial erosion problems when vegetation cover is removed.

Figure 6. Photos illustrating a highly sustainable side-hill trail (gentle trail grade and steep landform grade) (A), a trail in flat terrain that can't be drained (susceptible to muddiness, rutting, and widening) (B), a non-sustainable fall-line trail segment (lower sections) and sustainable side-hill alignment (uppermost section) with intermediate landform slopes (C), and a very non-sustainable fall-line trail segment up a steep landform grade (D). Colors of letter blocks equate to sustainability color-coding in Table 3.

Mean and median values for trail grade, landform grade, and slope ratio are presented in Table 5. Examining the trail grade and landform values reveals the trails located in predominantly flat terrain: Bottomland Nature Trail, RLCH Connection Trail, Fox Creek Trail, and Ranch Legacy Trail (omitting the short connector trails). Trails located in the steepest terrain include: Southwind Nature Trail, Davis Trail, and the Palmer Creek Loop. Slope ratio values closer to 1 are least sustainable with alignments closer to the fall-line, suggesting the least sustainable trails are the Gas House Cutoff, West Branch Trail, Ranch Legacy, and Lantry Lane (Table 5). The most sustainable trails based on slope ratio are Southwind Nature Trail, Bottomland Nature Trail, Fox Creek, and Two Section. Given that most of the trails are situated in flatter terrain and that side-hill alignments are rare we shouldn't put too much emphasis on these characterizations based solely on slope ratio, which also do not penalize side-hill trails with nearly flat trail grades.

The distribution of trail grades for all trails is presented in Table 6, providing a more accurate method for identifying the trails with the steepest grades that should be examined for possible relocations. Both row percentage and actual lineal distances are provided for each trail. For example, for the 4.6 mile Fox Creek Trail, 63.6% (2.9 mi) is essentially flat (0-2% trail grade), while 1.5% (0.1 mi) has a grade of 15% or greater. Unfortunately,

Table 5. All trails by name, trail code, mean trail grade, landform grade, and slope ratio, and trail length.

Trail Name	Trail Grade (%)	Landform Grade (%)	Slope Ratio[1]	Trail Length
	Mean	*Mean*	*Mean*	*Sum*
Bottomland Nature Trail (BNT)	1.44	3.32	0.53	0.94
Crusher Hill Loop (CHL)	3.31	5.27	0.59	2.13
Davis Trail (DT)	3.65	6.35	0.58	2.24
Fox Creek Trail (FCT)	2.35	4.27	0.55	4.58
Gas House Cutoff (GHC)	3.31	4.75	0.70	1.31
Lantry Lane (LL)	3.46	4.25	0.63	0.24
Palmer Creek Loop (PCL)	3.90	6.61	0.57	2.26
Prairie Fire Loop (FPF)	3.05	4.97	0.60	5.18
Ranch Legacy (RLT)	2.42	3.47	0.65	2.15
RLCH Connection Trail[2]	1.53	2.71	0.57	0.47
Scenic Overlook Trail (SOT)	2.96	4.87	0.59	3.19
Schoolhouse Spur (SST)	1.89	3.90	0.49	0.27
Southwind Nature Trail (SNT)	5.16	10.86	0.49	1.74
Two Section Trail (TST)	2.70	4.81	0.55	3.17
WBPC Connection Trail[3]	4.22	7.56	0.58	0.20
WBPFL Connection Trail[4]	1.86	3.65	0.46	0.17
West Branch Trail (WBT)	3.19	4.43	0.66	1.10
Z Bar Spur (ZBS)	3.22	5.43	0.57	0.40
All	3.05	5.21	0.58	31.75

1 – Slope Ratio = trail grade/landform grade; fall-line trails have values close to 1, side-hill trails have values close to 0.
2 – Connector trail between Ranch Legacy and Crusher Hill Loop Trails.
3 – Connector trail between West Branch and Palmer Creek Trails.
4 – Connector trail between West Branch and Prairie Fire Loop Trails.

Table 6. All trails by trail grade categories (row percent and miles).

Trail	Trail Grade Categories					
	0-2	2.1-5	5.1-10	10.1-15	15+	All
	Row %/mi	*Row %/mi*	*Row %/mi*	*Row %/mi*	*Row %/mi*	*Row %/mi*
Bottomland Nature Trail	75.0 / 0.7	22.9 / 0.2	2.0 / 0	0 / 0	0 / 0	100 / 0.9
Crusher Hill Loop	45.1 / 1.0	29.6 / 0.6	20.6 / 0.4	4.2 / 0.1	0.4 / 0	100 / 2.1
Davis Trail	34.1 / 0.8	45.7 / 1.0	15.1 / 0.3	3.3 / 0.1	1.8 / 0	100 / 2.2
Fox Creek Trail	63.6 / 2.9	26.6 / 1.2	7.1 / 0.3	1.2 / 0.1	1.5 / 0.1	100 / 4.6
Gas House Cutoff	47.3 / 0.6	31.3 / 0.4	14.8 / 0.2	4.9 / 0.1	1.7 / 0	100 / 1.3
Lantry Lane	61.6 / 0.1	30.9 / 0.1	4.5 / 0	0 / 0	3.0 / 0	100 / 0.2
Palmer Creek Loop	46.8 / 1.1	28.4 / 0.6	15.6 / 0.4	6.5 / 0.1	2.7 / 0.1	100 / 2.3
Prairie Fire Loop	50.4 / 2.6	30.5 / 1.6	14.5 / 0.8	3.7 / 0.2	0.8 / 0	100 / 5.2
Ranch Legacy	58.6 / 1.3	28.8 / 0.6	10.1 / 0.2	2.1 / 0	0.4 / 0	100 / 2.2
RLCH Connection Trail	68.6 / 0.3	31.4 / 0.1	0 / 0	0 / 0	0 / 0	100 / 0.5
Scenic Overlook Trail	49.3 / 1.6	33.9 / 1.1	12.6 / 0.4	3.3 / 0.1	0.9 / 0	100 / 3.2
Schoolhouse Spur	56.4 / 0.2	40.2 / 0.1	3.4 / 0	0 / 0	0 / 0	100 / 0.3
Southwind Nature Trail	28.8 / 0.5	34.0 / 0.6	22.7 / 0.4	10.6 / 0.2	3.9 / 0.1	100 / 1.7
Two Section Trail	56.8 / 1.8	26.7 / 0.8	13.4 / 0.4	3.0 / 0.1	0.2 / 0	100 / 3.2
WBPC Connection Trail	18.8 / 0	49.1 / 0.1	30.4 / 0.1	1.7 / 0	0 / 0	100 / 0.2
WBPFL Connection Trail	68.3 / 0.1	24.1 / 0	6.4 / 0	1.1 / 0	0 / 0	100 / 0.2
West Branch Trail	45.7 / 0.5	37.7 / 0.4	10.6 / 0.1	3.7 / 0	2.3 / 0	100 / 1.1
Z Bar Spur	56.9 / 0.2	31.3 / 0.1	5.2 / 0	3.0 / 0	3.6 / 0	100 / 0.4
All	51.3 / 16.3	31.1 / 9.9	12.9 / 4.1	3.5 / 1.1	1.3 / 0.4	100 / 31.8

there are a few instances where steep trail grades occurred in riparian zones where eroded soils are entering streams (see photos for the Crusher Hill Loop and the Fox Creek Trail in a following section). Trails with at least 0.1 miles of grades >15% include the Fox Creek Trail, Palmer Creek Loop, and Southwind Nature Trail; only the Bottomland Nature Trail had no instances of grades >15%. The Southwind Nature Trail and the Prairie Fire Loop also had at least 0.2 miles of grades in the 10-15% category, with seven other trails having 0.1 miles in this category. Three trails had essentially flat grades (0-2%) for >60% of their mileage: Bottomland Nature Trail, RLCH Connection Trail, Fox Creek Trail, and Lantry Lane.

The percentage and mileage of trail within each of four trail slope ratio categories is presented in Table 7. The trails with the greatest mileage in the least sustainable "fall-line" category include the Prairie Fire Loop (2.1 mi), Fox Creek Trail (1.7 mi), Scenic Overlook Trail (1.2 mi), Two Section Trail (1.1 mi), and Ranch Legacy (1.0 mi). The most sustainable side-hill aligned trails based on mileage include the Fox Creek Trail (1.4 mi) and the Prairie Fire Loop (1.2 mi). However, recall that slope ratio does not reflect a negative "cost" for side-hill trail segments that are close to flat, which can retain water in concave or rutted sections that have poor tread drainage.

Table 7. All trails by trail slope ratio category (row percent and miles).

Trail	Trail Slope Ratio Category[1] 0-0.25	0.5-0.75	0.25-0.5	0.75-1	All
	Row %/mi	*Row %/mi*	*Row %/mi*	*Row %/mi*	*Row %/mi*
Bottomland Nature Trail	34.0 / 0.3	6.7 / 0.1	23.5 / 0.2	35.7 / 0.3	100 / 0.9
Crusher Hill Loop	22.2 / 0.5	17.7 / 0.4	22.8 / 0.5	37.3 / 0.8	100 / 2.1
Davis Trail	21.4 / 0.5	18.4 / 0.4	26.1 / 0.6	34.1 / 0.8	100 / 2.2
Fox Creek Trail	30.1 / 1.4	9.9 / 0.5	23.6 / 1.1	36.4 / 1.7	100 / 4.6
Gas House Cutoff	12.9 / 0.2	16.8 / 0.2	21.2 / 0.3	49.1 / 0.6	100 / 1.3
Lantry Lane	24.2 / 0.1	11.0 / 0	16.6 / 0	48.2 / 0.1	100 / 0.2
Palmer Creek Loop	22.9 / 0.5	19.4 / 0.4	25.3 / 0.6	32.3 / 0.7	100 / 2.3
Prairie Fire Loop	23.7 / 1.2	13.9 / 0.7	21.1 / 1.1	41.4 / 2.1	100 / 5.2
Ranch Legacy	21.4 / 0.5	10.6 / 0.2	19.5 / 0.4	48.5 / 1.0	100 / 2.2
RLCH Connection Trail	23.6 / 0.1	16.7 / 0.1	27.0 / 0.1	32.7 / 0.2	100 / 0.5
Scenic Overlook Trail	23.0 / 0.7	15.3 / 0.5	24.6 / 0.8	37.1 / 1.2	100 / 3.2
Schoolhouse Spur	30.9 / 0.1	16.8 / 0	29.4 / 0.1	22.9 / 0.1	100 / 0.3
Southwind Nature Trail	33.9 / 0.6	16.2 / 0.3	23.5 / 0.4	26.5 / 0.5	100 / 1.7
Two Section Trail	29.3 / 0.9	12.9 / 0.4	22.6 / 0.7	35.2 / 1.1	100 / 3.2
WBPC Connection Trail	15.8 / 0	23.8 / 0	31.6 / 0.1	28.8 / 0.1	100 / 0.2
WBPFL Connection Trail	37.3 / 0.1	15.0 / 0	26.8 / 0	20.9 / 0	100 / 0.2
West Branch Trail	16.5 / 0.2	16.4 / 0.2	22.6 / 0.2	44.6 / 0.5	100 / 1.1
Z Bar Spur	25.4 / 0.1	14.3 / 0.1	25.6 / 0.1	34.8 / 0.1	100 / 0.4
All	24.9 / 7.9	14.3 / 4.6	23.2 / 7.4	37.6 / 11.9	100 / 31.8

1 – Slope Ratio = trail grade/landform trail grade; fall-line trails have values close to 1, side-hill trails have values close to 0.

Individual Trail Summaries

In the following sections we include only the named trails (short connectors omitted) and present information about their sustainability, including a table of trail grade by landform grade, information about tread conditions and excessive impacts, and a summary of some inventoried features. Representative photos and a map illustrating the sustainability ratings are also included. Note that these data are a brief summary of more comprehensive data and many additional photos that can be accessed through a geospatially linked GIS database that is also provided as a product of this research. Trail name codes are included to facilitate linkage with GIS datasets.

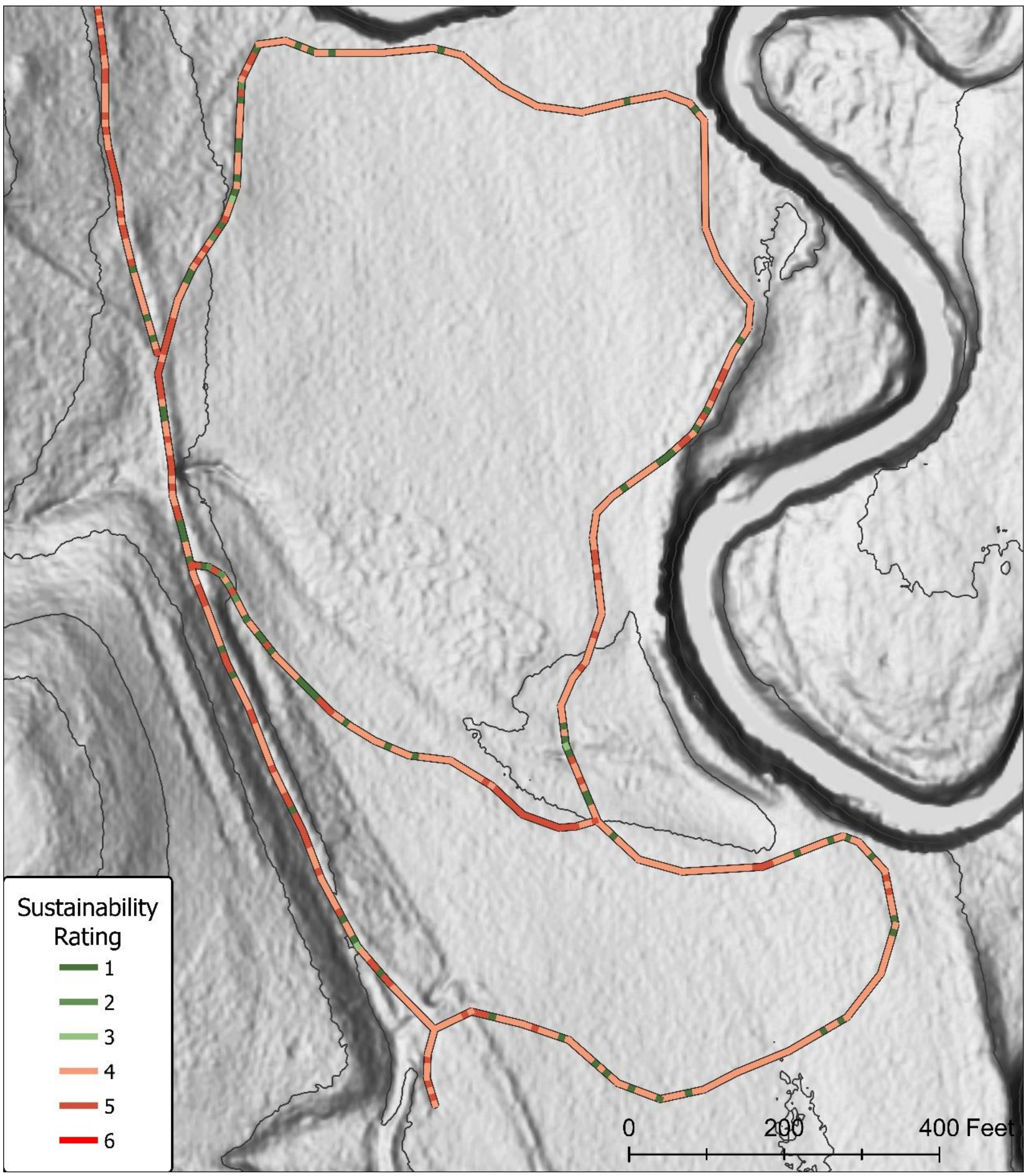
Bottomland Nature Trail (BNT)

This is a 0.9 mi long graveled accessible trail in the Bottomland section of the Preserve. This trail averages 6-8 ft in width and is environmentally sustainable due to its flat terrain and graveled surface (see photos). Transect data indicates 70-80% gravel cover with vegetation growing through to varying extents (which may interfere with accessibility if not cut low). During wet seasons drainage can be a problem; we saw some areas with flowing/standing water on the tread. This is a well-used trail that's easy to walk and navigate but you can hear and see the highway. There are sitting benches (7), resting areas, passing spaces, interpretive signs (5), and some shade. Just one stream crossing, which has slabs of limestone that could be sufficiently rough to pose an accessibility problem for some visitors and at the start of the trail is an area of somewhat uneven terrain.

While the majority of the tread is flat (76.6%), 1.9% is in the 5-10% trail grade category, which may be problematic for an accessible trail. Three minor problem sections were identified: 1) limited erosion of gravel (30 ft section) exposing the underlying geotextile material, 2) some excessive muddiness with water buildup (100 ft section), and 3) a few areas of compacted substrates causing depressions that are filled with water.

Table 8. Bottomland Nature Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	**Landform Grade Categories**				
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	38.2	25.6	12.2	0.6	76.6
2.1-5		12.9	7.9	0.9	21.7
5.1-10			1.3	0.6	1.9
All	38.1	38.5	21.4	2.0	100


Sustainability Rating
1
2
3
4
5
6
0
200
400 Feet

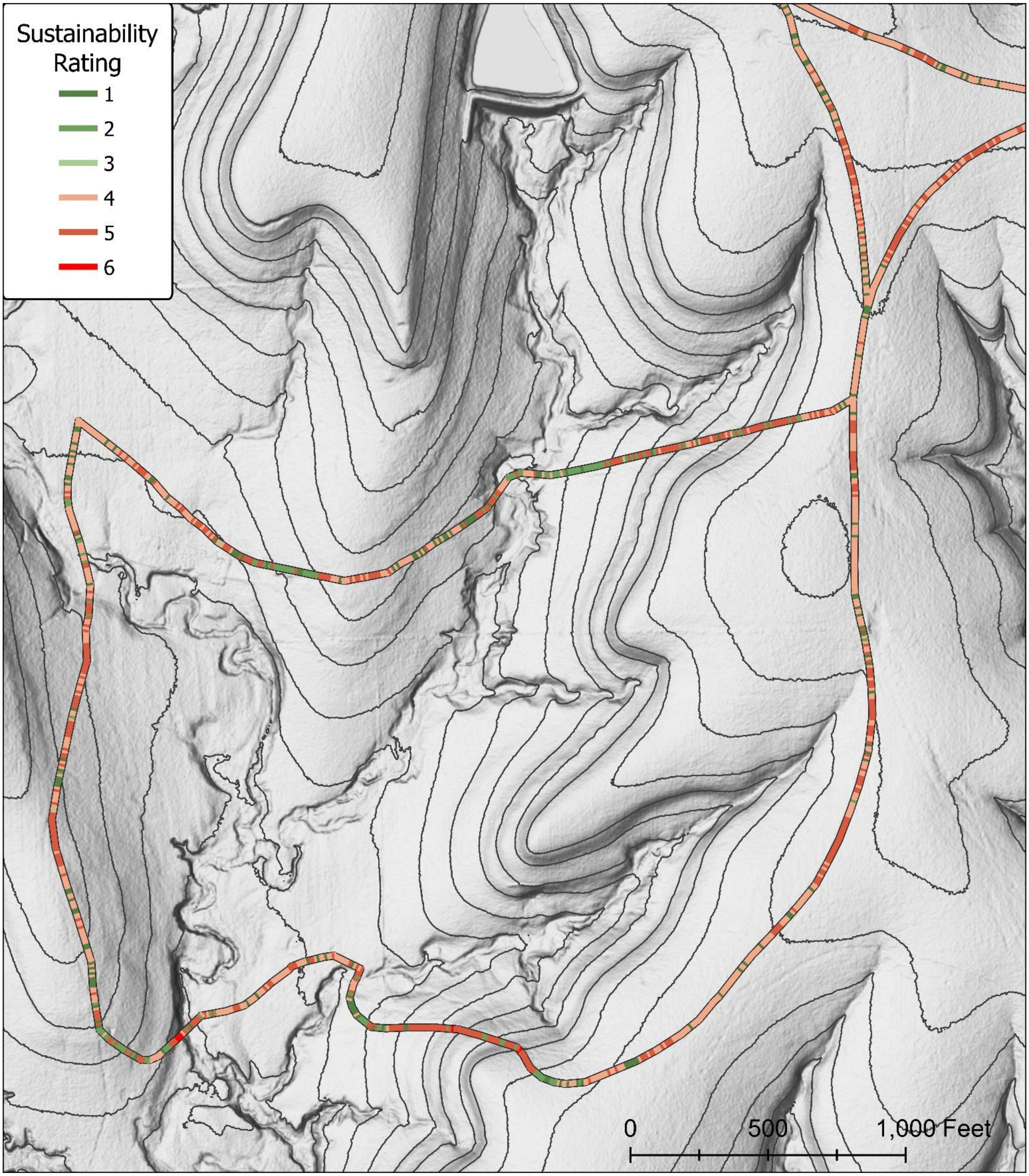
Crusher Hill Loop (CHL)

This is a 2.1-mile loop trail through the Red House and Crusher Hill Pastures. It is 8 ft wide and unsurfaced with mowed prairie vegetation. The flat ridgetop areas have several problem spots with muddiness and standing water, though these are likely ephemeral. At stream crossings there is some exposed rock and steep slopes, and soil erosion is apparent. The majority of the trail is in good condition with healthy mowed prairie grasses in the tread. The landscape is quite scenic, but the trail is a ranch road with trampling and degradation from cattle evident in some areas, including contributing to soil erosion into streams. Transect data indicates that the tread is 80-90% vegetation cover with the balance rock or mud. This trail has four stream crossings and three have resource protection concerns. One has an exposed culvert that was washed out and two have significant soil loss and drain adjacent steeper slopes directly into the creek.

The trail grade is essential flat (0-2%) for 45.9% of its length, with 49.8% ranging from 2-10%; only 0.4% of the trail exceeds 15% grade. Five segments of excessive muddiness totaling 1120 ft were identified and one segment of excessive soil loss affecting 40 ft (see photos).

Table 9. Crusher Hill Loop: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	15.2	23.4	7.1	0.2	0	45.9
2.1-5		14.8	13.4	0.8	0	29.0
5.1-10			15.8	4.6	0.4	20.8
10.1-15				2.6	1.4	4.0
15+					0.4	0.4
All	15.2	38.2	36.3	8.2	2.2	100


Sustainability Rating
1
2
3
4
5
6
0
500
1,000 Feet

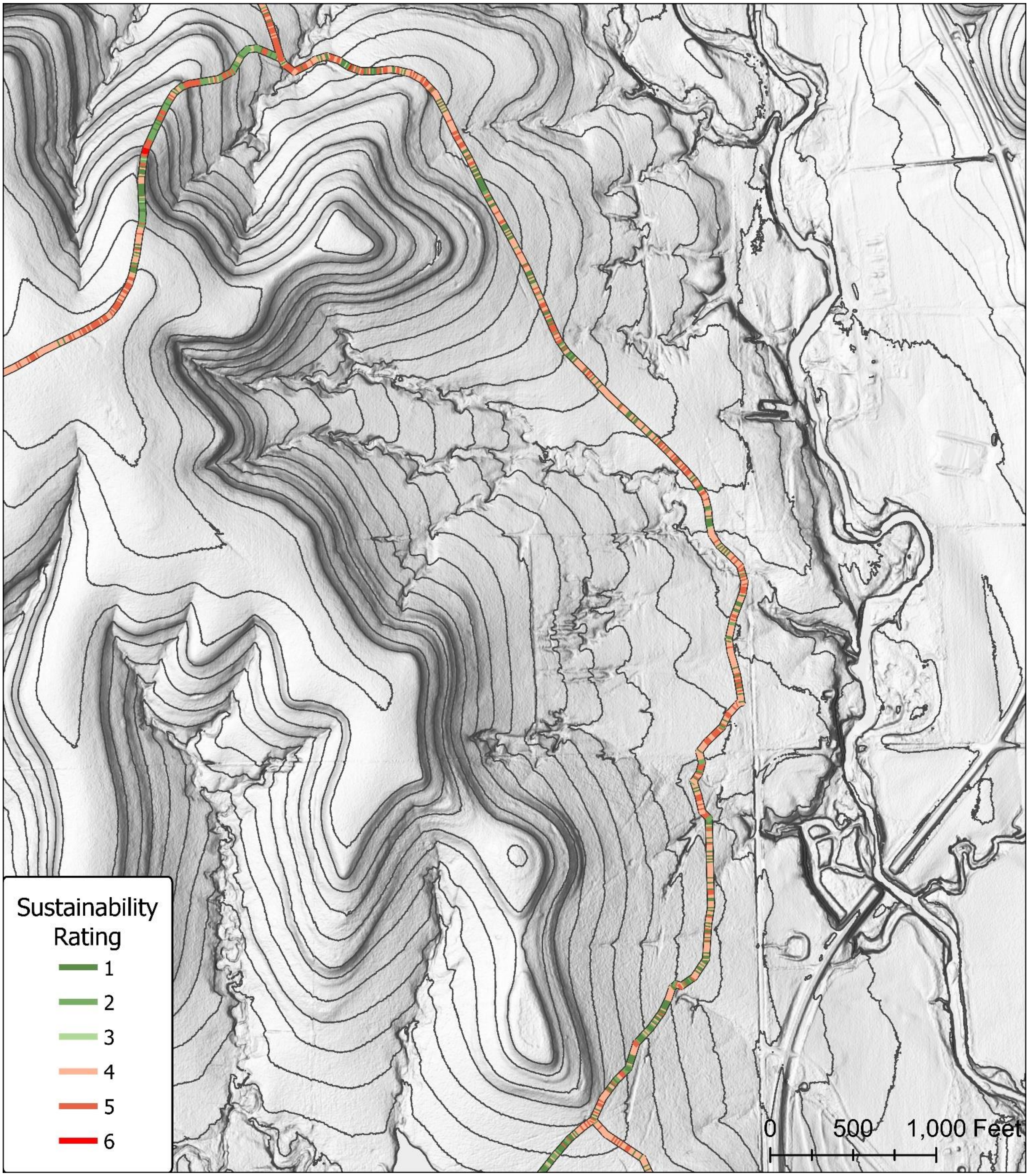
Davis Trail (DT)

This 2.2 mi trail runs through gently sloping terrain in Big Pasture and West Traps Pasture. The tread averages 6-8 ft in width, has native soil substrates, and transect data reveal 60-85% prairie vegetation cover or mud/exposed soil. Water drainage is an ephemeral problem in the flatter areas, with some tread rutting, though there are a few side-hill alignments. There are 4 stream crossings, 3 gates, and 1 40 ft segment of excessive soil loss on a fall-line. The stream crossings are gradual with only one exhibiting limited soil loss. One 2 ft culvert pipe was found but the lower end was completely buried in soil.

About 35% of the trail has a flat (0-2%) grade, the majority (82.7%) is in gently sloping terrain (2-10%) with some in side-hill positions. However, 1.7% of the trail has grades exceeding 15%, with a fall-line alignment.

Table 10. Davis Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	5.8	14.6	12.4	1.0	1.2	35.0
2.1-5		18.4	24.8	1.9	0.2	45.3
5.1-10			12.6	1.8	0.4	14.8
10.1-15				2.7	0.6	3.3
15+					1.7	1.7
All	5.8	32.9	49.8	7.4	4.1	100


Sustainability Rating
1
2
3
4
5
6
0
500
1,000 Feet

Fox Creek Trail (FC)

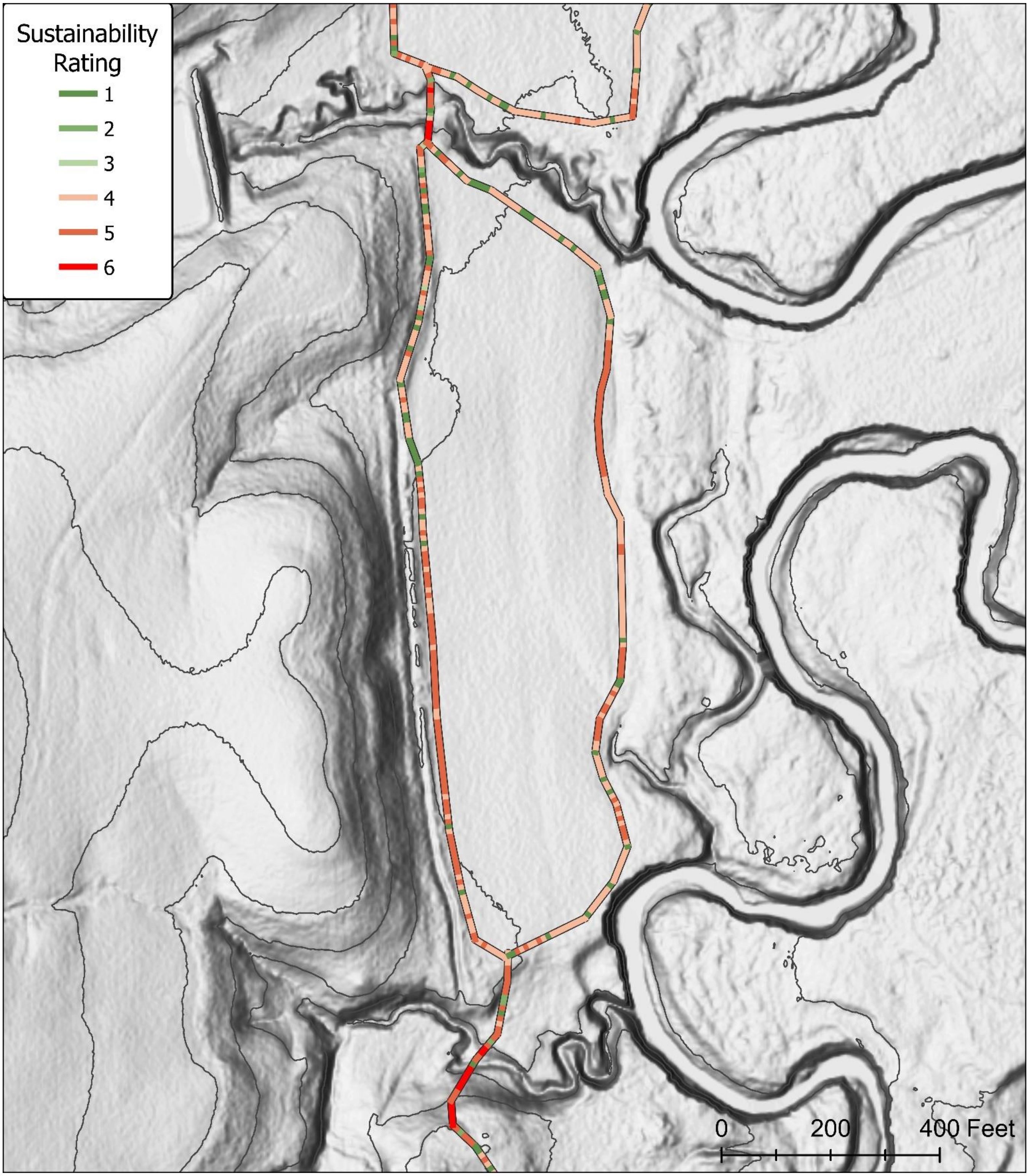
This 4.6 mi trail runs through very flat terrain in the East Traps Pasture and Bottomland Field with limited opportunities to drain water in some areas. The trail ranges from 3-8 ft in width, often depending on mowing width, with some sections revealing little use and 100% vegetation cover, other areas have two distinct paths from vehicle tires, sometimes non-vegetated. Some areas are overgrown (more mowing is needed to define the trail and facilitate visitor use). In forested/shady areas a greater proportion of the tread is exposed soil. Muddiness is a common problem, with 5 significant occurrences affecting 477 lineal feet of trail. Given the low flat terrain we suspect that some of these muddiness problems must also persist into drier periods, spot graveling would be an appropriate solution to remedy mudholes and deep ruts. Five excessive erosion problem segments including 280 lineal feet were also identified; many are steep fall-line (non-sustainable) stream-crossing approaches with significant soil loss into streams.

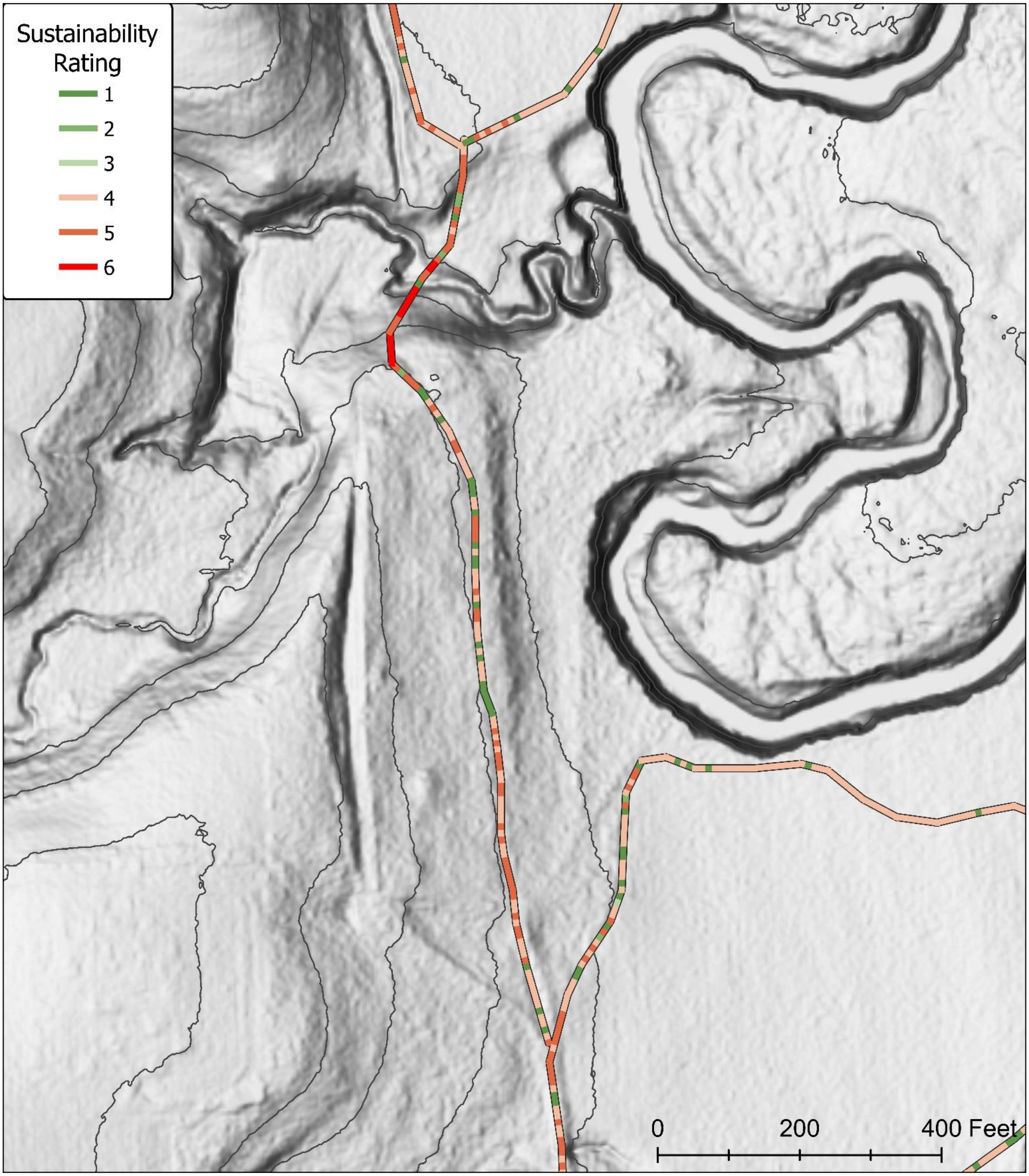
About a quarter (26.4%) of this trail is in flat terrain (0-2%), but 65.1% of this trail has a flat trail grade. Surprisingly there are some very steep segments (1.4% > 15% trail grade), limited to riparian terrain and stream crossings – these are the eroded segments that are contributing soil to the creek.

Table 11. Fox Creek Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	26.4	26.7	11.3	0.6	0	65.1
2.1-5		16.0	8.9	0.9	0.1	26.0
5.1-10			5.3	0.8	0.2	6.3
10.1-15				0.7	0.4	1.1
15+					1.4	1.4
All	26.4	42.8	25.5	3.1	2.2	100


Sustainability Rating
1
2
3
4
5
6
0
200
400 Feet


Sustainability Rating
1
2
3
4
5
6
0
200
400 Feet


Sustainability Rating
1
2
3
4
5
6
0
200
400 Feet

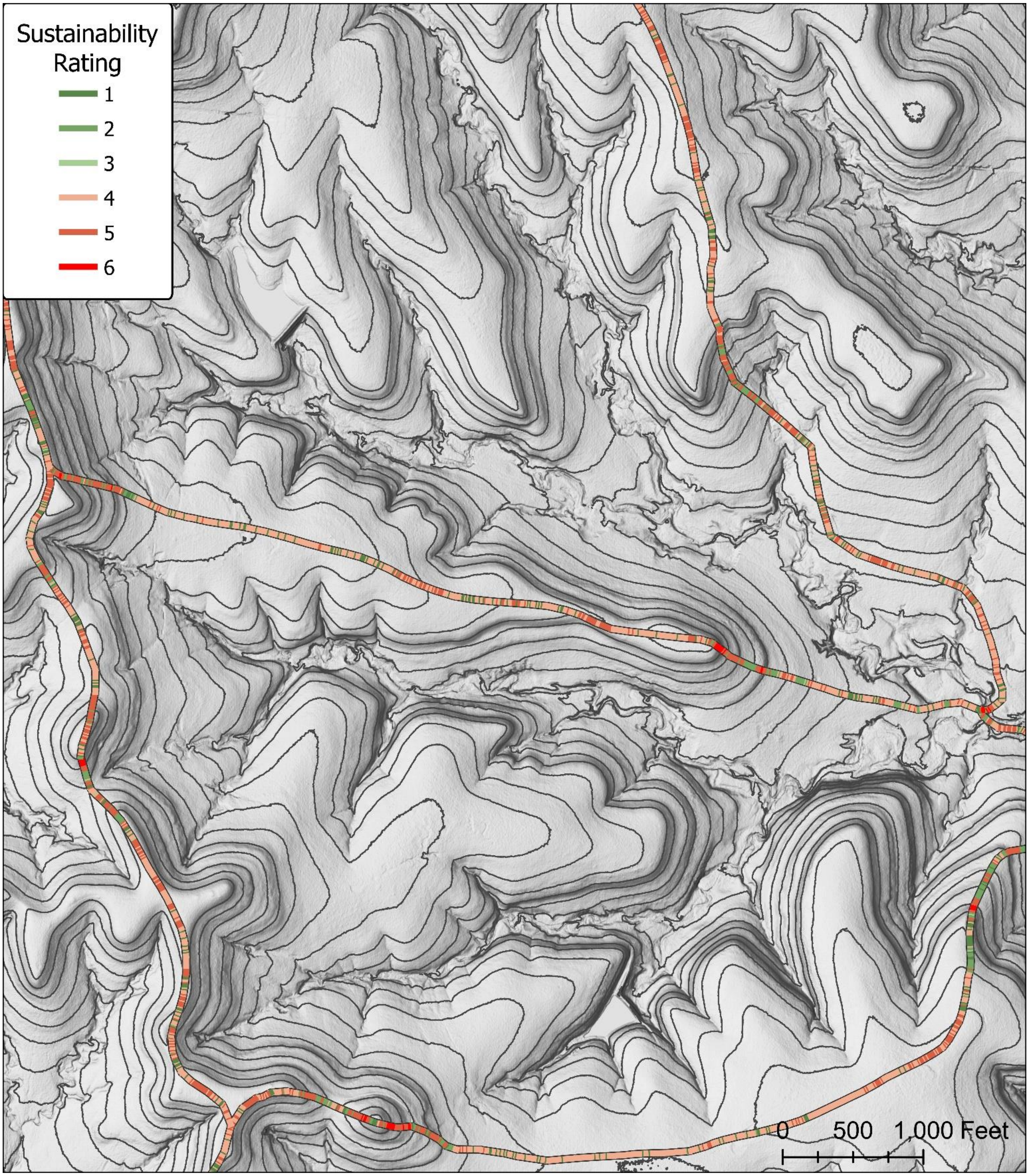
Gas House Cutoff (GHC)

This 1.3 mi trail runs through the Big Pasture bisecting the middle of the Prairie Fire Loop. This trail is generally about 8 ft wide and crosses mostly flat to gently sloping terrain. The tread is native soils and prairie vegetation; mostly in good condition due to low use except for muddiness, one segment about 20 ft in length, and two steeper fall-line eroded segments affecting 90 lineal ft with exposed rock and native gravel.

About a quarter of the trail (24.8%) is in completely flat terrain where drainage is a problem, but 48.5% of the trail has a flat trail grade (0-2%). The eroded sections with exposed soil occur in 1.5% of the trail with a fall-line alignment and >15% grade.

Table 12. Gas House Cutoff: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	24.8	20.1	3.3	0.3	0	48.5
2.1-5		26.5	4.0	0	0.1	30.6
5.1-10			9.3	2.6	2.5	14.4
10.1-15				2.4	2.5	4.9
15+					1.6	1.6
All	24.8	46.6	16.6	5.3	6.7	100


Sustainability Rating
1
2
3
4
5
6
0
500
1,000 Feet

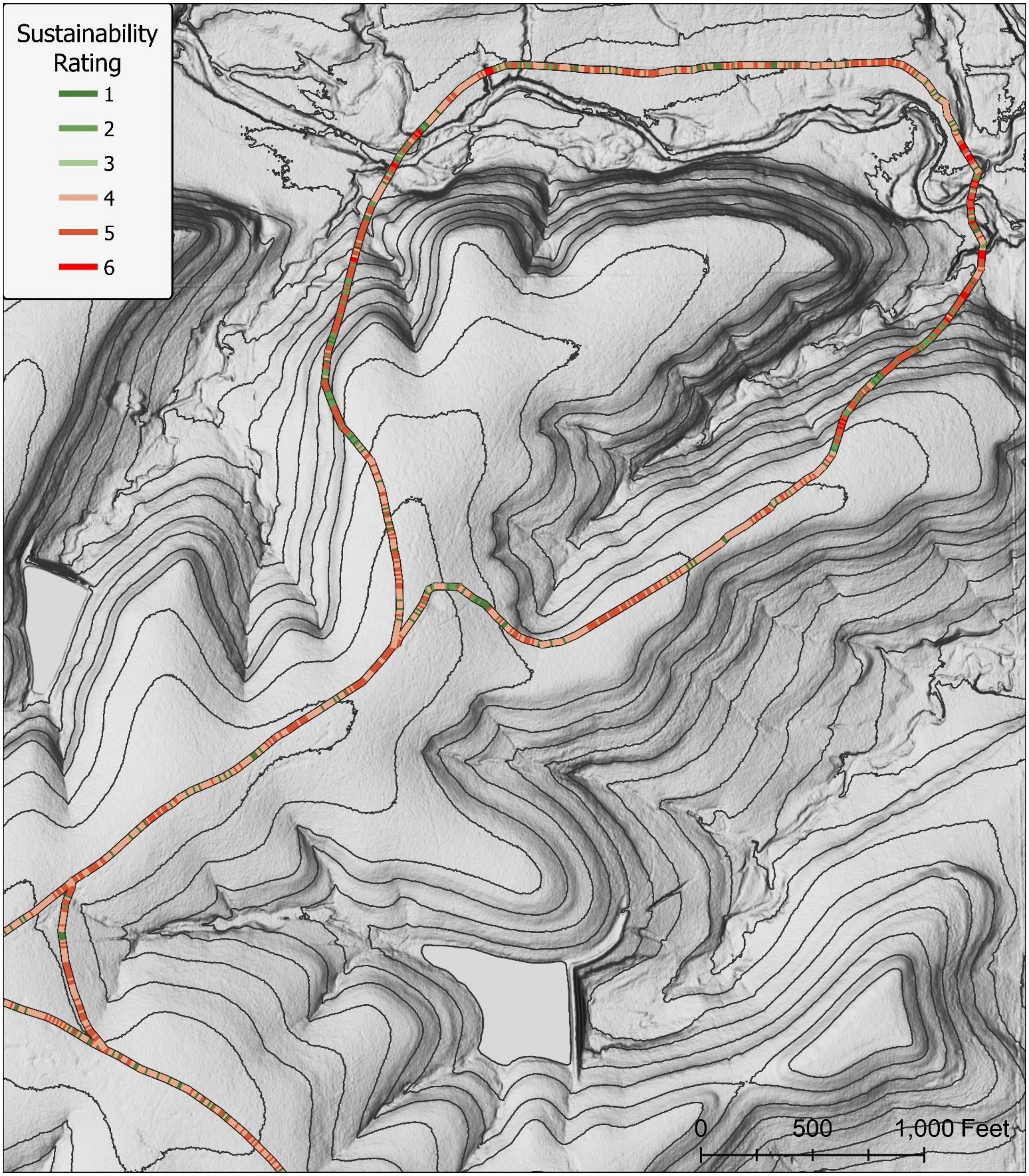
Palmer Creek Loop (PCL)

This 2.26 mi trail is located in the northeast corner of the Big Pasture. The tread is native soils and prairie vegetation, generally with 100% plant cover except in areas of tree cover. The trail is generally 8 ft wide with native soils and full prairie vegetation cover, except in the forested areas where shade reduces tread vegetation, and near stream crossings where native rock is exposed. There is one instance of excessive soil loss affecting 50 lineal feet where the trail descends an exceptionally steep muddy stream embankment near Palmer Creek to cross a side tributary. This effectively ends the trail for vehicle use and even hiking use is very challenging. This section needs to be rerouted and marked to fix these problems. There are two creek crossings, one is normally dry (more of a swale) and one has a gentle approach with native gravel (pictured).

Nearly half (48.1%) of the trail has flat (0-2%) trail grades and nearly two-thirds (62.1%) is situated in sloping terrain (2-10%) slopes. Some sections have excellent well-drained side-hill alignments, though 2.6% is fall-line trail with >15% grades.

Table 13. Palmer Creek Loop: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	**Landform Grade Categories**					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	16.6	22.7	7.5	0.9	0.4	48.1
2.1-5		18.9	6.6	1.6	0.7	27.8
5.1-10			6.4	6.2	2.5	15.1
10.1-15				3.1	3.4	6.5
15+					2.6	2.6
All	16.5	41.6	20.5	11.8	9.5	100

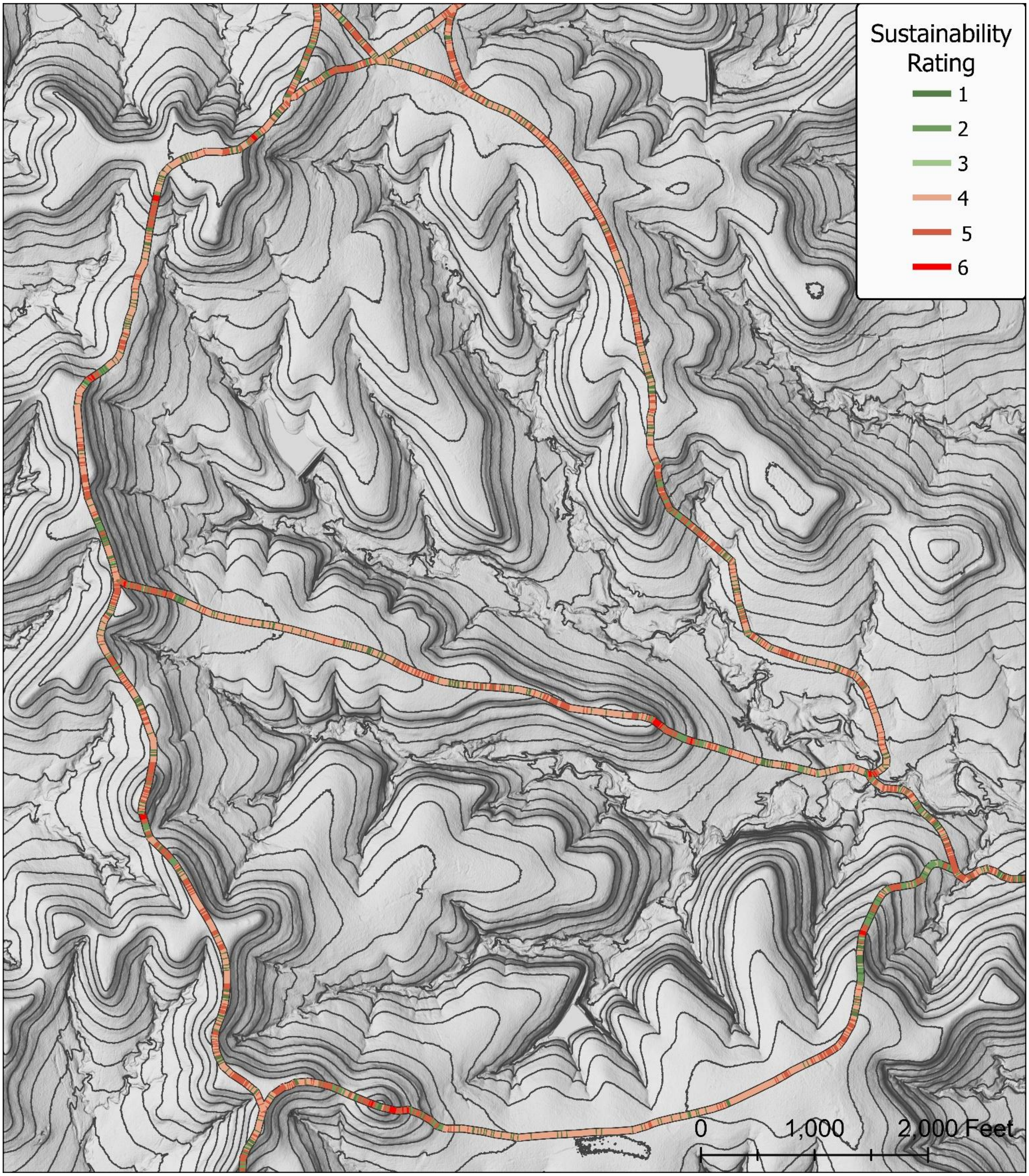

Sustainability Rating
1
2
3
4
5
6
0
500
1,000 Feet

Prairie Fire Loop (FPF)

This 5.18-mile loop trail circumvents the middle of the Big Pasture. Except for the short graveled portion to the Scenic Overlook, this long trail loop has native soils and vegetation. It traverses flat terrain through cow pastures with extensive cattle trampling/muddiness impacts in a few areas. The rest is mostly gently sloping terrain where the trail generally stays high with a gentle fall-line alignment. There are two stream crossings (pictured) that have gradual approaches with natural gravel in the tread; however, some erosion into the stream is evident at both. There are also 6 occurrences of excessive muddiness that total 490 lineal ft and one instance of excessive trail width from cattle that runs 60 ft. The muddiness is caused predominantly by the fall-line alignment and heavier vehicle use that has created deeper ruts that retain water and create muddiness in several different areas. These ruts and the excessive muddiness created by the cattle (predominantly at mineral licks) make this a substantially less attractive and functional trail for Preserve visitors.

Table 14. Prairie Fire Loop: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	20.0	21.1	8.5	1.2	0.2	51.0
2.1-5		18.8	9.7	1.1	0.3	29.9
5.1-10			10.8	3.1	0.4	14.3
10.1-15				3.0	0.6	3.6
15+					0.9	0.9
All	20.0	40.0	29.1	8.5	2.4	100


Sustainability Rating
1
2
3
4
5
6
0
1,000
2,000 Feet

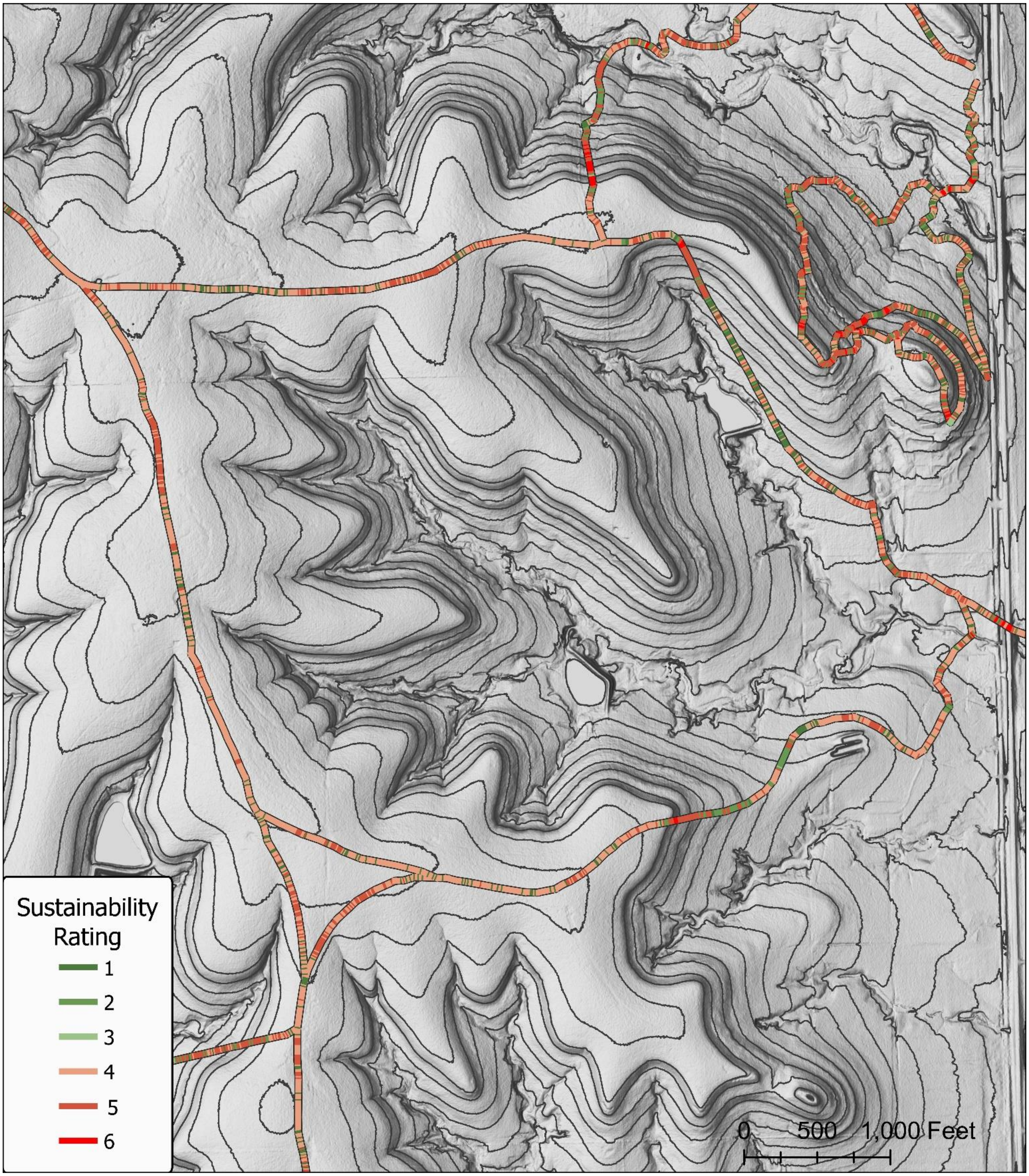
Ranch Legacy (RLT)

This 2.15 mi trail runs through the Red House Pasture. This aptly named trail crosses a lot of flat terrain or has a mostly fall-line alignment in sloping terrain. It is generally 8 ft wide with native prairie soil and vegetation cover. Some sections are muddy with standing water in rutted tire tracks: we found 4 occurrences of excessive muddiness that total 255 lineal ft along with a large mineral lick for cattle that is also been churned to mud (pictured). There were two gates but no water crossings on this trail.

Surprisingly, 60.1% of the trail has a flat grade and 0% has a side-hill sustainable alignment.

Table 15. Ranch Legacy: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	31.5	23.8	4.8	0	0	60.1
2.1-5		23.0	5.0	0	0	28.0
5.1-10			9.0	0.6	0	9.6
10.1-15				1.9	0.1	2.0
15+					0.4	0.4
All	31.4	46.8	18.8	2.5	0.5	100


Sustainability Rating
1
2
3
4
5
6
0 500 1,000 Feet

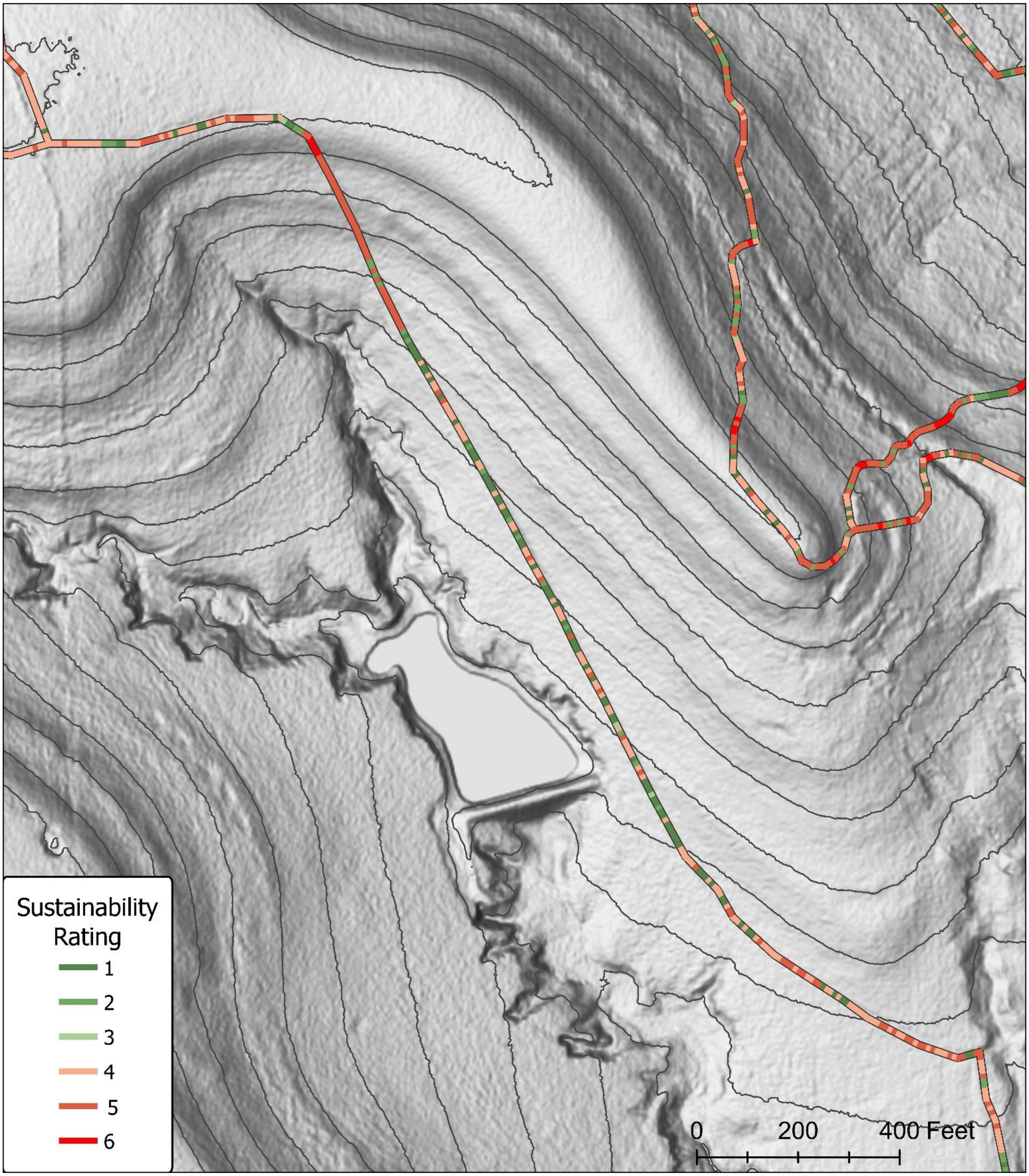
Scenic Overlook Trail (SOT)

This trail has two sections. Section 1 is from the Visitor Center through the buffalo pasture (Windmill Pasture) to the second gate. This section is well graveled and much wider (10-15 ft) due to busses and a visible parallel foot trail, likely created by hikers who dislike hiking on the loose gravel. This section supports heavier traffic from ranch and Preserve vehicles, buses, and hikers. Two types of gravel are evident, including clean sorted loose gravel which is readily moved by traffic, and crush and run gravel, which is more static. Section 2 is from the second gate to the Scenic Overlook and bus turnaround. This section is less wide, appears to receive less traffic, and has crush and run gravel filling two ruts with grasses growing in the middle. Excessive soil loss, in this case eroded gravel, was found at 7 locations affecting 133 ft (see photo). One section recorded as excessive muddiness was backed up standing water in a swale and another spot had evidence of significant water flow over the road that washed gravel out into the prairie (pictured). Another 80 ft section was assessed as non-sustainable due to a steep fall-line segment up-hill from a stream, with gravel washed into the stream and adjacent prairie areas.

While 18.3% of this trail of this trail is in flat terrain (0-2%), 50.2% of the trail has a flat grade. The majority of the trail is fall-line with only 0.6% with more sustainable side-hill alignments.

Table 16. Scenic Overlook Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	2.1-5	5.1-10	10.1-15	15+	All
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	18.3	21.4	10.2	0.3	0	50.2
2.1-5		18.4	14. 4	0.5	0	33.3
5.1-10			9.2	3.1	0.1	12.4
10.1-15				2.9	0.5	3.4
15+					0.8	0.8
All	18.3	39.8	33.8	6.7	1.4	100


Sustainability Rating
1
2
3
4
5
6
0
200
400 Feet

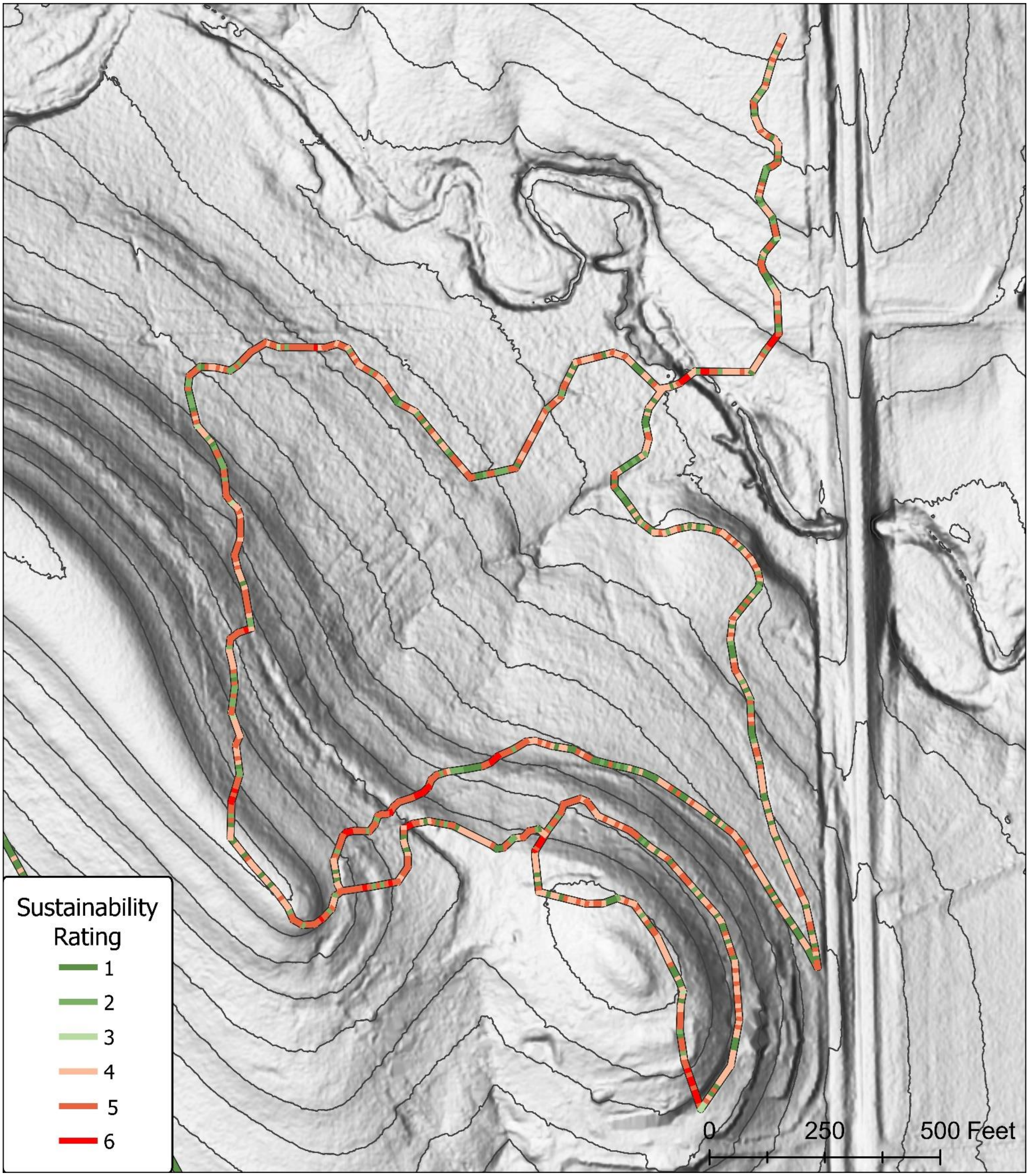
Southwind Nature Trail (SNT)

This 1.74 mi interpretive trail is near the Preserve's visitor center and farm complex. This trail runs through some woods initially and out into the meadow on the ridgetop and down to the creek with steep side-hill and/or fall-line alignments. The creek crossing is very steep and badly eroded. Fine gravel has been applied in some locations but is easily eroded and there is evidence of that in many places (see photos). Trail grades are too steep in many places and while there are steps, additional tread work is needed to repair and improve the trail with careful attention to adding drainage features. Several areas require additional maintenance work (looks neglected). The tread varies from grassy vegetation, to bare prairie soil, to fine gravel, with several eroded sections evident.

This trail has the highest average trail grade (5.16%) and cannot be made accessible. This trail has more side-hill alignments than any other trail but even much of this is too steep (see photos). In contrast to other Preserve tails, only 1.8% is in completely flat terrain and 28.3% has flat trail grades (0-2%). Fifty-five percent of the trail occurs in steeper (>10%) landform grades and 14.6% of the trail grades exceed 10%.

Table 17. Southwind Nature Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	2.1-5	5.1-10	10.1-15	15+	All
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	1.8	4.4	8.9	10.1	3.1	28.3
2.1-5		6.6	12.1	12.0	3.9	34.6
5.1-10			11.3	7.6	3.8	22.7
10.1-15				5.5	5.0	10.5
15+					4.1	4.1
All	1.7	11.0	32.3	35.2	19.8	100

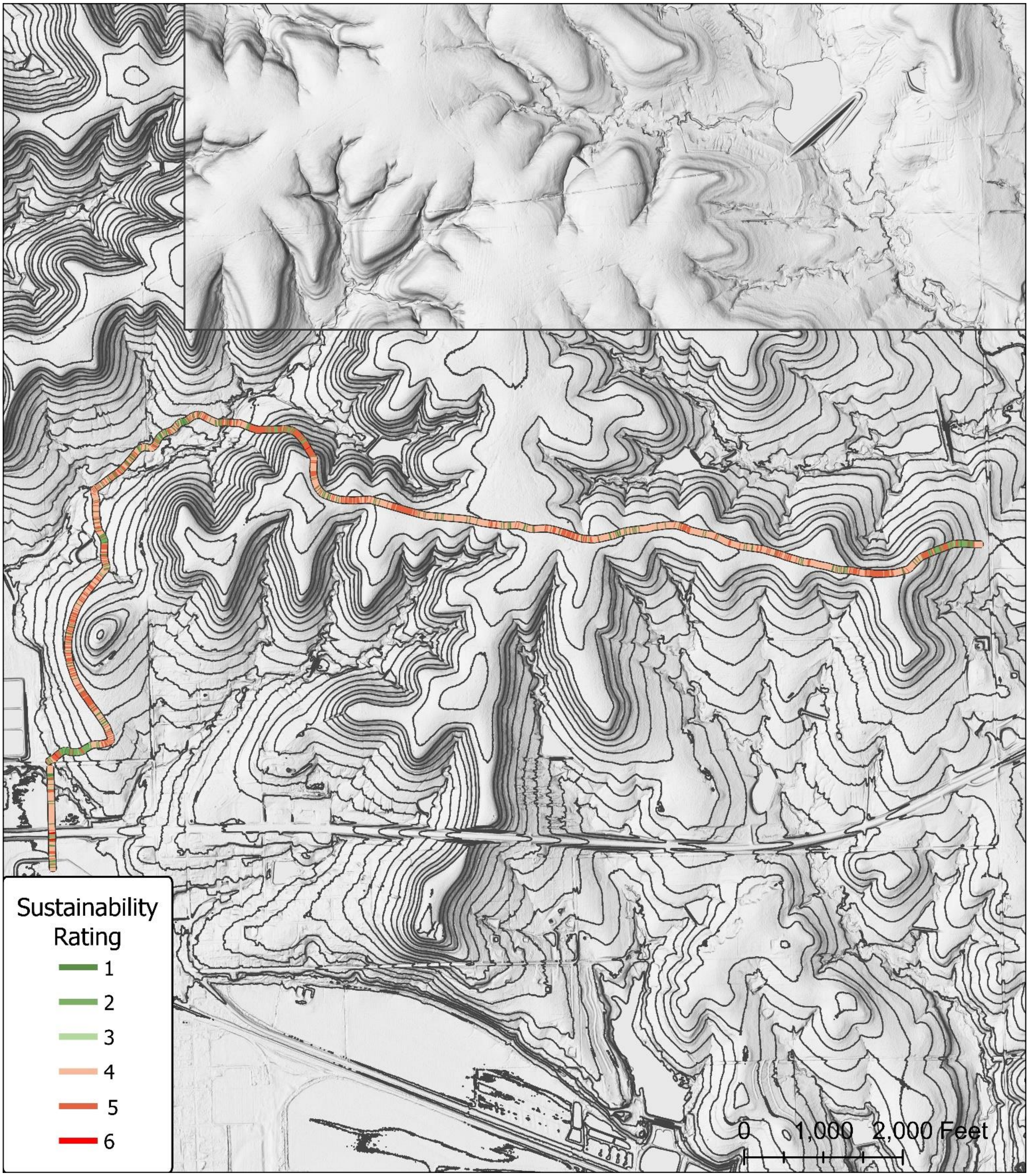

Sustainability Rating
1
2
3
4
5
6
0
250
500 Feet

Two Section Trail (TS)

This 3.17 mi trail runs through the Two Section Pasture and East Traps Pasture with a 8-10 ft wide tread of native prairie soil and vegetation. The Two Section portion has numerous muddy cattle trails with many areas of poor drainage that pool with water. The East Traps segment, which has not been grazed since 2005, is in better condition, though muddiness remains a problem due to flat terrain and poor drainage. There are conflicts between the cows and hikers and the road noise/visibility is also an issue. This trail has two gates and one stream crossing.

Table 18. Two Section Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	2.1-5	5.1-10	10.1-15	15+	All
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	19.2	26.1	8.8	2.1	0	56.2
2.1-5	1.4	15.8	9.0	0.6	0	26.8
5.1-10	0	0.3	10.5	2.6	0.3	13.8
10.1-15	0	0	0.1	1.8	1.1	3.1
15+	0	0	0	0	0.2	0.2
All	20.6	42.2	28.4	7.2	1.6	100


Sustainability Rating
1
2
3
4
5
6
0 1,000 2,000 Feet

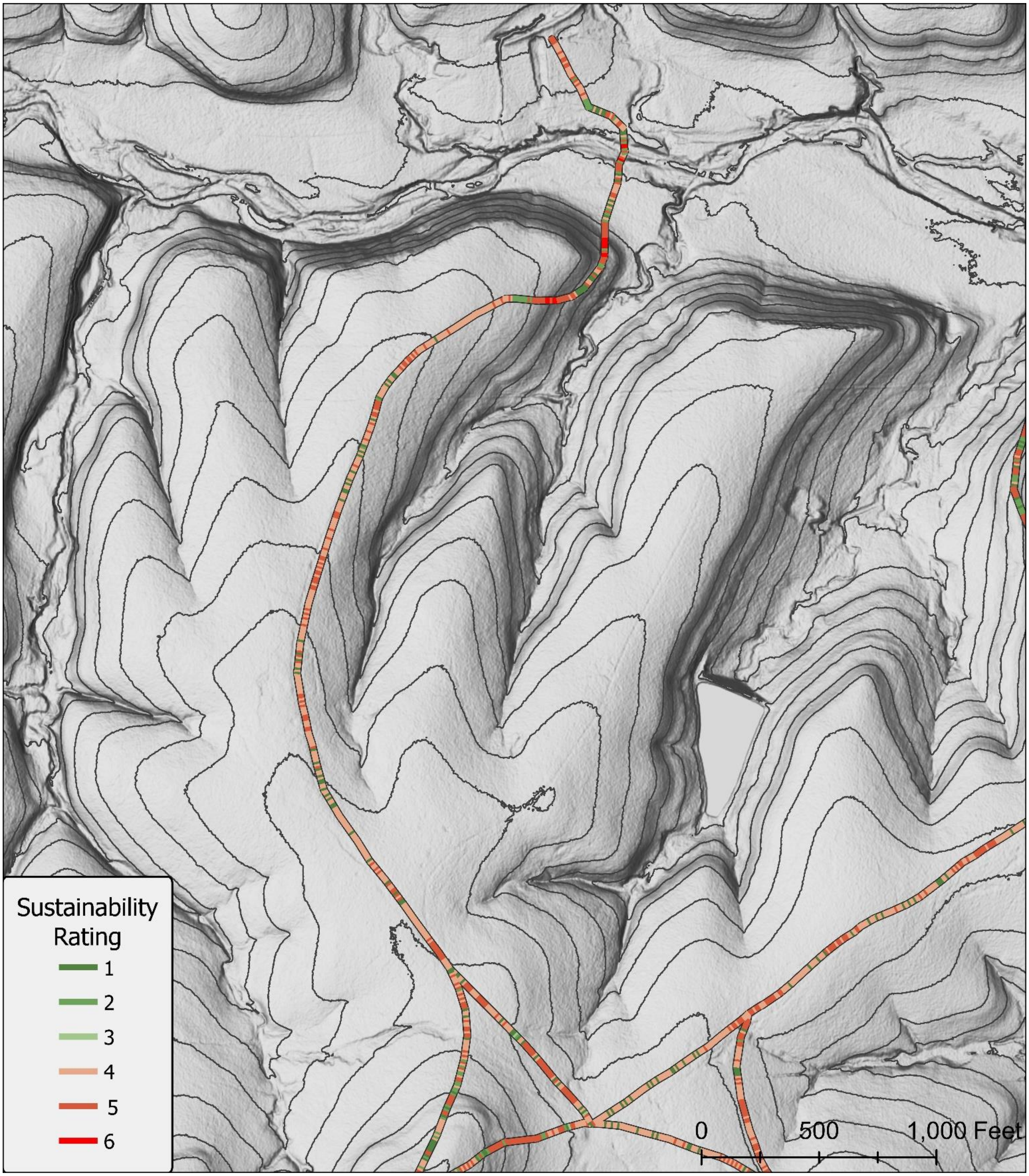
West Branch Trail (WBT)

Nice grassy ridge trail descending down to the Palmer Creek and a beautiful "hidden" pond, great for a picnic lunch. The initial section has some deep muddy ruts with a few intermittent mud holes, but it also has a section of attractive ridge trail with nice vistas. Use levels are exceptionally low due to its remote location. There is some natural gravel at a stream crossing.

This trail traverses both flatter and sloping terrain yet most of the trail is fall-aligned, is in flat terrain (17.5%), or has flat trail grades (47%).

Table 19. West Branch Trail: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	**2.1-5**	**5.1-10**	**10.1-15**	**15+**	**All**
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	17.5	26.1	3.4	0	0	47.0
2.1-5		30.3	7.6	0.2	0	38.1
5.1-10			7.4	1.8	0	9.2
10.1-15				3.0	0.8	3.8
15+					1.9	1.9
All	17.6	56.4	18.4	5.0	2.7	100



Sustainability Rating
1
2
3
4
5
6
0
500
1,000 Feet

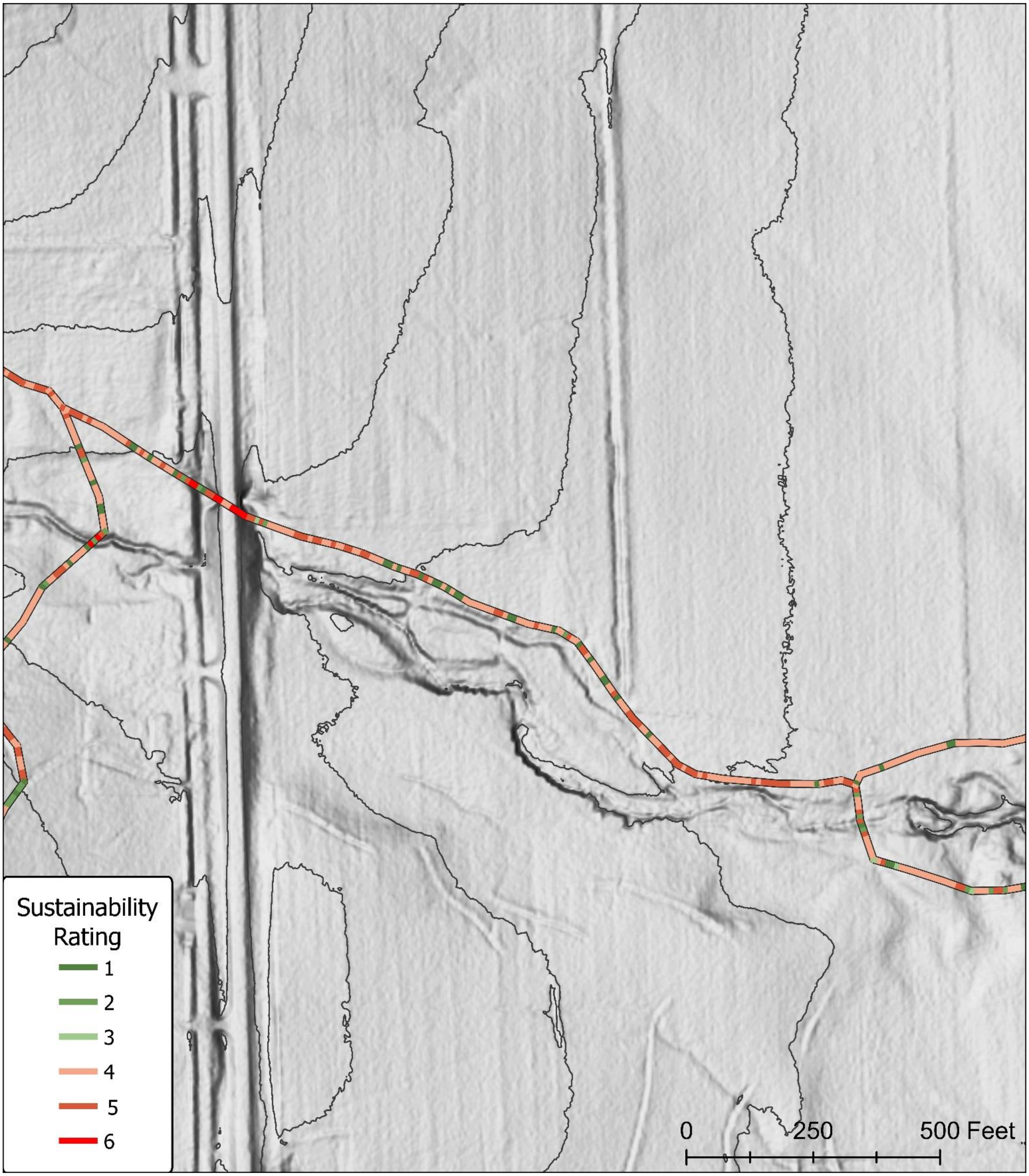
Z Bar Spur (ZBS)

This 0.4 mi road is primarily a ranch infrastructure route, though it does provide access from the visitor center area to the Fox Creek Trails. This route is generally about 8 ft wide and has native soil and vegetation cover. In some flat areas there is considerable exposed soil and muddiness from the cattle, including some eroded streambanks from cattle trampling. Navigation is a bit confusing around the visitor center. Not in a way that people will get lost as the visitor center is always visible but there is a confusing network of trails with few markers and it is unclear which trail is the official one. Recommend improving signage and potentially closing out some of the excessive additional routes. Three segments were identified as excessively muddy totaling 130 ft; these areas were associated with the cattle at a feeding tank and near gates. On section has excessive soil loss (100 ft) due to deep tire rutting and a section assessed as unsustainable (100 ft) was both muddy and rutted with a fall line alignment near a stream.

Much of this trail (75%) is in flat terrain (0-5% grade) and 58.3% of the trail has a flat grade (0-2%). However, there are opportunities in some steeper terrain for additional side-hill alignments.

Table 20. Z Bar Spur: trail grade categories by landform grade categories (percent of total).

Trail Grade Categories	Landform Grade Categories					
	0-2	2.1-5	5.1-10	10.1-15	15+	All
	% of Total	*% of Total*	*% of Total*	*% of Total*	*% of Total*	*% of Total*
0-2	19.3	31.1	6.6	1.3	0	58.3
2.1-5		24.5	5.3	0.9	0.4	31.1
5.1-10			2.6	1.3	0.0	3.9
10.1-15				1.3	1.8	3.1
15+					3.5	3.5
All	19.3	55.7	14.5	4.8	5.7	100


Sustainability Rating
1
2
3
4
5
6
0
250
500 Feet

Informal (Visitor-Created) Trails

Field staff found only two informal (visitor-created) trails, both on the Scenic Overlook Trail. The first trail (148 ft long, pictured) departed from the road to access a small pond located adjacent to the road. The second trail (165 ft) departed from the road at a right-angle bend just prior to the buffalo pasture gate to access a scenic overlook. Both these trails departed from the formal trails and accessed visitor attraction features. While we saw many other side-trails elsewhere in the Preserve we judged them to have been created by cattle or buffalo as opposed to visitors, though it's possible we missed a few. Regardless, the creation/proliferation of informal trails is clearly not a visitor management problem currently in the Preserve. We also note that it requires a substantial amount of visitor traffic to create and maintain visible trails in prairie vegetation.

Inventory of Trail System Features

Field staff recorded locations, condition comments, GPS locations, and took photos for each occurrence of seven trail system features (

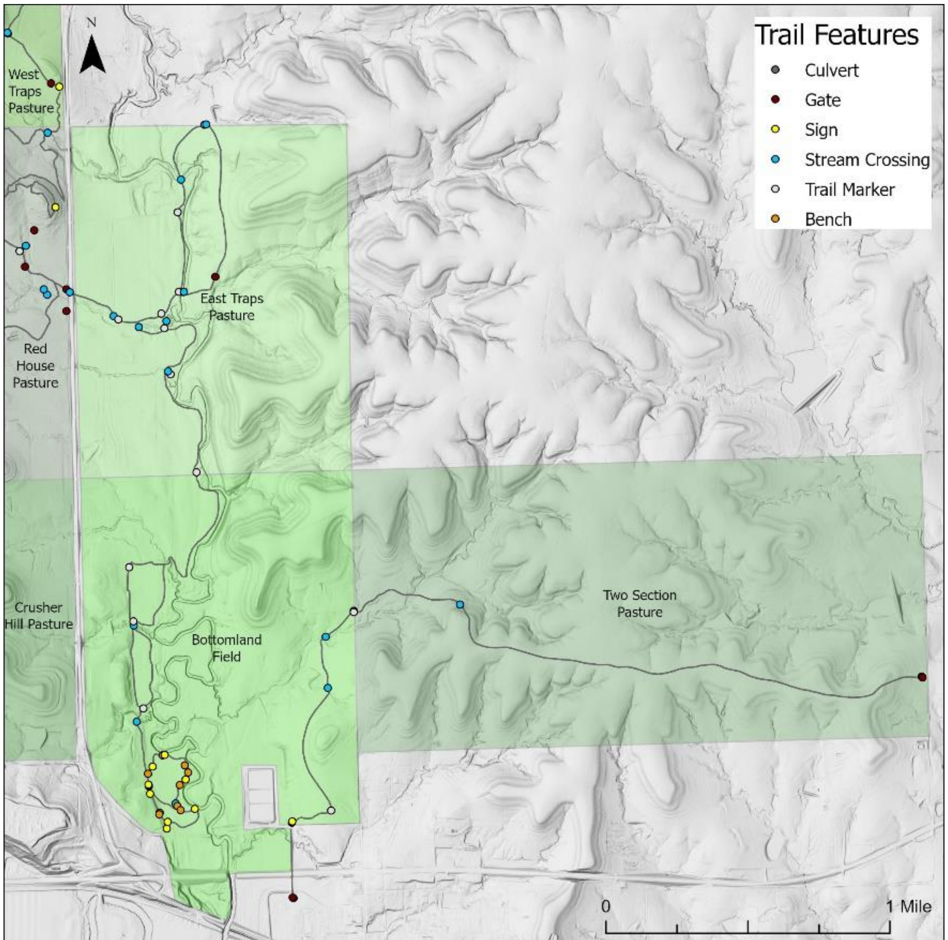
Table 21). A geospatial GIS databased of these features is a product of this research, allowing staff to select each feature to see its location, photo, condition, or comment information (Figure 7). Representative photos of these features are included below. As an example, we recorded the locations and took photos of all 38 trail system markers (pictured below). Sixteen informational signs were located, including those at gate locations. Twenty gates were inventoried but only four culverts were found. Ten visitor benches were found, including blocks of stone and those constructed of plastic wood (pictured). Finally, we identified 32 stream crossings, again captured with one or more photos and comments that can be used to begin evaluating their condition and possible threats to water quality. Also included in Table 22 is a listing of each watershed with GIS-calculated "upstream" watershed sizes – larger watersheds should contribute greater volumes of water during rain events and can help to inform decisions about alternative management options such as no action, armoring with large stone, culverts, or bridges. As previously discussed, some stream crossings with steep embankment grades revealed clear evidence of soil runoff directly into streams and further evaluation by specialists seems warranted. Many of these were pictured on the individual trail summary pages.

Table 21. Inventory of trail system features (all trails).

Feature Type	Number
Trail Marker (TM)	38
Signs (S)	16
Bench (B)	10
Stream Crossing (SC)	33
Culvert (C)	4
Drainage Feature (DF)	9
Gate (G)	20

Table 22. All park trail stream crossings with GIS-calculated upstream watershed sizes.

Stream Crossing	Watershed (Acres)	Stream Crossing	Watershed (Acres)
1	67.67	17	626.63
2	0.03	18	103.65
3	3.65	19	578.48
4	15.62	20	799.68
5	13.06	21	44.95



6	0.03	22	0.14
7	134.39	23	0.11
8	626.45	24	1.52
9	10.60	25	12.46
10	0.34	26	22.29
11	5.89	27	13,812
12	36.31	28	0.21
13	0.14	29	13,932
14	0.11	30	0.03
15	0.02	31	588.71
16	970.25	32	1.44

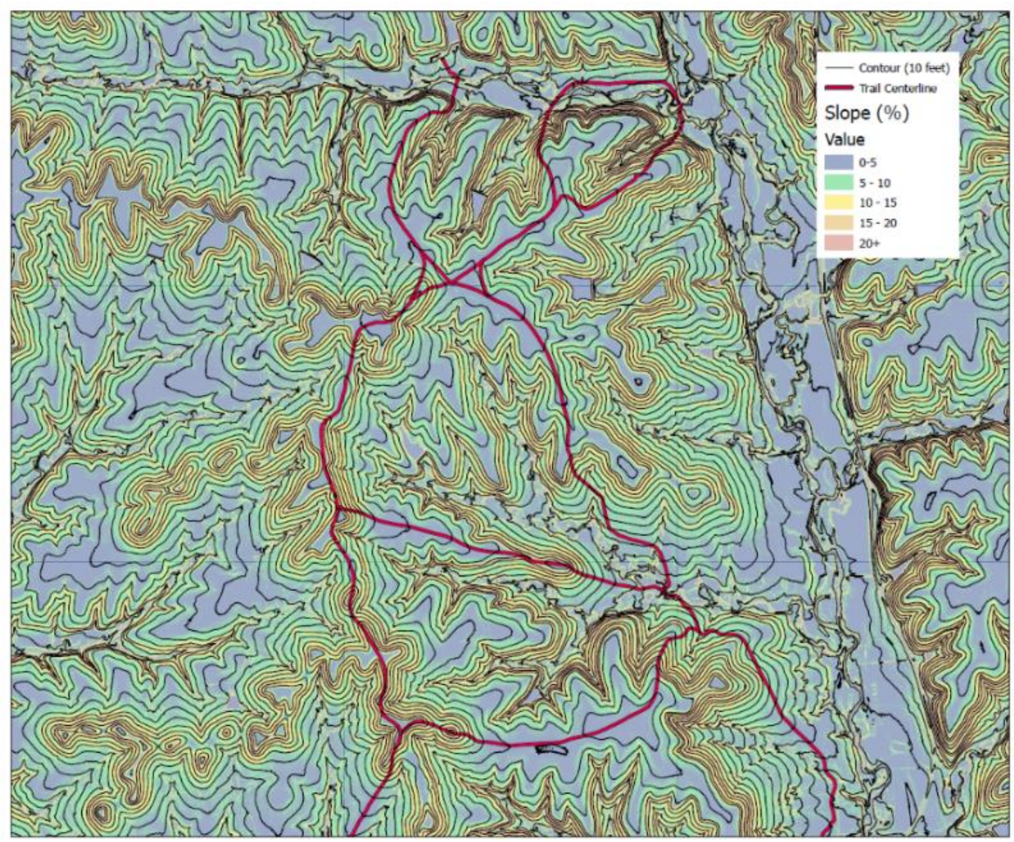
Figure 7. Preserve map illustrating the georeferenced trail features inventory.

Finally, we have included four Preserve slope maps created using GIS software to enable visual inspections of trail sustainability (Figure 8, Figure 9). The following bullets provide guidance for interpreting these figures:

- **Steepest terrain** – When trails cross the most tightly packed contour lines, often at stream embankments, significant soil erosion can occur. Of particular interest is whether the trail intersects these steep areas at right angles to the contour lines (fall-line – non-sustainable) or at an oblique angle (side-hill – sustainable). Close inspection of the slope maps in Figure 8 reveal numerous instances of both types of trail alignments in steep terrain. The highest priority would be to further investigate locations with the steepest terrain and fall-line trail alignments near stream crossings with larger watersheds. However, fall-line trails crossing steep

(>15% grade) and intermediate (10-15% grade) terrain in other areas remain a concern to prevent significant trail rutting and soil loss.

- **Flat terrain** – Red trail lines crossing the sky blue color indicates the portions of trails that are in relatively flat terrain (0-5%) where drainage problems and muddiness/widening can easily occur during wet seasons and after rains. Note that the 10 ft contour lines are more widely spaced in these areas. In Figure 8 the slope maps reveal options for relocating trails to nearby side-hill alignments. Note that to sustainably relocate existing trails to side-hill alignments in steeper terrain (optimally 10-20% landform grades) will generally require longer, more circuitous routings. Side-hill trail construction is also required and can be expensive. In Figure 9 the Bottomland and Fox Creek Trails are essentially flat flood-plain trails and more sustainable relocations are generally not possible. Graveling and paving are the more sustainable options for these trails, particularly if they are to be used during wet periods.



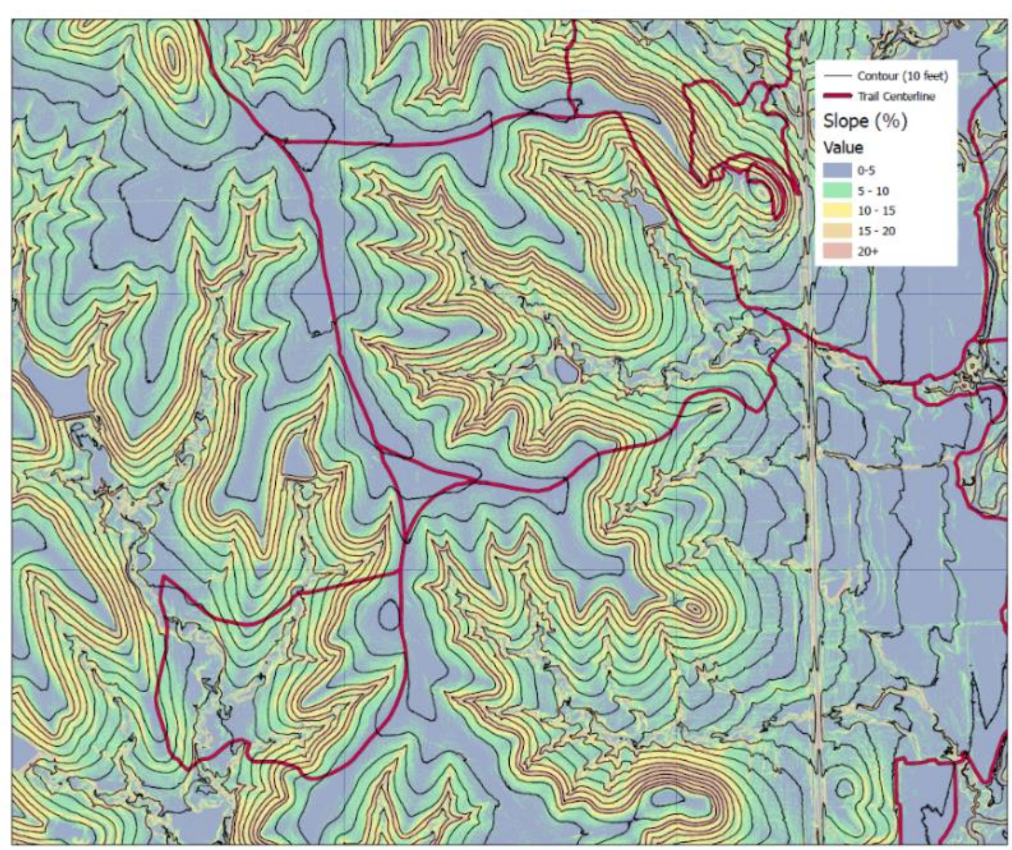
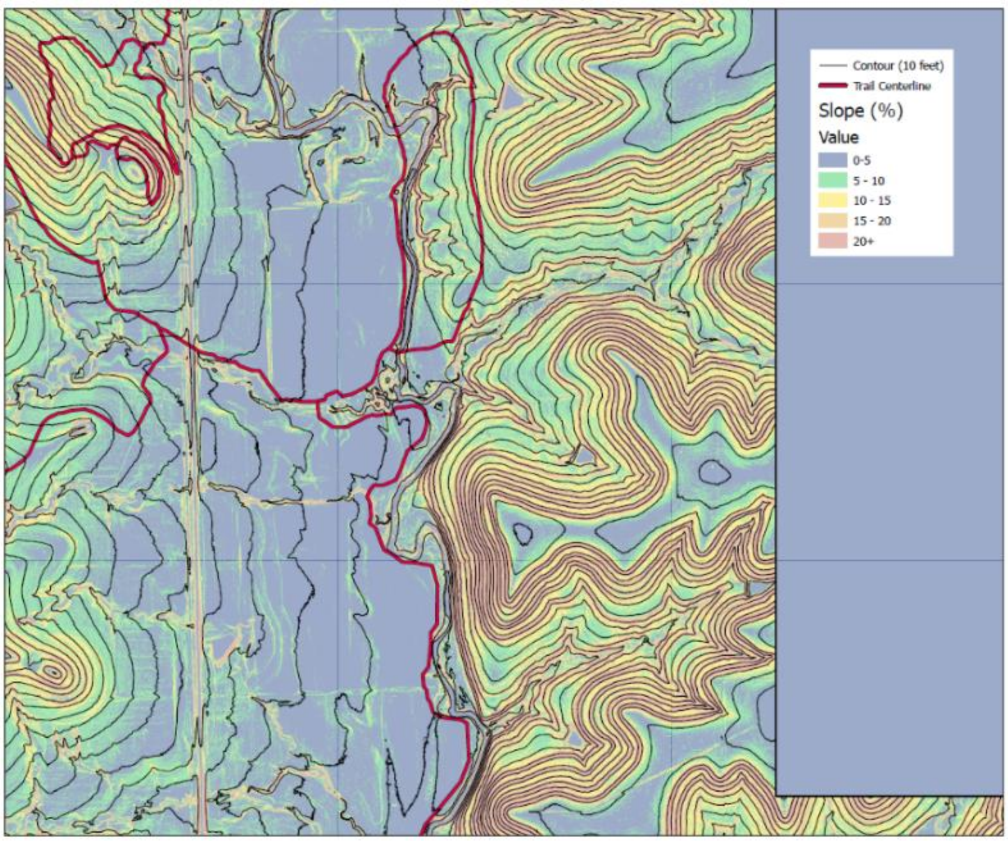


Figure 8. Slope maps with five color-coded categories showing trail system for the western side of the Preserve.



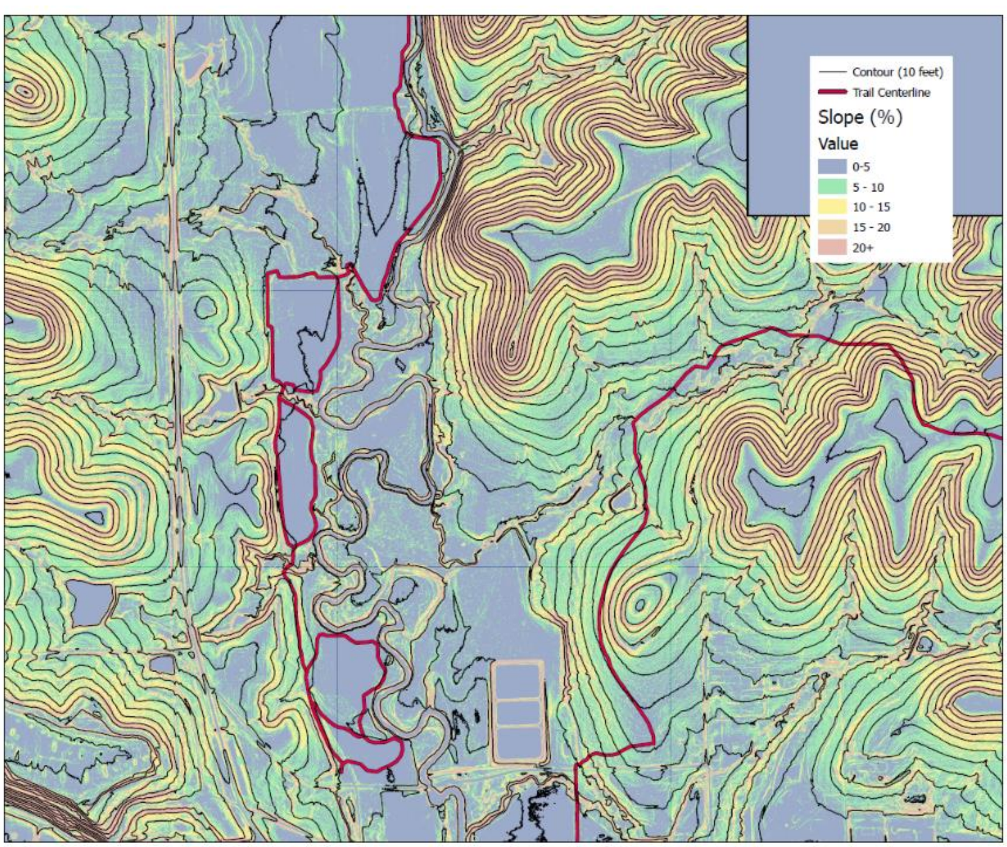


Figure 9. Slope maps with five color-coded categories showing trail system for the eastern side of the Preserve.

Discussion

The limited range in landform grades and the large proportion of the Preserve that has landform grades in the 0-5% range (Figure 8, Figure 9) makes it challenging to design a sustainable trail system. As previously described, trails in flat terrain are inherently difficult to drain, so muddiness during wet periods is frequently a problem. Trail users encountering mud inevitably seek to avoid the mud and in flat terrain trail widening and creation of alternative bypass routes can easily occur. Fortunately, most of the Preserve's trail system appears to receive relatively little visitation, particularly during wet periods as we observed very few instances of deeper rutting or chronic muddiness. As noted, we conducted our survey during a very wet period so our assessments of muddiness and report photos can be considered "atypical." The extreme muddiness we documented in many flat areas appears to be ephemeral and if Preserve managers can reduce vehicular use during wet periods, we don't anticipate significant problems.

Alternative management responses for managing the trails in flatter terrain are varied. Limiting traffic, particularly by heavy trucks, during periods when soils are wet will limit deeper rutting (soil displacement). Using the lighter 6-wheel Ranger vehicles is a preferred alternative during wet periods when access is essential – ground pressures are substantially reduced. If deeper ruts do develop in some areas that begin to retain water and create chronic muddiness that trail users avoid, then applying a mixture of crushed angular gravel and native mineral soil to the ruts can be an effective solution as this ensures that traffic can remain on the designated trail (Figure 10). If this is inappropriate or ineffective, then relocating the affected trail segments to adjacent side-hill alignments with low trail grades (3-5%) is a more sustainable long-term practice (Figure 6). We also encountered a few locations along the trails where cattle are provided with minerals/salt that create excessive muddiness for trail users, and significantly degrade aesthetics and viewsheds (Figure 10). Perhaps these locations might be shifted annually (rest-rotation) or moved to less visible locations away from trails and streams.

Figure 10. Prairie Fire Loop lower swale area (intermittent drainage) that could be spot fixed with gravel (left). Mud generated by cattle hooves along the Prairie Fire Loop Trail (right).

Another substantial proportion of the Preserve has landforms in the 5-10% range, which permit better trail drainage options and is preferred. However, we continued to find that most trail alignments are fall-line rather than side-hill in their orientation to the prevailing landform slopes. Fall-line alignments capture and funnel water run-off along trail treads/ruts, eroding soils directly downhill. These cannot be drained because both trail-sides have slightly higher elevations, which also enable trail users to widen these segments to either side if the designated tread is muddy or eroded (Figure 6). Fall-line alignments in gently sloping terrain are often tolerable provided the trails receive low use, particularly during wet periods. However, if ruts develop on fall-line segments soil can be eroded downhill, deepening the ruts and sending eroded soils into waterways.

Corrective management responses are like those discussed for flatter terrain. Limiting wet season use and/or graveling deeper ruts can be effective, possibly with slightly larger aggregate (1.5-inch vs .75-1-inch) that is less likely to erode or be displaced downhill. If ineffective, then relocating problem segments to side-hill alignments is preferred as a more optimal long-term solution. In all areas, including the graveled segments, more attention is needed to accommodate cross-trail water flow during large rain events. We found evidence of flows at low points along the graveled segments where water has carried gravel well-away from the road out into the prairie. Constant tread out-sloping is one solution, particularly in areas of lower use and vegetated treads. On higher use non-vegetated treads consider ditching along the uphill side draining to armored swales or culverts, to carry the flow across or under the road. New or relocated trails should incorporate an appropriate density of tread grade reversals, as described in the literature review (Figure 2).

It is somewhat surprising but quite fortunate that despite the prevalence of less sustainable trail alignments inherited from the "legacy" ranching roads that the Preserve's trail system is primarily in good condition. For most Preserve trails located in these 0-10% landform grade areas, there are very few locations with deep ruts or chronically wide muddy boggy areas. Attention to stream crossings is needed to ensure that they are adequately protected (discussed below). As mentioned previously, we attribute these "better-than-expected" tread conditions to be a function of the following: relatively low use, particularly during wet periods, wide use of very low ground pressure vehicles (6-wheel Gators), prairie vegetation in full sunlight that has very high trampling resistance and resilience (ability to quickly recover) and graveling in higher traffic areas. We also found some evidence that during the ranching era some larger 2-4 inch rock may also have been placed in trail ruts, though this could simply be emerging natural stone.

Somewhat greater management attention is needed in areas of steeper terrain (>10% landform grades). These areas can be visually identified in Figure 8 and Figure 9 by their lighter colors and dense, closely spaced contour lines. When trails cross these areas at an oblique angle the trails have side-hill alignments that are generally easily drained to lower side-slopes so they don't capture and transport water along their treads down to stream crossings (Figure 6A) – with good maintenance and tread drainage they can be "hydrologically" invisible – with water draining across treads and continuing downhill. In somewhat steeper landform grades (>15%) the steep side-slopes (above and below the trail) also compel trail users to remain "centered" on the trail, preventing trail widening. However, when trails cross steeper terrain (>10% landform grades) at angles approaching 90^o (perpendicular) to contour lines (Figure 6D) their fall-line alignments permit more rapid and substantial soil loss. These segments, which generally do erode with visible deep ruts, are more pressing candidates for relocation, particularly when eroded soils may be entering streams. It may be possible to effectively address fall-line segments in the 10-15% grades through the addition of large angular aggregate (3+ inch), particularly in areas away from streams. Adaptive experimentation is likely needed to find practices that work overtime, otherwise relocation to side-hill alignments will prove best, with little further need for annual maintenance.

Our survey did reveal several stream crossings with excessively steep fall-aligned trails that are clearly introducing soils into the streams, some with clear evidence of substantial soil loss and/or deposition in foot-slope shoreline areas. In many instances there was evidence that the erosion was causally related to both vehicles and cattle, which often also use the trails to cross streams. Project photos available as a product of this study depict these more salient problem areas, as illustrated below by stream crossings on the Crusher Hill Loop and Z Bar Spur Trail (see also photos included above for the Crusher Hill, Fox Creek, Prairie Fire Loop, and Two-Section Trail). These are clearly the most significant natural resource threats identified by this study and additional surveys and remedial actions are indicated.

Taylor *et al*. (1999) compared the environmental effects of fords, bridges, and culverts on stream water quality. They concluded that sediment production was highest for fords and lowest for bridges and sediment production was highest for all structures during the installation phase. After stabilization, the greatest source of sediment for all structures was due to the stream approach which provided over 90% of the total sediment. Bridges are also critical resource protection facilities on horse and motorized trails, uses that are more apt to loosen tread soils, making them more susceptible to erosion. Fords have historically been successful when located at places where the stream is wide, shallow, and has a hard bottom. Fords work well in such locations, but still have the potential to cause water quality problems by allowing direct contact between water and the traffic. For example, fords allow direct inputs of horse manure from horse trails. Another common problem is that fords are sometimes used in situations where the bottoms are soft. These require some sort of surfacing with stone or concrete. The stone and concrete should be similar physically and chemically to native stream material. Geotextiles such as geoweb provide an excellent mechanism for stabilizing stone in stream fords (Aust *et al*. 2003).

"Best Practice" guidance for stream crossings includes the following options:

1) Avoid routing trails near streams, for example, moving a trail from flood plain positions to side-hill positions on lower slopes away from streams.

2) Minimize the number of stream crossings (e.g., keeping the trail on one side of the stream and using side-hill alignments on slopes rather than multiple crossings to access flat terrain).

3) When stream crossings are necessary, scout carefully to select the most resistant location for a ford. Look for rocky banks and stream bottoms and embankment soils with larger amounts of native rock.

4) Design fords so the trail descends to the stream on a gradual (<6%) side-hill grade oriented downstream to cross the stream and ascends gradually on the other side in an upstream direction. These alignments prevent stream water from flowing along the trail and eroding it.

5) Achieve and maintain >3% tread out-sloping to drain trails as they approach stream crossings. Using out-sloped treads promotes well-dispersed "sheet-flow" that allows ground vegetation and organic litter to filter sediment-laden water prior to entering streams. Avoid tread drainage using features like drainage dips, grade reversals, or water bars as these produce larger accumulations of water in riparian areas that lack sufficient distance and time for filtering.

6) Armor trails at stream fords with larger rock, geotextiles, and large gravel to prevent erosion. Tread armoring requires angular stone of sufficient size and anchoring to resist displacement by both trail traffic and flood waters. This option is best in smaller watersheds (e.g., smaller flows during flood events).

7) Consider using well-maintained culverts and elevated treads to cross smaller intermittent or permanent streams but ensure that culvert sizes are designed to accommodate the expected size of large, rare, flood events (e.g., 100-yr floods). Armor and protect abutment soils with large angular rock.

8) Bridges represent more effective but expensive options and must be professionally engineered to accommodate large flood events without erosion of the abutments and treads. Further evaluations by soil conservation specialists with road engineering expertise seems warranted, perhaps funded by a major NRPP funding project to develop and execute the necessary professional guidance and solutions.

Horse and Bike Trail Considerations

We had been asked to also examine the existing trail system to evaluate its potential for accommodating horses and bikes. The existing studies indicate that horse riding is a much “heavier” use that must be accommodated by restricting it to dry soils with greater rock content to support the higher ground pressures and soil displacement forces. In contrast, mountain biking differs relatively little from hiking in its contribution to soil impacts, though soil displacement can more easily occur on turns and steep grades. Both uses could be accommodated at the Preserve, though such uses should be restricted to specific trails with additional management actions to ensure their use is sustainable, as described below. One final point to consider, is that mountain bikers, like horse and vehicle users, travel further than hikers due to their higher speed of travel. This means that their use may require more miles of trails and on a per-unit time basis can affect/degrade more miles of trail than hikers.

Another important concern for both potential new uses is their potential for conflict with existing trail system uses. As noted in the literature review, many studies have demonstrated conflict between horse and hiker users, often over the greater trail degradation of horses or the potential for hikers and mountain bikers to spook horses. We would expect much less conflict between hikers and mountain bikers as the Preserve trail system is predominantly in open prairie vegetation allowing good visibility and time for bikes to slow down when passing hikers. However, it would be prudent to avoid shared uses on accessible trails.

Option 1

This preferred option would remove hikers from the Scenic Overlook Trail to a new sustainably designed trail from the Visitor Center complex out to the buffalo pasture (Figure 11). This trail would have a very low easily hiked grade (80 ft elevation gain over .65 mi, 1.3 mi round trip) and shifts hikers from the graveled road with vehicular traffic (including busses), to a gentle handicapped accessible grade. Crushed gravel (.5 inch to dust) could be applied to provide a durable surface able to support baby strollers and wheelchairs. An elevated observation platform might also be placed at the end of this trail and a watering trough and/or mineral feeding station could be added here to “attract” buffalo to this area for viewing. Horses and/or bikes could then be permitted on the Scenic Overlook Trail out to the Overlook and back (3.5 mi). This road is already sufficiently graveled to accommodate their use. A horse trailer parking area may need to be added to the south end of the Visitor Center parking lot. This option allows the greatest number of visitors easy access to the buffalo pasture to see original prairie vegetation and scenery, including the charismatic buffalo to provide the largest number of high-quality visitor experiences.

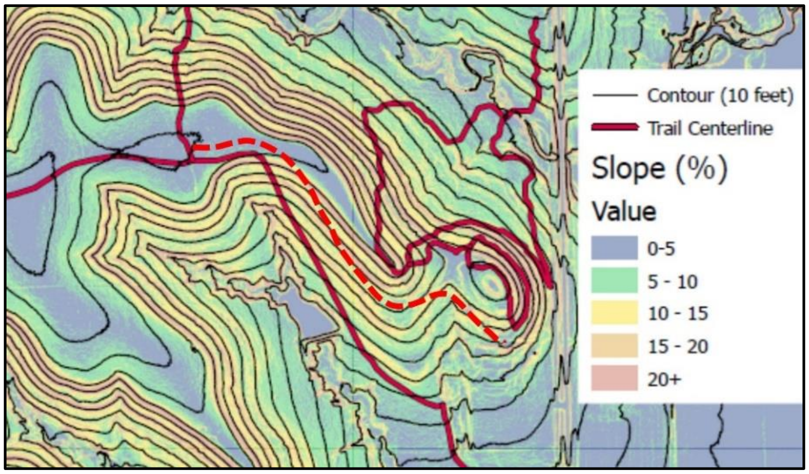


Figure 11. Suggested sustainable hiking trail (dashed red line) from the Visitor Center to the buffalo pasture.

Option 2

The Two Section Trail could make a good horse trail given that there are two well-established trailheads and it provides a longer trail ride 6.2 miles out and back. We are uncertain but there seems to be limited hiking use on this trail and the numerous cows can be somewhat intimidating to hikers but would not be an issue for horseback riders. The U Road trailhead seems sufficiently large for easy horse trailer access. Of greatest concern is that this trail currently has native prairie soil substrates so some graveling would be necessary prior to horse use. One option would be to examine and improve the two stream crossings with the guidance provided above, including armoring with large rock and gravel. We also suggest examining the steeper sections for possible side-hill relocations and/or use of gravel to prevent soil loss. Our data indicate that 1.8% of this trail is fall-line at 10-15% grade and 0.2% is fall-line at >15% grade – these would be the higher priority sections for reroutes or graveling. Examination and improvement of tread drainage may also be needed. Following that, a trial period of one to two years for horse use with restrictions preventing use during wet periods could be run as an "adaptive management" case study. We expect that this level of work would likely accommodate horse use in dry periods. If year-round traffic is desired, then gravel may need to be applied to most of the trail that is close to level (56.2% of the trail), as these areas are likely to retain water and allow muddiness. Alternately the entire trail could be graveled. Note that horse riders generally do not prefer to ride on graveled roads and other research (Aust et al. 2004) suggests mixing crush and run gravel (1.5 in to dust) with native mineral soil to create a sustainable but naturally appearing tread substrate. The thickness of this layer should be 6-10 inches.

Option 3

This option is proposed for mountain biking but could alternately be for horseback riding. The trailhead would be developed at the south end of the Visitor Center parking lot where users would access the Ranch Legacy Trail and the Crusher Hill Loop and return (about 3.6 mi total). This route has many of the same concerns: three stream crossings, 3% of the Crusher Hill Loop has fall-line segments at grades >10%, and 45% has flat (0-2%) trail grades and could create problems if use occurred during wet periods. The same previously discussed guidance applies to this option. A longer option is also possible, permitting a link north to the Scenic Overlook trail to the overlook and back on the Ranch Legacy trail (about 10.5 mi total).

General comments: Most trail users do not enjoy hiking or riding on loose gravel surfaces and prefer more natural appearing substrates as long as they are not excessively rutted or muddy. A preferred compromise seems to be the use of crush and run gravel mixed with native mineral soil. The stone and binders in crushed gravel and soil provide both the density and cohesion necessary to provide a durable tread surface for most types of trail use, particularly during dry seasons. Unfortunately, gravel does become somewhat less stable and can be displaced or eroded when soils are wet, so attention to tread drainage remains important, i.e., not allowing water to be intercepted and channeled along trail treads. Shifting to a larger aggregate size can help, particularly on steeper slopes but this can also create significant problems for any future horse traffic, as stones in the 2-3 inch range are more apt to cause a foot bruise, which when severe can cause a horse to become lame.

Neither horse or bike use is recommended for the Palmer Creek Loop unless the final section is rerouted and fixed. The Bottomland Nature Trail is also not recommended due to conflict with accessible trail users, and the unsurfaced Fox Creek trails have a much higher potential for extreme muddiness and likely a longer “mud” season due to their flood plain location. The Fox Creek trails seem more ideal for pedestrian hiking, nature study, and trail running, though improvements in stream fords are needed to lessen soil erosion, and tread drainage or graveling to address muddiness.

Conclusions

This research sought to provide objective trail system data to better inform staff of the Tallgrass Prairie National Preserve and The Nature Conservancy on the condition and sustainability of their trail system, “Best Management” practices for improving trail system design, maintenance, and management, and providing improved recreational opportunities for Preserve visitors. This report includes an extensive review of the literature on potential trail system impacts to Preserve vegetation, soils, and water, and guidance related to accepted practices for improving the trail system’s sustainability to accommodate visitation for a variety of existing and potential new trail users.

Though the Preserve inherited a legacy network of primitive roads and trails that are largely unsustainably designed, the Preserve’s trails are in surprisingly good condition. This is attributed to relatively low use and the exceptional resistance and resilience of the native prairie vegetation. The most significant resource protection concerns relate to the numerous stream crossings (fords), some of which appear to be introducing larger quantities of soil into the streams.

Suggested management responses to improve the sustainability of the trail system to accommodate current and future uses are provided, based both on the scientific and technical literature, and research findings from fieldwork. A georeferenced dataset describing the Preserve’s trail system, resource conditions, features, and photographs is also included as a product of this research project. The principal author also remains available for future consulting as needed.

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Appendix 1:
Trail Assessment Manual

Tallgrass Prairies National Preserve

(*version 5/17/21*)[1]

This manual describes procedures for conducting an assessment of resource conditions on the Appalachian Trail treadway. These procedures are designed so that they can be replicated, allowing future reassessments for monitoring trail conditions over time. Some indicators are included to characterize factors expected to influence trail conditions or assess trail design attributes and sustainability.

Trail conditions will be characterized from measurements taken at the sample point transect locations and from a problem assessment that identifies trail segments with excessive soil loss, width, or muddiness. Measurements will document the trail's width, depth, substrate, slope, alignment and other characteristics. These procedures take several minutes to apply at each sample point.

The Fulcrum phone app was used to record all data and four forms were developed (General Comments, Informal Trail, Transects, and Feature Inventory). Each time a new record is opened to record a comment, informal trail, transect, or feature the app automatically saves the date, time, and a GPS position using the smartphones internal GPS (accuracy approximately 20 ft). The phone app also directly links to the phone's camera for photos, and it records a unique linked photo name for each photo. All photos are also georeferenced and permanently associated with their data records.

Materials (Check before leaving for the field)

- ✓ Day pack w/x-tra clothing, rain gear, lunch/snacks, water, hat, sunscreen, tick repellent, first aid kit, phones, wallets, car key, fanny pack, umbrella, trash bags to cover packs in rain, other?
- ✓ Phones w/Fulcrum app and 3 data entry files, charged battery plus power bank and connector cord
- ✓ Garmin 64 GPS unit w/charged & spare batteries
- ✓ This manual
- ✓ Keson flexible transect line tape measure in tenths of a foot (50 ft retractable)
- ✓ Pocket measure for max incision measures (12 ft retractable)
- ✓ Small notebook and pens
- ✓ Stakes (2)
- ✓ Metal binder clips (4+) to attach tape to stakes
- ✓ Compass/clinometer combo

1 - Developed by Dr. Jeff Marion, DOI, U.S. Geological Survey, Eastern Ecological Science Center, Virginia Tech Field Station, Dept. of Forestry (0324), Blacksburg, VA 24061 (540/230-2138) Email: jmarion@vt.edu

General Comments Form

1) **Trail Name:** Record the trail name code.
2) **Trail Segments:** Record the trail segment (section of trail, or All).
3) **Environmental Sustainability:** Describe comments related to the trail's environmental sustainability.
4) **Social/Experiential Sustainability:** Describe comments related to the trail's social/experiential sustainability.
5) **Reasonable Current User Types:** Describe comments related to the trail's current user types.

6) **Potential User Types Comments:** Describe comments related to the trail's potential user types (e.g., bikers or horses).

7) **General Comments:** Describe any general comments to describe the trail, its conditions, problems, or needs.

8) **Accessibility**
Tread Surface: Substrate smoothness, firmness, veg cover, obstacles like rocks, roots, ruts, etc. >2 inches tall. Could it be used as a walker or wheelchair?
Typical Trail Width (ft): What is the "typical" width (ft)?
Slope: TG: <5% grade is best with 12% max. Cross slope: 5% max
Resting Spots: For trail grades >5% there must be some resting spots that are flat (Accessibility).
Passing Spaces: Trails with clear widths <60 inches should have wider passing sections every 1000 ft (Accessibility).
Barriers: Gates, Stream Crossings, Cattle Guards, Mudholes (Accessibility)

Transect Form

Trail monitoring will be focused on locating and assessing both "typical" and "problem" trail segments. Representative "typical" transects are designed to characterize general trail segment conditions, with additional records added to characterize the trail if conditions change (e.g., a section of tread with natural soil substrates to a section where ruts have been filled with gravel). When significant tread degradation occurs the "problem" transects are also added to identify the type of degradation, frequency, locations, lineal length, and corrective suggestions so that management can efficiently plan and execute corrective solutions and evaluate their efficacy over time. Three core types of trail impacts will be evaluated: excessive soil loss, muddiness, and widening, each with a recorded begin and end point and comment field. Problem transects are only assessed when one of the three problems affects more than ten lineal feet of the tread.

1) **Trail Name:** Record the trail segment's name.

2) **Transect Type:** Excessive Soil Loss (ES), Excessive Trail Width (EW), Excessive Muddiness EM), Typical (TP)

Excessive Soil Loss (ES): Sections of tread (≥10 ft long) with soil erosion exceeding 6 inches in depth within current tread boundaries.

3) **Begin Photo:** Take a photo that includes foreground and the affected section of tread.

4) **End Photo:** Walk to the other end of the problem section take a photo that includes foreground and the affected section of tread.

5) **Problem Length:** Measure or estimate the length of the tread problem and record.

6) **Comments:** Describe and characterize the problem in more detail along with potential causes (e.g., steep grade, fall-aligned, flat/wet areas) *and* suggested solutions (tread work or relocation).

Excessive Trail Width (EW): Sections of tread (≥10 ft long) that exhibit expansion in width that is >4ft wider than the "norm" or "design width" of the trail, caused by human pedestrian or vehicle traffic (e.g., walking/driving around an eroded, rocky, or muddy section).

7) **Begin Photo:** Take a photo that includes foreground and the affected section of tread.

8) **End Photo:** Walk to the other end of the problem section take a photo that includes foreground and the affected section of tread.

9) **Problem Length:** Measure or estimate the length of the tread problem and record.

10) **Comments:** Describe and characterize the problem in more detail along with potential causes (e.g., steep grade, fall-aligned, flat/wet areas) *and* suggested solutions (tread work or relocation).

Excessive Muddiness (EM): Sections of tread (≥10 ft long) that exhibit excessive muddiness with standing/running water and/or mud that lasts a week or more after rain, i.e., include dried up mudholes if assessed during extended dry weather and be very conservative in these assessments during/after rainy weather. Hold phone in the middle of problem segment when you open the indicator as it records a location at this time. Then walk to the beginning of the problem and place a yellow stake.

11) **Begin Photo:** Take a photo that includes foreground and the affected section of tread.

12) **End Photo:** Walk to the other end of the problem section take a photo that includes foreground and the affected section of tread.

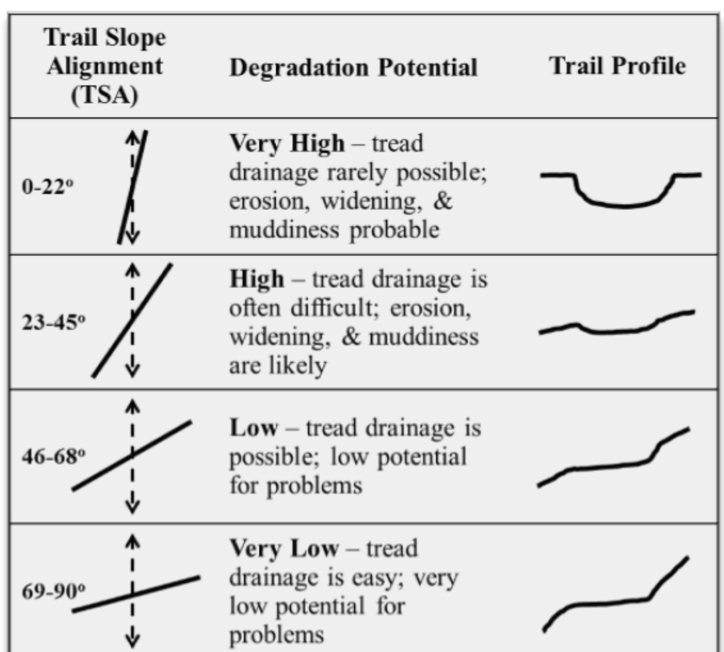
13) **Problem Length:** Measure or estimate the length of the tread problem and record.

14) **Comments:** Describe and characterize the problem in more detail along with potential causes (e.g., steep grade, fall-aligned, flat/wet areas) *and* suggested solutions (tread work or relocation).

15) **Upslope Trail Grade (%):** The two field staff should position themselves at the transect and about 10 ft in an uphill direction **on the trail** from the transect. Use the clinometer to determine the grade by sighting and aligning the horizontal line inside the clinometer with a spot on the opposite person at the same height as the first person's eyes. Note and record the nearest ***percent*** (right-side scale, record as a positive value). If at a local high point (everything within 10 ft is lower, record a neg. grade value).

16) **Landform Grade (%):** Two field staff should position themselves at the transect and about 10 ft in an uphill direction along the fall line beginning above any "cut" slope. Your objective is to measure the prevailing landform slope in the vicinity of the transect. Look in the clinometer side window and record the nearest ***percent*** (positive value) off the visible scale. If at a local high point (everything within 10 ft is lower, record a neg. grade value).

17) **Trail Slope Alignment Angle:** Looking directly uphill from the sample point, identify and project the fall-line across the trail. Identify the fall line by thinking about where you would need to pour a bucket of water such that the water would run downhill and intercept the middle of the transect. Ignore the influence of adjacent large rocks and focus on averaged water movement over the uphill landscape. Chose the direction along the trail that makes an acute angle (<90°) with the fall line. Sight the peep-hole compass along the trail in the acute angle direction (10 ft segment) and record as "Trail Bearing°" the compass azimuth. Repeat to assess and record the azimuth of the fall line as "Fall Line Bearing°". The Trail Slope Alignment angle is calculated by subtracting the smaller from the larger azimuth



Trail Slope Alignment (TSA)	Degradation Potential	Trail Profile
0-22°	**Very High** – tread drainage rarely possible; erosion, widening, & muddiness probable	
23-45°	**High** – tread drainage is often difficult; erosion, widening, & muddiness are likely	
46-68°	**Low** – tread drainage is possible; low potential for problems	
69-90°	**Very Low** – tread drainage is easy; very low potential for problems	

(computed by Fulcrum) – ensure that it is <90°. If at a local high point (everything within 10 ft is lower, record a -1).

18) **Secondary Treads:** Count the number of trails differentiated from the main tread by strips (>20 inches) of mostly undisturbed vegetation or organic litter, regardless of their length, that closely parallel the main tread at the transect. *Do not count the main tread.*

Trail Tread Boundaries: Examine the Figure 1 photos illustrating different types of tread boundary determinations. Tread boundaries are defined as the most pronounced outer boundary of visually obvious human disturbance created by trail use (not trail maintenance like vegetation clearing). These boundaries are defined as pronounced trampling-related changes in ground vegetation height (trampled vs. untrampled), cover, composition (broadleaf herbs vs. grasses), or when vegetation cover is reduced or absent, changes in organic litter (intact vs. pulverized) (see photo illustrations in Figure 1). The objective is to define the trail tread that receives the majority (>95%) of traffic, selecting the most visually obvious outer boundary that can be most consistently identified by you and future trail surveyors. Where helpful it is appropriate to examine the adjacent 10 ft on either side of the transect location to project trail boundaries from there to define the tread boundaries at the transect point.

- Include any secondary parallel treads within the transect only when they are not differentiated from the main tread by strips (>20 in) of mostly undisturbed vegetation or organic litter.
- If the trail is on stonework (rock steps, armored treads, stepping stones) use the width of stonework unless there is visible evidence of walking on bordering rocks or around them. Omit incision measure (record a -1).

Measurement Procedure: Hammer the steel border stakes in at each tread boundary making sure that the transect line will be perpendicular to the tread at that location. If stakes can't be inserted into the ground then have your partner hold it in place during the measurements, or move large rocks to sandwich the stake between them. The stakes have black markings, when possible insert the stakes so that the post-construction tread surface aligns with one of these markings. Place binder clips on the stakes so that the bottom of the binder clip aligns with what you judge to be the post-construction pre-use tread surface.

Stretch the transect measurement tape between the stakes configured using your best judgment to reflect the post-construction pre-use tread surface at the bottom of the tape. The tape on the left side should be affixed with a binder clip ***so the stake is at the "0" point of the tape***, secure the opposite end by pulling the tape tightly, then wrapping it around the stake and securing with another binder clip. The tape needs to be tight - any bowing in the middle will bias measurements.

19) **Tread Width:** See prior "Trail Tread Boundary" guidance. Measure and record the length of the transect (tread width between the tread boundary stakes) to the nearest 0.5 inch (e.g., 45.0, 45.5, 46.0 in). Omit when tread boundaries are indistinguishable (record a 0).

20) **Maximum Incision:** Select and measure along the transect line the maximum incision value, recorded to the nearest 0.25 inch (e.g., 4.0, 4.25, 5.75 in).

21) **Tread Drainage Feature:** In 20-foot increments up to 100 feet, estimate the distance to any reasonably effective tread drainage feature located in an up-slope trail direction from the sample point. Tread drainage features could include: Wood water bar, rock water bar, drainage dip, grade reversal (natural or manmade), tread outsloping, natural rocks, exposed roots, and other.

22) **Tread Drainage Feature Type:** Record the type of feature: Wood water bar (1), Rock water bar (2), Drainage dip (3), Grade reversal (natural or man-made) (4), Tread out-sloping (5), Natural rocks (6), Exposed roots (7), Too Far (8)

Figure 1. Photographs illustrating different types of boundary determinations. Trail tread boundaries are defined as the most pronounced outer boundary of visually obvious human disturbance created by trail use (not trail maintenance like vegetation clearing). These boundaries are defined as pronounced changes in ground vegetation height (trampled vs. untrampled), cover, composition, or, when vegetation cover is reduced or absent, as pronounced changes in organic litter (intact vs. pulverized).

<u>Tread Condition Characteristics:</u> Along a 8 inch band centered on the transect, estimate to the nearest 10% (5% where necessary) the aggregate proportion occupied by any of the mutually exclusive *<u>tread surface</u>* categories listed below. **Be sure that your estimates sum to 100%**.

23) Soil:	All soil types including sand and organic soils, excluding organic litter unless highly pulverized and occurs in a thin layer or smaller patches over bare soil.
24) Litter:	Surface organic matter including intact or partially pulverized leaves, needles, or twigs that mostly or entirely cover the tread substrate.
25) Vegetation:	Live vegetative cover including herbs, grasses, mosses rooted within the tread boundaries. Ignore vegetation hanging in from the sides.
26) Rock:	<u>Naturally-occurring</u> rock (bedrock, boulders, rocks, cobble, or natural gravel). If rock or native gravel is embedded in the tread soil estimate the percentage of each and record separately.
27) Mud:	Seasonal or permanently wet and muddy soils that show imbedded foot or hoof prints from previous or current use (omit temporary mud created by a very recent rain). The objective is to include only transect segments that are frequently muddy enough to divert trail users around problem.
28) Gravel:	<u>Human-placed</u> (imported) gravel on trail or road.
29) Roots:	Exposed tree or shrub roots.
30) Water:	Portions of mud-holes with water, or water from seeps or creeks.
31) Wood:	<u>Human-placed</u> wood (water bars, bog bridging, decking).
32) Other:	Specify: e.g., paved road or sidewalk.

13) **<u>Transect Photos:</u>** Take two transect photos: **<u>Oblique photo</u>** – move the phone back or forward along the trail until you capture the entire transect plus about 2 ft of adjacent terrain on either side. Position the phone so that the background looking down the trail beyond the transect is also captured. **Vertical photo** – hold the phone directly above the transect and take a photo that shows the tread conditions. *<u>Check both photos for focus and exposure and retake them when needed.</u>*

Trail Feature Inventory Form

1) **Trail Name:** Record the trail name code.
2) **Feature Type:** Stream Crossing (SC), Culvert (C), Sign (S), Gate (G), Trail Marker (TM), Drainage Feature (DF), Bench (B)
3) **Photos:** Take one or more photos of each feature.
4) **Comments:** Where appropriate, describe the feature and comment on its condition, sustainability, suggestions, etc.

Informal Trail Survey

Use a Garmin GPS unit to record all informal (visitor-created) trails. Label each trail with a unique waypoint number and record in Fulcrum file #3.

1) **Trail Name:** Record the trail name that the informal trail intersects with.
2) **Garmin GPS Waypoint #:** Record the informal trail's reference number assigned within the Garmin GPS.
3) **Trail Width:** Record typical width to nearest inch.
4) **Condition Class:** Record typical condition class rating.
    - **1** – Trail distinguishable; slight loss of vegetation cover and/or minimal disturbance of organic litter.
    - **2** – Trail obvious; vegetation cover lost and/or organic litter pulverized in center of tread in most places.
    - **3** – Vegetation cover and organic litter lost across the majority of the tread.
    - **4** – Soil erosion in the tread beginning in some places.
    - **5** – Soil erosion is common along the tread.
5) **Comment:** Describe any additional relevant comments like why the trail is present and if it seems necessary or unnecessary, corrective actions, etc.