Factors influencing informal trail conditions: Implications for management and research in Urban-Proximate parks and protected areas

Bettina S. Spernbauer [a,b], Christopher Monz [a,b], Ashley D'Antonio [c], Jordan W. Smith [a,b,*]

[a] *Institute of Outdoor Recreation and Tourism, Utah State University, Logan, UT 84321, USA*
[b] *Department of Environment and Society, Utah State University, Logan, UT 84321, USA*
[c] *Department of Forest Ecosystems and Society, Oregon State University Corvallis, Oregon 97331, USA*

HIGHLIGHTS

- Informal trail networks in urban-proximate parks can cause extensive resource impacts.
- Rapid assessment trail data can be analyzed with predictor effect plots.
- Visitor use should be concentrated considering factors influencing trail conditions.
- Sampling protocols for more precise indicator measures on informal trails are needed.

ARTICLE INFO

ABSTRACT

With growing urban populations in close proximity to natural environments, recreation resource managers in parks and protected areas (PPAs) are increasingly confronted with challenges such as high levels of visitation and severe resource impacts. Additionally, urban-proximate PPAs, particularly informal trails in these areas, have received little research attention relative to more remote PPAs and formal trails. The formation of informal trail networks in urban-proximate PPAs can lead to extensive resource impacts such as loss of vegetation cover and soil erosion. Use-related, environmental, and managerial factors have been found to influence trail conditions and degradation on formal trails. We use a well-established rapid assessment field protocol and GIS-derived calculations to analyze informal trail conditions, and the factors influencing those conditions in a high alpine urban-proximate PPA. We find informal trail networks are extensive and that informal trails are influenced by use-related, environmental, and managerial factors in a similar fashion as formal trails. Additionally, results from predictor effect plots allow us to derive valuable management implications focused on where to concentrate use and minimize environmental impacts. Our study concludes with implications to further advance research related to informal trails, such as the need for sound sampling designs and the potential of trail research as a basis for further analysis on environmental susceptibility.

1. Introduction

Visitation to many parks and protected areas (PPAs) has been rising in recent years, increasing the demands placed on natural resources and the outdoor recreation experiences they provide (Balmford et al., 2015). One reason for rising visitation in urban-proximate PPAs is the growth of adjacent urban populations, which account for a high proportion of visitors (English, Froemke, & Hawkos, 2015). The U.S. Forest Service (USFS), one of numerous agencies managing urban-proximate PPAs in

the U.S., defines urban national forests as forests located within 50 miles (80.5 km) of population centers with >1 million people (Dwyer & Chavez, 2005). Compared to more remote PPAs, such as national parks and wilderness areas, urban-proximate PPAs have received considerably less research attention (Kyle & Graefe, 2007). Urban-proximate PPAs provide important ecosystem services such as outdoor recreation opportunities, drinking water, and improvements to air quality (Andereck & Knopf, 2007; Ewert, 1993). For example, escaping heat, noise, and pollution, are some of the most important "activities" for visitors in the

Fig. 1. Approach Trails and Buffers for Informal Trail Assessment.

Table 1
Trail Condition Class Categories.

Class	Description
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 primary use areas.
3	Vegetation cover lost and/or organic litter pulverized within the center of the tread, some bare soil exposed.
4	Nearly complete or total loss of vegetation cover and organic litter within the tread, bare soil widespread.
5	Soil erosion severe, as indicated by exposed roots and rocks and/or gullying.
R	Trail is predominantly on rock surfaces, so the effects of trampling are difficult to see/assess.

Sources: Monz, Marion, et al., (2010), Marion (personal communication, September 2021).

Central Wasatch mountains located next to Salt Lake City, Utah (USA) (Lamborn, Burr, Kim, & Kessler, 2015). Because of their proximity to large populations, these areas also exhibit unique characteristics and challenges, including very high levels of recreational use, shorter visits relative to less urban-proximate PPAs, greater diversity among visitor ethnicities and activities, complex stakeholder involvement processes, and severe resource impacts (Andereck & Knopf, 2007; Dwyer & Chavez, 2005; Ewert, 1998; Ng, 2022; Wilkinson, 2004).

Between 1990 and 2010, the number of people living within 50 miles of national forests within the U.S. has increased by 36 %, and this trend is predicted to continue into the future (English et al., 2015). Additionally, visitation to national forests increased significantly during the COVID-19 pandemic (USDA Forest Service, 2021). Subsequently, pressures on infrastructure providing access to these natural areas, such as recreational trails, have been increasing. Trails are one of the most important means for urban populations to experience their nearby natural environments. While formal trail networks are usually deliberately planned and maintained to minimize impacts, additional informal trails are created and used by visitors to access attraction sites, such as waterbodies or viewpoints, or as shortcuts between formal trails (D'Antonio, Monz, Larson, & Rohman, 2016; Leung, Shaw, Johnson, & Duhaime, 2002; Monz, Marion, et al., 2010; Salesa & Cerdà, 2020; Wimpey & Marion, 2011). Informal trails often occur where visitors disperse and can be extensive. For instance, Monz, Marion, et al. (2010) found 2.57 km of discontinuous trail fragments on the heavily developed and visited summit of Cadillac Mountain in Maine (USA). Despite providing people with an important way to access natural areas, trails come with a variety of environmental impacts and can be prone to degradation if not built in a sustainable way. For example, Ng (2022) found significantly more degradation on hiking trails in Hong Kong that were not surfaced with durable materials.

To address growing concerns about resource degradation in urban-proximate PPAs, our study aims at characterizing the extent and conditions of informal trails in an urban-proximate national forest; we also identify factors influencing trail conditions and their spatial distribution. Our study was conducted in Little Cottonwood Canyon within the Uinta-Wasatch-Cache National Forest and adjacent to the fast-growing metropolitan area of Salt Lake City, Utah (USA). With a population within 50 miles that has grown 22 % between 2000 and 2010, and the expectation to see the highest increase in the nation from 2010 to 2020, the Uinta-Wasatch-Cache National Forest is exemplary of the challenges

Table 2
Response and Predictor Variables from Field Data Collection and GIS Analyses[a].

Variable	Source	Description	Type/Categories
Response Variables			
Condition Class	Field data collection	Written descriptions that serve as indicator for trail conditions	Class 1–5 (see Table 1)[b]
Trail Width	Field data collection	Estimated width as an indicator for trail disturbance	< 50 cm, 50–100 cm, 1–2 m, >2 m
Predictor Variables			
Use Level[c]	*StreetLight Data Inc.*	Average daily trips (May-October) passing through defined zones [d]	Continuous (count)
Surrounding Vegetation	Field data collection	Vegetation type surrounding trail segments	Forested, Open Grassland/Meadow, Other (incl. Rock & Shrubs)[e]
Trail Grade[c]	GIS; average slope of 1 m sections based on a 0.5 m LiDAR DEM	Steepness of trail sections	Continuous (%)
Trail Slope Alignment	GIS; difference between average line bearing and average aspect of each trail section	Difference between azimuth of prevailing landform slope and the trail alignment angle	Continuous (degree)
Distance to Formal Trails	GIS	Nearest distance from trail section to formal trail	Continuous (m)
Distance to Lake Shore	GIS	Nearest distance from trail section to lake shore	Continuous (m)

[a] We also collected data on substrate type, trail position, and generated data for landform grade; however, those variables were dropped due to lack of variability, lack of counts per outcome category, and multicollinearity (landform grade and trail grade, Pearson's correlation coefficient $r = 0.662$).
[b] Condition class *rock* was dropped for analysis because of the small number of rock sections.
[c] log-transformation was used for model estimation.
[d] Trip counts are the total number of trips passing through each trail segment in which a user did not stop for longer than 5-minutes.
[e] *rock, shrub,* and *other* was collapsed into one category due to sparseness of counts.

associated with increasing recreational pressure in urban-proximate PPAs (English et al., 2015; Utah Department of Transportation, 2022; Wilkinson, 2004). The purpose of our research is to provide actionable guidance land management agencies and their partners can take to reduce the impacts from, and degradation of, informal trails. Our work also intends to contribute to the advancement of ways to characterize informal trails and further analyze data collected in the field.

2. Literature review

2.1. Impacts of recreational trails

The predominant ecological impacts of recreational trails are loss of vegetation cover, soil compaction, and soil erosion (Ballantyne & Pickering, 2015; Hammitt, Cole, & Monz, 2015). While only small differences between the impacts of informal and formal trails have been found, informal trails have been repeatedly found to account for a greater cumulative loss of vegetation due to their greater overall extent relative to formal trails (Ballantyne & Pickering, 2015; Barros & Pickering, 2017; Pickering & Norman, 2017). Vast informal trail networks also contribute to habitat fragmentation, causing landscape level damage and potentially detrimental effects to wildlife (Ballantyne, Gudes, & Pickering, 2014; Barros & Pickering, 2017; Leung, Newburger, Jones, Kuhn, & Woiderski, 2011; Primack & Terry, 2021). Informal trails often proliferate over time (Hammitt et al., 2015; Leung et al., 2002; Lucas, 2020; Marion & Leung, 2011) and since they often experience less use, they may still be prone to rapid degradation in their early stages (Havlick, Billmeyer, Huber, Vogt, & Rodman, 2016; Monz, Pickering, & Hadwen, 2013). Additional environmental impacts can occur when trails form in ecologically sensitive locations (Leung et al., 2002). The loss of vegetation cover, braided trails, soil compaction, and soil erosion can also have impacts on the visitor experience, as they can scar landscapes and reduce their aesthetic appeal, as well as cause safety and liability concerns (D'Antonio, Monz, Newman, Lawson, & Taff, 2012; Marion, Leung, & Nepal, 2006; Peterson, Brownlee, & Marion, 2018; Rodway-Dyer & Ellis, 2018; Verlič, Arnberger, Japelj, Simončič, & Pirnat, 2015). Despite these complex and wide-ranging impacts, informal trails have received less research attention relative to formal trails (Ballantyne & Pickering, 2015).

Informal trails are difficult to manage and of particular concern to managers in urban and urban-proximate PPAs (D'Antonio et al., 2016; Marion & Leung, 2011; Primack & Terry, 2021). For instance, Reed, Larson, Crooks, and Merenlender (2014) found informal trails make up an average of 45 % of the total trail networks in San Diego County (USA) nature reserves, an area providing outdoor recreation opportunities for over 3 million people.

2.2. Factors influencing trail conditions

Previous investigations have thoroughly examined the factors influencing the conditions and degradation of formal trails (Salesa & Cerdà, 2020). Conditions are most commonly measured at fixed intervals along trail segments, with indicators including trail width (Farrell & Marion, 2001; Meadema, Marion, Arredondo, & Wimpey, 2020; Nepal & Way, 2007; Tomczyk, Ewertowski, White, & Kasprzak, 2017; Wimpey & Marion, 2010) as well as measures of erosion such as cross-sectional area (Marion & Wimpey, 2017; Nepal & Way, 2007; Olive & Marion, 2009) and maximum incision (Farrell & Marion, 2001; Meadema et al., 2020). Fewer studies have used census approaches and categorical indicators such as trail erosion categories or general condition classes, which consider combined attributes of vegetation loss and soil erosion (Bratton, Hickler, & Graves, 1979; Monz, Marion, et al., 2010; Nepal, 2003). Even though results vary, research has identified several general use-related, environmental, and managerial factors influencing trail conditions (Hammitt et al., 2015; Leung & Marion, 1996). Use level has repeatedly been found to influence trail conditions (Farrell & Marion, 2001; Nepal, 2003; Nepal & Way, 2007; Tomczyk et al., 2017). For example, Dixon, Hawes, and McPherson (2004) found trail use to be the most significant factor influencing the width of over 1000 km of trail in Western Tasmania. As for environmental factors, several studies have found vegetation type (Bratton et al., 1979; Farrell & Marion, 2001; Nepal, 2003; Tomczyk et al., 2017), the grade of the landform on which a trail is located (Dixon et al., 2004; Meadema et al., 2020; Tomczyk et al., 2017), and soil texture (Eagleston & Marion, 2020; Olive & Marion, 2009) can affect trail conditions. Finally, trail slope alignment (TSA) and trail grade[1] are important managerial factors

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[1] A visual illustration of landform grade, trail grade, and trail slope alignment is provided in Appendix A.
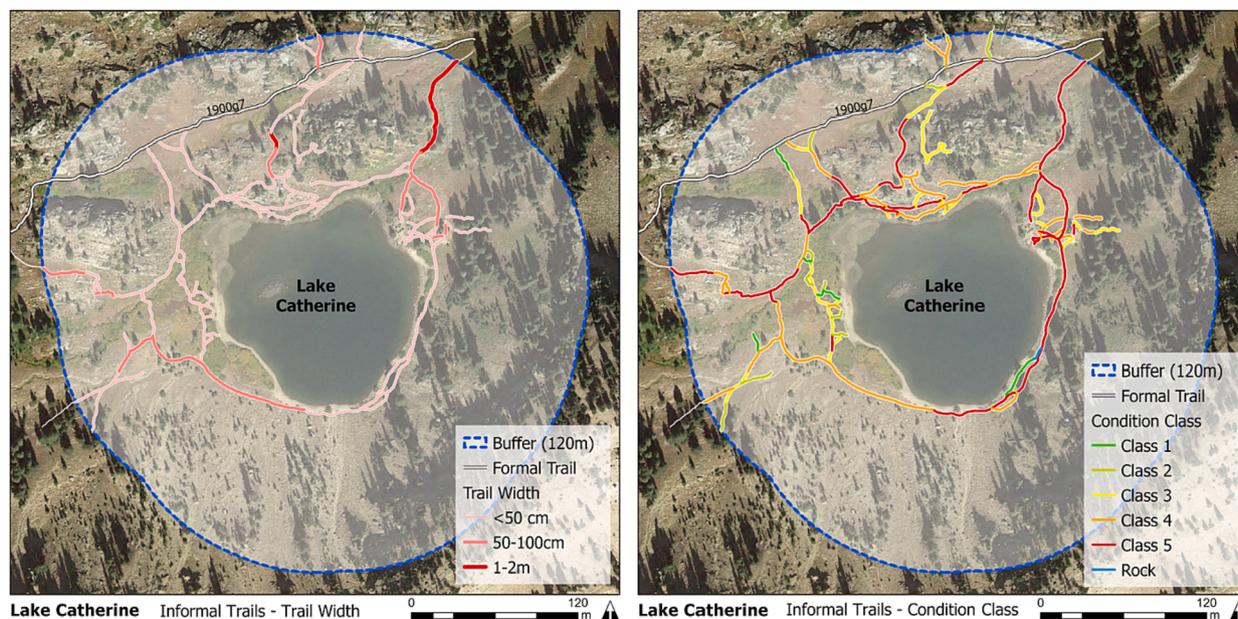
Fig. 2. Location and extent, width (left), and condition class (right) of informal trails around Lake Catherine (maps for other study locations can be found in Appendix I).

Table 3
Summary of Length of Assessed Trails, Buffer Size, and Informal Trail Density.

Lake	Formal Trail Length (m)	Informal Trail Length (m)	Buffer Size (ha)	Density (m/ha)
Lake Catherine	3,131.0	2,175.3	10.4	209.2
Cecret Lake	2,639.8	1,979.3	10.7	184.9
Red Pine Lake	4,862.0[a]	2,438.0	14.4	168.8
White Pine Lake	8,835.4	681.4	11.1	61.3
[a]Length from the White Pine Lake/Red Pine Lake Junction.				

and strongly define the sustainability of a trail (Marion & Wimpey, 2017). Trail grade is the slope of the trail itself, with steep trails being especially prone to soil erosion (Bratton et al., 1979; Dixon et al., 2004; Farrell & Marion, 2001; Marion & Olive, 2006; Marion & Wimpey, 2017; Meadema et al., 2020; Nepal, 2003). Additionally, Marion and Wimpey (2017) highlight the potential for increased trail widening and muddiness associated with lower trail grades, and Nepal (2003) notes worse condition class ratings on flat terrain and steep grades. TSA refers to the difference in the bearing of the trail and the aspect of the prevailing landform. Trails aligned at a greater angle to the landform (side-hill) generally show less severe soil erosion and widening than trails aligned along the fall-line of a slope (Marion & Olive, 2006; Marion & Wimpey, 2017; Meadema et al., 2020; Olive & Marion, 2009; Tomczyk et al., 2017; Wimpey & Marion, 2010).

2.3. Considerations for informal trails

Relative to formal trails, considerably less research has been done on factors influencing the conditions of informal trails. Informal trails are not intentionally built, often improperly located in relation to surrounding topography, less used, and often receive no maintenance. Given informal trails are not built with trail grade and TSA in mind, these trails might have an increased potential for degradation relative to formal trails (Leung et al., 2002; Marion et al., 2006; Rodway-Dyer & Ellis, 2018; Wimpey & Marion, 2011). One comparative study found informal trails are steeper, located in steeper terrain, more closely aligned to the fall-line, and narrower than formal trails (Wimpey & Marion, 2011). Farrell and Marion (2001) found that while the number of informal trails does not differ by amount of use and trail position, the

number of informal trails does differ by vegetation type with significantly more informal trails found in grassland environments. Studies investigating the relationship between use level and the proliferation of informal trails report mixed results (D'Antonio et al., 2016; Primack & Terry, 2021).

As inferred by the limited literature above, there is a need for further research on the characteristics as well as factors influencing conditions of informal trails. There are notable difficulties in the assessment and analysis of informal trails, such as the initially unknown location and extent of these trails and the limitations for further analysis due to the categorical nature of commonly used indicators such as condition class (Marion et al., 2006); these factors are likely to have contributed to the limited research on informal trails. Understanding the conditions and extent of informal trails, as well as the factors influencing trail conditions and the spatial distribution of all these variables can provide a valuable basis to inform management actions. In our study, we use data collected in the field, calculations based on Geographic Information Systems (GIS), and statistical analyses to answer the following research questions at four high alpine lakes in Little Cottonwood Canyon (LCC):

1) How are visitor use levels and trail condition indicators manifested across informal trail networks in an urban-proximate PPA?
2) What are the relationships between use-related, environmental, and managerial factors and trail condition class and trail width on informal trails?

The rapid population growth of the Salt Lake City metropolitan area and increases in visitation to LCC have resulted in these lakes experiencing many of the manifold challenges faced by urban-proximate PPAs.
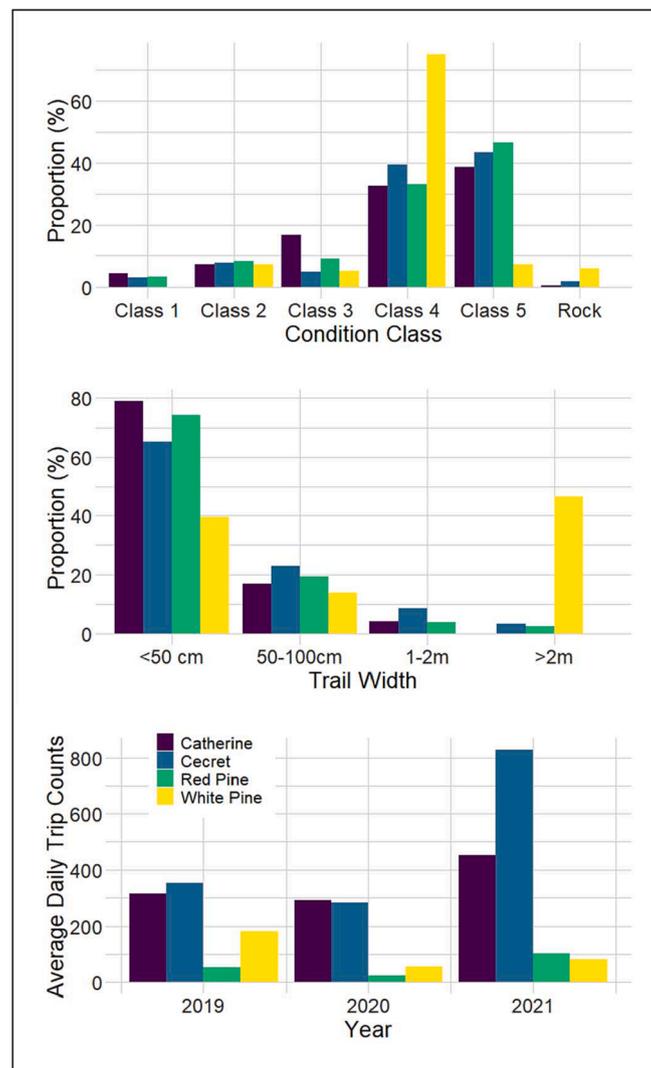
Fig. 3. Condition class (top), trail width (middle), and use levels (bottom) on informal trails across the study locations.

The findings from this study provide detailed guidance on how to sustainably manage informal trails in heavily used urban-proximate recreation settings.

3. Methods

3.1. Study Site

The study locations were four high alpine lakes (Lake Catherine, Cecret Lake, Red Pine Lake, White Pine Lake) in LCC (Fig. 1). Two of them (Lake Catherine and Cecret Lake) are within the Alta ski resort and have relatively short approach trails (about 1.5–3 km one way). White Pine and Red Pine Lake, which are located further down the canyon, have longer approach trails (>8 km one way). All informal trails assessed around the lakes are used by hikers only. The locations were identified by stakeholders as areas where increasing levels of use may be negatively affecting resource conditions as well as visitors' experiences (Smith, Miller, Lamborn, Monz, & Rumore, 2021).

LCC is dominated by steep, rugged mountains with vegetation types that include aspen forests, coniferous woodlands, shrublands, alpine meadows and grasslands, as well as high alpine bedrock and scree. Due to its proximity to Salt Lake City, LCC is a popular outdoor recreation destination in both winter and summer; activities include hiking, mountain biking, rock climbing, and skiing and the majority of visitors

are residents from Salt Lake County (Lamborn et al., 2015). In 2013, visitation to LCC was estimated at >2.1 million visitors per year; based on current traffic data and the rapid population growth in Utah, this estimate can be assumed to have gone up considerably since then (English et al., 2015; Lamborn & Burr, 2016; Smith et al., 2021; Census Bureau, 2022). In August 2020, the trail to Cecret Lake alone received over 27,000 trips (Smith et al., 2021). At the same time, LCC is one of the main watersheds providing drinking and irrigation water for nearly half a million people living in the Salt Lake Valley (Utah Department of Transportation, 2022). High recreation use has also recently led to problems of traffic congestion and local transportation agencies are evaluating alternative transportation solutions such expanding public transit throughout the canyon (Utah Department of Transportation, 2022).

3.2. Data collection and processing

We collected data in October 2021 using a rapid assessment protocol. Rapid assessment protocols are an efficient monitoring technique often used for informal trails (Marion et al., 2006, 2011; Marion & Leung, 2011). All data were collected using high-accuracy Trimble® global positioning (GPS) units (Monz, Marion, et al., 2010; Trimble, 2022). We identified and walked all informal trails within a 120 m buffer area around each lake, recording line segments and their respective
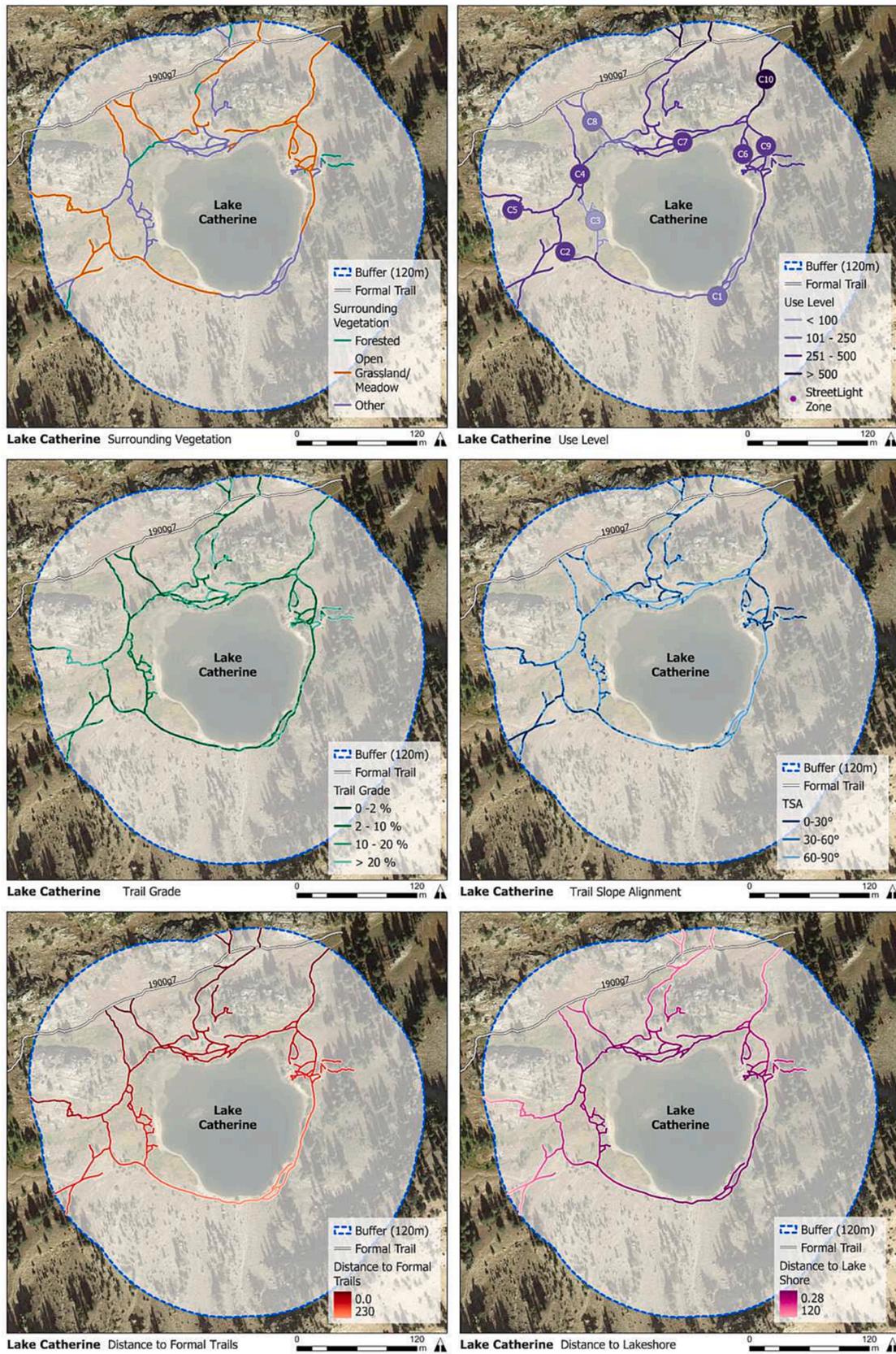
Fig. 4. Spatial distribution of predictor variables around Lake Catherine (maps for other study locations can be found in Appendix I).

Table 4
Summary Statistics of Predictor Variables.

Variables	Min.	Mean	Max.	Count	Percent
Continuous					
Trail Grade (%)[a]	0.0	14.6	112.3		
TSA (deg)	0.0	49.5	90.0		
Distance to Formal Trails (m)	0.0	82.0	233.1		
Distance to Lakeshore (m)	0.3	44.9	119.6		
Use Level (trip counts)[a]	26.0	260.0	1,016.0		
Categorical					
Vegetation (segments)					
Forested				2,506	35.9
Open Grassland/Meadow				2,888	41.4
Other (including Rock and Shrub)				1,586	22.7
[a]Log-transformation was used in the model					

attributes. We chose this buffer distance based on its ability to capture the majority of the disturbance around the lakes within the time available for field work; the decision was based on the extent of visible impacts on high resolution areal imagery and in the field.

We used condition class (a scale from *1 to 5*, Table 1), a common indicator used to characterize overall levels of resource impact, and categories of estimated trail width (*<50 cm, 50–100 cm, 1–2 m, >2 m*) to assess trail conditions (D'Antonio et al., 2016; Marion et al., 2006; Marion & Leung, 2011; Monz, Marion, et al., 2010). Additionally, we collected data on the surrounding vegetation type (*forested, open grassland/meadow, shrub, rock, other*) (Farrell & Marion, 2001; Olive & Marion, 2009).

We post-processed all GPS data in Trimble® GPS Pathfinder® Office prior to cleaning in ArcGIS Pro® and analysis in RStudio®.

3.3. GIS-derived variables

To calculate additional factors that may influence the condition of informal trails, our methods integrate the diverse GIS-approaches developed in past studies on trail degradation (Cakir, 2005; Eagleston, 2016; Eagleston & Marion, 2020; Mitchell, 2020; Wimpey & Marion, 2011).

The length of individual informal trail segments collected in the field ranged from 1.5 m to 149 m; to have a uniform base for calculations we split the line segments into 1 m sections. We then used a 0.5 m LiDAR Digital Elevation Model (DEM) (Utah Geospatial Resource Center, 2022) to derive trail grade and TSA. Trail grade was derived as average slope of trail sections. To calculate TSA, we added the line bearing and the azimuth to each line section and then calculated the difference following Cakir (2005). To achieve values between 0 and 90 degrees we subtracted 90 from values over 90 degrees (back bearing).[2] Since the accessibility and location of informal trail sections may also influence their condition, we included two additional locational variables – the Euclidean distance to the closest formal trail and the Euclidean distance to the shoreline of the lake.

3.4. Use level

To estimate use on informal trails, we used mobile device data provided by the *StreetLight InSight* platform (StreetLight Data, Inc., 2022). The platform utilizes mobile location data, derived from location-based services embedded in a variety of 3rd party applications installed on mobile phones. These data provide high spatial precision even without cell service (StreetLight Data, Inc., 2020). The applications collect users' geographic position and subsequently sell these data to developers like *StreetLight Data, Inc.* who then manipulate the data to make them useful

for specific use cases, like transportation planning. In the case of *StreetLight Data, Inc.*, their manipulation process involves creating trips out of discrete users' mobile location data (i.e., connecting the geographic coordinates), and 'snapping' those trips to the closest trail (the platform uses the OpenStreetMap (OSM) Pedestrian layer). A distinct trip begins/ends when the mobile device has been stationary for 5-minutes (Gische, 2022). Consequently, trip counts are the total number of trips passing through each trail segment in which a user did not stop for longer than 5-minutes.

The platform provides a *Pedestrian Tool* which allows users to estimate average daily trips passing through user-defined zones (i.e., polygons) which intersect the OSM Pedestrian layer. We used the OSM Pedestrian layer as overlay for the recorded informal trails and placed zones at the midpoints between trail intersections within the 120 m buffer (including between informal as well as between formal and informal trails), at the midpoints between informal trails that cross the buffer and trail intersections within the buffer, and at the intersection between the formal trail and the buffer. We deleted overlapping zones and those which did not provide enough data to obtain results from the *StreetLight InSight* platform. Use levels for each trail segment were assigned the closest available zone for further analysis (see Appendix B for an example of where zones were established and how use levels were assigned to trail segments).

The *StreetLight InSight* platform also allows for the 'calibration' of trip counts using data collected through traditional on-site methods such as infrared trail counters. We used 40 TRAFx counters (TRAFx Research, 2022) to calibrate trip count estimates (Appendix C). After calibration, we downloaded an estimate of average daily trips over the summer months (May – October) from 2019 to 2021 for each zone; those average daily trips accounts form our predictor variable "use level". Previous research has found estimates derived from the *Streetlight Insight* platform are not significantly different from and highly correlated with visitor use estimates derived from traditional monitoring techniques such as trail counters (Creany et al., 2021).

3.5. Data analysis

To assess the influence of use, environmental, and managerial factors on trail condition class and trail width, we conducted multinomial logistic regression analyses with six predictor variables (Table 2). Multinomial logistic regression is used for categorical response variables with more than two categories and is appropriate for continuous as well as categorical predictors (Agresti, 2019). To enhance interpretability and assess the practical importance of predictors we additionally generated predictor effects plots; allowing us to visually interpret the effect of each predictor on each categorical outcome (Fox & Weisberg, 2018; 2020). To assess the significance of each predictor, we conducted likelihood ratio tests. More detailed information on the methods can be found in Appendix D.

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[2] A visual illustration of landform grade, trail grade, and trail slope alignment is provided in Appendix A.
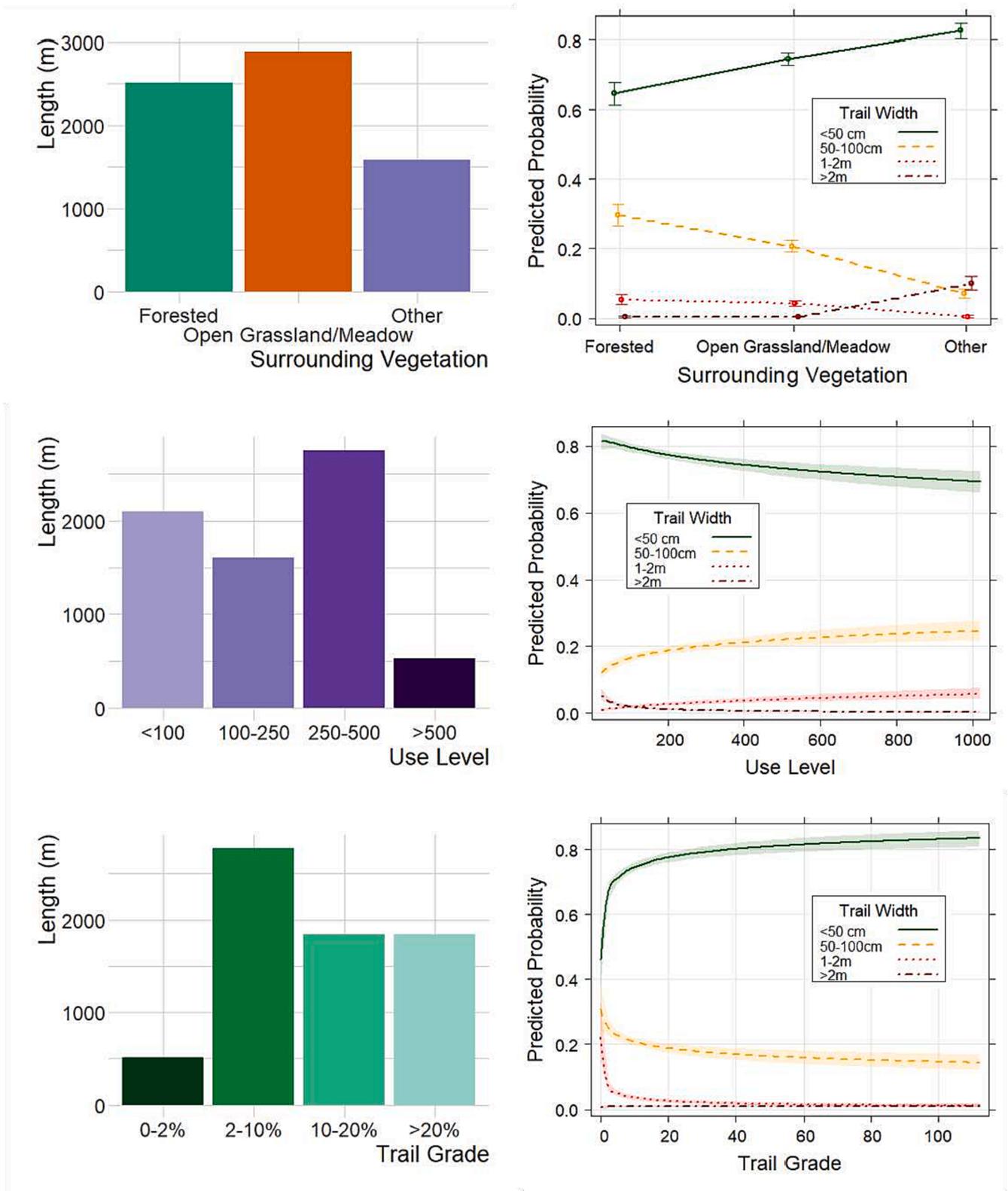
Fig. 5. Overall Distribution (left) and Predictor Effect Plots (right) For Surrounding Vegetation (top), Use Level (middle), and Trail Grade (bottom).
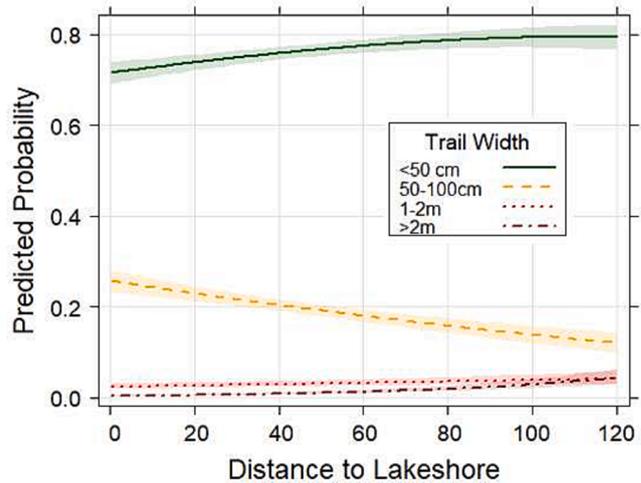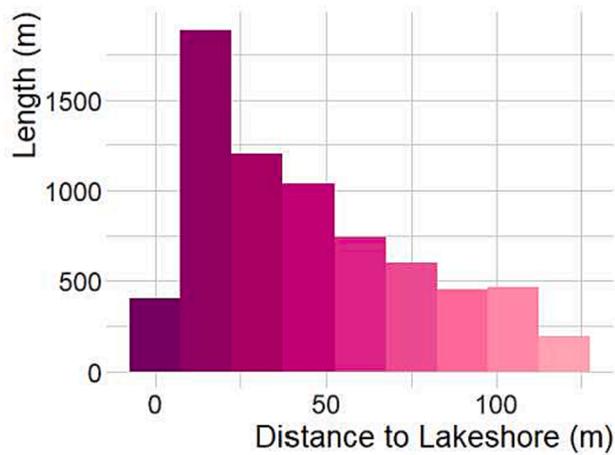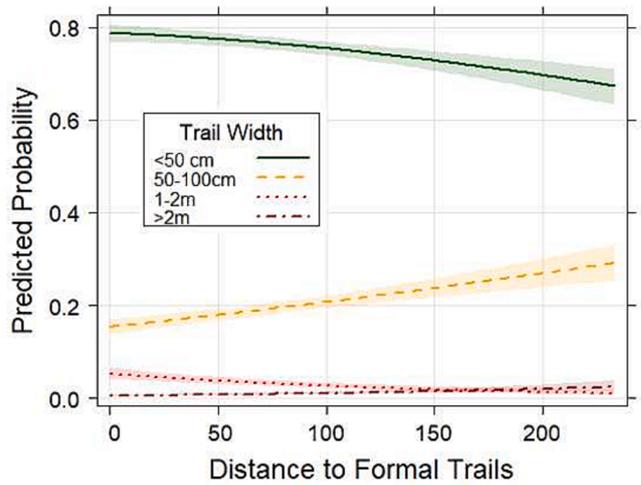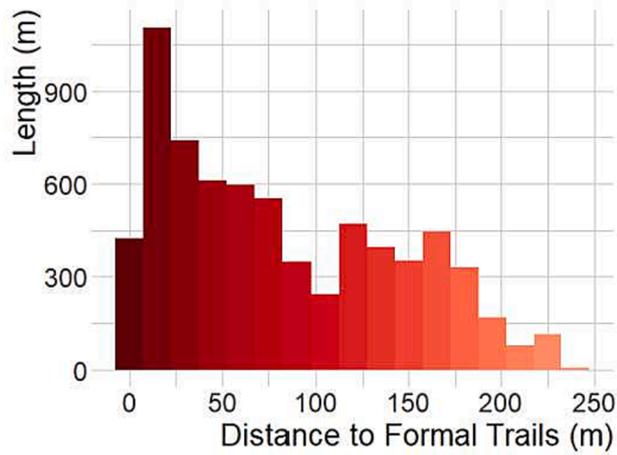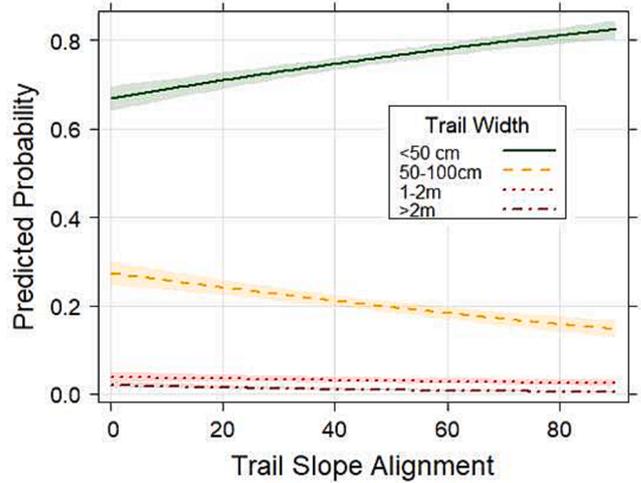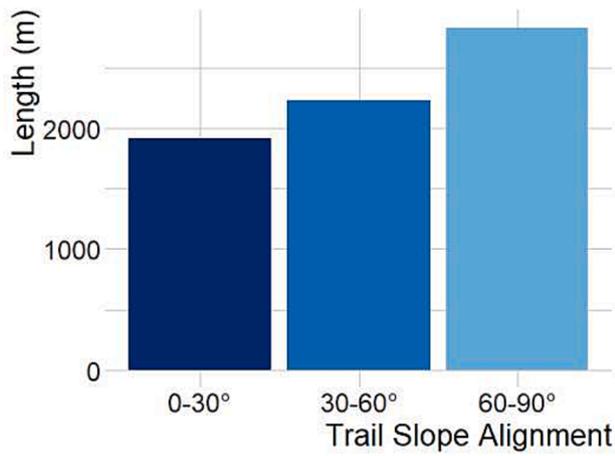
Fig. 6. Overall Distribution (left) and Predictor Effect Plots (right) for Trail Slope Alignment (top), Distance to Formal Trails (middle), and Distance to Lakeshore (bottom).

Table 5
Likelihood Ratio Test Results for the Trail Width Model, Measuring the Improvement in Fit for Each Predictor Variable.

Likelihood Ratio Tests	Chi-square	df	p-value
Surrounding Vegetation	718.2	6	<0.001
Use Level	155.4	3	<0.001
Distance to Lake Shore	137.7	3	<0.001
Distance to Formal Trails	106.1	3	<0.001
Trail Grade (log)	87.7	3	<0.001
Trail Slope Alignment	82.1	3	<0.001

4. Results

4.1. Conditions and use levels on informal trails

We mapped and assessed a total of 7.3 km of informal trails within the buffers around the four lakes (Fig. 2). While Red Pine Lake had the greatest total length of informal trails (~2.4 km), Lake Catherine had the highest density (length of trails divided by buffer area) of trails relative to the size of the buffer (209.2 m/ha) (Table 3). White Pine Lake had the smallest extent and density of informal trails; one reason for this is the dominance of scree and rock around the lake which affects the creation of informal trails. Generally, informal trails served to access the lakes' shorelines, surrounding campsites, and view sites and were concentrated in relatively accessible terrain. Most informal trails were visibly degraded, with the most prevalent condition classes being *class 5* (39.7 %) and *class 4* (38.7 %) (Fig. 3 and Appendix E). Most informal trail segments were estimated as being *< 50 cm* (69.9 %) wide, followed by segments between *50 and 100 cm* (19.2 %) (Fig. 3 and Appendix E). White Pine Lake had relatively more *class 4* than *class 5* and notably more wide trails (*>2 m*) relative to the other lakes.

Mean daily trip counts were highest in 2021 (Fig. 3). Mean daily trip counts were also considerably higher at the formal trail-buffer intersection than on the informal trail segments (Appendix F), indicating the dispersal of visitors once they reach the area around the lake. Estimated use through zones on informal trails varied greatly, from <30 to over 1,000 mean daily trip counts per day (Fig. 4 and Appendix F). Estimates were highest at Cecret Lake and Lake Catherine; this is likely due to the fact these lakes have multiple and very short approach trails.

4.2. GIS-derived variables

Summary statistics and (categorized) distributions of all predictors

can be found in Table 4 and Figs. 4, 5 and 6. A large proportion of informal trail sections have TSAs over 30 degrees, which is within the recommended range (Marion & Wimpey, 2017). However, many informal trail sections exhibit less ideal trail grades (<2 % and >10 %) (Marion & Wimpey, 2017). Most sections are surrounded by open grasslands and meadows (40.9 %), followed by forests (35.9 %), and most sections are closest to zones with use estimates of <500 mean daily trip counts per day. Trail sections are generally closer to lake shores than formal trails.

4.3. Multinomial logistic regression model and predictor effect plots

Detailed model outputs can be found in Appendix G. The proportion of correct predictions was 49.1 % for the condition class model and 70.9 % for the trail width model, indicating the predictor variables more accurately predict trail width than condition class. Additionally, model coefficients and predictor effect plots did not produce clear results for the condition class model (Appendix G and H); we therefore limit the discussion of further results to the trail width model.

Likelihood-ratio tests (Table 5) show all predictors improve the model significantly ($p < 0.01$). The direction and relative divergence or convergence of the predictor effect plot curves for each output category provide insight into the direction of the relationship (Figs. 5 and 6). The overall change in predicted probabilities relates to the amount of change, or practical importance, of the variable for each output category. With all other predictors held constant, trails with higher TSA are relatively more likely to be *<50 cm* wide, less likely to be *50–100 cm* wide, and have small effects on the wider categories. Results for trail grade show lower trail grades have considerably more influence, and that trails are relatively more likely to be *<50 cm* than *50–100 cm* or *1–2 m* as trail grade increases. Use level is more influential at lower use levels and trails are relatively less likely to be *<50 cm* wide as use increases (the change in the *>2 m* category at very low use levels can likely be attributed to the higher proportion of *>2 m* trails and low use levels at White Pine Lake). Informal trails are relatively more likely to be *<50 cm* than *50–100 cm* in grasslands and meadows than in forests. Furthermore, trails are relatively more likely to be *<50 cm* and *>2 m* wide and relatively less likely to be *50–100 cm* and *1–2 m* in other environments. Trails closer to formal trails, and further from lakeshores, are relatively more likely to be *<50 cm* wide than *50–100 cm*.

When looking at practical importance, or change in predicted probabilities, trail grade has by far the biggest effect, with substantial changes in predicted probabilities as trail grades increase from 0 to 20 %. All other predictors demonstrate less notable changes in predicted
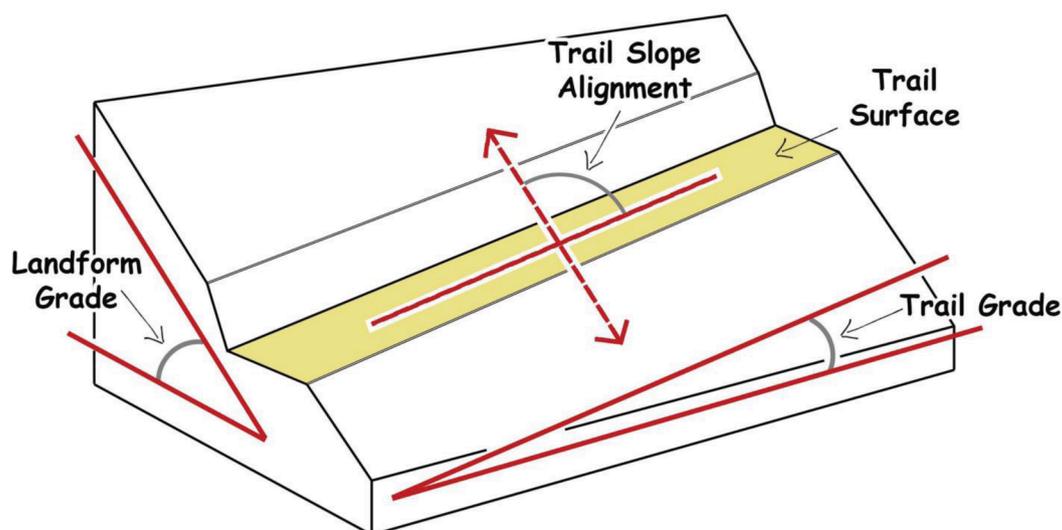

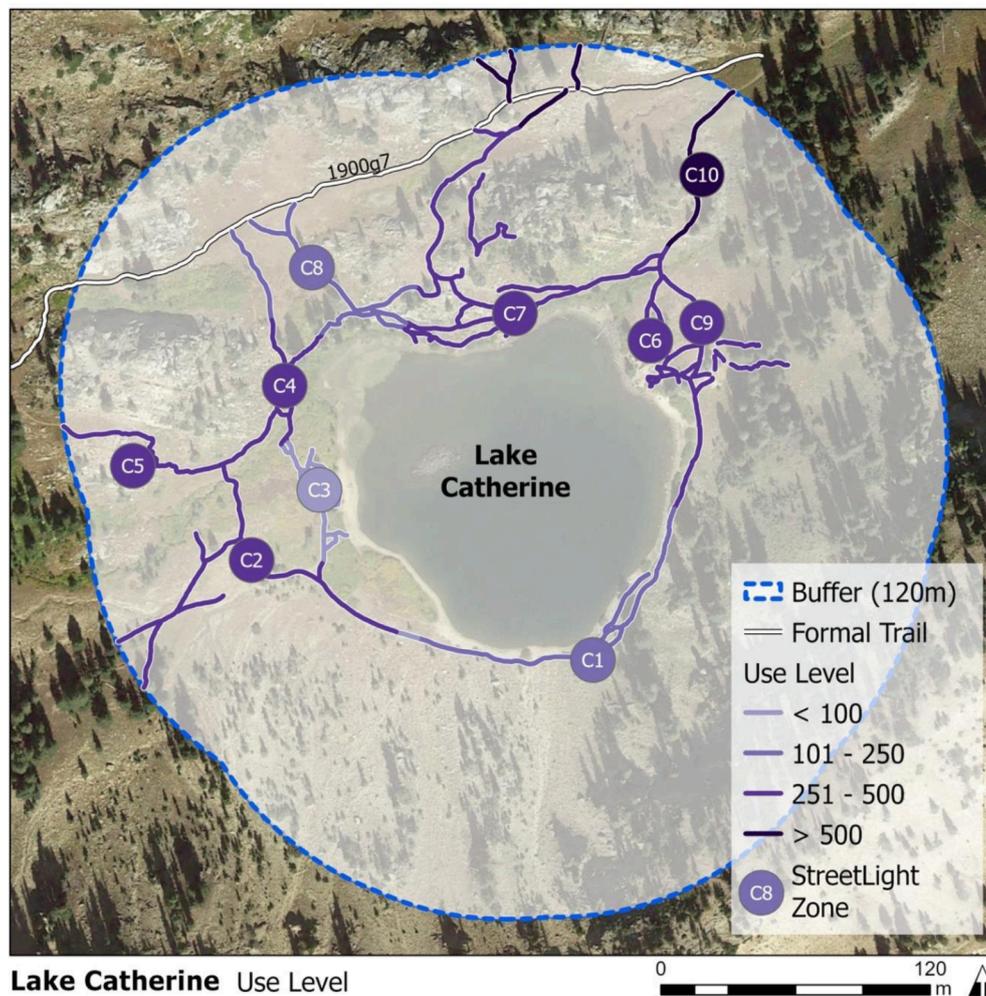**Fig. A1.** Illustration of Trail Measurements.

Fig. B1. Example of Where Streetlight Zones were Established (Lake Catherine).

probabilities. The effect of use level is relatively marginal when seen in context of the change in magnitude on the x-axis *(<100 to >1,000)*. The results from the statistical analysis with the spatial distribution of current trail conditions and predictor variables (Figs. 2 and 4) allows us to derive important management implications which we detail below.

5. Discussion

With growing urban populations in close proximity to PPAs, recreation resource managers face unique challenges such as high levels of use and severe resource impacts (Dwyer & Chavez, 2005). Those challenges are present on informal trail networks in LCC. Past research has identified several use-related, environmental, and managerial factors that influence trail conditions (particularly trail width, cross-sectional area, and maximum incision measured at sampling points) on formal trails. Few studies have attempted to understand these relationships using rapid assessment protocols with categorical indicators across a census of trail segments (Bratton et al., 1979; Nepal, 2003), and even fewer studies have investigated these factors on informal trail networks (Marion, Wimpey, & Park, 2011). We used a combination of widely available GIS applications, high-resolution DEMs, and mobile device data to complement a rapid field assessment protocol and explored alternative analysis approaches for these kinds of data. Multinomial logistic regression modelling, based on the six predictor variables *surrounding vegetation, use level, trail grade, TSA, distance to formal trails*, and *distance to lakeshores* suggests informal trails are influenced by use-

related, environmental, and managerial factors in a similar fashion as formal trails. Predictor effect plots facilitated insights into the relationships between the predictor variables and trail width categories; they also provide an easy to interpret and managerially relevant way to analyze categorical trail data beyond descriptive characterizations.

5.1. Management implications

Informal trail use in sampled zones was much lower than where the formal trail meets the buffers of the lakes. This, and the present extent of informal trail networks, indicate visitor use is concentrated on approach trails and disperses near the area surrounding the lakes; this is a similar pattern to what has been observed on mountain summits (Monz, Marion, et al., 2010). Informal trails serve as access to lakeshores, campsites, and view sites. However, the uncontrolled dispersal of visitor use in areas experiencing high use levels is generally undesirable and leads to greater extents of disturbed area, rapid degradation, and impacts to sensitive locations (Hammitt et al., 2015). Concentrating use on fewer, but well-developed informal trails is an effective management strategy allowing for continued access while also minimizing the impacts caused by informal trails (Barros & Pickering, 2017; Hammitt et al., 2015). Influencing visitor (spatial) behavior by developing and encouraging use on some and closing and restoring other trails can be an effective approach to accomplish the concentration of use on informal trails (Lucas, 2020; Marion & Leung, 2011; Stein, 2005). These are viable options for managers if the development, or even integration into the formal trail
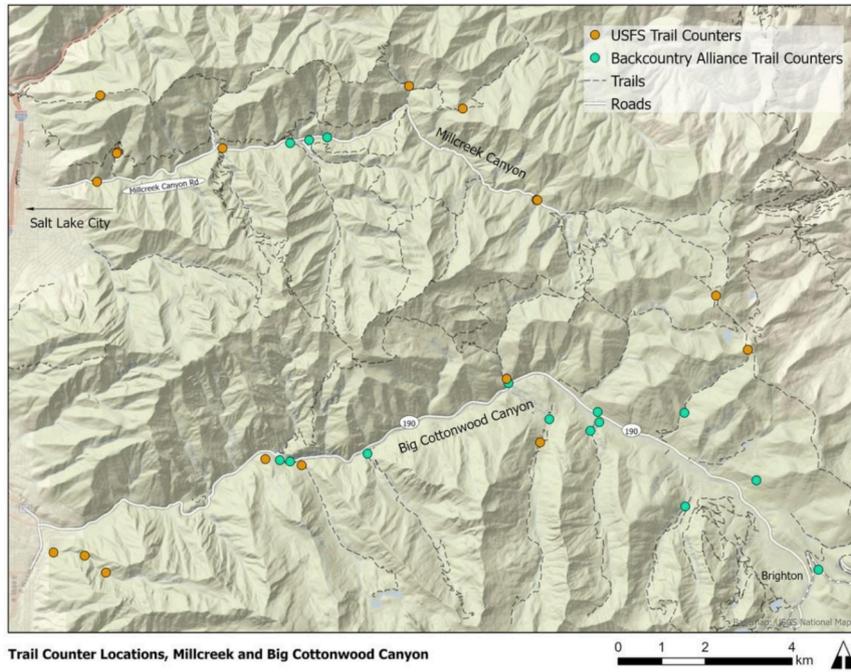
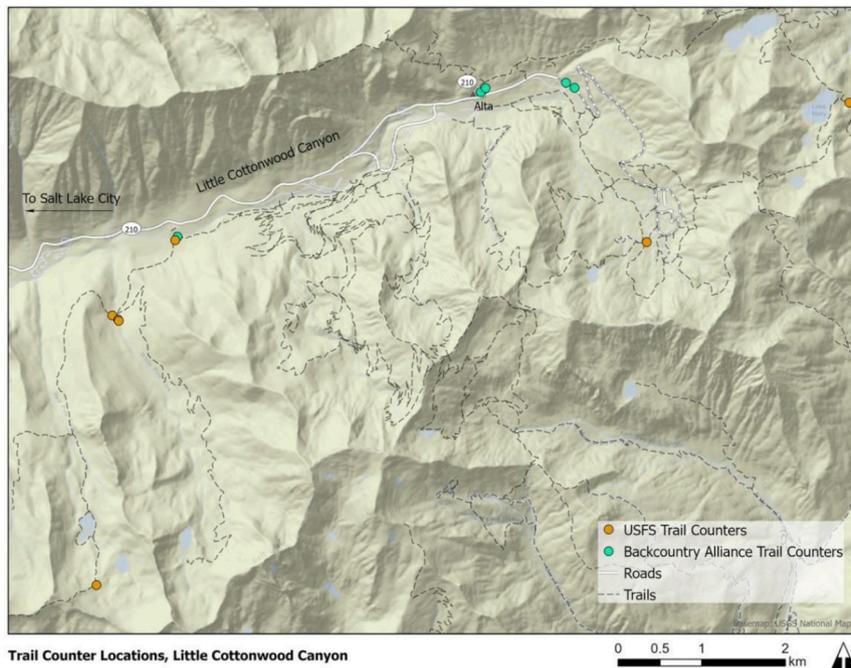**Fig. C1.** Locations of Trail Counters in Millcreek and Big Cottonwood Canyons.

Fig. C2. Locations of Trail Counters in Little Cottonwood Canyon.

Table C1
Summary Statistics for Observed and Estimated Daily Trail Use Counts.

	Mean	S.D.	Lower Bound	Upper Bound
Observed ($n = 12,353$)	205.4	352.7	0.0	6,704.0
Estimated ($n = 60,920$)	246.5	519.6	3.6	8,118.9

network, of informal trails does not undermine the long-term goals of an agency; otherwise managers can focus on more subtle measures, such as deterring use on informal trails that are in especially sensitive locations.

Results from the characterization of informal trail networks and further analysis conducted in our study, combined with established knowledge, provide information on current conditions and can be synthesized into four guidelines on which informal trails use should be concentrated and where use should be deterred.

Trails that are not yet heavily impacted, receive low use levels, and do not fulfil critical functions for visitors should be closed and restored and use should be concentrated on trails that are already well established, receive high levels of use, and appear necessary for visitors. The level of use occurring on specific segments of informal trail networks, combined with the current level of impact, has important implications for the concentration of use. In line with the commonly generalized use-impact relationship (Monz et al., 2013) and similar to Wimpey and Marion (2010), predictor effect plots from our analysis revealed the biggest effect of use level on trail width occurs at low use levels, and that trails are relatively less likely to be narrow as use increases. This knowledge indicates trails not yet heavily impacted should receive timely attention to avoid rapid degradation as use continues. Despite the high proportions of *condition classes 4* and *5*, we found use levels varied on informal trails around the lakes and areas with low impact and low use levels still exist. The distribution of use levels also allow for some inference to the importance of respective trails to visitors; trails receiving low use levels may not fulfil crucial functions for visitors and are therefore less needed (Walden-Schreiner & Leung, 2013).

Visitors should be concentrated on durable surfaces when available and trails close to waterbodies should be hardened where possible. Trails on durable surfaces are generally less prone to degradation (Hammitt et al., 2015; Ng, 2022) and the large absence of visible informal trails on rock and scree, such as at White Pine Lake, aligns with this generalization.

Table C2
Covariates used to fit the model predicting trail use.

	Levels
Canyon	1 = Millcreek Canyon
	2 = Big Cottonwood Canyon
	3 = Little Cottonwood Canyon
Month	1 = January
	2 = February
	3 = March
	4 = April
	5 = May
	6 = June
	7 = July
	8 = August
	9 = September
	10 = October
	11 = November
	12 = December
Year	2017
	2018
	2019
	2020
	2021
	2022
Weekend (Friday & Sunday)	0 = Monday – Thursday
	1 = Friday – Sunday
Weekend (Saturday & Sunday)	0 = Monday – Friday
	1 = Saturday – Sunday

Additionally, informal trails in LCC were largely concentrated around the lake shores, even though swimming and wading is prohibited, and were slightly likely to be wider closer to the water. Recreation disturbance in close proximity to water is of particular concern to recreation resource managers because soil erosion can lead to nutrient influxes and affect water quality (Hammitt et al., 2015; Marion & Leung, 2011; Wimpey & Marion, 2011). Even though deterring use is difficult in those locations, they should receive special attention to make sure trails are as sustainable as possible.

Management actions, like bordering trails, should focus on open grasslands and meadows to prevent further proliferation. Similar to Farrell and Marion (2001), we found more informal trails occur in open grasslands and meadows relative to forests and other vegetation types. This indicates informal trails may be more likely to form in open grasslands and meadows and warrant management action. While we found trails surrounded by grasslands and meadows are more likely to fall into the narrowest (*<50 cm*) category compared to forests and other environments, previous studies found no significant differences in trail width between trails located in grasslands and forested areas (Farrell & Marion, 2001; Nepal & Way, 2007).

Use should be concentrated on trail sections with sustainable TSAs (>30 %) and trail grades (2–10 %). Despite not initially being deliberately planned, managers can use attributes such as TSA and trail grade to inform decisions about management of informal trails. Like others (Meadema et al., 2020; Tomczyk et al., 2017; Wimpey & Marion, 2010), we found side-hill trails (higher TSA angle) are relatively more likely to be narrower. They have also been found to be less prone to soil loss (Olive & Marion, 2009). Trail grade had the largest effect on trail width of all the variables we considered; we found trails at very low trail grades (*<2%*) to be considerably more likely to be wider than trails at steeper grades. While high trail grades were often found to be more susceptible to soil erosion (Farrell & Marion, 2001; Olive & Marion, 2009), our findings align with previous research noting flat trails are more prone to widening (Marion & Wimpey, 2017; Nepal, 2003). Our results, combined with categories defining the sustainability of trails regarding soil loss (Marion & Wimpey, 2017), can provide guidance for the concentration of use on informal trails based on TSA and trail grade, which can potentially also enhance the experience for visitors. Since many informal trail sections at our study locations fall into less sustainable ranges of trail grade (*>10 %*) as well as trail grades prone to widening (*<2 %*), they are likely to be prone to degradation and warrant management attention; this finding is similar to Wimpey and Marion (2011).

Besides the specific findings from our study, managers and planners in areas with known attraction sites, like alpine lakes, can focus on proactively limiting the establishment and proliferation of informal trails around those sites. Given hiking off *designated* trails to reach attraction sites is most likely a careless or thoughtless violation of regulations, an appropriate proactive strategy would be to educate visitors about the negative impacts of veering off designated routes (Dawson & Hendee, 2009). Establishing desired resource conditions in specific locations where informal trails are likely to proliferate can also inform where management actions are warranted (Interagency Visitor Use Management Council, 2016). Additionally, if the long-term goals of an agency allow for it, building sustainable trails in areas where sites are likely to attract great visitor numbers that tend to disperse *before* informal trails are formed can help to channel use from the start.

The findings from our study can point managers towards more effective active management actions to address issues of high use and

Table C3
Results of the final population-averaged negative binomial model predicting trail use.

	Coef.	S.E.	IRR	S.E.	z	p > z
Canyon						
Big Cottonwood Canyon	2.199	0.088	9.013	0.794	24.960	0.000
Little Cottonwood Canyon	1.841	0.119	6.303	0.751	15.460	0.000
Month						
February	−0.176	0.038	0.839	0.032	−4.580	0.000
March	−0.117	0.037	0.889	0.033	−3.170	0.002
April	−0.396	0.038	0.673	0.025	−10.500	0.000
May	0.569	0.053	1.766	0.093	10.780	0.000
June	1.281	0.063	3.599	0.226	20.440	0.000
July	1.378	0.056	3.968	0.222	24.630	0.000
August	1.019	0.054	2.772	0.149	18.930	0.000
September	1.089	0.054	2.972	0.159	20.350	0.000
October	0.695	0.054	2.005	0.108	12.960	0.000
November	−0.061	0.062	0.940	0.058	−1.000	0.320
December	−0.211	0.034	0.810	0.028	−6.170	0.000
Weekend (Saturday & Sunday)	0.701	0.020	2.016	0.040	35.000	0.000
Site ID						
4	1.145	0.045	3.141	0.143	25.210	0.000
5	−0.064	0.057	0.938	0.053	−1.130	0.259
6	1.009	0.147	2.743	0.405	6.840	0.000
7	0.474	0.056	1.607	0.090	8.450	0.000
8	0.618	0.045	1.855	0.084	13.720	0.000
9	−0.123	0.057	0.884	0.050	−2.170	0.030
10	−0.825	0.060	0.438	0.026	−13.860	0.000
11	0.370	0.233	1.447	0.337	1.590	0.112
14	0.202	0.109	1.223	0.133	1.850	0.064
15	0.433	0.111	1.542	0.171	3.910	0.000
16	2.002	0.109	7.406	0.809	18.320	0.000
17	0.492	0.120	1.635	0.197	4.090	0.000
19	3.110	0.084	22.418	1.879	37.110	0.000
20	4.317	0.084	74.962	6.279	51.540	0.000
22	0.932	0.071	2.539	0.181	13.080	0.000
25	1.677	0.073	5.348	0.389	23.070	0.000
26	0.222	0.077	1.248	0.096	2.900	0.004
27	−0.724	0.165	0.485	0.080	−4.390	0.000
28	−1.401	0.166	0.246	0.041	−8.450	0.000
29	1.112	0.092	3.039	0.280	12.050	0.000
30	1.673	0.112	5.330	0.597	14.940	0.000
33	0.903	0.119	2.467	0.295	7.570	0.000
34	0.063	0.120	1.065	0.128	0.530	0.599
35	−1.061	0.154	0.346	0.053	−6.890	0.000
36	0.640	0.108	1.896	0.205	5.930	0.000
	Coef.	S.E.	IRR	S.E.	z	p > z
38	1.677	0.086	5.350	0.459	19.560	0.000
39	1.972	0.085	7.188	0.614	23.070	0.000
40	2.873	0.083	17.684	1.459	34.820	0.000
41	5.258	0.101	192.128	19.335	52.250	0.000
42	1.116	0.114	3.052	0.346	9.830	0.000
43	0.645	0.101	1.906	0.192	6.410	0.000
44	0.000	(omitted)	1.000	(omitted)		
50	−1.100	0.108	0.333	0.036	−10.230	0.000
51	−0.027	0.102	0.974	0.100	−0.260	0.796
52	1.232	0.105	3.428	0.359	11.760	0.000
53	1.289	0.133	3.631	0.482	9.720	0.000
54	1.243	0.121	3.468	0.419	10.280	0.000
55	0.000	(omitted)	1.000	(omitted)		
_cons	1.664	0.082	5.282	0.431	20.400	0.000

*n = 12,353, locations = 39, obs per location = 19 (*min*), 316.7 (*mean*), 959 (*max*)*
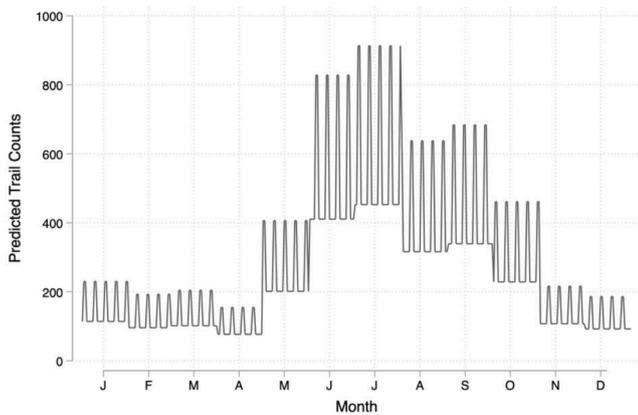*Wald chi2(50) = 34,771.56, p < 0.05*

Fig. C3. Estimated daily trail counts for White Pine Trail in Little Cottonwood Canyon.

severe resource impacts in urban-proximate PPAs, focusing on the concentration of use and reducing the potential for degradation in desired locations and deter use from undesired locations.

Overall, concentrating use on trails with hard surfaces and/or trails with favorable TSA and trail grades and deterring use from newly developing trails that are not crucial for visitors and prone to erosion and widening is strongly recommended. Additionally, management

actions are needed on trails close to waterbodies. Specifically, resource managers can create clear visual borders as guidance (e.g., with rocks), harden trails where use is encouraged or inevitable, or block trails where use should be discouraged with natural materials (Barros, Gonnet, & Pickering, 2013; Hammitt et al., 2015; Hockett, Marion, & Leung, 2017; Stein, 2005). Future monitoring efforts can then help to understand if management actions were successful, if conditions (including the extent of informal trail networks) have improved or at least stayed the same, and inform adaptive management strategies.

5.2. Implications for further research

Our study also contributes to informal trail assessment methodology and analysis, highlights the limitations of commonly used monitoring protocols, and identifies needs for future research.

First, the capabilities of GIS should be leveraged to calculate the attributes of trails. This use of GIS applications has been recognized in the literature (Eagleston & Marion, 2020; Leung et al., 2002; Wimpey & Marion, 2011) but standard protocols (such as those that already exist for field procedures) are still lacking. While we did use GIS to calculate attributes of trails in this study, we were not able to validate them in the field. The research community would greatly benefit from validating and updating these methods in the field to realize their potential as a complement to field data collection efforts.

Second, the potential of commercially available mobile device data is

Table C4
Estimated Annual Pedestrian Traffic (APT) and Annual Average Daily Pedestrian Traffic (AADPT) for each trail counter location.

Site Name	Site ID	Estimated APT	Estimated AADPT
BCCBearTrap	1	41,692	114
BCCCardiff	4	130,964	359
BCCDaysFork	5	39,098	107
BCCGuardsman	6	114,374	313
BCCMillBSouth	7	66,983	184
BCCMillD	8	77,358	212
BCCMineralFork	9	36,861	101
BCCSilverFork	10	18,265	50
BCCSpruces	11	60,334	165
BroadsForkComb	50	9,702	27
ButlerComb	51	28,394	78
GloriaComb	53	105,864	290
LCCOurLady	14	35,671	98
LCCOurLadyEast	15	44,950	123
LCCSummerRoad	16	215,943	592
LCCSummerRoad2	17	47,675	131
MCCPorter	19	103,701	284
MCCRoad	20	346,764	950
MCCTerraces	21	4,626	13
RattlesnakeComb	54	101,102	277
USFSBCCBlanche01	22	105,837	290
USFSBCCDonut	25	222,958	611
USFSBCCFerguson0	26	52,040	143
USFSBCCFerguson0	27	20,206	55
USFSBCCFerguson0	28	10,274	28
USFSBCCLakeMary	29	126,721	347
USFSLCCCecret	30	155,403	426
USFSLCCLctrail01	33	71,939	197
USFSLCCLctrail02	34	31,055	85
USFSLCCLctrail03	35	10,090	28
USFSLCCRedPine	36	55,294	151
USFSMCCAire	38	24,748	68
USFSMCCCrest	39	33,249	91
USFSMCCDesolatio	40	81,805	224
USFSMCCGate	41	888,756	2,435
USFSMCCGranduer	42	14,117	39
USFSMCCLambs	43	8,819	24
USFSMCCMeadows	44	4,626	13
UpperPipelineCom	55	29,157	80
WhitePineComb	52	99,938	274

Table D1

Supplementary descriptions on methodology.

What	Process/Tools
Data cleaning	Eliminating extraneous points based on position accuracy, connecting individual line segments, clipping informal trails to the buffer around each lake
Streetlight zones	Zones were placed at midpoints between trail intersections within the 120 m buffer (including between informal as well as between formal and informal trails), at the midpoints between informal trails that cross the buffer and trail intersections within the buffer, and at the intersection between the formal trail and the buffer on the OSM Pedestrian layer (where it overlapped with the recorded trails). Overlapping zones and zones that didn't provide enough data to obtain results from the platform were deleted.
Splitting trails into 1 m sections	*Generate Points Along Lines* and *Split Line at Point* tools in ArcGIS Pro; removal of all trail sections below 0.8 m; check for representativeness with a Chi-square Goodness of fit test for condition class (p-value = 0.9986) and trail width (p-value = 0.9718)
Trail grade	*Add Surface Information* tool in ArcGIS Pro
Trail slope alignment	*Add Geometry Attributes* (line bearing) and *Add Surface Information - Mean-Z from aspect raster* (azimuth of line section) tools in ArcGIS Pro
Landform grade	*Add Surface Information* tool in ArcGIS Pro
Distance to formal trail and lake shore	*Near* tool in ArcGIS Pro
Correlation matrix	*ggpair()* function from the *ggplot2* package in R Studio
Multinomial logistic regression model	*multinom()* function from the *nnet* package in R Studio
Predictor effect plots	*predictorEffects* function from the *effects* package in R Studio
Proportion of correctly predicted outcomes	*predict* function in R Studio

being increasingly recognized in outdoor recreation research and management. With tools, such as those provided by *StreetLight Data, Inc.,* and options to calibrate these data with traditional visitor use monitoring methods, new possibilities for monitoring use levels arise. While studies have looked at the accuracy of these data in urban-proximate PPAs (Creany et al., 2021), their value has yet to be assessed in more remote areas and on finer spatial scales. We found these data are available for informal trails on OSM layers and that they roughly match trail counter data from the region, but we were not able to provide more detailed comparisons between the mobile device and trail counter data within the scope of this paper. More research is still needed to fully exploit this new data source and understand its accuracy and applicability.

Third, we found the utility of condition classes as a response variable for analysis beyond descriptive statistics was limited. While multinomial logistic regression analysis and predictor effect plots provided a valuable way to analyze trail width categories, the condition class model produced considerably less predictive power and respective predictor effect plots produced inconsistent relationships between response and predictor variables (Appendix H). Those limitations are not exceptionally surprising, as issues of subjectivity and limited sensitivity of condition classes as an indicator are already widely recognized (Marion et al., 2006). This does not mean the condition class measure is useless as it does have managerial relevance. However, if it is to be used for further analysis, we suggest the adoption of more detailed definitions of condition classes such as used by Nepal (2003) and Bratton et al. (1979) and general caution with using data collected through rapid assessments as input for statistical models.

Fourth, developing sampling procedures suitable for informal trail networks based on rapid assessments, such as stratified random point sampling or spatially balanced sampling approaches (as used by Meadema et al. (2020)), could allow not only for the validation of variables derived from GIS analysis at sampling points in the field, but also the assessment of more detailed trail condition indicators (cross-sectional area, maximum incision, measured trail width) on informal trails. Those indicators provide managers with more detailed information on trail conditions as well as more flexibility and better data for further analysis. This is especially important since data collected through rapid assessments are not an ideal input for statistical models (as our analysis has also shown in the case of condition class). Additionally, relating initial condition class assessments to more detailed, sampled measures in the field, such as initiated by Wimpey and Marion (2011), could contribute to the validation and further development of condition class definitions.

Fifth, future research can advance the understanding of factors influencing the presence, density, and proliferation of informal trails. While we did not investigate this question in this research, future work can help shed light onto the topic.

Sixth, all recreation use in our study area occurs via hiking. Consequently, the findings of our work should be placed within the context of informal trail networks where pedestrian use dominates. In trail networks where mountain biking, e-biking, or off-highway vehicle use occur, trail conditions are likely to respond differently to use-related, environmental, and managerial factors. Havlick et al. (2016) provides a starting point for researchers interested in understanding the varying response functions that exist across different modes of use.

Table E1

Descriptive Statistics for Conditions on Informal Trails.

Condition Class	Lake									
	Catherine		Cecret		Red Pine		White Pine		Total	
	m	%	m	%	m	%	m	%	m	%
Class 1	94.7	4.4	55.1	2.8	74.2	3.0			224.0	3.1
Class 2	154.7	7.1	153.7	7.8	196.9	8.1	49.4	7.3	554.6	7.6
Class 3	362.2	16.7	91.5	4.6	220.3	9.0	33.4	4.9	707.4	9.7
Class 4	708.4	32.6	783.1	39.6	809.4	33.2	510.9	75.0	2,811.7	38.7
Class 5	843.6	38.8	861.0	43.5	1,137.3	46.7	48.4	7.1	2,890.3	39.7
Rock	11.7	0.5	34.8	1.8			39.3	5.8	85.8	1.2
Trail Width										
<50 cm	1,713.5	78.8	1,291.8	65.3	1,806.6	74.1	269.8	39.6	5,081.7	69.9
50–100 cm	371.1	17.1	454.0	22.9	478.1	19.6	95.3	14.0	1,398.5	19.2
1–2 m	90.6	4.2	170.4	8.6	91.2	3.7			352.2	4.8
>2m			63.1	3.2	62.2	2.6	316.3	46.4	441.7	6.1

Table F1

Estimated Average Daily Trip Counts for Summer (May – October) (2019–2021) Derived from the StreetLight Data, Inc. InSights Platform in Zones on Formal and Informal Trails in Little Cottonwood Canyon (maps of zone locations are shown in Fig. 4 and Appendix J; additional zones were at trailheads and the intersection between the buffer and the formal trail).

Lake Catherine	2019	2020	2021
Formal Trail			
Trailhead	820	576	1,768
Formal Trail – Buffer Intersection	871	612	1,376
Average	846	594	1,572
Informal Trails			
C1	239	205	211
C2	210	276	359
C3	27	49	115
C4	236	227	385
C5	349	354	408
C6	319	168	351
C7	307	380	560
C8	232	210	266
C9	307	276	550
C10	932	773	1,343
Average	316	292	455
Cecret Lake	**2019**	**2020**	**2021**
Formal Trail			
Trailhead	2,286	1,945	4,169
Formal Trail – Buffer Intersection 1	3,597	2,804	6,330
Formal Trail – Buffer Intersection 2	198	280	402
Average	2,027	1,676	3,634
Informal Trails			
CE1	211	292	578
CE2	168	213	572
CE3	656	565	1,678
CE4	388	184	544
CE5	861	412	1,573
CE6	222	297	656
CE7	209	211	616
CE8	123	104	402
Average	355	285	827
Red Pine Lake	**2019**	**2020**	**2021**
Formal Trail			
Junction	1,923	1,227	1,191
Formal Trail – Buffer Intersection	793	456	427
Average	1,358	842	809
Table D-1 *cont.*			
Red Pine Lake	**2019**	**2020**	**2021**
Informal Trails			
RP1	29	11	43
RP2	0	15	123
RP3	13	21	43
RP4	13	19	102
RP5	14	8	59
RP6	339	121	77
RP7	0	4	84
RP8	68	43	203
RP9	28	0	196
RP10	13	0	75
Average	52	24	101
White Pine Lake	**2019**	**2020**	**2021**
Formal Trail			
Junction	930	505	2,308
Formal Trail – Buffer Intersection	210	55	82
Average	570	280	1,195
Informal Trails			
WP1	181	55	82
White Pine Overlap	**2019**	**2020**	**2021**
Trailhead	3,274	2,742	7,246

Table G1

Model Output for the Multinomial Logistic Regression Model for Trail Width.

Variable	Coefficient	St. Error	z	p-value	Risk Ratio
Model for < 50 cm vs 50–100 cm					
TSA	−0.0092	0.0014	−6.7084	0.0000	0.9908
(log) Trail Grade	−0.1995	0.0371	−5.3841	0.0000	0.8191
Distance to Formal Trails	0.0034	0.0006	5.9979	0.0000	1.0034
Distance to Lake Shore	−0.0072	0.0012	−6.1156	0.0000	0.9928
Surrounding Vegetation (in reference to Forested)					
Open Grassland/ Meadow	−0.5028	0.0960	−5.2371	0.0000	0.6048
Other	−1.6746	0.1234	−13.5657	0.0000	0.1874
(log) Use Level	0.2336	0.0420	5.5614	0.0000	1.2632
Model for < 50 cm vs 1–2 *m*					
TSA	−0.0074	0.0025	−2.9924	0.0028	0.9927
(log) Trail Grade	−0.5250	0.0620	−8.4662	0.0000	0.5915
Distance to Formal Trails	−0.0062	0.0013	−4.7668	0.0000	0.9938
Distance to Lake Shore	0.0037	0.0019	1.9181	0.0551	1.0037
Surrounding Vegetation (in reference to Forested)					
Open Grassland/ Meadow	−0.3689	0.1610	−2.2906	0.0220	0.6915
Other	−2.6573	0.3826	−6.9451	0.0000	0.0701
(log) Use Level	0.5358	0.0715	7.4891	0.0000	1.7088
Model for < 50 cm vs > 2 *m*					
TSA	−0.0179	0.0029	−6.2742	0.0000	0.9822
(log) Trail Grade	−0.0003	0.0871	−0.0038	0.9970	0.9997
Distance to Formal Trails	0.0072	0.0011	6.3938	0.0000	1.0072
Distance to Lake Shore	0.0199	0.0022	9.0377	0.0000	1.0201
Surrounding Vegetation (in reference to Forested)					
Open Grassland/ Meadow	0.0164	0.2771	0.0593	0.9527	1.0166
Other	2.8904	0.2166	13.3456	0.0000	18.0014
(log) Use Level	−0.7170	0.0925	−7.7501	0.0000	0.4882

Tomczyk & Ewertowski, 2011; Whinam, Chilcott, Ling, & Wyatt, 2003). This closely reflects the factors influencing trail conditions and they therefore provide a valuable basis for further analysis on the susceptibility of trail networks. While Sahani and Ghosh (2021) provide an example of this on the Singalila Pass and Poktey Dara trails in India, the need to further advance the mapping of environmental susceptibility and potential degradation of formal as well as informal trail networks is still great. Future research could build on the combination of field assessments, GIS, and statistical analysis to map susceptibility and inform proactive management to minimize resource impacts.

6. Conclusion

Our study characterized the proliferation and conditions of informal trail networks at four high alpine lakes in an urban-proximate PPA in Utah (USA). The results of our analysis enabled us to derive management implications to minimize resource impacts and advance recreation ecology research. We used well-established rapid assessment protocols, GIS analysis, and mobile device data to generate our data and multinomial logistic regression modelling and predictor effects plots to analyze these data. The model for trail width resulted in considerably more correct predictions than the model for condition class and

Finally, the need for understanding and mapping environmental susceptibility has long been recognized (Liddle, 1997; Monz, Cole, et al., 2010) and some research has integrated findings on resistance of vegetation types from trampling studies as well as factors such as aspect, elevation, and slope to determine the susceptibility of both previously undisturbed environments and existing trails (Arrowsmith & Inbakaran, 2002; D'Antonio, 2015; Dixon et al., 2004; Sahani & Ghosh, 2021;

Table G2
Model Output for the Multinomial Logistic Regression Model for Condition Class.

Variable	Coefficient	St. Error	z	p-value	Risk Ratio
Model for Class 5 vs Class 4					
TSA	−0.0058	0.0012	−4.6803	0.0000	0.9942
(log) Trail Grade	−0.0256	0.0334	−0.7687	0.4421	0.9747
Distance to Formal Trails	0.0003	0.0005	0.6027	0.5467	1.0003
Distance to Lake Shore	0.0143	0.0011	13.3055	0.0000	1.0144
Surrounding Vegetation (in reference to Forested)					
Open Grassland/Meadow	−0.1916	0.0872	−2.1972	0.0280	0.8256
Other	0.3660	0.0966	3.7897	0.0002	1.4419
(log) Use Level	0.1750	0.0367	4.7706	0.0000	1.1913
Model for Class 5 vs Class 3					
TSA	−0.0059	0.0020	−2.9953	0.0027	0.9941
(log) Trail Grade	0.3117	0.0580	5.3763	0.0000	1.3657
Distance to Formal Trails	−0.0044	0.0008	−5.2108	0.0000	0.9956
Distance to Lake Shore	0.0132	0.0016	8.0443	0.0000	1.0133
Surrounding Vegetation (in reference to Forested)					
Open Grassland/Meadow	−0.4678	0.1425	−3.2828	0.0010	0.6264
Other	1.3682	0.1374	9.9543	0.0000	3.9283
(log) Use Level	0.0091	0.0553	0.1653	0.8687	1.0092
Model for Class 5 vs Class 2					
TSA	−0.0104	0.0021	−4.8665	0.0000	0.9896
(log) Trail Grade	−0.3921	0.0587	−6.6850	0.0000	0.6756
Distance to Formal Trails	0.0034	0.0009	3.7115	0.0002	1.0034
Distance to Lake Shore	0.0384	0.0017	22.1627	0.0000	1.0392
Surrounding Vegetation (in reference to Forested)					
Open Grassland/Meadow	0.9084	0.1563	5.8123	0.0000	2.4805
Other	2.1536	0.1647	13.0781	0.0000	8.6161
(log) Use Level	−0.0595	0.0585	−1.0162	0.3095	0.9423
Model for Class 5 vs Class 1					
TSA	−0.0098	0.0031	−3.1673	0.0015	0.9902
Table G-2 *cont.*					
(log) Trail Grade	−0.1903	0.0880	−2.1619	0.0306	0.8267
Distance to Formal Trails	0.0120	0.0014	8.8268	0.0000	1.0120
Distance to Lake Shore	0.0262	0.0027	9.7748	0.0000	1.0265
Surrounding Vegetation (in reference to Forested)					
Open Grassland/Meadow	2.8045	0.2601	10.7811	0.0000	16.5194
Other	3.0193	0.2661	11.3471	0.0000	20.4772
(log) Use Level	−0.6428	0.0856	−7.5116	0.0000	0.5258

relationships emerging from predictor effect plots confirm results from previous studies on formal trails for informal trails. Synthesizing the results of our statistical analysis with the spatial distributions of dependent and predictor variables, combined with previous research allows for tangible management implications. Specifically, this work has led to implications focused on the concentration of use and how to determine *where* to most effectively do so. Overall, our study adds to the sparse research literature on informal trails and in urban-proximate PPAs and contributes to the sustainable management of outdoor recreation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

Appendix A:. Illustration of trail Measurements

Landform grade is the slope of the landform surrounding each trail segment. Trail grade is the slope of the trail itself. Trail slope alignment is the smallest difference in the bearings of the alignment of the trail and the aspect of the prevailing landform (between 0° and 90°). Trails with small TSA values are more closely aligned with the fall line of the prevailing landform while trails with high TSA values are considered "sidehill trails" (Fig. A1).

Appendix B:. Example of where streetlight zones were established and how use levels were assigned to trail segments

We used the OSM Pedestrian layer as overlay for the recorded informal trails and placed zones at the midpoints between trail intersections within the 120 m buffer (including between informal as well as between formal and informal trails, e.g. C1 and C8), at the midpoints between informal trails that cross the buffer and trail intersections within the buffer (e.g. C10), and at the intersection between the formal trail and the buffer (not pictured here). We deleted overlapping zones and those which did not provide enough data to obtain results from the *StreetLight InSight* platform (Fig. B1).

Appendix C:. Calibration of streetlight data

Calibration requires an estimate of Average Annual Pedestrian Traffic for at least one location within the study area. We calibrated all trail use data using data collected from 40 infrared trail counter
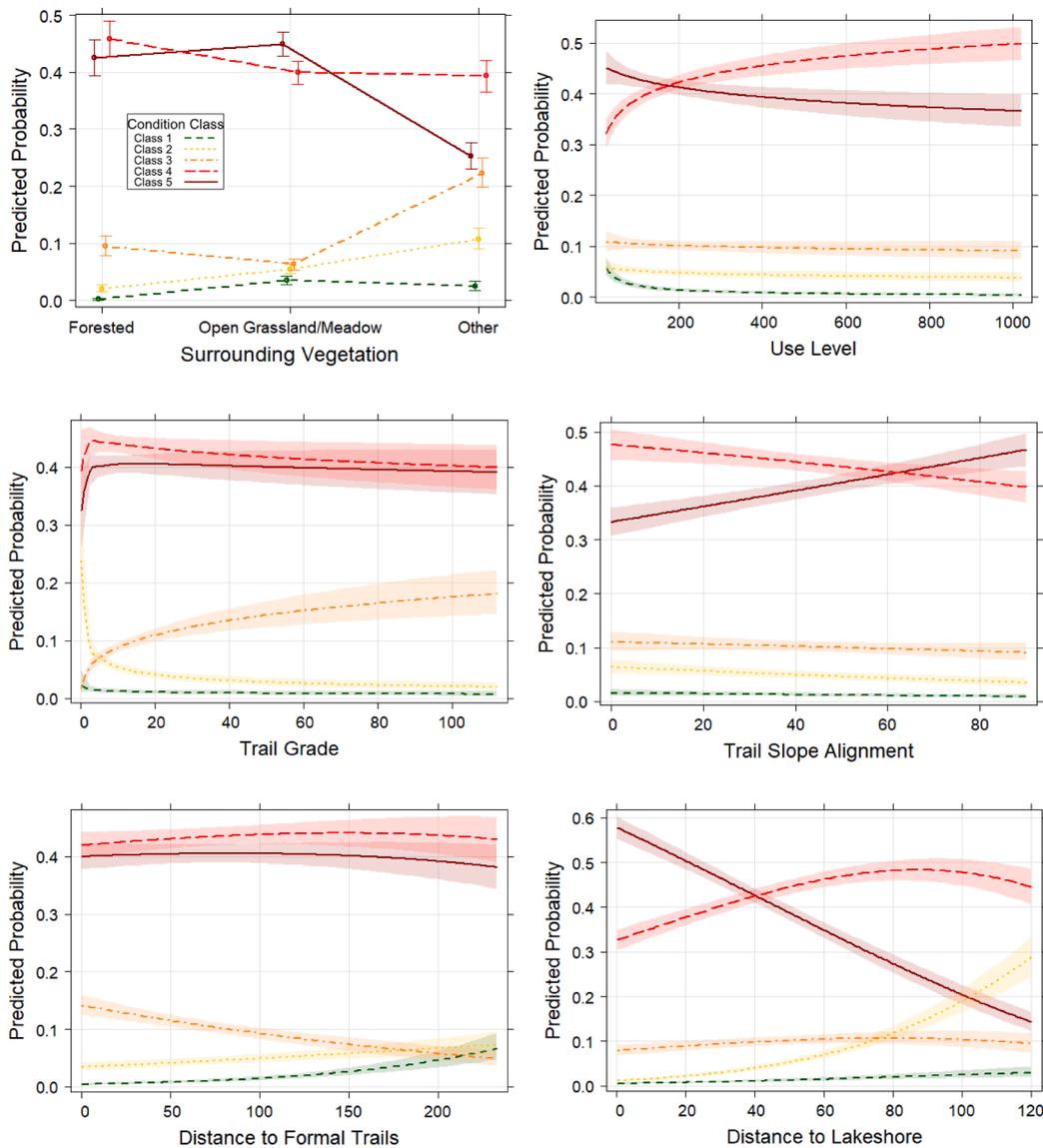
Fig. H1. Predictor Effect Plots for the Condition Class Model.

locations throughout the Central Wasatch (Millcreek Canyon, Big Cottonwood Canyon, and Little Cottonwood Canyon). The counters were set up and are maintained by the Wasatch Backcountry Alliance and the USDA Forest Service. Counter locations for Millcreek Canyon and Big Cottonwood Canyon are shown in Fig. C1; locations for Little Cottonwood Canyon are shown in Fig. C2. The counters have been in use since December 1, 2017. However, the individual counters are moved from location to location as the seasons change (many areas of the Central Wasatch are designated as closed for the winter due to snow). Consequently, trail counter data is not continuous which prohibits the direct estimation of Average Annual Pedestrian Traffic, the required measure to calibrate the mobile location data.

We constructed a statistical model using data from all 40 counter locations to generate estimates of Annual Average Daily Pedestrian Traffic. By pooling data all 40 counter locations, we are able to apply our understanding of the inferential relationships between specific factors believed to affect trail use from a counter location where data were collected for a particular period of time, to other counter locations where data were not collected for that time period.

The summary statistics describing the trail use data from the 40 counter locations is shown in Table C1. Given the data are overdispersed (as is common with trail use data), and that they are in a panel time-

series format (locations as panels and days as time-periods), we fit them with a population-averaged negative binomial panel time-series model.

The covariates we included in the model to predict trail use included *canyon*, *year*, *month*, *weekend_FrSu* (a dummy variable for if the day was between Friday and Sunday), and *weekend_SaSu* (a dummy variable for if the day was either Saturday or Sunday). These covariates are described in Table C2. The model was fit in Stata 16.1 with the *xtnbreg* command and the *pa* (population-averaged) option.

The final model results are shown in Table C3. The model suggests:

- *Canyon* has a significant effect on trail use, with the rate of trail use in both Big and Little Cottonwood Canyons being 9.013 and 6.303 times that of trail use in Millcreek Canyon. This finding was expected.
- *Month* has a significant effect on trail use, with trail use peaking in July. This was also to be expected given the seasonal nature of trail use in the three canyons.
- *Weekend_SaSu* has a significant effect on trail use, with the rate of trail use on Saturdays and Sundays being 2.0 times that of trail use during other days of the week.
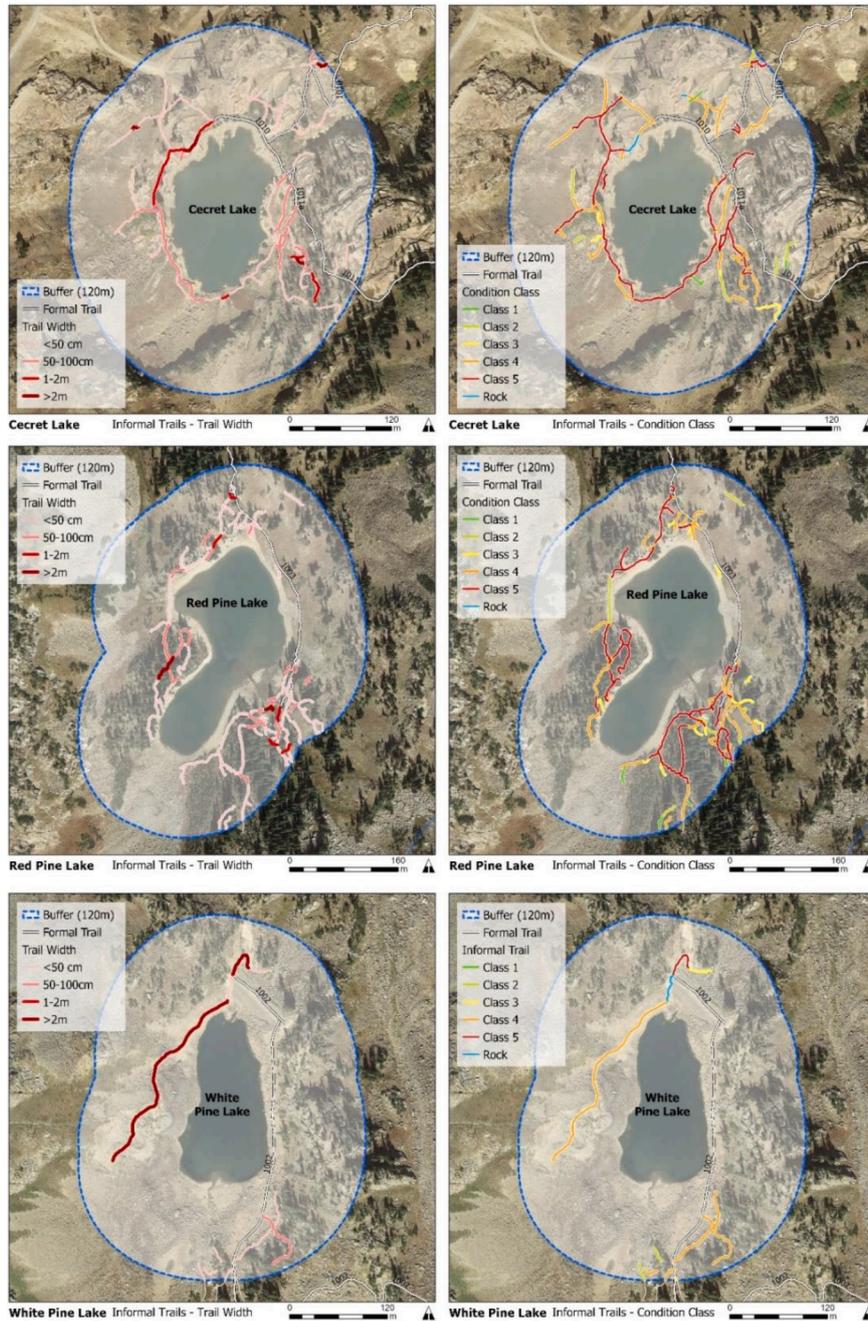
Fig. I1. Trail Width (left) and Condition Class (right) of Cecret Lake (top), Red Pine Lake (middle), and White Pine Lake (bottom).
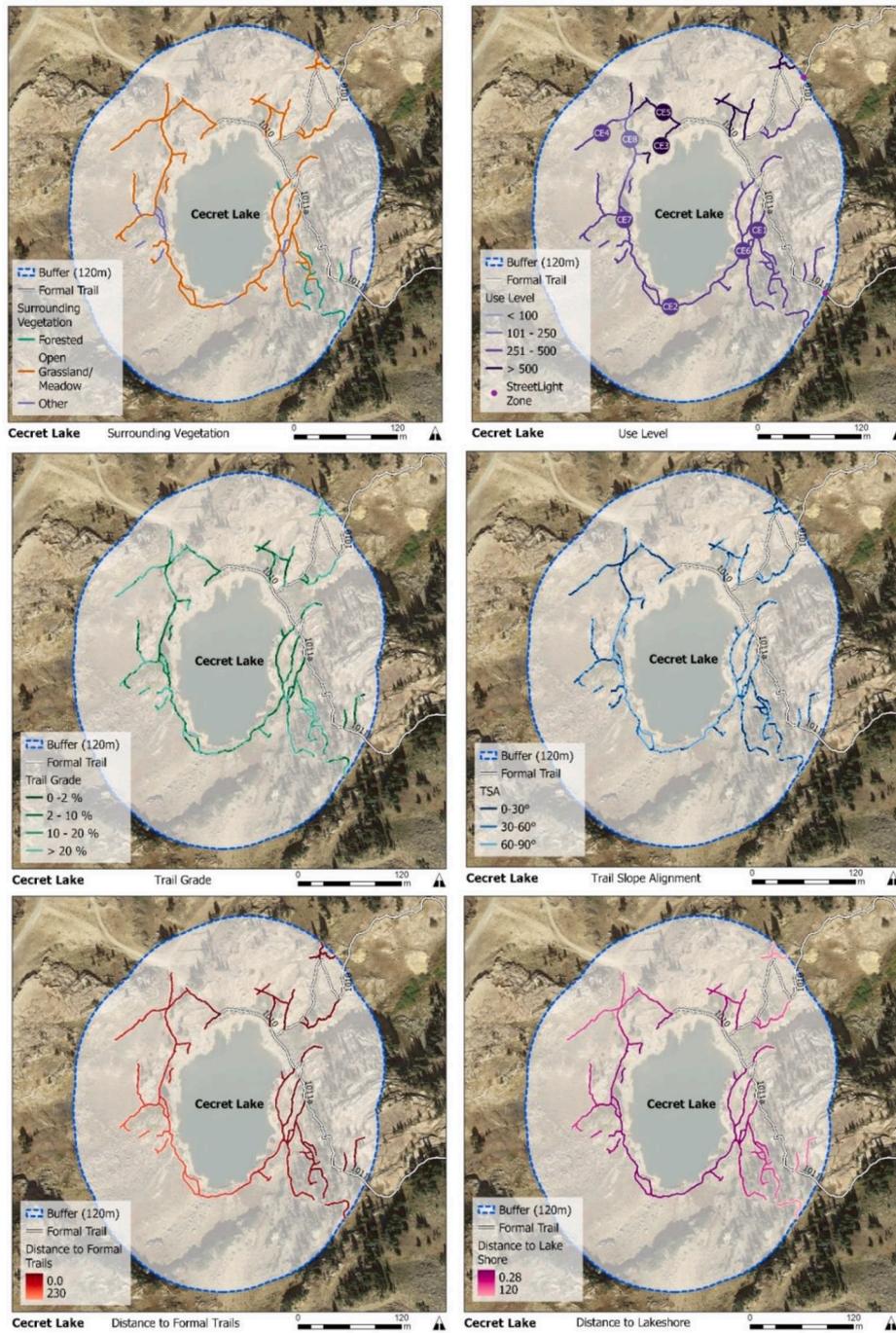
Fig. J1. Spatial Distribution of Predictor Variables around Cecret Lake.
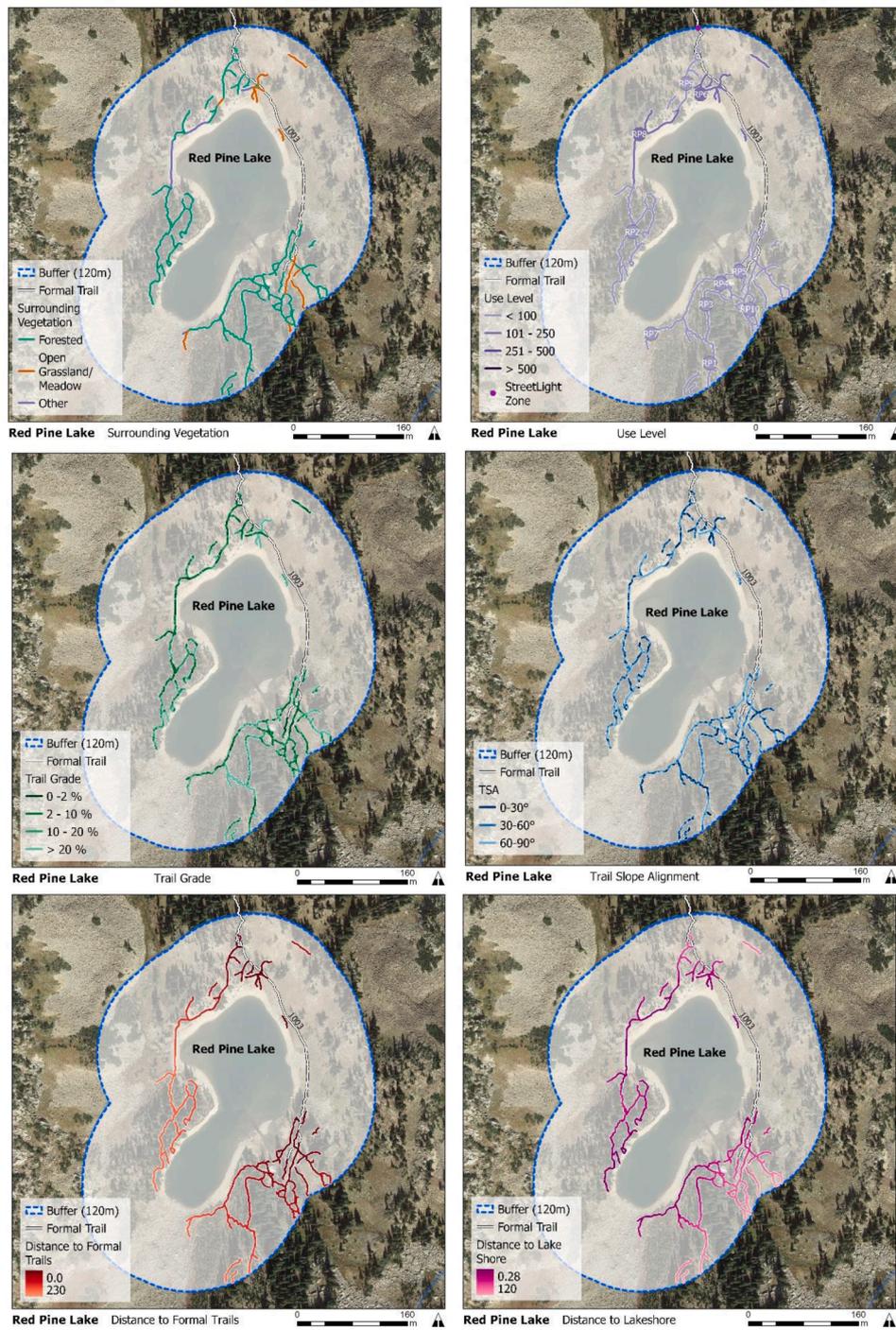
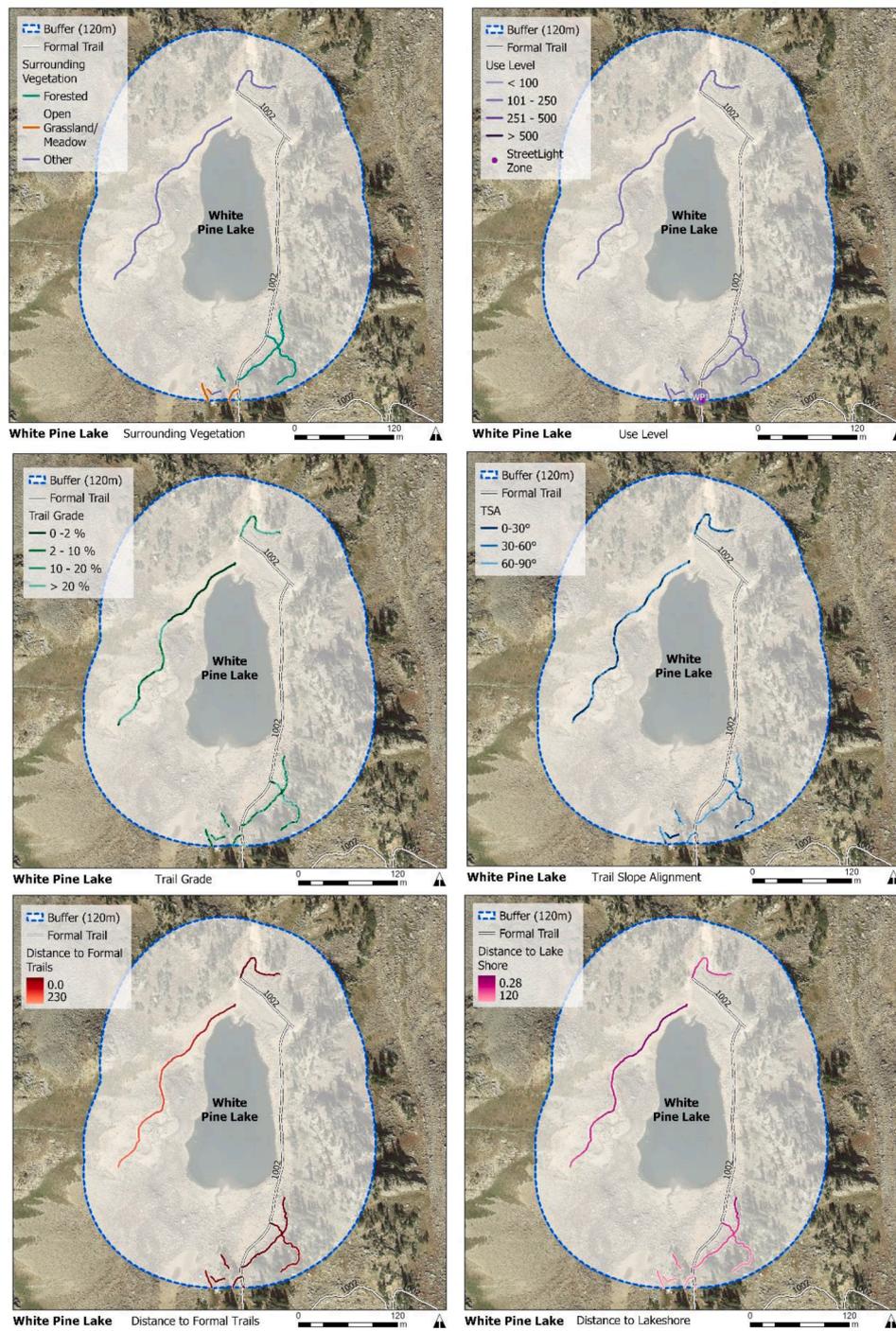**Fig. J2.** Spatial Distribution of Predictor Variables around Red Pine Lake.

Fig. J3. Spatial Distribution of Predictor Variables around White Pine Lake.

- *Year* has no effect on trail use, and as a result was subsequently dropped from the model.
- *Weekend_FrSu* had a significant effect on trail use, but not as significant as *Weekend_SaSu* and subsequently was dropped from the model.

The final model was used to predict trail use across all trail counter locations and days (using the *predict mu* postestimation command in Stata). An example of predicted trail use for one traffic counter location is shown in Fig. C3. The predicted daily trail use values were similar to the raw data from the trail counters (Table C1). We summed the predicted trail use data by year to estimate the Annual Average Daily Pedestrian Traffic required of the *Streetlight Data, Inc. Insights* platform (Table C4).

Appendix D:. Details on methodology

(See Table D1).

Appendix E:. Descriptive statistics

(See Table E1).

Appendix F:. Use level data

(See Table F1).

Appendix G:. Model results

(See Table G1)Table G2.

Appendix H:. Predictor effect plots

(See Fig. H1).

Appendix I:. Conditions of informal trails

(See Fig. I1).

Appendix J:. Predictors at all lakes

(See Figs. J1 to J3).

References

Agresti, A. (2019). *An introduction to categorical data analysis* ((3rd ed.).). Wiley.

Andereck, K. L., & Knopf, R. C. (2007). The relationship between experiences sought, preferred settings, resource conditions, and management preferences in an urban-proximate recreation area. *Journal of Park and Recreation Administration, 25*(4), Article 4. https://js.sagamorepub.com/jpra/article/view/1350.

Arrowsmith, C., & Inbakaran, R. (2002). Estimating environmental resiliency for the Grampians National Park, Victoria, Australia: A quantitative approach. *Tourism Management, 23*(3), 295–309. https://doi.org/10.1016/S0261-5177(01)00088-7

Ballantyne, M., Gudes, O., & Pickering, C. M. (2014). Recreational trails are an important cause of fragmentation in endangered urban forests: A case-study from Australia. *Landscape and Urban Planning, 130*, 112–124. https://doi.org/10.1016/j.landurbplan.2014.07.004

Ballantyne, M., & Pickering, C. M. (2015). Differences in the impacts of formal and informal recreational trails on urban forest loss and tree structure. *Journal of Environmental Management, 159*, 94–105. https://doi.org/10.1016/j.jenvman.2015.05.007

Ballantyne, M., & Pickering, C. M. (2015). The impacts of trail infrastructure on vegetation and soils: Current literature and future directions. *Journal of Environmental Management, 164*, 53–64. https://doi.org/10.1016/j.jenvman.2015.08.032

Balmford, A., Green, J. M. H., Anderson, M., Beresford, J., Huang, C., Naidoo, R., … Manica, A. (2015). Walk on the wild side: Estimating the global magnitude of visits to protected areas. *PLoS Biology, 13*(2), Article e1002074. https://doi.org/10.1371/journal.pbio.1002074

Barros, A., Gonnet, J., & Pickering, C. (2013). Impacts of informal trails on vegetation and soils in the highest protected area in the Southern Hemisphere. *Journal of Environmental Management, 127*, 50–60. https://doi.org/10.1016/j.jenvman.2013.04.030

Barros, A., & Pickering, C. M. (2017). How networks of informal trails cause landscape level damage to vegetation. *Environmental Management, 60*(1), 57–68. https://doi.org/10.1007/s00267-017-0865-9

Bratton, S. P., Hickler, M. G., & Graves, J. H. (1979). Trail erosion patterns in Great Smoky Mountains National Park. *Environmental Management, 3*(5), 431–445. https://doi.org/10.1007/BF01866582

Cakir, J. F. (2005). *Modeling trail degradation using field and GIS methodologies.* North Carolina State University [Master's thesis].

Creany, N. E., Monz, C. A., D'Antonio, A., Sisneros-Kidd, A., Wilkins, E. J., Nesbitt, J., & Mitrovich, M. (2021). Estimating trail use and visitor spatial distribution using mobile device data: An example from the nature reserve of orange county, California USA. *Environmental Challenges, 4*, Article 100171. https://doi.org/10.1016/j.envc.2021.100171

D'Antonio, A. (2015). *Modeling the ecological consequences of visitor behavior in off-trail areas of dispersed recreation use.* Utah State University [Doctoral dissertation].

D'Antonio, A., Monz, C., Larson, N., & Rohman, A. (2016). An application of recreation resource assessment techniques to inform management action in an urban-proximate natural area. *Journal of Outdoor Recreation and Tourism, 14*, 12–21. https://doi.org/10.1016/j.jort.2016.04.002

D'Antonio, A., Monz, C., Newman, P., Lawson, S., & Taff, D. (2012). The effects of local ecological knowledge, minimum-impact knowledge, and prior experience on visitor perceptions of the ecological impacts of backcountry recreation. *Environmental Management, 50*(4), 542–554. https://doi.org/10.1007/s00267-012-9910-x

Dawson, C. P., & Hendee, J. C. (2009). *Wilderness management: Stewardship and protection of resources and values* ((4th ed.).). Fulcrum Publishing.

Dixon, G., Hawes, M., & McPherson, G. (2004). Monitoring and modelling walking track impacts in the Tasmanian Wilderness World Heritage Area, Australia. *Journal of Environmental Management, 71*(4), 305–320. https://doi.org/10.1016/j.jenvman.2004.02.006

Dwyer, J. F., & Chavez, D. J. (2005). The challenges of managing public lands in the wildland-urban interface. In S. W. Vince, M. L. Duryea, E. A. Macie, & L. A. Hermansen (Eds.), *Forests at the wildland-urban interface: Conservation and management* (pp. 269–283). CRC Press.

Eagleston, H. (2016). *Integrating geospatial technology and ecological research in the analysis of sustainable recreation infrastructure.* Virginia Tech University [Master's thesis].

Eagleston, H., & Marion, J. L. (2020). Application of airborne LiDAR and GIS in modeling trail erosion along the Appalachian Trail in New Hampshire, USA. *Landscape and Urban Planning, 198*, Article 103765. https://doi.org/10.1016/j.landurbplan.2020.103765

English, D. B. K., Froemke, P., & Hawkos, K. (2015). Paths more traveled: Predicting future recreation pressures on America's national forests and grasslands-A forests on the edge report (FS-1034). U.S. Department of Agriculture, Forest Service.

Ewert, A. W. (1993). The wildland-urban interface: Introduction and overview. *Journal of Leisure Research, 25*(1), 1–5. https://doi.org/10.1080/00222216.1993.11969905

Ewert, A. W. (1998). A comparison of urban-proximate and urban-distant wilderness users on selected variables. *Environmental Management, 22*(6), 927–935.

Farrell, T. A., & Marion, J. L. (2001). Trail impacts and trail impact management related to visitation at Torres del Paine National Park. *Chile. Leisure/Loisir, 26*(1–2), 31–59. https://doi.org/10.1080/14927713.2001.9649928

Fox, J., & Weisberg, S. (2018). Visualizing fit and lack of fit in complex regression models with predictor effect plots and partial residuals. *Journal of Statistical Software, 87*, 1–27. https://doi.org/10.18637/jss.v087.i09.

Fox, J., & Weisberg, S. (2020). *Predictor effects graphics gallery.* https://cran.r-project.org/web/packages/effects/vignettes/predictor-effects-gallery.pdf.

Gische, K. (2022, October 17). *How does a trip start and end?* https://support.streetlightdata.com/hc/en-us/articles/360018550852-How-does-a-trip-start-and-end-.

Hammitt, W. E., Cole, D. N., & Monz, C. A. (2015). *Wildland recreation: Ecology and management* ((3rd ed.).). Wiley Blackwell.

Havlick, D. G., Billmeyer, E., Huber, T., Vogt, B., & Rodman, K. (2016). Informal trail creation: Hiking, trail running, and mountain bicycling in shortgrass prairie. *Journal of Sustainable Tourism, 24*(7), 1041–1058. https://doi.org/10.1080/09669582.2015.1101127

Hockett, K. S., Marion, J. L., & Leung, Y.-F. (2017). The efficacy of combined educational and site management actions in reducing off-trail hiking in an urban-proximate protected area. *Journal of Environmental Management, 203*, 17–28. https://doi.org/10.1016/j.jenvman.2017.06.073

Interagency Visitor Use Management Council. (2016). *Visitor use management framework: A guide to providing sustainable outdoor recreation* (p. 130). Interagency Visitor Use Management Council. https://visitorusemanagement.nps.gov/Content/documents/highres_VUM%20Framework_Edition%201_IVUMC.pdf.

Kyle, G. T., & Graefe, A. R. (2007). Introduction to the issues confronting the management of urban-proximate natural resource recreation areas. *Journal of Park and Recreation Administration, 25*(4), 1–5.

Lamborn, C. C., & Burr, S. W. (2016). *An estimation of visitor use in Little Cottonwood, Big Cottonwood, and Millcreek Canyons* (p. 6). Institute of Outdoor Recreation and Tourism. https://extension.usu.edu/iort/files/Tri_Canyon_Visitor_Use_Estimate.pdf.

Lamborn, C. C., Burr, S. W., Kim, M.-K., & Kessler, B. A. (2015). *2014-2015 Central Wasatch Visitor Use Study: Follow-up e-survey: Final report* (IORT-PR-2015-3; p. 80). Institute of Outdoor Recreation and Tourism. https://extension.usu.edu/iort/files/CWVUS_2014_2015_Follow_Up_Survey_CWVUS.pdf.

Leung, Y.-F., & Marion, J. L. (1996). Trail degradation as influenced by environmental factors: A state-of-the-knowledge review. *Journal of Soil and Water Conservation, 51*(2), 130–136.

Leung, Y.-F., Newburger, T., Jones, M., Kuhn, B., & Woiderski, B. (2011). Developing a monitoring protocol for visitor-created informal trails in Yosemite National Park, USA. *Environmental Management, 47*(1), 93–106. https://doi.org/10.1007/s00267-010-9581-4

Leung, Y.-F., Shaw, N., Johnson, K., & Duhaime, R. (2002). More than a database: Integrating GIS data with the Boston Harbor Islands visitor carrying capacity study. *The George Wright Forum, 19*(1), 69–78.

Liddle, M. J. (1997). *Recreation ecology: The ecological impact of outdoor recreation and ecotourism.* Chapman & Hall Ltd.

Lucas, E. (2020). A review of trail-related fragmentation, unauthorized trails, and other aspects of recreation ecology in protected areas. *California Fish and Wildlife*, 95–125.

Marion, J. L., & Leung, Y.-F. (2011). Indicators and protocols for monitoring impacts of formal and informal trails in protected areas. *Journal of Tourism and Leisure Studies, 17*(2), 215–236.

Marion, J. L., Leung, Y.-F., & Nepal, S. K. (2006). Monitoring trail conditions: New methodological considerations. *The George Wright Forum, 23*(2), 36–49.

Marion, J. L., & Olive, N. (2006). *Assessing and understanding trail degradation: Results from Big South Fork National River and Recreational Area* (p. 80). U.S. Geological Survey. https://pubs.er.usgs.gov/publication/5200309.

Marion, J. L., & Wimpey, J. (2017). Assessing the influence of sustainable trail design and maintenance on soil loss. *Journal of Environmental Management, 189*, 46–57. https://doi.org/10.1016/j.jenvman.2016.11.074

Marion, J. L., Wimpey, J., & Park, L. O. (2011). The science of trail surveys: Recreation ecology provides new tools for managing wilderness trails. *Park Science, 28*(3), 60–65.

Meadema, F., Marion, J. L., Arredondo, J., & Wimpey, J. (2020). The influence of layout on Appalachian Trail soil loss, widening, and muddiness: Implications for sustainable trail design and management. *Journal of Environmental Management, 257*, Article 109986. https://doi.org/10.1016/j.jenvman.2019.109986

Mitchell, J. (2020). *Trail impact monitoring in Forest Park.* Portland State University [Master's thesis].

Monz, C. A., Cole, D. N., Leung, Y.-F., & Marion, J. L. (2010). Sustaining visitor use in protected areas: Future opportunities in recreation ecology research based on the USA experience. *Environmental Management, 45*(3), 551–562. https://doi.org/10.1007/s00267-009-9406-5

Monz, C. A., Marion, J. L., Goonan, K. A., Manning, R. E., Wimpey, J., & Carr, C. (2010). Assessment and monitoring of recreation impacts and resource conditions on mountain summits: Examples from the Northern Forest, USA. *Mountain Research and Development, 30*(4), 332–343. https://doi.org/10.1659/MRD-JOURNAL-D-09-00078.1

Monz, C. A., Pickering, C. M., & Hadwen, W. L. (2013). Recent advances in recreation ecology and the implications of different relationships between recreation use and ecological impacts. *Frontiers in Ecology and the Environment, 11*(8), 441–446. https://doi.org/10.1890/120358

Nepal, S. K. (2003). Trail impacts in Sagarmatha (Mt. Everest) National Park, Nepal: A logistic regression analysis. *Environmental Management, 32*(3), 312–321. https://doi.org/10.1007/s00267-003-0049-7

Nepal, S. K., & Way, P. (2007). Characterizing and comparing backcountry trail conditions in Mount Robson Provincial Park, Canada. *AMBIO: A Journal of the Human Environment, 36*(5), 394–400. https://doi.org/10.1579/0044-7447(2007)36[394:CACBTC]2.0.CO;2.

Ng, S. L. (2022). Is surfacing a good choice for trail management? Evidence from four high-use hiking trails in Hong Kong. *Journal of Soil and Water Conservation, 77*(6), 600–608. https://doi.org/10.2489/jswc.2022.00143

Olive, N. D., & Marion, J. L. (2009). The influence of use-related, environmental, and managerial factors on soil loss from recreational trails. *Journal of Environmental Management, 90*(3), 1483–1493. https://doi.org/10.1016/j.jenvman.2008.10.004

Peterson, B. A., Brownlee, M. T. J., & Marion, J. L. (2018). Mapping the relationships between trail conditions and experiential elements of long-distance hiking. *Landscape and Urban Planning, 180*, 60–75. https://doi.org/10.1016/j.landurbplan.2018.06.010

Pickering, C. M., & Norman, P. (2017). Comparing impacts between formal and informal recreational trails. *Journal of Environmental Management, 193*, 270–279. https://doi.org/10.1016/j.jenvman.2016.12.021

Primack, R. B., & Terry, C. (2021). New social trails made during the pandemic increase fragmentation of an urban protected area. *Biological Conservation, 255*, Article 108993. https://doi.org/10.1016/j.biocon.2021.108993

Reed, S. E., Larson, C. L., Crooks, K. R., & Merenlender, A. M. (2014). *Wildlife response to human recreation on NCCP reserves in San Diego County.* Wildlife Conservation Society.

Rodway-Dyer, S., & Ellis, N. (2018). Combining remote sensing and on-site monitoring methods to investigate footpath erosion within a popular recreational heathland environment. *Journal of Environmental Management, 215*, 68–78. https://doi.org/10.1016/j.jenvman.2018.03.030

Sahani, N., & Ghosh, T. (2021). GIS-based spatial prediction of recreational trail susceptibility in protected area of Sikkim Himalaya using logistic regression, decision tree and random forest model. *Ecological Informatics, 64*, Article 101352. https://doi.org/10.1016/j.ecoinf.2021.101352

Salesa, D., & Cerdà, A. (2020). Soil erosion on mountain trails as a consequence of recreational activities. A comprehensive review of the scientific literature. *Journal of Environmental Management, 271*, Article 110990. https://doi.org/10.1016/j.jenvman.2020.110990

Smith, J. W., Miller, A. B., Lamborn, C. C., Monz, C., & Rumore, D. (2021). Outdoor recreation use and indicators of the ecological, physical, and social characteristics of recreation settings in the Central Wasatch: Phase 1 interim report. Institute of Outdoor Recreation and Tourism, Utah State University. https://digitalcommons.usu.edu/extension_curall/2206/.

Stein, T. V. (2005). Planning and managing for recreation in the wildland-urban interface. In S. W. Vince, M. L. Duryea, E. A. Macie, & L. A. Hermansen (Eds.), *Forests at the wildland-urban interface: Conservation and management* (pp. 139–157). CRC Press.

StreetLight Data, Inc. (2020). *Bike and pedestrian metrics methodology, data sources, and validation.* https://learn.streetlightdata.com/hubfs/White Papers/Multimode Data Sources and Methodology/StreetLight_Active Mode_Methodolgy and Validation_March2020_FINAL_FULL.pdf.

StreetLight Data, Inc. (2022). *StreetLight Insight.* www.streetlightdata.com.

Tomczyk, A. M., & Ewertowski, M. (2011). Degradation of recreational trails, Gorce National Park, Poland. *Journal of Maps, 7*(1), 507–518. https://doi.org/10.4113/jom.2011.1195

Tomczyk, A. M., Ewertowski, M. W., White, P. C. L., & Kasprzak, L. (2017). A new framework for prioritising decisions on recreational trail management. *Landscape and Urban Planning, 167*, 1–13. https://doi.org/10.1016/j.landurbplan.2017.05.009

TRAFx Research, Ltd. (2022). *TRAFx Research, Ltd.*

Trimble, Inc. (2022). *Trimble, Inc.*

Census Bureau, U. S. (2022). Quick facts. UT/POP010210 *U.S. Census Bureau.* https://www.census.gov/quickfacts/fact/table/saltlakecitycityutah,.

USDA Forest Service. (2021). *U.S. Forest Service—National Visitor Use Monitoring survey results—National summary report: Data collected FY 2017 through FY 2021.* USDA Forest Service. https://www.fs.usda.gov/sites/default/files/2021-National-Visitor-Use-Monitoring-Summary-Report.pdf.

Utah Department of Transportation. (2022). *Draft Environmental Impact Statement: Little Cottonwood Canyon.* https://littlecottonwoodeis.udot.utah.gov/draft-eis/.

Utah Geospatial Resource Center. (2022). *Elevation and terrain data.* Utah Geospatial Resource Center. https://gis.utah.gov/data/elevation-and-terrain/.

Verlič, A., Arnberger, A., Japelj, A., Simončič, P., & Pirnat, J. (2015). Perceptions of recreational trail impacts on an urban forest walk: A controlled field experiment. *Urban Forestry & Urban Greening, 14*(1), 89–98. https://doi.org/10.1016/j.ufug.2014.12.004

Walden-Schreiner, C., & Leung, Y.-F. (2013). Spatially characterizing visitor use and its association with informal trails in Yosemite Valley Meadows. *Environmental Management, 52*(1), 163–178. https://doi.org/10.1007/s00267-013-0066-0

Whinam, J., Chilcott, N., Ling, R., & Wyatt, P. (2003). A method for calculating environmental sensitivity to walker trampling in the Tasmanian Wilderness World Heritage Area. In R. Buckley, C. Pickering, & D. B. Weaver (Eds.), *Nature-based tourism, environment, and land management* (pp. 151–165). CABI.

Wilkinson, J. (2004). The new competing uses: Balancing recreation with preservation in Utah's Wasatch Mountains. *Journal of Land, Resources, & Environmental Law, 24*(3), 561–586.

Wimpey, J., & Marion, J. L. (2010). The influence of use, environmental and managerial factors on the width of recreational trails. *Journal of Environmental Management, 91*(10), 2028–2037. https://doi.org/10.1016/j.jenvman.2010.05.017

Wimpey, J., & Marion, J. L. (2011). A spatial exploration of informal trail networks within Great Falls Park, VA. *Journal of Environmental Management, 92*(3), 1012–1022. https://doi.org/10.1016/j.jenvman.2010.11.015