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Natural Resource Stewardship and Science

Data Analysis and Assessment of High Elevation Wilderness Meadows Surveyed from 2008 to 2011, Yosemite National Park

Resources Management and Science

Natural Resource Report NPS/YOSE/NRR—2014/926

ON THE COVER
Photograph of Dorothy Lake Meadow, July 2010.
Photograph courtesy of the National Park Service.

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Contents

Page

Figures

Page

Tables

Page

Tables (continued)

Page

Appendices

Executive Summary

Purpose

Sierra Nevada meadows provide a disproportionate number of ecological services in comparison with their relatively small extent on the landscape. Yosemite National Park has identified these ecosystems as important resources targeted for protection and preservation in formal planning efforts, including the park's 2020 strategic vision and the final environmental impact statements for the Merced Wild and Scenic River Plan and the Tuolumne Wild and Scenic River Plan.

The purpose of this report is to analyze existing data from high elevation wilderness meadows in Yosemite National Park to inform future meadow monitoring and the management of pack stock use, particularly in the context of free-range grazing by horses and mules. Such use is commensurate with park regulations, and may be included within the scope of Yosemite's upcoming Wilderness Stewardship Plan.

A management decision framework for the determination of suitability for use could be based on assessment of meadow condition and vulnerability, amount of use, use behavior, and site evaluations for special resource concerns at each site. The decision framework could be subsequently informed by feedback and additional data collection from on-going resource monitoring programs.

This report evaluates condition and vulnerability data from 53 high elevation wilderness meadow sites (sites) in Yosemite National Park, with the following objectives:

- To provide a comparative assessment of site baseline conditions by ranking sites by each of three assessment categories: ecological condition, vulnerability to disturbance, and observed use-related disturbance;

- To investigate potential meadow response to stock use, by evaluating relationships among ecological condition, stock use levels, and use-related disturbance, and informed by site vulnerability to disturbance, and;

- To illustrate the use of assessment categories and rankings to infer suggested suitability for use ratings and to identify meadows-of-concern , as an example and interpretation of these results for applied management.

Our approach in this report evaluates suitability for use based on one component (assessment of site condition and vulnerability) of a comprehensive framework that could be developed for meadow management. Additional components for a determination of suitability,might include metrics or indicators that quantify ecosystem trends, resiliency, or site-specific concerns (e.g., presence of rare or special status species, sensitive habitats, archeological sites, or potential use-type conflicts.

For this comparative evaluation, we define three assessment categories:

- **Ecological condition**: a relative measure of meadow health, informed by multiple metrics of meadow and streambank (when present) condition, and relating to ecosystem processes, function, and ecosystem services.

- **Vulnerability to disturbance**: a relative measure of meadow susceptibility to physical disturbance from use, as influenced by physical and topographic factors and constraints.

- **Use-related disturbance:** a relative measure of the presence/absence, quantity, extent, or density of observable disturbance associated with human and/or pack stock use of meadows.

Methods

We evaluated data from three survey protocols implemented at 53 meadows (sites) between 2008 and 2011. From gridpoint plot surveys (n = 53) we evaluated five metrics for meadow ecological condition—bare ground cover, total vegetation cover, late seral species cover, early seral species cover, and litter depth. From stream monitoring (n = 19) we evaluated five metrics for streambank ecological condition—ecological status, upland species cover, vegetation biomass, shade index, and streambank stability ratings. From use-related disturbance mapping (n = 53) we evaluated five metrics—formal trails, informal trails, trampled areas, roll pits, and meadow fire rings. We evaluated seven metrics, obtained from various spatial data, that comprise vulnerability to disturbance (n = 53) including elevation, slope, streambank area, lakeshore area, pond area, dry meadow area, and wet meadow area. We considered each of these metrics as important aspects of ecological condition, vulnerability, or disturbance, and sought to develop summary scores by which each site could be ranked.

To develop summary scores for each site, we first used principal component analyses (PCA) and linear regression to identify patterns of correlation among metrics within each assessment category. Strong correlation among metrics would indicate potential redundancy in explanatory power, and suggest the presence of artificial weighting within summary score calculations. To reduce the presence of artificial weighting, we used loading values from the PCA to identify groups of correlated metrics, and selected the single metric indicating the strongest relationships to each other metric (i.e., p-value from linear regression) and omitted the other correlated metrics from summary score calculations.

To standardize metrics in various units of measure into summary scores, we calculated relativized scores for each metric as a percent of the maximum value among all sites. We then calculated summary scores for each site, by summing relativized scores for the selected metrics within each assessment category. For vulnerability to disturbance, we chose to double-weight the metric for meadow wetness due to the sensitivity of wet soils to physical disturbance and for the potential presence of fens in wet meadows. We then ranked summary scores for each site relative to other sites for each assessment category. We then rated scores as high, moderate, and low by delineating the 10^{th} and 90^{th} percentiles for the ranges of calculated summary scores for each assessment category. We used high and low ratings for those same percentiles from stream ecological condition score to qualitatively inform meadow ecological condition score, since only 19 of 53 sites had stream data.

To explore potential meadow response to use-related disturbance and reported stock use, we used model selection based on Akaike's information Criterion (AICc) values to explore parsimonious relationships among summary scores for meadow and streambank ecological condition, vulnerability, disturbance, and for reported stock use levels. In addition, we explored relationships for bare ground cover and streambank stability with vulnerability, disturbance, and reported stock use, due to their proposed use as monitoring indicators in the Wild and Scenic River Plans. Results from the AIC technique indicate which model exhibits the best fit to data for each response variable.

Lastly, we illustrate a potential management application of these results by plotting summary scores for meadow ecological condition with vulnerability to disturbance, and suggest categories for meadow suitability. In addition, we identify meadows-of-concern and meadows of potential concern based on suitability for use ratings in context with use-related disturbance scores and reported stock use levels.

Results and Discussion

Results from PCA analyses and linear regression indicated correlation among streambank stability, vegetation biomass, and upland species cover on streambanks. Results also indicated correlation among all metrics in the use-related disturbance assessment category except for formal trails (i.e., informal trails, roll pits, trampled area, and meadow firerings were correlated). Strong correlation among metrics in the meadow ecological condition and vulnerability to disturbance assessment categories was not detected. Correlation among metrics suggests possible options to streamline monitoring efforts. For instance, variation in vegetation biomass or upland species cover may be at least partially captured by monitoring streambank stability. Similarly, use-related disturbance may be adequately captured by assessing formal trails, and monitoring either informal trails, roll pits, trampled area, and meadow firerings. Nonetheless, such targeted monitoring has inherent tradeoffs, and should be considered only when logistical constraints preclude monitoring a full suite of metrics.

To reduce correlation and redundancy among metrics within our determination of summary scores, we chose to omit vegetation biomass from calculations of streambank ecological condition summary scores, and to omit trampled area, roll pits, and meadow fire rings from calculations of use-related disturbance summary scores. Metrics used for our determination of summary scores include: meadow ecological condition—bare ground cover, total vegetation cover, late seral species cover, early seral species cover, and litter depth; streambank ecological condition—ecological status, upland species cover, shade index, and streambank stability rating; vulnerability to disturbance—elevation, slope, streambank area, lakeshore area, pond area, dry meadow area, and wet meadow area, and; use-related disturbance—formal trails and informal trails.

From evaluation of the 53 sites for meadow ecological condition, Merced Lake-West and Washburn Lake sites exhibited the highest summary scores, while Elbow Hill and Rodgers Meadow had the lowest. Turner Lake and Twin Lakes sites had the highest streambank ecological condition scores of the 19 sites evaluated, and Upper Lyell- South and Middle Lyell yielded the lowest scores. For vulnerability to disturbance, Washburn and Doc Moyle's- West sites had the highest summary scores, and Elbow Hill and Cold Canyon had the lowest. For use-related disturbance, Smedberg Lake and Merced Lake- Shore sites had the highest scores while 6 of the 53 sites evaluated scored zero because formal and informal trails were not observed. Delineating high and low ratings, according to the 10th and 90th percentiles, resulted in six sites with low and high ratings for each summary score, except in the case of streambank ecological condition, where the fewer number of sites resulted in only two sites being ranked with low and high ratings.

The model selection using AIC to evaluate relative goodness of fit of the suite of models, indicated the following were the best fit for each variable:

- For bare ground cover: the interaction of maximum stock use per unit area by vulnerability to disturbance, suggesting that as vulnerability to disturbance increases, the effect of the density of maximum stock use on bare ground cover also increases.

- For streambank stability: the interaction of informal trails by upland species cover, suggesting that as upland species cover increases along streambanks, the negative effect of informal trails on streambank stability also increases.

- For meadow ecological condition summary scores: elevation, suggesting that meadow ecological condition scores decrease as elevation increases.

- For streambank ecological condition summary scores: the interaction of use-related disturbance by vulnerability to disturbance, suggesting that as vulnerability to disturbance increases, the negative effect of disturbance on streambank ecological condition is reduced.

Considering relatively low r-squared values (i.e., ranging from 0.22 to 0.48 for the best models), low sample size for the streambank data sets, and concerns for assumptions of linear regression, we found greatest suppport for model selection results for the bare ground cover test. Results of model selection for meadow ecological condition and streambank ecological condition were qualified by concerns regarding the fit of the best model to normal distributions and potential non-constant variance. In light of these concerns, we suggest caution for inferences made from AIC test results for meadow ecological condition and streambank ecological condition.

Lastly, we contrasted meadow ecological condition scores with vulnerability to use scores to determine relative suitability for use ratings. Using a stratification, based on 10th and 90th percentiles, which roughly aligns with natural breaks in these summary scores, resulted in seven meadows rated as high, forty as moderate, and six as low suitability. This illustrates one approach to interpret study results in an applied management context. Nonetheless, an effective management approach could also be based on site-specific objectives and continuous site rankings rather than as discrete categories used for this example.

Our examination of suitability ratings in conjunction with ratings for disturbance score and use levels identified four meadows-of-concern and nine potential meadows-of-concern . Meadows-of-concern (Castle Camp, Miller Lake- North, Smedberg Lake, and Tilden Lake- South) exhibited low to moderate suitability ratings and had high disturbance and use levels. These factors suggest these sites have a greater relative risk for decline in condition, and warrant additional investigation and monitoring, and may need management actions to protect or improve ecological condition. We identified potential meadows-of-concern because minor changes in use patterns or ecological conditions could shift ratings for these sites to meadow of concern. Potential meadows-of-concern include: Emeric Lake, Merced Lake- East, Merced Lake- Shore, Benson Lake, Hook Lake, Matterhorn Canyon, Miller Lake- South, Tilden- North and Upper Lyell- North.

We acknowledge some challenges and limitations of this study, including: metrics used to determine site summary scores are based on single point-in-time surveys; sample size; site selection was not random; and potential inaccuracies in pack stock use data. There is also an inherent level of subjectivity and professional judgement used in defining the suggested suitability for use categories, and additional metrics could be considered. Nonetheless, several potentially valuable tools emerge from this approach. Relativized scores and summary scores provide ways to quantify conditions from multiple metrics, and could be augmented with other, or additional metrics, such as species functional group ratings and natural vegetation datum index as a metric for site moisture conditions. Principal component and regression analyses can be used to discern the relative influence of a metric (or group of metrics) at a given site, and can help to streamline monitoring.

The suggested suitability for use and meadow of concern ratings presented here help identify sites for management consideration, but alternative delineations for these categories could be explored. The approach used here could be used to inform the development of a comprehensive framework for meadow management that also considers other factors important park objectives such as special status or rare species, sensitive habitats, archeological resources, potential user conflicts, or site resilience.

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We thank the San Francisco Public Utilities Commission for their ongoing support of meadow studies to aid in pack stock management at Yosemite. Funding from the Division of Planning and Wilderness Branch at Yosemite enabled data collection for meadows outside the Tuolumne Watershed. We thank Jeff Holmquist (UCLA) for his valuable feedback in the early stages of our analysis. We thank reviewers Monica Buhler (NPS), Mitch McClaran (University of Arizona), Jim Roche (NPS), Peggy Moore (USGS), Steve Ostoja (USFS), Judi Weaser (NPS), Linda Mazzu (NPS), Laura Jones (NPS), Erik Frenzel (NPS), Jan Van Wagtendonk (NPS), and Linda Mutch (NPS) for their helpful comments. Finally, we greatly appreciate the hard work of our field crews who backpacked countless miles over the past summers to collect quality data for this project, particularly Joy Baccei, Erin Babich and Kate Wilkin who worked during multiple years for this project; this study would not have been possible without their efforts.

1. Introduction

Yosemite National Park (Yosemite) prioritized conservation of meadow ecosystems through the park's strategic vision (NPS 2012) and has identified meadow condition as a component of outstandingly remarkable values (ORVs) in the final environmental impact statements for the Merced Wild and Scenic River Plan and the Tuolumne Wild and Scenic River Plan (NPS 2014a; NPS 2014b). The Sierra Nevada Network Inventory and Monitoring Program has selected specific meadow types (wet meadows and fens) in their vital signs monitoring program, since these types integrate a range of physical and biotic ecosystem processes, and changes in these types may indicate broader ecological change (Mutch et al. 2008). The Organic Act of 1916, Wilderness Act of 1964, and Wild and Scenic River Act of 1968 provide legal mandates that help guide meadow management on National Park Service (NPS) lands. Moreover, the compatibility of use types permitted within designated wilderness areas , including meadows, will be encompassed within Yosemite's upcoming Wilderness Stewardship Plan.

The purpose of this report is to analyze existing data from high elevation wilderness meadows in Yosemite and to inform future meadow and pack stock use monitoring and management, particularly in the context of free-range grazing by horses and mules (see Acree et al. 2010). Our objectives are as follows:

- To provide a comparative assessment of site baseline conditions by ranking sites by each of three assessment categories: ecological condition, vulnerability to disturbance, and observed use-related disturbance;

- To investigate potential meadow response to stock use, by evaluating relationships among ecological condition, stock use levels, and use-related disturbance, and as qualified by site vulnerability to disturbance, and;

- To illustrate the use of assessment categories and rankings to infer suggested suitability for use ratings and to identify meadows-of-concern .

For these objectives, we evaluated meadow sites based on summary scores for ecological condition (for meadows and streambanks), vulnerability to disturbance, and use-related disturbance. A particular advantage of summary scores, whereby the relative condition of many metrics are summed into a single score for each assessment category, is that comparisons among sites is driven by the state of many metrics, rather than being overly sensitive to fluctuations within a single metric. We define the assessment categories as:

- **Ecological condition**: a relative measure of meadow health, informed by multiple metrics of meadow and streambank (when present) condition, and relating to ecosystem processes, function, and services.

- **Vulnerability to disturbance**: a relative measure of meadow susceptibility to physical disturbance from use, as influenced physical and topographic factors and constraints.

- **Use-related disturbance:** a relative measure of the presence/absence, quantity, extent, or density of observable disturbance associated with human and/or pack stock use of meadows.

1.1 Sierra Nevada meadows: characteristics and importance

Contrary to a common belief that most meadows are in transition to forest, both palynological and stratigraphic evidence suggests that many Sierra Nevada meadows are as stable over time as surrounding forests (Wood 1975). However, these ecosystems often occupy the ecotone between terrestrial and aquatic or semi-aquatic systems and may be more sensitive to change due to their strong linkages to regional and local hydrological processes (Wood 1975). Upper montane and subalpine meadow ecosystems generally occur in low-gradient valleys with poor drainage, along streams, as level or gently sloping treeless expanses within coniferous forests, and within sediment-filled areas previously occupied by glacial lakes and ponds. The hydrogeomorphic classification described by Weixelman et al. (2011) described the range of variation among Sierra Nevada meadow ecosystems, differentiated by hydrologic regimes, proportional composition of vegetation communities, and edaphic characteristics. These authors further described meadows as integrated systems comprising a mosaic of stream channels, riparian floodplains and wetlands, as well as mesic and upland herbaceous communities. Meadow vegetation is typified by species in the grass (Poaceae), sedge (Cyperaceae), and rush (Juncaceae) families and supports a diverse array of herbaceous species (Ratliff 1985). Woody species such as willow (*Salix* spp.) can be common and locally abundant, but are not typically dominant at the meadow scale.

Despite their relatively small contribution in terms of area, meadows are critically important ecosystems due to their often broad-scale functional importance to the greater landscape. In the Sierra Nevada, meadows range in size from a few hundred square meters to hundreds of hectares (Benedict and Major 1982, Allen 1987), but occupy less than 10% of the overall landscape (Ratliff 1985). Meadows occupy less than 3% of Yosemite National Park (Moore et al. 2000). Ecological processes associated with meadows provide such wide arrays of habitats that meadows have been qualified as biodiversity hotspots (UC Davis 2007). For instance, high biodiversity in terms of flora (Ratliff 1985, Debinski et al. 2000), fauna (Kauffman et al. 1997), avian species (Graber 1996), invertebrate species (Kattelman 1996), and soil arthropods (Lattin 1990) have been reported. In addition, Sierra Nevada meadows provide important habitat for special status species such as mountain yellow legged frogs (*Rana mucosa*) and Yosemite toads (*Bufo canorus*) (Stebbins 2003). Reported meadow ecosystem services include capturing and cycling nutrients, accumulating and filtering sediments, attenuating floods, enhancing streambank stability, and providing conditions for clean water downstream. Millions of people living downstream from Yosemite rely on the Tuolumne and Merced watersheds as renewable sources of clean water. Functioning meadow complexes within these watersheds are integral to an expansive suite of ecosystems services that ultimately affect downstream water flow regimes and water quality.

1.2 Meadow ecological condition

We define meadow ecological condition as the capacity of these ecosystems to provide desired function, processes, and services. This definition aligns with Naeem et al. (1999), who described ecological function as the collective effects of the biological activities of an ecosystem upon the physical and chemical condition of the environment. Meadow ecological condition reflects the connectivity and feedback among physical and biotic processes involving hydrology, vegetation, and groundwater dynamics, where impacts to any component would inevitably affect the others (Purdy and Moyle 2006). Factors such as soil characteristics, vegetation, nutrient cycling and stream geomorphology affect the processes that contribute to meadow ecological condition (Table 1-1).

Table 1-1. Factors driving ecological processes, function, and desired ecosystem services associated with meadow condition.

Factor	Relationship to processes, function, and services associated with meadow ecological condition
Connectivity between surface water and groundwater	Water input recharges meadow sub-surface storage and occurs as precipitation, snowmelt, overbank flows, storm runoff, and groundwater from contributing hillslopes. Meadow ecosystems achieve a dynamic equilibrium among input, storage, evapotranspiration, and outflow. The primary factor in determining the composition of meadow plant communities is depth to water table (i.e., groundwater and rooting zone connectivity) (Loehide et al. 2008). Local hydrology has been reported as the primary determinant of vegetation types and distribution in meadows (Wood 1975, Ratliff 1985, Allen-Diaz 1991, Patterson and Cooper 2007, Hammersmark et al. 2008).
Vegetation productivity	Productivity of meadows is related to elevation, vegetation type, range (e.g., ecological) condition, nutrient availability, and degree of herbivory (Ratliff 1985). Aboveground productivity positively effects: habitat and forage for wildlife (Kauffman et al. 1997) and macroinvertebrates, shade (Gregory et al. 1991), organic matter inputs to streams and soils (Naiman and Decamps 1997, Lewis et al. 2003), and increased roughness of stream banks and floodplains that dissipates hydraulic energy and entraps sediment (Emmett and Leopold 1964, Bennett et al. 2002). Belowground biomass affects subsurface biogeochemical processes (Dwire et al. 2004, Blank et al. 2006), floodplain development (Girel and Patou 1997), and greatly contributes to stabilization of soils (Oades 1993) and streambanks (Micheli and Kirchner 2002, Simon and Collison 2002). Furthermore, these relationships suggest that productivity contributes to site resiliency, or the ability and rate of a meadow to recover from disturbance.
Sediment deposition	Meadow vegetation and soils, in conjunction with meadow size and low topographic relief, facilitate the slowing of runoff and sediment filtration. The dynamic equilibrium of erosional and depositional processes governs stream channel form (Rosgen 1996), and influences meadow hydrology. Underlying processes associated with deposition and erosion are spatially and temporally variable, thereby generating intra- and inter-site variability. Sediment deposition results in the expansion of habitable (vegetated) surfaces (Girel and Patou 1997), nutrient pulses (Junk et al. 1989), and creates a mosaic of soil patches across a floodplain varying by texture and associated characteristics (water-holding capacity, matric potential, and cation exchange capacity, among others). Depending on their size and depth, sediment deposits could create expanses of bare ground, thus reducing meadow productivity.
Soil Characteristics, nutrient cycling, sequestration, and contribution	Moist meadow soils generally have more organic matter and higher water-holding capacities than upland soils, thus providing higher volumes of plant-available carbon, nitrogen, and water (Lewis et al. 2003, Blank et al. 2006, Norton et al. 2011). Accumulated nutrients from overland and over-bank flows help to maintain meadow productivity and downstream water quality (Junk et al. 1989, Lewis et al. 2003). Vigorous rooting activity and nutrient uptake by riparian vegetation in good condition could ensure that plants sequester readily available soil nutrients during the growing season, thereby lessening the potential for degradation of downstream water quality (Blank et al. 2006). Conversely, feedback mechanisms from vegetation to stream channels provide fine and coarse organic material that act as a base for many aquatic food chains (Kattelmann and Embury 1996, NPS 2009). Norton et al. (2011) suggested that meadow sites with degraded hydrologic conditions (i.e., non-functioning condition) contained only half the amount of soluble organic carbon and total nitrogen found at sites with proper functioning conditions.
Resistance and resiliency to dynamic disturbance regimes	Species, individuals, communities, populations, and landscapes, all vary in their abilities to resist and recover from disturbance (i.e., resistance and resilience) (Cole and Landres 1996). The typical high biodiversity within meadows (Kauffman and Krueger 1984, Mitsch and Gosselink 1993) is driven in part by heterogeneous responses of meadow ecosystems to the variable disturbance regimes (i.e., fluvial—erosion, deposition, flooding; and non-fluvial—fire, wind, pathogens, herbivory), which produce a spatially and structurally complex mosaic of habitats (National Research Council 2002). For example, some areas within a meadow may be resistant to erosion and therefore relatively fixed on a successional trajectory unless otherwise disturbed (Kauffman et al. 1997); conversely, successional processes may be renewed at areas of recent erosion or sediment deposition (Naiman and Decamps 1997, Winward 2000).

Notably, the array of human activities has often profoundly affected meadow ecosystem processes, function, and services (see Kinney 1996, Menke et al. 1996, UC Davis 2007, Ostoja et al., 2014).

Such activities include: intensive grazing regimes, by livestock (primarily cattle and sheep; Ratliff 1985, Snyder 2003) and by pack stock (Menke et al. 1996, Allen-Diaz et al. 1999); burning (McKelvey and Johnston 1992); mining (i.e., excess sediment yields from upstream hydraulic mining (Curtis 2005); road and trail building (Montgomery 1994, Wemple et al. 1996), and; anthropogenic activities that induce climate change (Debinski et al. 2010). Indeed, the legacy of effects from human activities may have induced a state transition in many meadows throughout the Sierra Nevada, whereby recovery to prior conditions is unlikely (Kauffman et al. 1997, Bestelmeyer 2006, Briske et al. 2008).

Ecological processes and functions such as those described above are often impossible or infeasible to measure directly. Instead, managers use indicator metrics as surrogates to assess or monitor ecological condition. Indicators are components of a system whose characteristics (e.g., presence or absence, quantity, distribution) provide an index of an attribute (e.g., hydrologic function) that is too difficult, inconvenient, or expensive to measure (Pellant et al. 2000).

1.3 Pack stock use and meadows

In the Yosemite Wilderness, meadow use is currently in the form of grazing by pack stock and human foot traffic. For this report, the terms "pack stock use" and "stock use" refer to all activities associated with horses, mules, and burros. Our analyses focuses on stock use associated with free-range pack stock in meadows, and we make no distinction between pack stock, riding stock or other stock uses.

Pack stock use has a rich history and tradition in Yosemite (Acree et al. 2010), having been associated with activities ranging from early pioneer expeditions, to support of sheep and cattle grazing, to use by NPS U.S. Cavalry patrols and support of large Sierra Club expeditions in the early 1900's. Historically, meadows throughout the Sierra Nevada were an essential food source for early pack stock expeditions and livestock production (Kinney 1996, Snyder 2003). Meadows have become popular destinations for hikers and backpackers since World War II (UC Davis 2007) and remain a focus of visitor use, especially for those who rely on meadows to provide forage for pack stock that facilitate their access to wilderness areas (Menke et al. 1996, Murrell-Stevenson et al. 2006).

Currently in Yosemite, pack stock use includes day-trips and overnight use by commercial, administrative, and private parties. Campsites near meadows open to stock use are common, facilitating stock access to these forage-rich areas. Free range grazing is allowed in wilderness areas where stock travel is permitted[1], with the exception of no-camping zones and areas near the High Sierra Camps. Overnight stock use is restricted to 3,873 stock nights[2] total for all commercial groups

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[1] Pack stock travel in Yosemite is permitted on nearly all trails, within ¼ mile of trails, and on certain authorized cross-country routes (36 CFR 2.16).

[2] Use is reported in units of "stock nights" (SN), where 1 SN equals one night of grazing for a horse or mule. For example, one trip with four head of stock for five nights equals 20 SN.

annually; though use has only ranged from 21-57% of this quota since 2004 (Wilderness Office stock records data, accessed December 10, 2011). Recorded annual administrative use has averaged 513 stock nights since 2006 (Wilderness Office stock records data), comprising 67% of total recorded stock use during that period. Private party stock use is estimated to comprise only 5% of total overnight stock use at Yosemite (Acree et al. 2010).

In general, pack stock use aligns with many park objectives, though some specific uses, such as free-range grazing in meadows or extensive trail use, could contribute to undesirable changes in ecological condition. The primary goal of pack stock management in meadows is to avoid unacceptable impacts to meadow structure, function, diversity and productivity while allowing access by pack stock users (Moore et al. 2000). Effective stock management maintains ecologically important processes and functions associated with meadow conditions and downstream water quality.

In examining pack stock effects on Sierra Nevada meadows, McClaran and Cole (1993) described potential effects of pack stock use on meadow function in terms of vegetation, soils, water quality, and wildlife through the mechanisms of defoliation (i.e., grazing), physical disturbance (i.e., trampling and rolling), nutrient input and potential contamination through defecation. Acree et al. (2010) postulated that potential impacts of pack stock use in Yosemite may be linked to soil compaction, disruption of sheetflow and surface water infiltration, decreased sediment and nutrient filtration of meadows, plant species composition shifts, loss of riparian vegetation and increased stream erosion.

Despite numerous potential effects of pack stock use upon meadow ecosystems, we found only three published experimental studies from the U.S. that investigated potential pack stock-specific effects on meadow condition. These studies primarily focused on grazing, but varied by intensity and/or duration of grazing and meadow type. Results from these studies documented reduced productivity, vegetation cover, and increased bare soil (Olson-Rutz et al. 1996b, Stohlgren et al. 1989, Cole et al. 2004), shifts in species composition (Cole et al. 2004), reduced standing biomass (Olson-Rutz et al. 1996a), and a strong preference by pack stock for grasses over forbs (Olson-Rutz et al. 1996a). Ultimately, where conditions have been studied in wilderness, direct links that isolate effects of pack stock use can be difficult to identify because they are superimposed on the effects of earlier or, in some cases, on-going use.

Given the paucity of pack stock-specific literature, managers draw from relevant aspects of range science to develop management strategies for pack stock use of meadows. For example, in their summary and review, McClaran and Cole (1993) used information pertaining to livestock studies to infer pack stock effects and to develop recommendations for monitoring and management . Although many disturbance characteristics associated with livestock are similar to those of pack stock, we acknowledge potential differences in grazing behavior and duration/intensity of typical use patterns between pack stock and livestock that could influence effects. McClaran (2000) stated that differences in spatial use patterns between production livestock and recreational livestock (i.e., pack stock) can lead to substantial differences in effects that should be considered in management objectives and actions. This report is concerned with potential effects of free-range grazing by pack stock in meadows, but uses information reported from livestock studies where information from pack stock specific studies is lacking, to infer potential pack stock effects on the meadow processes and ecological function (Table 1-2).

Table 1-2. Corroborated and inferred relationships between pack stock use of meadows and the factors that drive processes associated with meadow condition. Note: "grazing activities" refers to the actions involving both herbage consumption and trampling.

Factor	Known or inferred relationship to pack stock use
Connectivity between surface water and groundwater	Trampling by stock can fragment sod, compact soil, shear streambanks and lakeshores, decrease vegetative cover and increase bare ground (Liddle 1975a, b, 1991). Soil compaction, in particular, reduces connectivity between surface and groundwater in meadows by lowering water infiltration rates and increasing runoff (McClaran and Cole 1993, Wheeler et al. 2002). Channel widening or streambank incision may result from grazing activities, lowering the meadow water table (Kauffman et al. 1983, Knapp and Matthews 1996, Kondolf et al. 1996, Belsky et al. 1999), thus reducing available water needed to sustain meadow plant communities. Channel widening or incision can result from bank loss caused directly by trampling (physical shearing), or from increased erosion potential due to soil disturbance, sod fragmentation, and reduction in the stabilizing vegetation on streambanks (Trimble and Mendel 1995). In addition, trailing through meadows and across streams may create preferential flow paths that can erode and deepen (Trimble and Mendel 1995), potentially forming headcuts and gullies that may further decrease groundwater holding potential and soil moisture (Ratliff 1985, Kattleman and Embury 1996, Stunk 2003).
Vegetation productivity	Depending on intensity and duration, grazing can reduce vegetation productivity, height, cover, and fecundity (Miller and Donart 1981, Edwards 1985, Stohlgren 1986, Olson-Rutz et al. 1996b, Fahnestock and Detling 2000, Cole et al. 2004). Trampling can produce similar results (Liddle 1975a, b, 1991, Cole 1995a) with the added effect of soil compaction that may inhibit root growth and water infiltration (Cole 1987, Gilman et al. 1987, Unger and Kaspar 1994, Pietola et al. 2005) and create anaerobic conditions that inhibit plant growth (Drew and Lynch 1980). Thus, both above- and below-ground productivity may decrease with grazing activities. Compensatory growth (i.e., increased productivity) can result from low grazing intensities (Stohlgren et al. 1989, Cole et al. 2004). Generally however, productivity declines with increased grazing pressure by pack stock based on experimental evidence from grazing and clipping treatments (Pond 1961, Stohlgren et al. 1989, Fahnestock and Detling 2000, Cole et al. 2004).
Sediment deposition	Literature has suggested that grazing activities can alter stream morphology and fluvial processes (Kaufman and Krueger 1984, Trimble and Mendel 1995), and thereby affect erosional and depositional processes. Grazing activities have been linked to increased sediment loading (Platts 1991) through physical disturbance of soils and vegetation removal (Kaufman and Krueger 1984). Shorter vegetation is less effective at entrapping debris, sediment, and nutrients (Clary et al. 1996). Thus, decreased vegetation cover, increased bare ground, and soil compaction could further contribute to sediment loading through augmented runoff and associated erosion.
Soil characteristics	Grazing activities have both direct and secondary effects on soils. Trampling directly compacts soils, and can thereby increase anaerobic conditions with secondary effects on soil chemistry, mineral solubility and transport (Lindsay 1979, Tiedje et al.1984). Trampling and grazing have been shown to decrease vegetation cover and increase bare ground (Miller and Donart 1981, Cole 1995a, Fahnestock and Detling 2000, Cole et al. 2004), which can ultimately result in soil loss since exposed soil is more susceptible to erosion (Smith and Weischmeier 1962, Morgan 1986). Furthermore, reduced vegetation cover or shifts in species composition could indirectly alter the rate of organic matter accumulation and nutrient dynamics in meadow soils.
Nutrient cycling, sequestration, and contribution	Grazing can redistribute nutrients at a site by removing vegetation from forage areas (i.e., meadows) and depositing manure and urine in resting areas that are often at the forest edges (Huber et al. 1995). Manure and urine input from livestock can relate to slightly increased levels of nitrate and ammonia in streams (Gary et al. 1983). These inputs have also been implicated as the potential cause for eutrophication of water bodies at livestock sites (Derlet et al. 2012). Furthermore, digested plant material (from manure) has more rapid nutrient turnover than what would occur in naturally senesced plant material (Chesson 1997). The reported effects of grazing, such as lower productivity, increased bare soil, species composition shifts, and increased soil compaction (see above), may affect nutrient cycling and sequestration by altering the type, amount, and availability of nutrients as well as the rate of return to soil through decomposition.

Table 1-2 (continued). Corroborated and inferred relationships between pack stock use of meadows and the factors that drive processes associated with meadow condition. Note: “grazing activities” refers to the actions involving both herbage consumption and trampling.

Factor	Known or inferred relationship to pack stock use
Resistance and resiliency to dynamic disturbance regimes	Reduction in vegetation productivity from grazing could slow recovery from disturbance, as indicated by observations of recovery in low productivity plant communities (Billings 1973, Webber and Ives 1978). Depending on the intensity and duration of grazing, selective preferences by grazers can alter plant competitive dynamics and lead to shifts in species composition (Magnusson and Magnusson 1994, Proulx and Maxumder 1998, Cole et al. 2004) that could have cascading effects on ecosystem resistance and resiliency to disturbances. Disturbance-favored and non-preferred species may increase through grazing activities, and these species could be insufficient to support meadow ecological function and ecosystem services in terms of soil stability, nutrient cycling, or habitat and forage for wildlife.

1.4 Meadow vulnerability to use-related disturbance

Vulnerability is an important concept that managers use to prioritize sites for protection in conservation planning. For example, Noss et al. (2002) developed vulnerability scores for land units being considered for protection, based on quantifying threats from nearby human populations and their projected growth trends (specifically urbanization, road construction, mining, logging and grazing). The concept of vulnerability can include more than quantifying obvious threats from disturbance, however; it can also attempt to quantify factors that affect ecosystem response to disturbance. This concept of vulnerability is often separated into the more specific components of resistance and resilience (Cole 1995b), where resistance refers to the ability of a system to resist change, and resilience refers to the ability of a system to recover following disturbance. Attributes that help explain variation among meadows in response to disturbance reflect resistance and resilience; these could be physical attributes such as elevation, geologic setting and soil moisture, or biotic attributes such as the composition or productivity of vegetation communities. For example, soil moisture may affect both resistance and resilience. Wet soils are less resistant to hoof impacts (Vallentine 1990), and a positive relationship between severity of cattle impacts (to vegetation and soil) and soil moisture has been noted (Clary 1995). However, soil moisture could also affect resilience due to differences in vegetation productivity for different meadow moisture types , with lower productivity implying a slower recovery rate (i.e., lower resilience). Meadow productivity is estimated to be lowest for dry meadows, approximately 60% lower than moist meadow productivity (Ratliff et al. 1987). Productivity is also inversely related to elevation in Sierra Nevada Meadows (Ratliff 1985, Ratliff et al. 1987), implying that resilience may decrease as elevation increases. Billings (1973) noted slower recovery from disturbance in alpine plant communities. Thus, although repeat monitoring would be necessary to directly quantify meadow resilience, quantifying attributes related to resistance/resilience and comparing them among sites can help inform management decisions on the type, amount, or timing of allowable use.

Meadows are often a mosaic of stream channels, riparian floodplains, wetlands, mesic, and upland herbaceous areas (Weixelman et al. 2011), all of which may respond differently to use-related disturbance. Therefore when assessing vulnerability at a meadow-wide scale, it is helpful to quantify the extent of such areas within this mosaic and consider the factors that contribute to the vulnerability inherent to each type. In addition, when evaluating vulnerability, managers may want to quantify the extent of area within meadows related to resources of special concern (such as archeological sites and rare or endangered species habitat). In Yosemite, the potential for use-related disturbance in high elevation wilderness meadows occurs mainly through pack stock use and human foot traffic. In alignment with the scope of this report, our assessment of meadow vulnerability (Table 1-3) is focused on physcial disturbance mechanisms associated with pack stock use, such as grazing, trampling, roll pits, and informal trails.

Table 1-3. Attributes contributing to meadow vulnerability to disturbance.

Attribute	Relationship to meadow vulnerability
Elevation	Vegetation productivity decreases with increasing elevation (Ratliff 1985, Ratliff et al. 1987). Productivity reflects the growth rate, amount of above- and belowground biomass, which can affect recovery from disturbance through mechanisms including soil stabilization and organic matter deposition. Low-productivity alpine communities and tundra are particularly slow to recover from use-related disturbance (Billings 1973, Webber and Ives 1978).
Slope	Increasing slope increases soil disturbance and vegetation damage from trampling, due to shear forces exerted at angles to the surface (Ratliff 1985). In addition, bare ground and soil loss could increase with slope (during disturbance), due to the greater erosive forces from runoff.
Streambank area	Grazing activities have been linked to physical disturbance of streambanks and associated stream processes that influence water availability in meadows (Trimble and Mendel 1995, Belsky et al. 1999), so the extent of stream present in a meadow can contribute to overall site vulnerability to trampling and grazing. Wet soils are more susceptible to hoof impacts (Vallentine 1990), and streambanks often remain wet long into the growing season. Once disturbed, streambanks are less resistant to erosion from the forces of stream flow and flooding.
Lakeshore area	Similar to streambanks, the wet banks along lake margins are more vulnerable to shearing and sloughing from hoof impacts, and can be subjected to the erosive forces from wave action or flooding. Human foot traffic often occurs along lake margins, causing compacted soil and informal trails. Trampling and trailing increases bare ground (Liddle 1975, Cole 1995a, Holmquist and Gengenbach 2008), providing more area susceptible to erosion. USFS (2003) included lakeshore presence and erodibility in quantifying site vulnerability for their assessment of wilderness meadow grazing suitability in the Inyo and Sierra National Forests.
Pond area	Ponds and pond margins are important habitat for various stages of Yosemite toads (Stebbins 2003), a species of special concern at Yosemite. Therefore, trampling of pond margins may be of particular concern. Any disturbance with potential for increasing sedimentation of ponds could reduce habitat quality and food sources such as algae, periphyton, and macroinvertebrates (Power 1990, Newcombe and MacDonald 1991).
Dry meadow area (UPL and FACU vegetation)	Vegetation productivity is lowest in dry meadow types, compared with mesic and wet meadow types and these sites tend to have lower species diversity (Ratliff 1985, Ratliff et al. 1987). Safford and Mallek (2011) discussed that species have varying tolerance to grazing disturbance, and reductions in diversity tends to be greater at more productive sites. Lower productivity and lower diversity translates to lower resilience from disturbance; once disturbed, dry meadow areas recover more slowly than their moist or wet counterparts. In addition, Cole et al. (2004) reported that pack stock grazing caused the greatest decreases in productivity for xeric shorthair sedge communities, compared with more mesic meadow types. This effect suggests that dry meadow areas are more vulnerable to decreases in productivity from high intensity grazing.
Wet meadow area (OBL vegetation)	Meadow soils are more susceptible to penetrating hoof impacts when wet (Vallentine 1990), so sites with extensive wet soils (i.e., a high proportion of wet meadow area) would be less resistant to effects from trampling such as soil shearing, compaction, and root severing. A dominance of obligate wetland plant species indicates perennially wet meadow types (Cowardin et al. 1979, Mitsch and Gosselink 2007), and these types have lower productivity than moist meadow types (Ratliff 1985, Ratliff et al. 1987). In addition to higher susceptibility to impacts, lower productivity implies that wet meadows may recover from disturbance slower than their moist counterparts. Fens are peat-forming wet meadows that provide particularly valuable ecosystem services such as carbon sequestration. Fens are thought to be particularly susceptible to impacts from stock use, with Sierra Nevada fens possibly exhibiting effects from heavy historic use (Cooper and Wolf 2006).

1.5 Management context: suitability for use and meadows-of-concern

Tools that prioritize sites for protection are common in conservation planning (Margules and Pressey 2000, Pressey and Cowling 2001, Noss et al. 2002). For example, Noss et al. (2002) rated sites for protection of threatened species habitat by quantifying vulnerability and “irreplaceability” (analagous to ecological condition) and assigning scores in these areas. Higher quality sites, in terms of ecological condition or habitat quality, rate higher in priority for protection, particularly in the face of higher vulnerability (Margules and Pressey 2000, Noss et al. 2002). We suggest quantifying suitability for use in a similar way, by identifying sites with high vulnerability and examining their relative ecological condition.

As one example of a possible application of results, we present an interpretation for relative suitability for pack stock use at these study sites by contrasting summary scores for ecological condition and vulnerability to disturbance. This example could be considered as one component of a more comprehensive management framework, that also incorporates trends in ecological condition over time, site-specific considerations for resources of special concern (i.e., cultural resources, threatened or endangered species , or their habitats), or other management objectives.

Examining suitability ratings in light of current information on amount of pack stock use and use-related disturbance for each site may help identify potential meadows-of-concern . For instance, a low-suitability meadow with currently high amounts of use or use-related disturbance may warrant management action such as more in-depth investigation and/or frequent monitoring to assess condition and trends, or use restrictions. It is important, however, to note that the suggested suitability and concern ratings in this report are based entirely on point-in-time surveys and the relative range of sites within these data sets. Therefore, these results provide relative comparisons among these 53 meadows only, under these conditions and current use patterns. We do not assume to have adequately captured the range of ecological condition or vulnerability of all meadows in the park, or to define thresholds for meadow suitability for use.

2. Methods

2.1 Study Area and Meadow Selection

This study took place at 53 meadows (sites) within the Merced and Tuolumne watersheds of Yosemite surveyed from 2008-2011 (Figures 2-1 and 2-2). Where possible, site names matched nearby place names from USGS topographic quadrangles, but in some cases, were modified to further depict location. For example, nomenclature used for multiple sites within the Lyell Fork of the Tuolumne River was based on relative position within the watershed (upper, middle, or lower) and was further modified when multiple meadows were in close proximity (i.e., Upper Lyell- South and Upper Lyell- North).

Study meadows were not randomly selected, but were chosen according to management needs and logistics such as timing and accessibility. Surveys in 2008 focused on comparing conditions in Tuolumne Watershed meadows for those sites receiving the most pack stock use with those sites receiving little to no stock use (Ballenger et al. 2010). Surveys efforts in 2009 expanded use-related disturbance monitoring to additional sites and initiated stream monitoring for meadows with a perennial stream. Surveys in 2010 included sites within the Merced Wild and Scenic River corridor, to provide baseline information on meadow condition for formal planning efforts. Surveys in 2011 added sites in the Tuolumne Watershed for assessing meadow condition that will help inform Yosemite's upcoming Wilderness Stewardship Plan.

A site fit our criteria for meadow if it comprised a meadow system dominated by herbaceous vegetation and had less than 50% collective cover of trees, shrubs, wood, and rock. We made no distinction among fens, marshes, wet, moist or dry meadows during data collection or analysis. Study sites included the entire meadow area. Sites ranged in size from 0.7 to 21.4 hectares (mean value 6.4; median value 4.2); data were slightly left-skewed, with the highest frequency (35 sites) ranging between 3.6 to 6.7 ha. Sites were located from 2,195 to 3,072m elevation (mean value 2,698m; median value 2,734m), based on the site centroid.

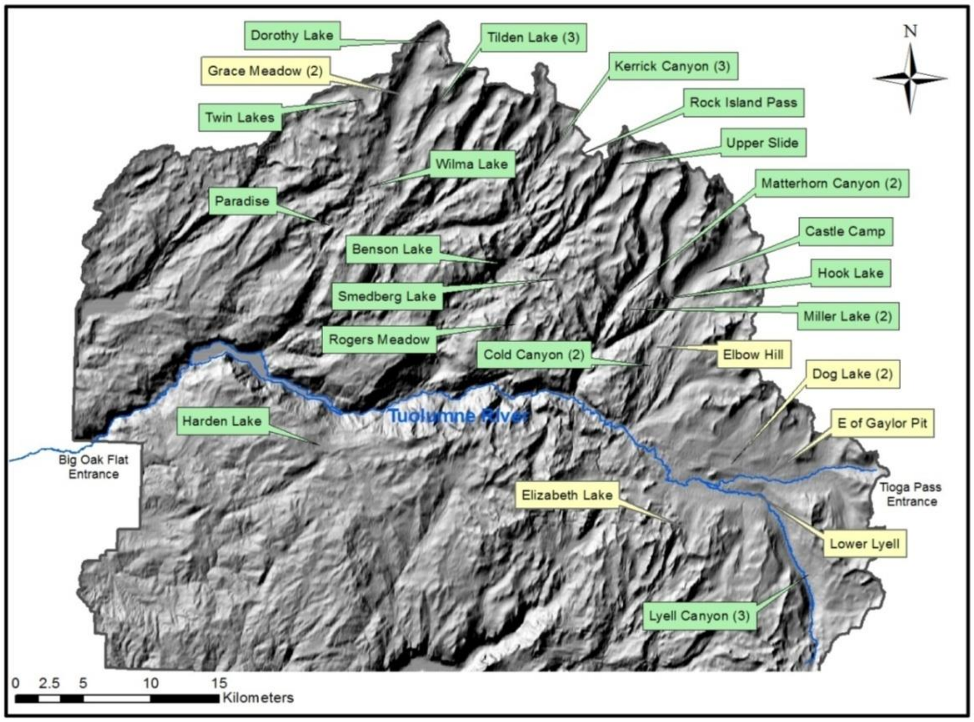


Figure 2-1. Locator map for study meadows in the Tuolumne Watershed of Yosemite National Park. Numbers in parentheses indicate the number of meadows when more than one polygon is present at a general location. Green labels indicate meadows with any reported stock use since 2004.

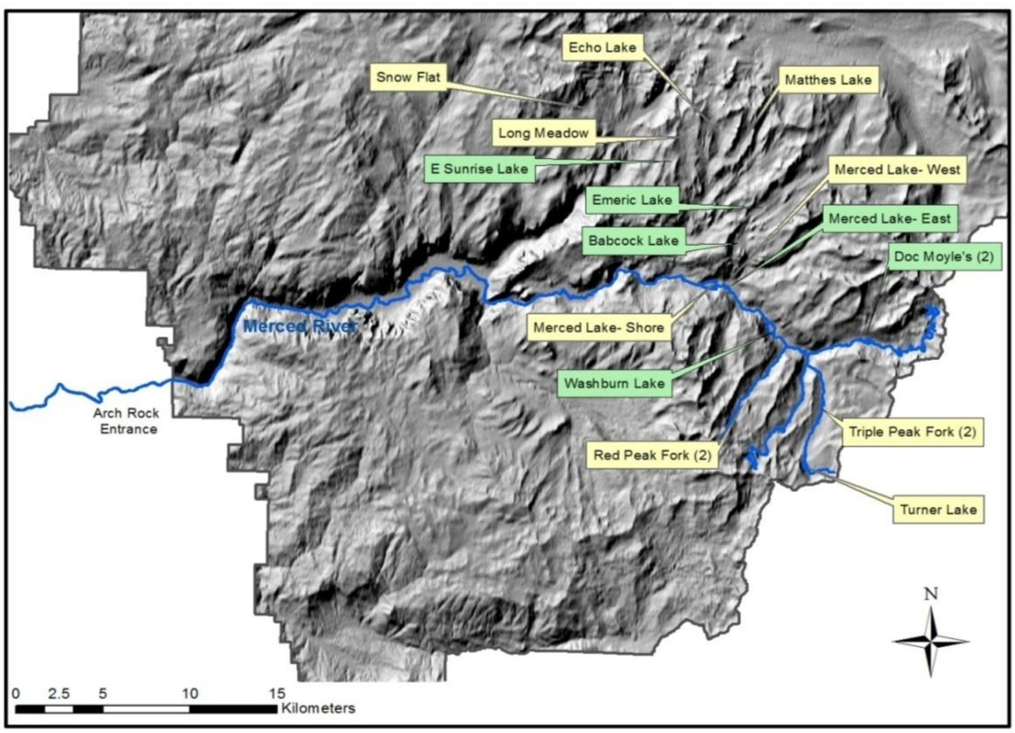


Figure 2-2. Locator map for study meadows in the Merced Watershed of Yosemite National Park. Numbers in parentheses indicate the number of meadows when more than one polygon is present at a general location. Green labels indicate meadows with any reported stock use since 2004.

2.2 Field sampling

We conducted multiple survey protocols between 2008 and 2011 at each site including gridpoint plot sampling, stream monitoring and use-related disturbance mapping (Table 2-1). All protocols were generally implemented between July and October, and on the same date when possible. Due to logistics or protocol constraints (i.e., stream monitoring required baseflow conditions), however, protocols were sometimes conducted during different years at the same site. We describe each protocol briefly in the sections below, and provide detailed descriptions or full survey protocols in Appendix A.

Table 2-1. Site coordinates, elevation, size, and year for protocol implementation. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Site locations and elevation are according to the site centroid; UTM coordinates are in NAD83 projection. Longitudinal gradient is the percent slope of a straight-line from the point of highest elevation in the meadow to the lowest; stream gradient is the percent slope of the stream (i.e., channel length) betweem the points that it enters and exits the meadow. “N/A” indicates meadows without perennial stream channel, “N/S” indicates meadows with channels that do not fit survey criteria, and blank cells indicate meadows with a perennial stream that have not been surveyed.

Site ID# and Name	Easting	Northing	Elev. (m)	Size (ha)	Longitudinal (Stream) Gradient (%)	Gridpoint plots	Use-rel. disturb.	Stream monit.
1 Babcock Lake	289004	4181911	2738	4.1	1.46 (N/A)	2010	2010	N/A
2 Doc Moyles-East	296474	4176074	2845	6.6	0.21 (0.19)	2010	2010	
3 Doc Moyles-West	296017	4176167	2836	2.8	1.49 (1.33)	2010	2010	2010
4 East Sunrise Lake	285066	4187009	2873	4.8	6.61 (N/A)	2008	2008	N/A
5 Echo Lake	287978	4188481	2852	7	2.71 (2.19)	2008	2008	
6 Emeric Lake	290212	4184049	2846	9.7	3.88 (2.38)	2009	2009	2010
7 Long Meadow	286060	4188200	2896	18.8	3.11 (2.88)	2008	2008	
8 Matthes Lake	289046	4187793	2938	12.9	2.3 (1.42)	2008	2008	
9 Merced Lk.-East	289055	4179088	2231	0.67	0.83 (N/A)	2011	2011	N/A
10 Merced Lk.-Shore	287688	4179479	2195	3.6	4.32 (N/A)	2010	2010	N/A
11 Merced Lk.-West	288400	4179609	2215	2	4.36 (N/A)	2010	2010	N/A
12 Red Peak-North	289879	4172239	2858	2.2	2.02 (1.41)	2010	2010	2010
13 Red Peak-South	288916	4171587	2894	3.7	1.01 (0.00)	2010	2010	N/S
14 Snow Flat	280382	4190163	2670	4	1.25 (1.35)	2008	2008	
15 Triple Peak-North	293891	4172275	2749	3.9	1.14 (0.98)	2010	2010	
16 Triple Peak-South	293567	4171164	2762	2	1.02 (0.1)	2010	2010	2010
17 Turner Lake	293070	4168240	2909	4.2	2.3 (1.49)	2010	2010	2010

Table 2-1 (continued). Site coordinates, elevation, size, and year for protocol implementation. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Site locations and elevation are according to the site centroid; UTM coordinates are in NAD83 projection. Longitudinal gradient is the percent slope of a straight-line from the point of highest elevation in the meadow to the lowest; stream gradient is the percent slope of the stream (i.e., channel length) between the points that it enters and exits the meadow. "N/A" indicates meadows without perennial stream channel, "N/S" indicates meadows with channels that do not fit survey criteria, and blank cells indicate meadows with a perennial stream that have not been surveyed.

Site ID# and Name	Easting	Northing	Elev. (m)	Size (ha)	Longitudinal (Stream) Gradient (%)	Gridpoint plots	Use-rel. disturb.	Stream monit.
18 Washburn Lake	291060	4176604	2318	2.9	1.23 (0.01)	2010	2010	N/S
19 Benson Lake	278355	4211211	2316	1.3	2.41 (N/A)	2008	2008	N/A
20 Castle Camp	293048	4210568	2673	2.9	2.26 (0.51)	2008	2008	2009
21 Cold Canyon	288707	4203720	2652	15.8	0.65 (0.53)	2008	2008	2011
22 Cold Canyon- North	289091	4204657	2658	9.1	0.66 (0.56)	2011	2011	
23 Dog Lake	294580	4196316	2795	3.2	1.75 (1.6)	2008	2008	N/S
24 Dog Lake East	295398	4195968	2816	1.9	0.33 (0.28)	2008	2008	N/S
25 Dorothy Lake	272716	4228245	2865	8	0.17 (N/A)	2008	2008	N/A
26 East of Gaylor Pit	297688	4195190	2841	2.8	3.32 (1.98)	2008	2008	2011
27 Elbow Hill	289446	4205358	2658	1.5	0.4 (N/A)	2011	2011	N/A
28 Elizabeth Lake	291689	4191420	2890	11.4	4.53 (4.07)	2008	2008	
29 Grace Meadows	270705	4224444	2646	17.4	1.16 (0.89)	2011	2011	2011
30 Grace North	270978	4225293	2658	1.3	0.52 (N/A)	2011	2011	N/A
31 Harden Lake	264479	4197509	2280	3.2	0.35 (N/A)	2011	2011	N/A
32 Hook Lake	288692	4208425	2865	3.4	1.34 (N/A)	2008	2008	N/A
33 Jose's Camp	279407	4215390	2755	4.1	5.52 (2.57)	2011	2011	
34 Lower Kerrick	280082	4216271	2560	12.7	0.93 (0.82)	2010	2010	2011

Table 2-1 (continued). Site coordinates, elevation, size, and year for protocol implementation. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Site locations and elevation are according to the site centroid; UTM coordinates are in NAD83 projection. Longitudinal gradient is the percent slope of a straight-line from the point of highest elevation in the meadow to the lowest; stream gradient is the percent slope of the stream (i.e., channel length) between the points that it enters and exits the meadow. "N/A" indicates meadows without perennial stream channel, "N/S" indicates meadows with channels that do not fit survey criteria, and blank cells indicate meadows with a perennial stream that have not been surveyed.

Site ID# and Name	Easting	Northing	Elev. (m)	Size (ha)	Longitudinal (Stream) Gradient (%)	Gridpoint plots	Use-rel. disturb.	Stream monit.
35 Lower Lyell	296404	4193661	2658	5.9	5.23 (0.00)	2008	2008	N/S
36 Matterhorn Canyon	287195	4209190	2569	10.2	0.41 (0.07)	2008	2008	2010
37 Middle Lyell	299604	4188795	2719	6.1	0.86 (0.82)	2011	2011	2011
38 Miller Lake-North	287621	4208020	2887	4.2	3.48 (N/A)	2008	2008	N/A
39 Miller Lake-South	287292	4207487	2896	3.68	4.83 (N/A)	2008	2008	N/A
40 Paradise	265347	4214244	2341	5.53	0.17 (0.15)	2011	2011	
41 Rock Island Pass	283712	4219453	3072	6.5	10.78 (N/A)	2011	2011	N/A
42 Rodgers Meadow	278938	4206837	2670	15.5	0.84 (0.65)	2011	2011	2011
43 S of Matterhorn	282024	4210104	2579	2	0.83 (N/A)	2008	2008	N/A
44 Smedberg Lake	286407	4207727	2810	4.6	1.39 (1.19)	2008	2008	2011
45 Tilden Lake North	272645	4221957	2731	7.8	1.14 (0.98)	2008	2008	
46 Tilden Lake South	273056	4222497	2713	4.7	0.49 (N/A)	2008	2008	N/A
47 Twin Lakes	267641	4223792	2719	2.7	3.1 (3.0)	2011	2011	2011
48 Upper Kerrick	282509	4221912	2835	21	1.39 (1.27)	2008	2008	
49 Upper Lyell- North	300749	4186397	2734	8.1	0.13 (0.13)	2008	2008	2010
50 Upper Lyell- South	300904	4185452	2734	14.7	0.37 (0.2)	2008	2008	2009
51 Upper Slide	286665	4218747	2792	4.6	0.86 (0.68)	2011	2011	2011
52 W of Tilden	270013	4221584	2542	5.9	1.41 (1.21)	2008	2008	2011

Table 2-1 (continued). Site coordinates, elevation, size, and year for protocol implementation. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Site locations and elevation are according to the site centroid; UTM coordinates are in NAD83 projection. Longitudinal gradient is the percent slope of a straight-line from the point of highest elevation in the meadow to the lowest; stream gradient is the percent slope of the stream (i.e., channel length) between the points that it enters and exits the meadow. "N/A" indicates meadows without perennial stream channel, "N/S" indicates meadows with channels that do not fit survey criteria, and blank cells indicate meadows with a perennial stream that have not been surveyed.

Site ID# and Name	Easting	Northing	Elev. (m)	Size (ha)	Longitudinal (Stream) Gradient (%)	Gridpoint plots	Use-rel. disturb.	Stream monit.
53 Wilma Lake	268128	4217106	2422	1.9	0.02 (N/A)	2011	2011	N/A

2.2.1 Gridpoint plots

Using GIS software, we generated regularly-spaced sample locations (gridpoints). Due to available sample time constraints, larger meadows were surveyed at wider spacing (i.e., 30m grid spacing), while smaller meadows were surveyed at tighter spacing (i.e. 20m). Using a GPS unit, we navigated to each gridpoint and established a 5x5m plot for data collection including vegetation cover and height, plant community type, cover for dominant plant species, litter depth, ground cover (i.e., bare ground, litter and moss), and disturbance features (i.e. pack stock sign). We recorded most data as ocular estimates of absolute cover, using cover classes in 10-percent increments except at the low end, where we recorded cover in finer detail (See Appendix A, Table A-2). To summarize certain metrics (such as vegetation cover, bare ground) we calculated the mean percent cover for each meadow. Other metrics required an analysis of species composition, i.e., a measure of the relative proportions of individual species to the total vegetative composition at each meadow. To calculate species percent composition, we summed the percent cover of each species for all plots at a meadow, divided by the total cover of all species recorded for all plots. We crosswalked species to their wetland ratings (U.S. Army Corps of Engineers 1996, NRCS 2006) and seral state categories (U.S. Forest Service 2009) to calculate an estimated proportion of meadow dominated by obligate wetland plants (OBL), upland (UPL) and facultative upland plants (FACU), as well as early, mid, and late seral vegetation.

We collected gridpoint plot data in two major sampling efforts (2008 and 2010-2011) with two different field crews, and methods for estimating cover evolved slightly between the two efforts. These modifications resulted in inherent differences in percent cover data for total vegetation and bare ground between the two sampling efforts. To standardize cover estimates across years for this report, we applied a correction factor to the vegetation cover and bare ground cover data for 2008. We determined the correction factor by comparing differences in total vegetation and bare ground cover for the most common plant communities (greater than 15 gridpoint plots) across all meadows sampled in 2008 with those communities sampled in 2010-2011. See Appendix B for more detail on this correction for vegetation and bare ground cover among years.

2.2.2 Stream monitoring

To further assess conditions of those meadows with a perennial stream, we initiated the Multiple Indicator Monitoring protocol (MIM; Burton et al. 2011) as a pilot protocol in 2009 and fully adopted as a monitoring program in 2010. These data were collected at 19 sites. Twenty-one sites lack defined stream channels, and surveys were not conducted at 13 potential sites due to logistical constraints (i.e., available staff time). Monitoring was typically conducted during the baseflow season (i.e., September and October).

The MIM protocol facilitates data collection for several metrics of the biological and physical conditions of streambanks. We collected vegetation data and information about bank stability in eighty 20 x 50 cm plots along the greenline of each bank. Plot interval was evenly-spaced, with spacing determined according to mean channel width. Among the suite of metrics assessed on the streambanks, we selected the following to include for this report: ecological status (i.e., seral state), relative cover of upland species, shade index, vegetation biomass, and streambank stability rating. We determined vegetation cover by relative ocular estimates for all plant species with ≥10% cover. We summarized data for each meadow site by calculating mean values for ecological status, shade, and streambank stability across all plots at a given meadow. Cover of upland species was calculated as relative to total vegetation cover for all species. Additional details are provided in Appendix A and the MIM technical reference (Burton et al. 2011).

2.2.3 Use-related disturbance mapping

Montioring was typically conducted after the majority of pack stock use had occurred (i.e., September and October) for that year. Field staff walked the entire area of each meadow and used a GPS unit to map and recorded information on all use-related disturbance features, including hoof punches, roll pits, trampled or grazed areas, and features such as informal trails. Additionally we mapped other features of interest that could aid in characterization of meadow condition and/or vulnerability, such as ponds, bare ground areas (greater than $10m^2$), and headcuts. Features within 25m of the GIS meadow boundary (derived from the 1997 Yosemite vegetation map) were included because of imprecision in delineating meadow boundaries and the potential for adjacent disturbance to affect meadows. We did not attempt to differentiate the age of disturbance features (i.e., all observable disturbance features were recorded whether they occurred within, or prior to, the survey year). To summarize data from this protocol, we divided the summed area of each feature type by meadow size (as defined by the GIS meadow boundary), to normalize for meadow area.

2.3 Data Analysis Procedures

2.3.1 Overview

This subsection provides a brief outline of the steps used to assess these data; detailed descriptions of procedures follow in the succeeding subsections. For these analyses, we typically employed multivariate approaches, such as principal component analyses and model selection techniques, to infer relationships within these complex ecosystems; analyses using single metrics can fail to adequately capture patterns and interactions within the data set (see Karr and Chu 1997).

To achieve the first objective of comparative meadow rankings for ecological condition, vulnerability, and use-related disturbance, we developed summary scores for each of these assessment categories. We first classified metrics from the field protocols and spatial data sets for each assessment category, and conducted principal component analyses (PCA) and linear regression on the observed data for each category. Based on analysis results, we selected a subset of metrics to reduce correlation among metrics. We then calculated relativized scores for each selected metric at each site, and summed relativized scores into summary scores for each assessment category at each site. Lastly, we ranked sites relative to all other sites by summary scores for each assessment category, and delineated low and high ratings based on the 10th and 90th percentiles for the ranges of scores.

To fulfill the second objective, evaluate potential meadow response to stock use, we used model selection to explore simple and parsimonious multivariate linear relationships between summary scores, select metric scores, and stock use numbers. We used Akaike Information Criterion (AIC) to identify the best-fit model to predict response variables, including meadow and stream ecological condition summary scores, relativized scores for percent bare ground, and relativized scores for streambank stability. Combinations of predictor variables used in the tested models included: reported amount of stock use, use-related disturbance summary score, vulnerability to disturbance summary score, and relativized scores for individual metrics within vulnerability and disturbance assessment categories.

Lastly, for the objective of illustrating a potential management application of these results, we plotted summary scores for meadow ecological condition and vulnerability to disturbance, and suggest categories of meadow suitability for use based the 10th and 90th percentiles. In addition, we identified meadows-of-concern and meadows of potential concern based on the suggested suitability for use ratings in context with use-related disturbance scores and reported stock use levels.

2.3.2 Metrics and Assessment Categories

We classified metrics from the field survey protocols into each assessment category—ecological condition for meadows and meadow streambanks (Table 2-2), vulnerability to use-related disturbance (Table 2-3), and use-related disturbance (Table 2-4). We incorporated additional metrics into the vulnerability to disturbance category through use of GIS and various spatial data sets for elevation, slope, streambank area, and lakeshore area.

Table 2-2. Metrics comprising the meadow ecological condition assessment category.

Metrics for ecological condition of meadows	
Metric name (abbreviation)	**Definition**
Bare ground cover (PercBG)*	Mean percent cover of bare ground per 5x5m gridpoint plot, from ocular estimates. Bare ground was defined as exposed soil (including ground beneath plant canopies) not covered by litter, moss, rock, wood, or plant stems. It included gravel less than 1cm diameter. Note: bare ground is not the inverse of basal vegetation cover, as substrate also includes litter, rock, wood, and moss.
Total vegetation cover (TotVegCvr)	Mean percent foliar cover of all vascular plant species per 5x5m gridpoint plot, from ocular estimates. This could not exceed 100% and did not account for layered vegetation. Desiccated or senesced vegetation at the end of the season was visualized in live condition (i.e., with leaves fully expanded).

Table 2-2 (continued). Metrics comprising the meadow ecological condition assessment category.

Metrics for ecological condition of meadows	
Metric name (abbreviation)	**Definition**
Late seral species cover (LateSer)	Relative percent composition of dominant plant species classified as late seral (US Forest Service 2009), from gridpoint plots. Note: this is not the inverse of percent cover early seral species, since many species are classified as mid seral.
Early seral species cover (EarlSer)*	Relative percent composition of dominant plant species classified as early seral (US Forest Service 2009), from gridpoint plots. Note: this is not the inverse of percent cover of late seral species, since many species are classified as mid seral.
Litter depth (LitDpth)	Mean litter depth from all gridpoint plot measurements (i.e., two measurements per plot). Litter included all ground-level plant material that was dead before the current year's growing season, either detached or present in the form of thatch (in perennial graminoid communities). It did not include moss, wood, or rock. Litter measurement in plots covered by shallow water were problematic due to floating litter; therefore litter values from inundated plots were discarded from this analysis.
Metrics for ecological condition of streambanks within meadows	
Ecological status (EcolStat)	Mean of ecological status (Winward 2000), or seral state, for species in greenline vegetation plots weighted according to their relative percent composition and seral state (Burton et al. 2011). Late seral species are double weighted. Seral state is compared to the expected potential natural community (Burton et al. 2011), based on Winward's riparian capability groups (Winward 2000) for site slope, substrate, and potential for rhizomatous woody species.
Upland species cover (FacUpl_S)*	Relative percent composition of species in greenline vegetation plots classified as upland (UPL) or facultative upland (FACU) from greenline vegetation plots, using wetland species ratings (U.S. Army Corps of Engineers 1996). This could not exceed 100% and did not account for layered vegetation. Only species comprising 10% or greater absolute foliar cover were recorded.
Vegetation biomass (VegBiom)	Estimated total biomass of vegetation along the greenline (Burton et al. 2011), calculated as the site mean of the following sums for each plot: the average stubble height of preferred forage species by relative percent composition, the mean height of woody vegetation by percent composition, and the mean cover.
Shade index (ShadInd)	The mean height of all woody species along the greenline divided by the mean channel width (Burton et al. 2011).
Streambank stability rating (StrmStab)	Mean value of estimated streambank stability ratings for greenline plots (Burton et al. 2011). Ratings are based on the combination of the presence or absence of depositional or erosional habitat types, erosional features (slump, slough block, fracture, active erosion), and the presence or absence of at least 50% vegetative cover.
* Denotes metrics where higher values suggest lower ecological condition.	

Table 2-3. Metrics comprising the vulnerability to disturbance assessment category.

Metrics for meadow vulnerability to disturbance	
Metric name (abbreviation)	**Definition**
Elevation (Elev)	Elevation, in meters, of the meadow centroid. We obtained this measure through GIS analysis of meadow polygons from the 1997 vegetation map of Yosemite National Park.
Slope	Mean percent slope, calculated through GIS analysis of meadow polygons based on digital elevation maps assembled from 10m resolution LiDAR data.
Streambank area (StrmArea)	Percent of meadow area occupied by the banks of a perennial stream. This measure was obtained in GIS by applying a 2m buffer to the stream centerline, for the length of stream within each meadow. The 2m buffer area approximates a bank width of 1m on each side of the stream.
Lakeshore area (LakeArea)	Percent of meadow area occupied by lakeshore. This measure was obtained in GIS by buffering a 1m area from edge of the meadow that intersects with a lake (i.e., permanent water body >1ha, usually having a name on USGS 7.5 minute maps.)

Table 2-3 (continued). Metrics comprising the vulnerability to disturbance assessment category.

Metrics for meadow vulnerability to disturbance	
Metric name (abbreviation)	**Definition**
Pond area (PondArea)	Percent of meadow area occupied by ponds, defined as shallow water bodies at least $10m^2$, having observable banks and containing water for most of the growing season. Amphibians may or may not be present, though some may represent suitable breeding habitat. Ponds were mapped with GPS in the field.
Dry meadow area (FACUPL)	Using vegetation as a surrogate for underlying soil moisture, this metric is the relative percent composition of dominant species classified as upland (UPL) or facultative upland (FACU; U.S. Army Corps of Engineers 1996) for each meadow, from gridpoint plots. Note: this is not the inverse of percent cover of obligate (OBL) species, since vegetation may also be classified as facultative (FAC) or facultative wet (FACW).
Wet meadow area (OBL)	Using vegetation as a surrogate for underlying soil moisture, this metric is the relative percent composition of dominant species classified as obligate wetland (OBL; U.S. Army Corps of Engineers 1996) for each meadow, from gridpoint plots. Note: this is not the inverse of percent cover or FACU or UPL species, since vegetation may also be classified as FAC of FACW.

Table 2-4. Metrics comprising the use-related disturbance assessment category.

Metrics for use-related disturbance of meadows	
Metric name (abbreviation)	**Definition**
Formal trails (FrmTrl)	Percent meadow area occupied by formal hiking trails (those depicted on USGS 7.5 minute quad maps). This measure was calculated though GIS analysis of trails and meadow polygon shapefiles, and assumed a 1m width for trails.
Informal trails (InfTrl)	Percent of meadow occupied by informal trails. Informal trails were defined according to the Visitor Use Impacts Monitoring Program protocols (Yosemite National Park 2009), as being discernible trail segments 7m or greater in length. We assumed a 0.5m width for informal trails when calculating trail area.
Trampled areas (Tramp)	Percent of meadow area mapped during the most recent late-season survey as trampled by pack stock. Trampled areas were at least $5m^2$ with multiple hoof punches, usually overlapping, often giving the ground a churned appearance.
Roll pits (RollPit)	Percent meadow area mapped as roll pits during the most recent late-season survey. Roll pits were disturbed areas of bare ground at least $10m^{2,}$ usually with a dished appearance, created by pack stock rolling or taking “dirt baths.”
Meadow fire rings (FireRings)	The number of separate (>25m apart) fire rings divided by meadow area. Fire rings were within the meadow polygon or within 25m outside the polygon boundary, and included both old fire rings and those showing signs of current use. In addition to the disturbance of a fire pit, this metric also points to areas with greater potential for trampling impacts from localized use by campers and stock.

2.3.3 Correlation among Metrics for Assessment Categories

We conducted PCA on observed values for all metrics within each assessment category, to identify correlated metrics. Correlation, in this case, reflects the redundancy among the metrics in terms of their explanatory power for the structure of the data within each category. The goal of PCA is to reduce redundancy within the dataset but maintain the original structure of the data to the greatest extent possible. In addition, we complimented the PCA with linear regressions of all pairwise combinations of metrics from within each category. Ultimately, where analyses indicated potential correlation among metrics, we chose to reduce the number of metrics included in calculations for site summary scores by excluding select metrics. Selections were based on the strength of correlation of metrics to the principal components, linear regression results, ubiquity of occurrence (i.e. for use-related disturbance features), and professional judgment. For each analysis, we used R statistical software (R Development Core Team 2008).

PCA evaluates the internal structure of multi-dimensional data sets (i.e., each metric represents a dimension) and displays data along the two orthogonal vectors, principal component one and two (PC1; PC2), that exhibit the greatest explanatory power for variance within the data set. Strength of correlation of each metric to each principal component is reflected by loading values (i.e., high loading values indicate that the metric has a strong common relationship with that component) and displayed as eigenvectors (i.e., length and trajectory are represented by arrows on PCA figures). The first component has the greatest explanatory power for variation in the data; thus, metrics with high loading values for principal component one have the greatest explanatory power. Each subsequent component has increasingly less explanatory power, as do those variables correlated with each successive component. Important aspects of the PCA results include: the distribution of sites relative to each eigenvectors (i.e., shown as site numbers and arrows for each metric, on PCA scatterplots); the percent of variance explained by PC1 and PC2, and; correlation of the eignenvectors for each metric to each principal component (i.e., loading values).

We used linear regression to further evaluate results inferred from PCA, and to understand basic relationships of metrics within each assessment category. Results from linear regression indicate whether the correlation is significant at an alpha level of 0.05. For each pairwise combination, we used traditional hypothesis testing relative to a null model suggesting no relationship, and where resultant p-values were equal to or greater than 0.05, we failed to reject the null. Assumptions of linear regression were evaluated by assessment of diagnostic plots prior to testing; comments in the Results section indicate when these plots suggest concerns for non-constant variance or non-linearity; such concerns could indicate variablilty in the goodness of fit of a model across the range of observed values (i.e., confidence in the observed relationship varies for different values of the x-axis), or could indicate a lack of fit to linear models.

In addition, we sought to assess effects of potential outlying values for each metric on PCA and linear regression results. For this, we used 3 standard deviations from the mean of each metric as a threshold to identify potential outliers. We ran separate analyses with and without these values and found consistent results from PCA, and only slight differences in linear relationships. Thus, we focus these analyses on the full data sets, and note where results for the inclusion or exclusion of outliers were inconsistent.

2.3.4 Calculating Relativized Metric Scores and Site Summary Scores

We calculated relativized scores for each metric by converting the observed values for a given site to a percent of the maximum value among all sites (McCune and Grace 2002). Relativized scores, therefore, range between 0 and 100%. To calculate relativized scores, we used the maximum observed value within 3 standard deviations of (i.e., above or below) the mean for each metric. This approach facilitated identification of atypical values within each data set that could have a disproportionate effect on relativized scores for all other sites by concentrating these values near the origin. This approach created a greater level of differentiation in metric scores for the majority of sites in the data sets. Burton and Gerritsen (2003) applied a similar approach to identify and address the effects of atypical maximum values for multimetric measures quantifying stream conditions. Nonetheless, sites with such atypical values are noteworthy and illustrate the possible range of conditions for the metrics. Rather than excluding sites with identified outlier values from subsequent calculation of summary scores, we assigned the minimum or maximum relativized score (i.e., 0 or

100%, depending on whether the value was above or below the threshold of three standard deviations) for that metric, thereby retaining these sites in datasets for analyses.

Summary scores are the sum of relativized scores for the selected metrics from each assessment category, and were calculated such that higher scores reflect higher ecological condition, greater vulnerability to disturbance, or greater amounts of use-related disturbance. For metrics that were converse to summary scores (i.e., metrics where higher values indicated lower ecological condition or vulnerability), we inverted the relativized score by subtracting the calculated score from 100%, before calculating summary scores. For example, the metrics bare ground cover and early seral vegetation are converse to higher meadow ecological condition, and were therefore inverted prior to their inclusion within calculations for meadow ecological condition summary scores.

All metrics were equally weighted except in the vulnerability to disturbance category, where score for wet meadow area was doubled. We chose to double-weight wet meadow area because of its importance in reflecting greater susceptibility to use-related disturbance and to emphasize the the potential presence of fens, as a resource of special concern (see Table 1-3, above). In addition, rather than attempting to quantitatively combine meadow ecological condition with streambank ecological condition, we only qualitatively infer whether streambank conditions would prompt a positive or negative change on meadow suitability for use. We used the 10^{th} and 90^{th} percentiles of streambank ecological condition scores to infer a positive or negative influence on meadow ecological condition score.

2.3.5 Meadow Response—Relationships among Metrics, Summary Scores, & Pack Stock Use

We used model selection based on the Akaike Information Criterion (AIC) to investigate potential meadow response—in terms of meadow ecological condition, streambank ecological condition, bare ground cover, and streambank stability—to use-related disturbance, and to reported stock use. We used R statistical software (R Development Core Team 2008) for each analysis. Model selection results are based on the strength of evidence for each model, are not restricted to specified levels of significance (Anderson et al. 2000; Anderson and Burnham 2002).

We conducted separate tests to predict each of four response variables, including summary scores for the ecological condition of meadows and streambanks, as well as relativized scores of bare ground cover and streambank stability, because of their potential utility as rapid survey indicators for ecological condition (Table 2-5). Predictor variables used in the tested models include: reported level of stock use (Table 2-6), use-related disturbance summary score, vulnerability to disturbance summary score, and relativized scores for individual metrics within the vulnerability or disturbance assessment categories. We included models for interactions among certain predictor variables to test if meadow response varied by site vulnerability or select ecological condition metrics.

Table 2-5. List of predictor variables used for linear regression models evaluated with AIC for relative goodness of fit to response variables**.** Separate tests were conducted to predict each of four response variables including: meadow ecological condition summary scores, streambank ecological condition summary scores, observed values for bare ground cover, and observed values for streambank stability. For each test, the primary (main) effects and interactions were tested as separate predictor models. Additional models tested for bare ground cover and streambank stability are noted.

Response Variables*	Primary effect	**Interaction** Term 1	Interaction Term 2
Meadow ecological condition **Stream ecological condition** **Bare ground**** **Streambank stability*****	StkUseMax	Vulnerability Score	
	StkUseCurr	Vulnerability Score	
	StkUsePrev	Vulnerability Score	
	StkUseMean	Vulnerability Score	
	StkUseMaxArea	Vulnerability Score	
	StkUseCurrArea	Vulnerability Score	
	StkUsePrevArea	Vulnerability Score	
	StkUseMeanArea	Vulnerability Score	
	Disturbance Score	Vulnerability Score	
	Formal trails		
	Fire Rings		
	Informal trails	Vulnerability Score	Formal trails
	Elevation		
	Vulnerability Score		

*Each predictor model (primary effect and interaction terms) was tested to evaluate goodness of fit to each individual response variable.
**Two additional predictor models were tested for Bare ground response variable, including: EarlSer (primary effect) and Informal Trails (interaction term 1), and; Fire Rings (primary effect) and Early Seral (interaction term 1).
***Two additional predictor models were tested for Streambank stability response variable, including: FacUpl_S (primary effect) and Informal Trails (interaction term 1), and; VegBiom (primary effect) and Informal Trails (interaction term 1).

Predictor variables for reported stock use include: current year (i.e., year of survey), previous year (i.e., year prior to survey), maximum annual use, and average annual use (Table 2-6). In addition, we also tested metrics for use level per unit area (nights per hectare) by dividing reported use level by meadow area.

Table 2-6. Variables quantifying pack stock use for regression analyses. Note: “SUN” is an abbreviation for “stock use nights.”

Variable (abbreviation)	Definition
Total stock use (TotStkUse)	Total sum of annual SUN for the years 2004-2011.
Mean stock use (MnStkUse)	Average annual SUN for the years 2004-2011.
Maximum stock use (MxStkUse)	Maximum annual SUN reported for any year between 2004-2011
Previous stock use (PrevStkUse)	Total annual SUN for the year prior to survey data collection (i.e., the year for this metric is site-specific, dependent on when meadow was surveyed)
Current stock use (CurrStkUse)	Total annual SUN for the same year as the survey data collection (i.e., the year for this metric is site-specific, dependent on when meadow was surveyed)
Use/hectare (StkUse…Area)	All above metrics were divided by meadow area, for AIC regression analyses.

We standardized observed values such that they reflected the number of standard deviations from the mean for each predictor variable to facilitate direct comparison of the influence of predictor variables. Variables were standardized by $[x - \mu_x]/sd_x$; where x is observed value for a given metric, μ_x is the mean of observed values for that metric, and sd_x is a single standard deviation from the mean of the observed values for that metric. For each test, we used a null model indicating no relationship among predictor variables and response variables, and models implying that the slope of the true relationship within the data set is influenced by the predictor variables.

For each test, the best model is the model that explains variation in the response variable while using the fewest predictor variables. Akaike's Information Criterion, AIC, is a metric used in model selection to rank models (Anderson and Burnham 2002). Differences among the best fit model and subsequent models is reflected in ΔAICc values (note: AICc is AIC adjusted for finite sample sizes), where, $\Delta AICc = AIC_i - AIC_{min}$. We report results according to Anderson et al. (2001) where: the best model has the lowest AICc; substantial support, in terms of strength of evidence, for models with ΔAICc <2, and; substantially less support for those models with ΔAICc values from 3-7. We also report Akaike weights (w_i; $w_i = e^{(-0.5*\Delta AICc)}$), which we used to calculate strength of evidence ratios (i.e. w_i/w_i) for the relative likelihood of one model to another (Anderson et al. 2001).

In addition, we report 95% confidence intervals for regression coefficients in models with substantial support (i.e., those models with ΔAICc <2). We assess the relative importance of each predictor variable in two ways: 1) the ranking of the models that include the covariate, and 2) the magnitude of the estimated regression coefficient for slope (slope estimate) and its 95% confidence interval. The sign of the slope estimate indicates a positive or negative relationship among the predictor and response variables. When resulting confidence intervals around the slope estimates for predictor variables do not include zero, we conclude that there is stronger support for the positive or negative correlation with the response variable. In addition, narrow confidence intervals infer greater precision around the slope estimate.

Lastly, we describe potential issues regarding non-constant variance and normality from visual assessment of diagnostic plots—plots of residuals by fitted values and quantile by quantile plots (Q-Q plots), not shown—for each best fit model. Non-constant variance and normality of residuals are two important assumptions for linear regression, and violation of those assumptions compromises inference. Based on these plots, where possible, we also note which sites exhibit disproportionate influence on the fit of the model and suggest possible interprations for potenital future data investigations.

Reported stock use levels were obtained from Wilderness Office records (accessed December 10, 2011) for overnight pack stock use from 2004-2011 that included commercial use since 2004 and administrative use since 2006 (Table 2-7). Stock use numbers are expressed as units of stock nights (SUN), equivalent to one night of grazing by one horse or mule. For example, a party with two horses and eight mules spending two nights at a meadow would equal 20SUN. Use level was not evenly distributed among sites; thirty sites have stock use reported annually since 2004, with amounts varying widely among sites. Although almost half of the sites (23) have no reported stock use since 2004, many likely received historic use by pack stock and/or livestock (Sharsmith 1961). They may have also received use by private parties, or adminstrative use prior to 2006.

Despite efforts by the Wilderness Office to track overnight pack stock use at Yosemite, many uncertainties exist in this data set, for a variety of reasons. First, general place names reported by pack stock users are often imprecise and could refer to many meadow sites within a general area. For example, several stock camps are located in the Lyell Fork of the Tuolumne River, so when use is reported for "Lyell Canyon", we are unable to discern which meadow received use. Secondly, at meadows surrounded by forest with an herbaceous understory, grazing activity commonly occurs outside the meadow, particularly once preferred forage species in the meadow have been grazed. This is the case at Castle Camp and Benson Lake, with use likely dispersed between meadow and forest understory. Stock use by private parties is not included in the compiled stock use records at Yosemite, and while it only comprises 5% of overall stock use park-wide (Acree et al. 2010), it may be a substantial proportion of use at some meadows. Finally, uncertainties exist for meadows where no stock use was reported but stock use signs such as manure and hoof punches were present at the site, along with signs that stock had been kept at a nearby campsite; this was the case for E Sunrise Lake, Long Meadow, Triple Peak- South, Turner Lake, and W of Tilden. These meadows could be receiving use from day rides, private stock parties, or unreported use. Efforts to improve the accuracy of stock use reporting in the park are continuing; this study relies on the best currently available information.

Table 2-7. Reported annual stock use from 2004-2011 (in units of stock nights) for study meadows**.** Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Meadows in bold have uncertainties regarding accuracy of use numbers. "NR"= none reported. Shaded cells indicate year(s) for data collection. Use ratings are based on maximum number of stock nights from 2004-2011. Categories are: Very High= >150, High= 75-150, Moderate= 25-74, Low= 1-24, and None= 0 or "NR" (none recorded).

Site Name	2004	2005	2006	2007	2008	2009	2010	2011	Mean*	Max*	Use rating
1-Babcock Lake	0	36	0	20	0	14	0	6	11.7	36	Moderate
2-Doc Moyle's- East	19	8	0	41	0	0	6	29	11.3	41	Moderate
3-Doc Moyle's- West	19	8	0	41	0	0	6	29	11.3	41	Moderate
4-E Sunrise Lake	0	25	0	0	0	0	56	26	6.3	25	Moderate
5-Echo Lake	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
6-Emeric Lake	135	104	85	66	48	78	72	123	86.0	135	High
7-Long Meadow	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
8-Matthes Lake	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
9-Merced Lake- East	27	24	36	374	124	438	328	108	170.	438	Very high
10-Merced Lake- Shore	0	0	0	0	0	0	0	0	0	0	None
11-Merced Lake- West	0	0	0	0	0	0	0	0	0	0	None
12-Red Peak- North	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
13-Red Peak- South	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
14-Snow Flat	0	0	0	0	0	0	0	0	0	0	None
15-Triple Peak- North	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
16-Triple Peak- South	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
17-Turner Lake	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None

Table 2-7 (continued). Reported annual stock use from 2004-2011 (in units of stock nights) for study meadows**.** Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Meadows in bold have uncertainties regarding accuracy of use numbers. "NR"= none reported. Shaded cells indicate year(s) for data collection. Use ratings are based on maximum number of stock nights from 2004-2011. Categories are: Very High= >150, High= 75-150, Moderate= 25-74, Low= 1-24, and None= 0 or "NR" (none recorded).

Site Name	2004	2005	2006	2007	2008	2009	2010	2011	Mean*	Max*	Use rating
18-Washburn Lake	23	36	20	0	28	0	28	0	17.8	36	Moderate
19-Benson Lake	120	90	118	201	173	78	84	84	132.	201	Very high
20-Castle Camp	531	418	409	239	576	56	147	126	399.	531	Very high
21-Cold Canyon	26	22	22	0	85	0	19	33	17.5	85	High
22-Cold Canyon- North	0	0	0	0	0	0	0	0	0	0	None
23-Dog Lake	0	0	0	0	0	0	0	0	0	0	None
24-Dog Lake East	0	0	0	0	0	0	0	0	0	0	None
25-Dorothy Lake	73	54	35	0	52	14	8	3	40.5	73	Moderate
26-E of Gaylor Pit	0	0	0	0	0	0	0	0	0	0	None
27-Elbow Hill	NR	NR	NR	NR	NR	NR	NR	NR	0	NR	None
28-Elizabeth Lake	0	0	0	0	0	0	0	0	0	0	None
29-Grace Meadows	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
30-Grace North	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
31-Harden Lake	0	0	0	20	0	0	NR	NR	2.9	20	Low
32-Hook Lake	8	0	0	0	76	20	3	0	2.0	76	High
33-José's Camp	21	8	7	7	54	18	16	0	18.7	54	Moderate
34-Lower Kerrick	21	8	7	7	54	18	16	0	19.2	54	Moderate
35-Lower Lyell	0	0	0	0	0	0	0	0	0	0	None
36-Matterhorn Canyon	100	67	110	270	336	221	79	83	136.	270	Very high
37-Middle Lyell	0	0	0	0	0	0	0	0	0	0	None
38-Miller Lake-North	123	0	0	11	20	29	3	30	33.5	123	High
39-Miller Lake-South	123	0	0	11	20	29	3	30	33.5	123	High
40-Paradise	0	3	0	0	0	0	0	0	0.4	3	Low
41-Rock Island Pass	0	0	0	0	34	0	0	0	4.9	34	Moderate
42-Rodgers Meadow	7	8	8	8	9	8	NR	NR	6.9	9	Low
43-S of Matterhorn	0	0	0	0	0	0	0	0	0	0	None
44-Smedberg Lake	68	11	0	60	90	73	6	0	34.8	90	High
45-Tilden Lake- North	163	128	75	0	21	84	26	0	91.5	163	Very high
46-Tilden Lake- South	163	128	75	0	21	84	26	0	91.5	163	Very high
47-Twin Lakes	28	0	0	0	24	14	0	20	9.4	28	Moderate
48-Upper Kerrick	57	22	44	11	0	29	0	46	33.5	57	Moderate
49-Upper Lyell- North	440	219	487	569	326	294	265	91	428.	569	Very High
50-Upper Lyell- South	440	219	487	569	326	294	265	91	428.	569	Very High
51-Upper Slide	14	0	0	0	0	18	0	0	4.6	18	Low
52-W of Tilden	0	NR	NR	NR	NR	NR	NR	NR	NR	NR	None
53-Wilma Lake	16	16	16	17	60	24	14	15	23.3	60	Moderate

2.3.6 Management context: suitability for use and meadows-of-concern

We present a potential management application of these results by examining summary scores for ecological condition and vulnerability to use-related disturbance, in the context of current disturbance and use levels. We plotted summary scores for site ecological condition versus vulnerability to disturbance, and delineated regions of this biplot based on low and high scores (according to the 10th and 90th percentiles) to assign suitability for use ratings (Table 2-8). Rather than try to quantitatively combine meadow ecological condition with streambank ecological condition for sites with stream data, we used rank of stream ecological condition score to qualitatively inform site location on the biplot. Those sites ranked higher than the 90th percentile for streambank ecological condition were assumed to have positive effects (denoted by an arrow in the positive direction for ecological condition) upon ecological conditions at the site. Those sites less than the 10th percentile were assumed to be negatively affected by poor streambank ecological conditions. We assumed sites with moderate streambank ecological conditions had no effect on meadow ecological condition.

To identify meadows-of-concern or potential concern , we examined suitability ratings in light of the reported use ratings and use-related disturbance scores at each meadow. Use ratings (see Table 2-7, above) were adapted from Yosemite Wilderness Office records to assign categories of use for each meadow (Mark Fincher, personal communication 2011), from low to very high. These ratings are based on the maximum amount of annual stock use at each meadow between 2004 and 2011. In defining use ratings, we chose maximum over mean stock use to reflect the potential effects that could result from one year of high use; our rationale being that one year of high use could create potentially long-lasting impacts at sites that otherwise tend to receive little use. From this classification, eight sites had “very high” use rating (>150 SUN), six had “High” (57-149 SUN), twelve were “Moderate” (25-74 SUN) and four were “Low” (1-24 SUN).

Table 2-8. Definitions for suitability for use ratings and meadows-of-concern.

Rating	**Definition/ Justification**
Low	All sites with high (≥90th percentile) vulnerability scores. These sites are more vulnerable to use-related disturbance relative to the other study sites, and therefore have the greatest relative risk for the decline in ecological condition from use-related disturbance.
Moderate	Sites with moderate vulnerability scores and low to moderate ecological condition, and sites with low vulnerability and low ecological condition. These sites have a relatively moderate risk for decline in ecological condition. Meadows with low ecological condition and low vulnerability are included as these sites may have potential for improved ecological condition through restoration or management action.
High	Sites with moderate to high ecological condition and low vulnerability scores, and sites with moderate vulnerability and high ecological condition. Low vulnerability sites have relatively low potential for decline in ecological condition. Sites with higher ecological condition and lower vulnerability have less potential for unacceptable levels of decline in ecological condition due to use-related disturbance.
Meadow of Concern	Sites with low to moderate suitability rating and with high (90th percentile) disturbance score and high to very high use rating. These sites show the highest disturbance levels among all study sites, and under current use patterns, may be at highest risk for decline in ecological condition given high levels of use-related disturbance.
Potential Meadow of Concern	Sites with low to moderate suitability and either high disturbance or high to very high use rating; as well as sites with high suitability, high disturbance and very high pack stock use. For the former, slight shifts in use patterns or increases in use-related disturbance will shift these meadows into meadow of concern category. For the latter, despite their high suitability rating, these sites are at relative risk of decline given that they have the highest amounts of disturbance and level of use among study sites.

3. Results

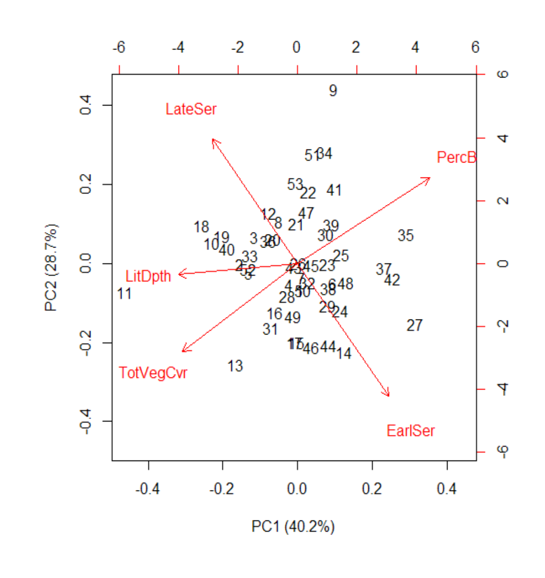
3.1 Summary Scores—ecological condition, vulnerability to disturbance, and use-related disturbance

Our objective with PCA and linear regression analyses was to reduce the dimensionality of summary scores by reducing the correlation of metrics within each assessment category. Ultimately, due to correlation indicated by analysis results described below, we chose to omit vegetation biomass from streambank ecological condition summary scores, and to omit trampled area, roll pits, and meadow fire rings from use-related disturbance summary scores. PCA scatterplots and loading matricies are shown (Figures 3-1 to 3-3); linear regression results are described in the text and shown (see Appendix D) as compliment to inferences drawn from PCA results.

For meadow ecological condition scores (Figure 3-1), the first two principal components explained roughly 68.9% of the variation in the data set (n = 53). In general, eigenvectors for the five metrics are well spread and do not indicate disproportionate correlation among any metric groupings. Loading values for bare ground cover, total vegetation cover, early seral species cover, late seral species cover, and litter depth are similar in magnitude for principal component one (PC1), and for principal component two (PC2)—with the exception that litter depth did not exhibit correlation to PC2. Notably, metrics for ground cover—bare ground cover (loading value: 0.538), and total vegetation cover (-0.467)—as well as litter depth (-0.484), exhibited the strongest correlation with PC1. Conversely, metrics for plant community composition, early seral species cover (-0.604) and late seral species cover (0.566), exhibited strong correlation with PC2. These results indicate that ecological condition summary scores are most prominantly influenced by metrics that characterize ground cover, and secondly by metrics representing species composition.

For stream ecological condition scores (Figure 3-2), the first two principal components explained roughly 70.5% of the variation in the data set (n = 19). In general, three of the five eigenvectors are well spread, while two metrics appear relatively aligned in terms of length and trajectory. These two metrics, streambank stability rating (loading value: 0.539) and vegetation biomass (0.446), along with upland species cover (-0.559), exhibit the strongest correlation with PC1. The negative loading value for upland species cover is juxtaposed with positive values for streambank stability and vegetation biomass along PC1. Ecological status (0.777) is the sole metric with strong correlation to PC2; while shade index (0.896) is strongly correlated with PC3 (not shown in scatterplot).

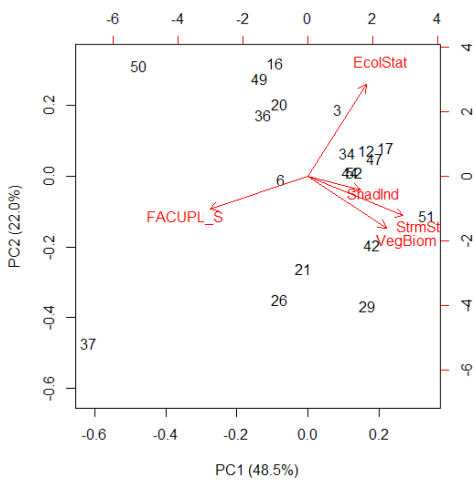
For vulnerability to disturbance (Figure 3-3), the first two principal components explained roughly 40.7% of the variation in the data set (n = 53). In general, eigenvectors for the seven metrics are well spread and do not indicate disproportionate correlation among any metric groupings. Wet meadow area (loading value: -0.596), dry meadow area (0.535), and elevation (0.497) exhibited the strongest correlation with PC1 and have the greatest explanatory power for this data set. Slope (-0.727), and to a lesser degree lakeshore area (-0.543) exhibited strong correlation to PC2. The remaining metrics, pond area and streambank area, exhibited correlation to principal components three and four, respectively, and are therefore less important to explain variation within this data set.



Loading values	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5
PercBG	0.538	0.392		0.357	0.652
TotVeg Cvr	-0.467	-0.399	-0.474	0.480	0.409
EarlSer	0.373	-0.604	-0.115	-0.580	0.384
LateSer	-0.345	0.566	-0.439	-0.538	0.281
LitDpth	-0.484		0.752	-0.130	0.425

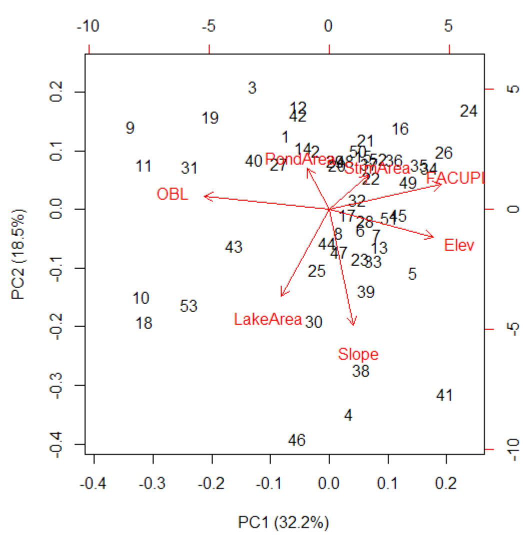
Figure 3-1. Principal component analysis results for metrics in the meadow ecological condition assessment category (n = 53), as comprised of five metrics including: bare ground cover (PercBG), total vegetation cover (TotVegCvr), late seral species cover (LateSer), early seral species cover (EarlSer), and litter depth (LitDpth). Data points are located at the centroid for each site number; eigenvectors for metrics are shown as labeled arrows. Loading values indicate correlation of metrics to each principal component; small loading values (i.e., values between 0.1 and -0.1) are omitted to emphasize higher values.

For use-related disturbance (Figure 3-4), the first two principal components explained roughly 81.3% of the variation in the data set (n = 53). Eigenvectors exhibit clustering for four of the five metrics within this data set. Each of the four metrics, informal trails (loading value: -0.545), roll pits (-0.528), meadow fire rings (-0.492), and trampled areas (-0.425), exhibit a similar level of correlation to PC1, and formal trails (0.924) is the sole metric with strong correlation to PC2.



Loading values	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5
EcolStat	0.330	0.777		-0.264	-0.465
FacUpl_S	-0.559	-0.277	0.170	-0.275	-0.712
VegBiom	0.446	-0.439	-0.409	-0.664	
ShadInd	0.299	-0.115	0.896	-0.279	0.131
StrmStab	0.539	-0.336		0.580	-0.510

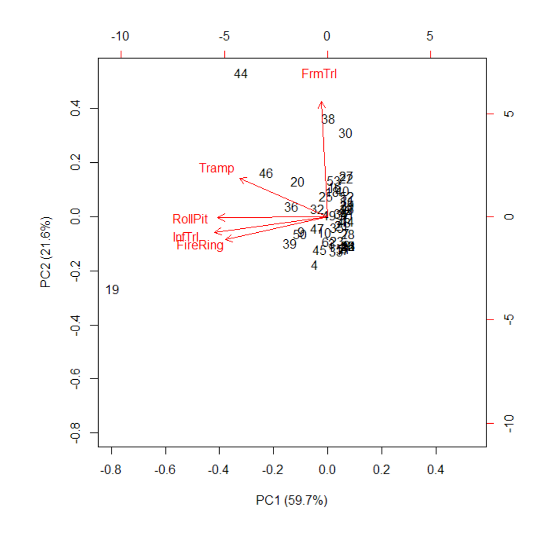
Figure 3-2. Principal component analysis results for metrics in the streambank ecological condition assessment category (n = 19), as comprised of five metrics including: ecological status (EcolStat), upland species cover (FacUpl_S), vegetation biomass (VegBiom), shade index (ShadInd), and streambank stability rating (StrmStab). Data points are located at the centroid for each site number; eigenvectors for metrics are shown as labeled arrows. Loading values indicate correlation of metrics to each principal component; small loading values (i.e., values between 0.1 and -0.1) are omitted to emphasize higher values.



Loading values	Comp. 1	Comp. 2	Comp. 3	Comp. 4
Elev	0.497	-0.174	0.388	-0.116
Slope	0.116	-0.727	0.309	
StrmArea	0.188	0.216		-0.843
LakeArea	-0.228	-0.543	-0.246	-0.485
PondArea	-0.105	0.260	0.775	-0.124
OBL	-0.596			-0.138
FACUPL	0.535	0.158	-0.297	

Loading values	Comp. 5	Comp. 6	Comp. 7
Elev	-0.153	0.615	0.397
Slope	0.442	-0.399	
StrmArea	0.432		-0.133
LakeArea	-0.596		
PondArea	-0.390	-0.374	-0.119
OBL	0.183		0.762
FACUPL	-0.233	-0.565	0.477

Figure 3-3. Principal component analysis results for metrics in the vulnerability to disturbance assessment category (n = 53), as comprised of seven metrics including: elevation (Elev), slope (Slope), streambank area (StrmArea), lakeshore area (LakeArea), pond area (PondArea), wet meadow area (OBL), and dry meadow area (FacUpl_M). Data points are located at the centroid for each site number; eigenvectors for metrics are shown as labeled arrows. Loading values indicate correlation of metrics to each principal component; small loading values (i.e., values between 0.1 and -0.1) are omitted to emphasize higher values.



Loading values	Comp. 1	Comp. 2	Comp. 3	Comp. 4	Comp. 5
FrmTrl		0.924	-0.374		
InfTrl	-0.545	-0.124	-0.111		0.818
Tramp	-0.425	0.311	0.775	0.335	
RollPit	-0.528			-0.734	-0.427
FireRing	-0.492	-0.183	-0.497	0.586	-0.367

Figure 3-4. Principal component analysis results for metrics in the use-related disturbance assessment category (n = 53), as comprised of five metrics including: formal trails (FrmTrl), informal trails (InfTrl), trampled area (Tramp), roll pits (RollPit), and meadow fire rings (FireRing). Data points are located at the centroid for each site number; eigenvectors for metrics are shown as labeled arrows. Loading values indicate correlation of metrics to each principal component; small loading values (i.e., values between 0.1 and -0.1) are omitted to emphasize higher values.

PCA results for the streambank ecological condition and use-related disturbance assessment categories suggest some redundancy or overlap among metrics. We complimented these results with linear regression analyses to further understand relationships among these metrics (Appendix D). From simple linear regression analyses, streambank stability rating and vegetation biomass exhibited a highly significant positive relationship. In addition, all use-related disturbance metrics, except for formal trails, showed significant positive correlations with each other. Linear regression results with outlying values excluded, were consistent for the streambank stability relationships. Whereas, results from exclusion of outliers for the use-related disturbance category, the positive relationships found for meadow firerings by informal trails, and meadow firerings by rollpits, were no longer significant.

Considering the overlap of explanatory power inferred from PCA results and linear regressions results that indicated significant positive relationships, we chose to reduce the dimensionality of summary scores for these assessment categories by omitting select metrics from subsequent calculations for site summary scores. We included streambank stability and omitted vegetation biomass for streambank ecological condition scores. For use-related disturbance, we included only formal trails and informal trails within summary score calculations, omitting trampled area, roll pits and meadow fire rings. Thus, summary scores by each assessment category included five metrics for meadow ecological condition, four for streambank ecological condition, seven for vulnerability to disturbance, and two for use-related disturbance. Maximum possible summary scores for each of the assessment category for a given site were therefore 500, 400, 700, and 200, respectively.

Table 3-1 provides summary statistics for observed values and relativized scores for each metric comprising summary scores for each assessment category. Appendix C provides the full data sets of observed values and relativized scores for each metric at each site. No site achieved the maximum possible summary score for any assessment category. Summary scores ranged from 201.2 to 464.5 for meadow ecological condition (40% to 93% of the maximum possible score), 125.0 to 374.5 for streambank ecological condition (31% to 94% of maximum), 206.0 to 477.3 for vulnerability to disturbance (29% to 68% of maximum), and 0 to 152.0 for use-related disturbance (0 to 76% of maximum). We identified outlier values for at least one metric within each assessment category, including: meadow ecological condtion—litter depth (1); streambank ecological condtion—upland species cover of streams (1); vulnerability to disturbance—slope (1), streambank area (1), lakeshore area (2) and pond area (1), and; use-related disturbance—formal trails (1), and informal trails (1).

Table 3-1. Summary statistics for metrics comprising assessment categories and summary scores. Sample size is 53 for all metrics except streambank ecological condition (n=19).

		Minimum Value (Score)	Maximum Value (Score)	Mean Value (Score)	Median Value (Score)	Standard Deviation	# of Outliers **
Meadow Ecological Condition	**Bare ground cover* - %**	1.9 (0)	36.9 (94.8)	17.3 (53)	16.7 (54.6)	7	None
	Total veg. cover - %	37.3 (61.5)	60.7 (100)	50 (82.4)	50.8 (83.6)	5.9	None
	Late seral cover - %	40.6 (40.6)	100 (100)	78.5 (78.5)	78.8 (78.8)	11.4	None
	Early seral cover* - %	0 (0)	28.4 (100)	11.3 (60.3)	12 (57.8)	8.2	None
	Litter depth – cm	0.52 (15.7)	7.9 (100)	1.9 (56.1)	1.8 (54.9)	1.1	1
Meadow Ecological Condition Summary Score		**201.2**	**464.5**	**330.3**	**329.1**	**59.5**	
Streambank Ecol. Condition	**Ecological status - unitless**	73 (73)	100 (100)	94.3 (94.3)	99 (99.0)	8.1	None
	UPL species cover* - %	0.1 (0)	28.6 (100)	5.6 (67.6)	3.4 (78.1)	6.9	1
	Shade index - unitless	0 (0)	0.07 (100)	0.018 (32.6)	0.010(20.0)	0.021	None
	Streambank stability- %	43 (43)	100 (100)	78.3 (78.3)	84.0 (84.0)	18.2 (18.2)	None
Streambank Ecological Condition Summary Score		**125.0**	**374.5**	**265.8**	**272.4**	**64.6**	
Vulnerability to Disturbance	**Elevation - m**	2195 (71.5)	3072 (100)	2697.7 (87.8)	2734 (89)	205.2	None
	Slope - %	1.3 (13.5)	9.6 (100)	3.7 (38.4)	3.1 (32.3)	2.1	1
	Stream-bank area - %	0 (0)	7.7 (100)	2.1 (39.1)	2 (35.9)	1.7	1
	Lake-shore area - %	0 (0)	3.1 (100)	0.4 (19)	0 (0)	0.8	2
	Pond area - %	0 (0)	12 (100)	1.8 (17.3)	0.5 (5.2)	2.8 (26.5)	1
	Dry meadow - %	0 (0)	55.8 (100)	16 (28.6)	14.2 (25.4)	13.7	None
	Wet meadow - %	1.3 (1.3)	97.6 (100)	29.3 (30.1)	24.1 (24.6)	23.7	None
Vulnerability to Disturbance Summary Score		**205.9**	**477.3**	**290.3**	**276.8**	**66.4**	
Use-rel. Dist	**Formal trails -%**	0 (0)	2.5 (100)	0.6 (24.1)	0.4 (18.7)	0.6	1
	Informal trails -%	0 (0)	3.3 (100)	0.3 (20.3)	0 (0)	0.5	1
Use-related Disturbance Summary Score		**0.0**	**152.0**	**38.0**	**30.3**	**35.9**	

*Denotes metrics converse to summary score calculations, where higher values suggest lower ecological condition. Scores for these metrics were calculated by subtracting the relativized score from 100%, before incorporating into summary scores.
**Outliers are values more than 3 standard deviations from the mean. Identified outliers included (metric, site, observed value): litter depth, Merced Lake-West, 7.9; upland species cover, Middle Lyell, 28.6; slope, Rock Island Pass, 9.9; streambank area, Twin Lakes, 7.7; lakeshore area, Washburn Lake, 3.0, and Wilma Lake, 3.1; pond area, Doc Moyle's-West, 12.0; formal trails, Miller Lake-North, 2.5; informal trails, Benson Lake, 3.3; trampled area, Smedberg Lake, 14.6; roll pits, Benson Lake, 0.4; fire rings in meadow, Benson Lake, 3.1.

By ranking sites, we noted sites at the upper and lower ends of scores for each assessement category. For meadow ecological condition, Merced Lake-West and Washburn Lake sites had the highest summary scores, while Elbow Hill and Rodgers Meadow had the lowest (Figure 3-5). Turner Lake and Twin Lakes sites had the highest streambank ecological condition scores, and Upper Lyell and Middle Lyell- South were lowest (Figure 3-6). For vulnerability to disturbance, Washburn and Doc Moyle's- West sites had the highest summary scores, while Elbow Hill and Cold Canyon had the lowest (Figure 3-7). Smedberg Lake and Merced Lake- Shore sites had the highest scores for use-related disturbance, while six sites had disturbance summary scores of zero (Figure 3-8). Delineating lowest and highest 10% of scores (i.e., according to the 10th and 90th percentiles) resulted in six sites with low and high ratings for each summary score, except in the case of streambank ecological condition, where a smaller sample size resulted in only two sites being ranked with low and high ratings.

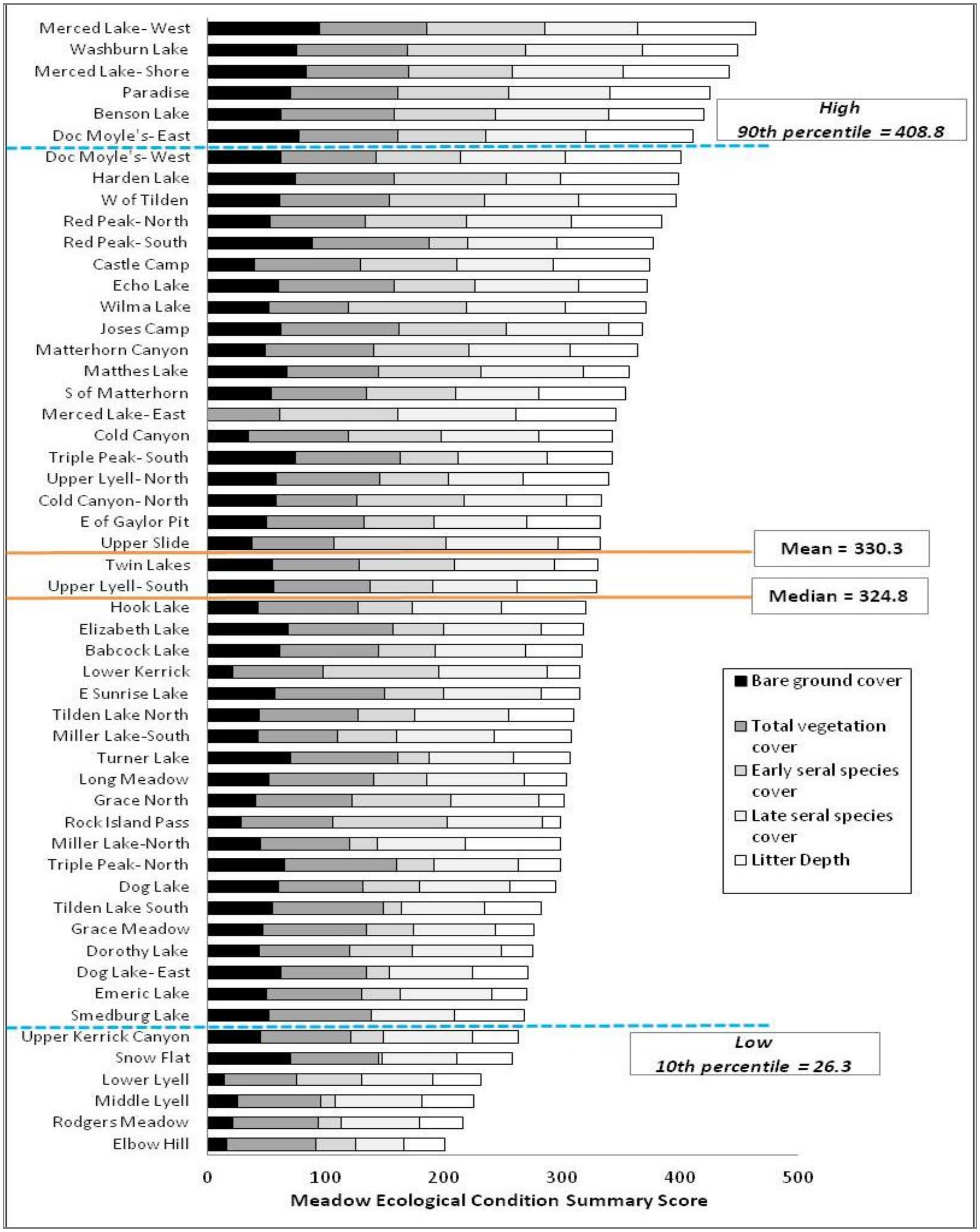


Figure 3-5. Meadow ecological condition summary scores by contributing metrics (n = 53). Dashed lines approximate the 10th and 90th percentile for the range of scores. Sites with summary scores greater than the 90th percentile are consider to have high meadow ecological condition, sites with summary scores less than the 10th percentile are consider to have low meadow ecological condition.

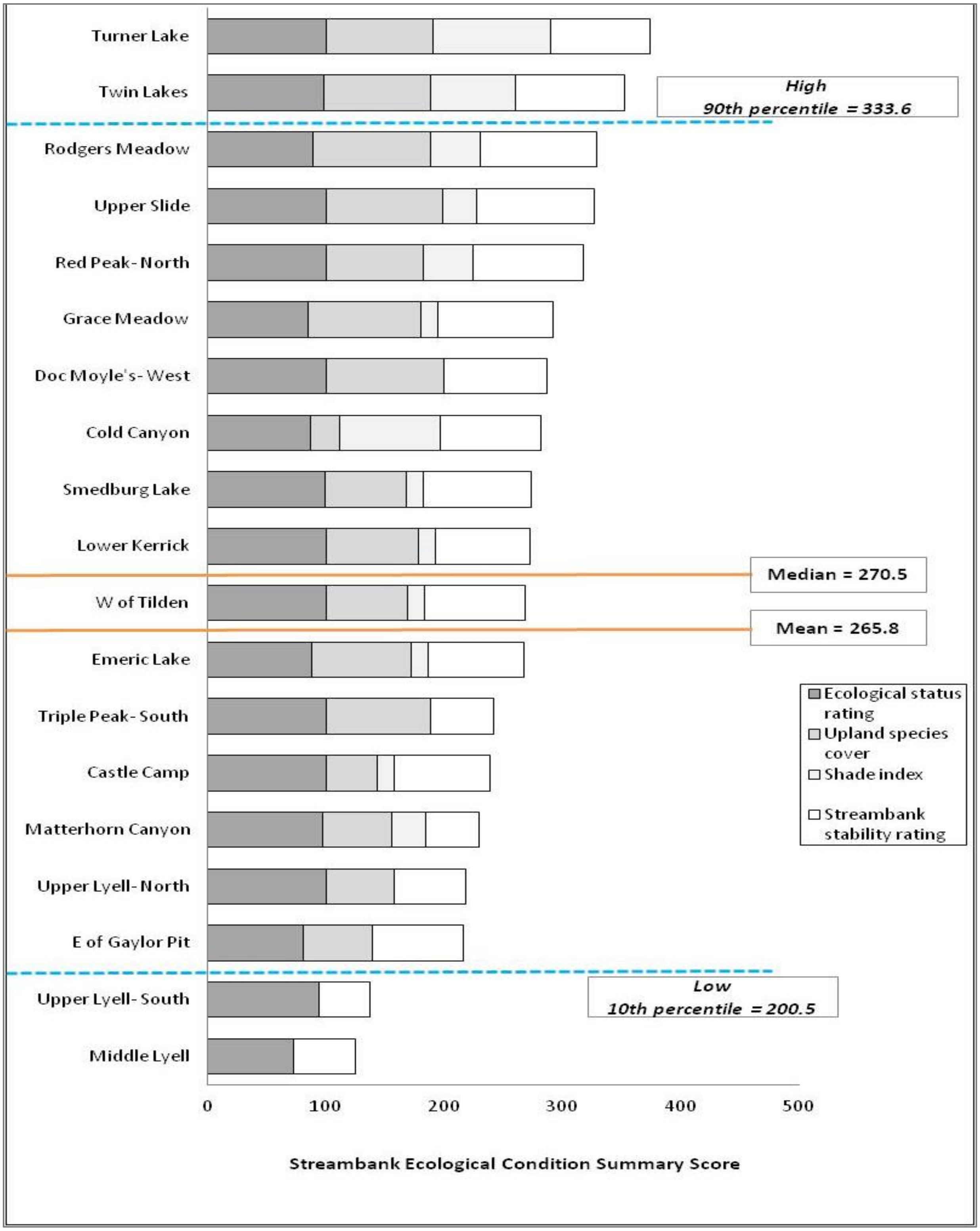


Figure 3-6. Streambank ecological condition summary scores by contributing metrics (n = 53). Dashed lines approximate the 10th and 90th percentile for the range of scores. Sites with summary scores greater than the 90th percentile are consider to have high streambank ecological condition, sites with summary scores less than the 10th percentile are consider to have low meadow ecological condition.

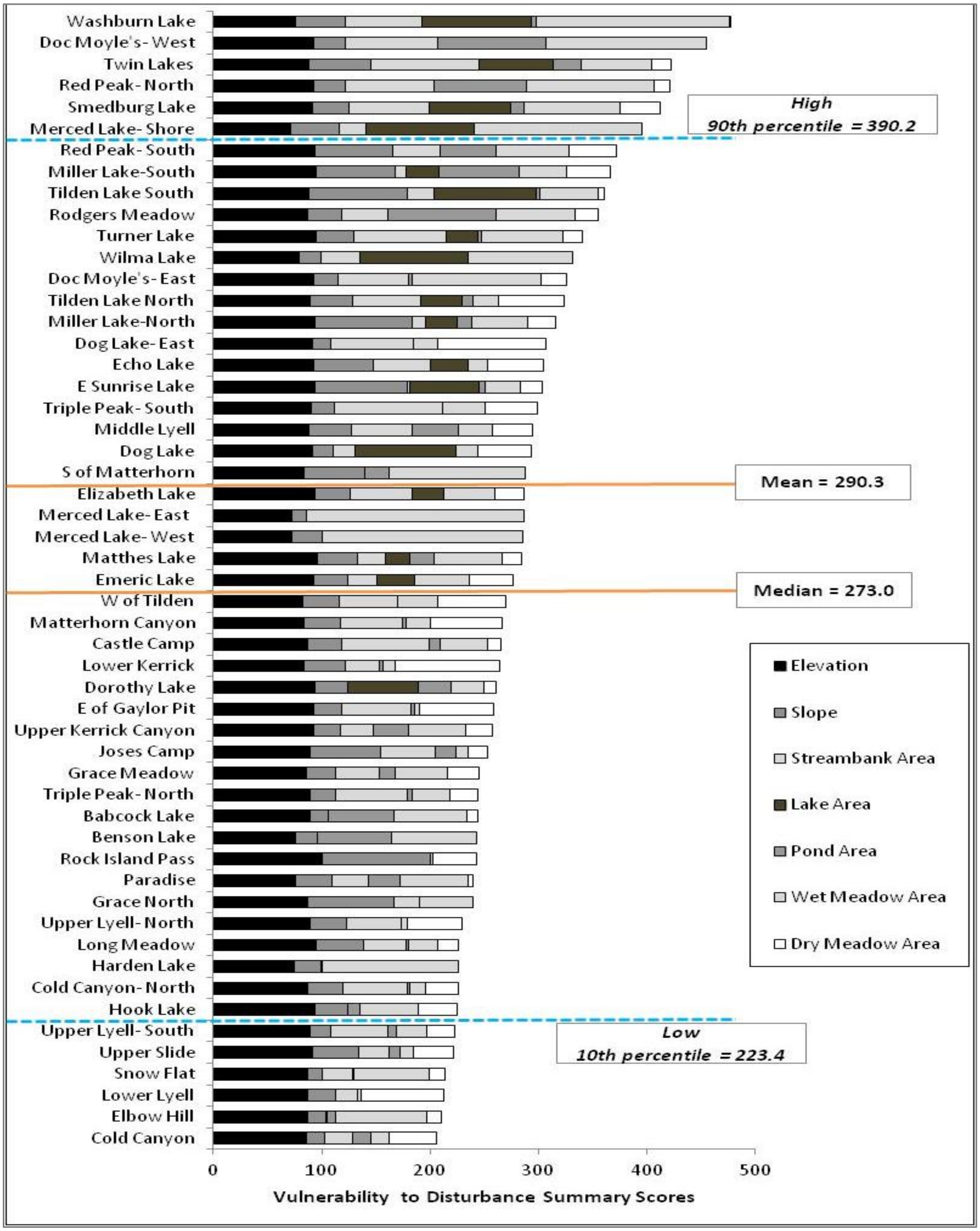


Figure 3-7. Vulnerability to disturbance summary scores by contributing metrics (n = 53). Dashed lines approximate the 10th and 90th percentile for the range of scores. Sites with summary scores greater than the 90th percentile are consider to have high vulnerability to disturbance, sites with summary scores less than the 10th percentile are consider to have low vulnerability to disturbance.

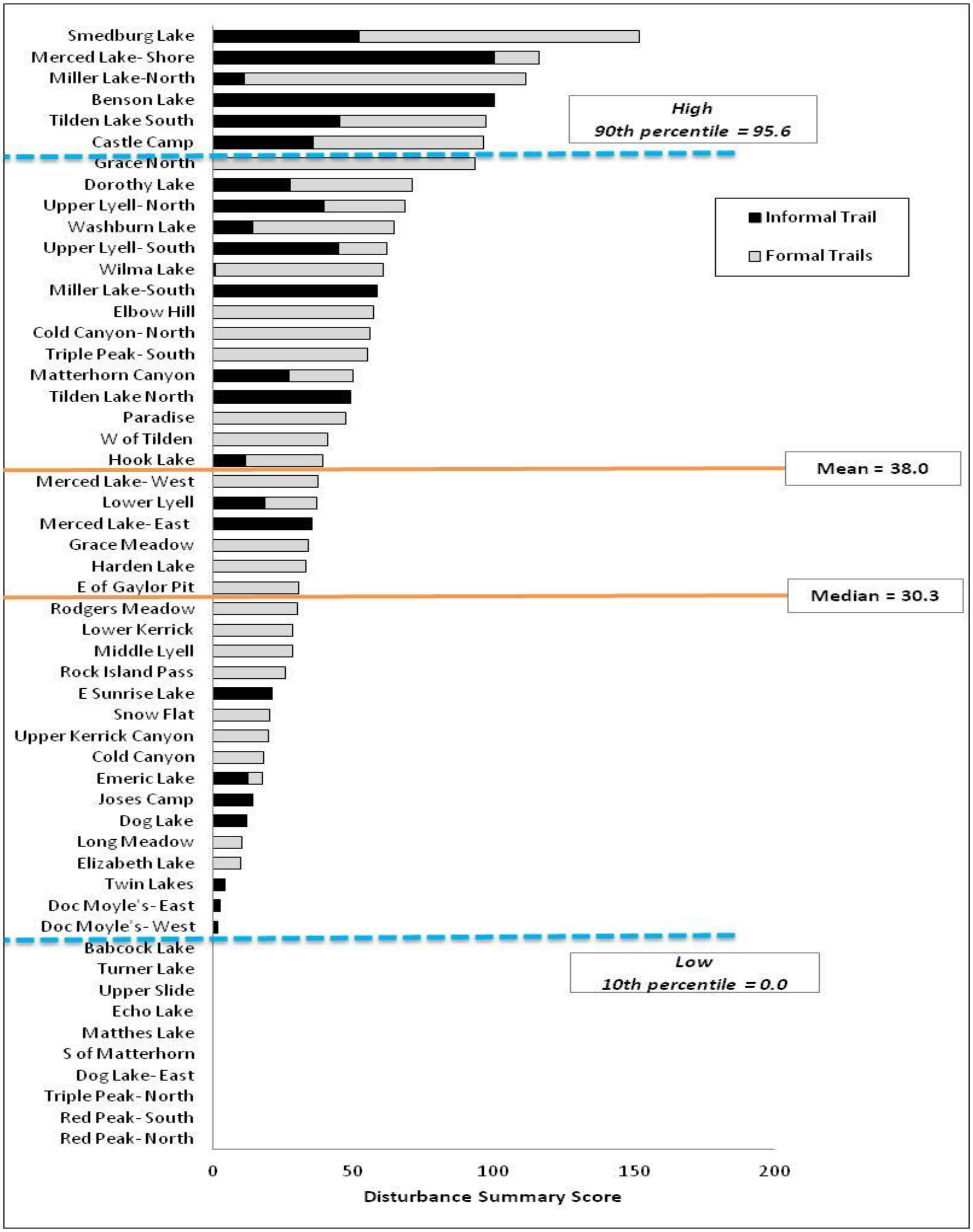


Figure 3-8. Use-related disturbance summary scores by contributing metrics (n = 53). Dashed lines approximate the 10th and 90th percentile for the range of scores. Sites with summary scores greater than the 90th percentile are consider to have high use-related disturbance, sites with summary scores less than the 10th percentile are consider to have low use-related disturbance.

3.2 Relationships among scores and use levels

We used model selection techniques (Table 3-2) based on linear regression and AICc values to evaluate the relative goodness of fit among a suite of models and identified the most parsimonious model of relationships for predictor variables and potential meadow response to stock use. Results indicate the best models of those tested for each predictor variable as: the interaction of maximum stock use per unit area by vulnerability to disturbance (MaxStkUseArea*Vuln) for bare ground cover; the interaction of informal trials by upland species cover (InfTrl*FacUpl_S) for streambank stability; elevation (Elev) for meadow ecological condition, and; the interaction of use-related disturbance by vulnerability to disturbance (Dist*Vuln) for streambank ecological condition. However, relatively low r-squared values (i.e., ranging from 0.22 to 0.48 for the best models), low sample size for the streambank data sets, as well as concerns regarding assumptions for linear regression, suggest caution for inferences made from these models.

Table 3-2. Model selection results from AIC analyses for bare ground cover, streambank stability, and for meadow and streambank ecological condition summary scores. Models with ΔAICc values less than 7.00 are shown, and models with strong support (ΔAICc less than 2.00) are indicated in bold font. Predictor variables, regression coefficients, and confidence intervals are of standardized data. Abbreviated column headings include: k, the number of model parameters; AICc, estimated AIC value adjusted for finite sample size; ΔAICc, difference between model and the best fit model; wi, Akaike weights.

Model (Standardized Predictor Variables)†	k	AICc	ΔAICc	w_i	r-square value	Standardized Regression Coefficient for Slope	Standardized 95% Confidence Interval
Bare Ground Cover Observed Values (n = 53)							
StkUseMaxArea*Vuln	**4**	**342.88**	**0.00**	**0.34**	**0.29**	**24.26**	**2.38, 46.15**
StkUseMeanArea*Vuln	**4**	**343.47**	**0.59**	**0.25**	**0.28**	**35.04**	**7.77, 62.30**
StkUseCurrArea*Vuln	4	345.23	2.35	0.11	0.26		
StkUsePrevArea*Vuln	4	345.46	2.58	0.09	0.25		
StkUseMax*Vuln	4	345.51	2.63	0.09	0.25		
StkUsePrev*Vuln	4	346.60	3.72	0.05	0.24		
StkUseMean*Vuln	4	349.39	6.51	0.01	0.20		
StkUseCurr*Vuln	4	349.49	6.61	0.01	0.19		
StkUseMaxArea	2	349.86	6.98	0.01	0.15		
Streambank Stability Rating Observed Values (n = 19)							
InfTrl*FacUpl_S	**4**	**156.55**	**0.00**	**0.22**	**0.48**	**-5.69**	**-16.51, 5.12**
StkUsePrev	**2**	**157.38**	**0.83**	**0.15**	**0.38**	**-11.23**	**-18.58, -3.88**
VegBiom	**2**	**157.82**	**1.27**	**0.12**	**0.36**	**11.01**	**3.57, 18.44**
FacUpl_S	**2**	**157.83**	**1.28**	**0.12**	**0.36**	**-11.00**	**-18.44, -3.56**
StkUsePrev*Vuln	4	159.37	2.81	0.05	0.40		
InfTrl*Vuln	4	159.77	3.21	0.04	0.38		
InfTrl*VegBiom	4	159.84	3.29	0.04	0.38		
StkUseCurr	2	160.12	3.57	0.04	0.28		
StkUseCurr*Vuln	4	160.79	4.24	0.03	0.35		
StkUseMax	2	160.92	4.37	0.02	0.25		
StkUseMean	2	160.98	4.43	0.02	0.25		
Dist*Vuln	4	161.01	4.46	0.02	0.34		
StkUseMax*Vuln	4	161.20	4.65	0.02	0.34		

Table 3-2 (continued). Model selection results from AIC analyses for bare ground cover, streambank stability, and for meadow and streambank ecological condition summary scores. Models with ΔAICc values less than 7.00 are shown, and models with strong support (ΔAICc less than 2.00) are indicated in bold font. Predictor variables, regression coefficients, and confidence intervals are of standardized data. Abbreviated column headings include: k, the number of model parameters; AICc, estimated AIC value adjusted for finite sample size; ΔAICc, difference between model and the best fit model; wi, Akaike weights.

Model (Standardized Predictor Variables)†	k	AICc	ΔAICc	w_i	r-square value	Standardized Regression Coefficient for Slope	Standardized 95% Confidence Interval
(continued) Streambank Stability Rating Observed Values (n = 19)							
StkUseMean*Vuln	4	161.22	4.67	0.02	0.33		
StkUseCurrArea*Vuln	4	162.89	6.33	0.01	0.27		
StkUsePrevArea*Vuln	4	163.19	6.64	0.01	0.26		
StkUseMeanArea*Vuln	4	163.34	6.79	0.01	0.26		
InfTrl	2	163.38	6.83	0.01	0.15		
StkUsePrevArea	2	163.54	6.99	0.01	0.14		
Meadow Ecological Condition Summary Score (n = 53)							
Elev	**2**	**499.85**	**0.00**	**0.63**	**0.22**	**-29.37**	**-43.92, -14.81**
Vuln	2	504.62	4.77	0.06	0.14		
StkUseMax*Vuln	4	504.83	4.97	0.05	0.18		
StkUseMean*Vuln	4	504.83	4.98	0.05	0.18		
StkUseMaxArea*Vuln	4	505.93	6.08	0.03	0.16		
StkUsePrev*Vuln	4	506.06	6.21	0.03	0.16		
StkUseMeanArea*Vuln	4	506.17	6.32	0.03	0.16		
Dist*Vuln	4	506.19	6.34	0.03	0.15		
StkUseCurr*Vuln	4	506.40	6.55	0.02	0.15		
StkUsePrevArea*Vuln	4	506.60	6.74	0.02	0.15		
Streambank Ecological Condition Summary Score (n = 19)							
Dist*Vuln	**4**	**206.93**	**0.00**	**0.18**	**0.41**	**19.24**	**0.91, 55.80**
StkUsePrev	**2**	**207.96**	**1.03**	**0.11**	**0.29**	**-34.81**	**-62.63, -6.99**
InfTrl*Vuln	**4**	**208.57**	**1.64**	**0.08**	**0.36**	**9.99**	**-16.69, 36.66**
StkUsePrev*Vuln	**4**	**208.77**	**1.84**	**0.07**	**0.35**	**-4.96**	**-112.02, 102.10**
StkUseCurr	2	209.00	2.07	0.06	0.25		
StkUseMean	2	209.19	2.26	0.06	0.24		
StkUseMax	2	209.25	2.32	0.06	0.24		
StkUseCurr*Vuln	4	209.25	2.32	0.06	0.34		
StkUseMean*Vuln	4	209.32	2.39	0.05	0.33		
StkUseMax*Vuln	4	209.56	2.63	0.05	0.32		
Vuln	2	210.47	3.54	0.03	0.19		
StkUseCurrArea*Vuln	4	210.63	3.70	0.03	0.29		
InfTrl	2	210.90	3.97	0.02	0.17		
StkUsePrevArea*Vuln	4	211.07	4.14	0.02	0.27		
StkUsePrevArea	2	211.27	4.34	0.02	0.16		
Disturbance	2	211.29	4.36	0.02	0.15		
StkUseMeanArea*Vuln	4	211.63	4.70	0.02	0.25		
StkUseCurrArea	2	211.88	4.95	0.01	0.13		
StkUseMaxArea*Vuln	4	212.24	5.31	0.01	0.22		
FrmTrl	2	212.79	5.86	0.01	0.09		
StkUseMeanArea	2	213.31	6.37	0.01	0.06		
Null	1	213.33	6.40	0.01	0.00		

Results from model selection for observed values of bare ground cover indicate the best model of those tested as the interaction of maximum stock use per unit area by vulnerability to disturbance, and suggests that as vulnerability to disturbance increases, the effect of the density of maximum stock use on bare ground cover also increases. The plot for standardized residuals by fitted values and the Q-Q plot for the best model do not indicate any obvious concerns for non-constant variance or normality of residuals. Standardized regression coefficient estimates for the best model are $\beta_{StkUseMaxArea}$ = -0.69, β_{Vuln}= -9.5, and $\beta_{StkUseMaxArea*Vuln}$ = 24.26. One additional model, mean stock use per area by vulnerability to disturbance (ΔAICc = 0.59), also has substantial support over other tested models (i.e., ΔAICc values less than 2.00). Calculated strength of evidence ratios ($w_{StkUseMaxArea*Vuln}$ / $w_{StkUseMeanArea*Vuln}$) indicate that the best model is 1.36 times more likely to be the best model of the data (i.e., over the next highest ranked model). The relatively low r-square value for the best model, 0.29, indicates that this model explains only 30% of variance in this data set. Confidence intervals for the slope estimates of the best model and the next ranked model do not encompass zero, which further supports a positive relationship between the density of stock use and the percent of bare ground at a site. Of the nine models with ΔAICc values less than 7.00, the top four ranked models indicate bare ground as function of site vulnerability to disturbance and the density of stock use (i.e., level of stock use per unit area).

Model selection results for observed values of streambank stability indicate the best model as the interaction between informal trails and upland species cover, suggesting that as upland species cover increases along streambanks, the negative effect of informal trails on streambank stability also increases. These results are from a relatively small sample size (n= 19), and the Q-Q plot for this model indicates minor concern for the fit of the data to a normal distribution, especially at low values. Though not shown, we ran a separate test for these data but excluded two sites with low values (and shown by the diagnostic plots as potentially problematic) and found consistent results to analyses for the full data set. Slope estimates from the best model are β_{InfTrl} = -3.048, β_{FacUpl_S} = -12.265, and $\beta_{Inftrl*FacUpl\_S}$ = -5.693. Strength of evidence ratios ($w_{InfTrl*FacUpl\_S}$ / w_i) indicate that the best model, is 1.47, 1.83, and 1.83, times more likely to be the best model of these data. The proportion of variance explained by best model, indicated by r^2 values, is 0.48. The confidence interval for slope estimate from the best model encompasses zero, but suggests a negative relationship given that it is skewed towards negative values. Three additional models have ΔAICc less than 2.00 and therefore have substantial support over other tested models for these data, including: previous year stock use (ΔAICc = 0.83), vegetation biomass (1.27), and upland species cover (1.28). However, we discount these models for the following reasons: previous year stock use for this data set contains many zero values (i.e., the distribution of sites clustered around the origin with few sites at higher values can bias observed relationships), and; diagnostic plots for both vegetation biomass and upland species cover exhibit concerns regarding fit to normal distributions and appear potentially non-linear.

Results from model selection for the meadow ecological condition data set (n = 53 sites) indicate the best model of those tested is elevation. The estimated coefficient for slope, -29.37, suggests a negative relationship between meadow ecological condition summary score and elevation. This model is the only model to have substantial support (i.e., ΔAICc value less than 2.00), and is further supported given that the confidence interval for slope estimate of this model, -43.92 to -14.81, does not encompass zero. Nonetheless, the low r-squared value for this best model, 0.22, indicates that elevation accounts for only a small portion of variance within this data set. In addition, from the diagnostic plots we noted concerns regarding the fit of the best model. The plots suggest violation of the assumption that residuals are normally distributed and variance in residuals is constant across values of the predictor variable. Residuals tend to be positive for small and large values and negative for intermediate values of meadow ecological condition.

Model selection results for the streambank ecological condition data set (n = 19) indicate the best model as the interaction between use-related disturbance by vulnerability to disturbance, suggesting that as vulnerability to disturbance increases, the negative effect of disturbance on ecological condition is reduced. Regression estimates for the best model are β_{Dist} = -38.61, β_{Vuln}= 28.36, and $\beta_{Dist*Vuln}$ = 19.24. Strength of evidence ratios ($w_{Dist*Vuln}$ / w_i) indicate that the best model, is 1.64, 5.13, and 5.85, times more likely to be the best model of the data than the next three ranked models, respectively. Four models had ΔAICc less than 2.00 and also have substantial support to explain portions of variance with these data. Caution should be exercised for inferences made from these results (i.e., for each of the four highest ranked models) due to the following reasons: the data set is a relatively small sample size (n = 19); plots of standardized residuals versus fitted values indicate minor concern regarding non-constant variance across the range of the predictor variables, and; Q-Q plots for these models indicate concern regarding the normality of the residuals.

3.3 Management context: Suitability for use and meadows-of-concern

From the biplot of ecological condition scores vs. vulnerability to disturbance (Figure 3-9), a large majority of meadows (40) rated as moderate suitability for use. Six meadows had a low suitability rating: Doc Moyle’s- West (site ID #3), Merced Lake- Shore (#10), Red Peak- North (#12), Washburn Lake (#18), Smedberg Lake (#44) and Twin Lakes (#47). Seven meadows received a high suitability rating: Doc Moyle’s- East (#2), Merced Lake- West (#11), Benson Lake (#19), Cold Canyon (#21), Paradise (#40), Upper Lyell- South (#50) and Upper Slide (#51). However, three of these high suitability meadows (#2, 50 and 51) were within 5% margin of shifting to moderate suitability. This shift could occur with either small shifts in metrics comprising vulnerability (sites #50 and 51) or ecological condition scores (site#2).

Sites in the upper 90th and lower 10th percentiles for streambank ecological condition summary scores are assumed to have positive and negative effects on meadow ecolgocial condition scores, respectively. These sites (4) are represented by left-facing (i.e., negative) and right-facing (i.e., positive) arrows in Figure 3-9. Low streambank ecological condition summary scores include Middle Lyell (site ID #37) and Upper Lyell- South (#50); sites with high summary scores include Turner Lake (#17) and Twin Lake (#47). However, because these sites are positioned in the middle of the suitability for use regions along the ecological condition axis, we assume that their streambank scores would not appreciably alter the suitability for use ratings at these sites.

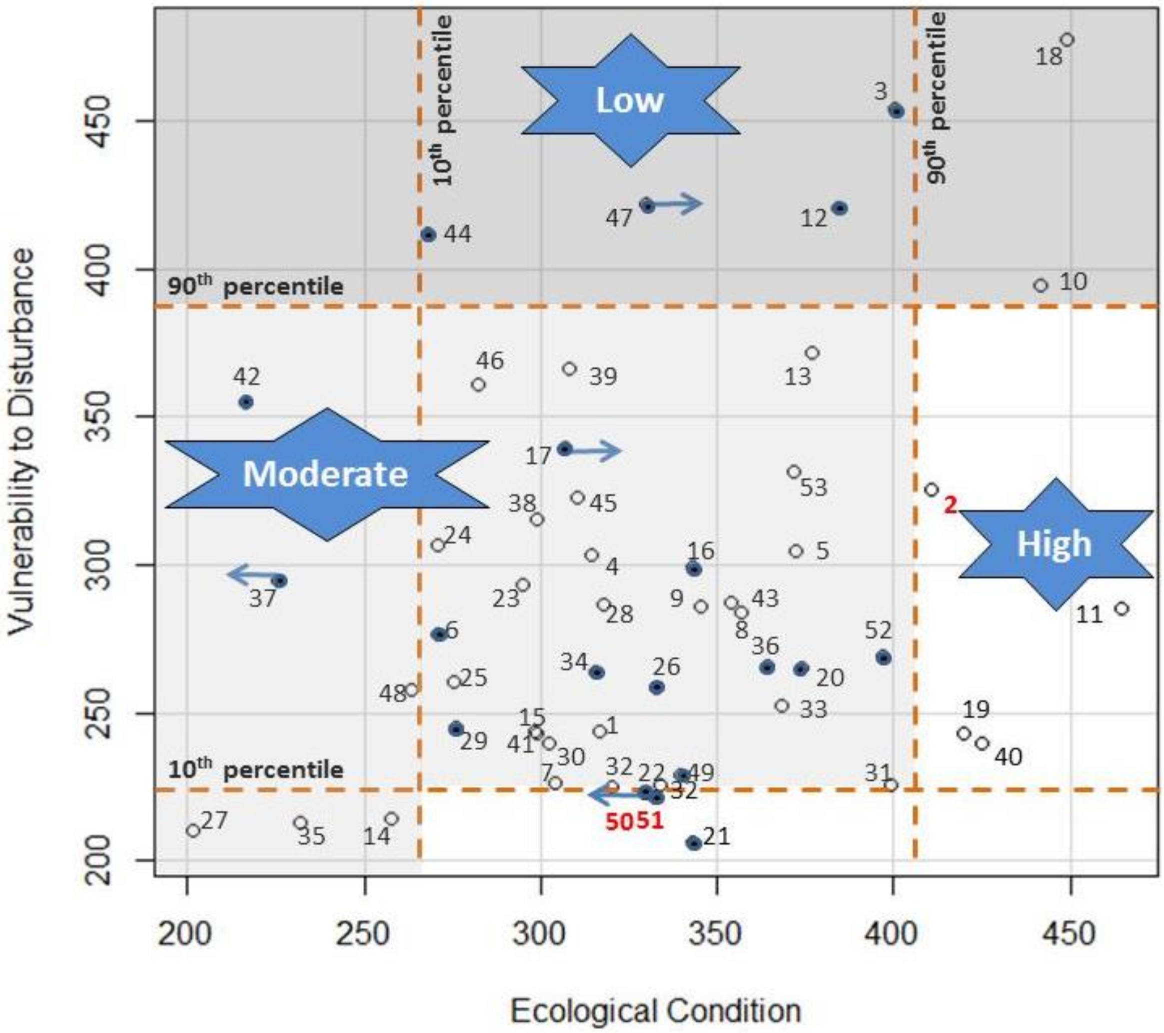


Figure 3-9. Biplot of suitability for use ratings based on relativized scores for ecological condition and vulnerability to disturbance. Dashed lines represent the 10th and 90th percentiles for the range of summary scores for each assessment category. Regions of the plots are color-coded according to suitability for use rating: dark grey = low; light grey = moderate, and white = high. Sites shown in larger red font are within 5% of a lower suitability rating. Sites with data for streambank ecological condition are depicted as solid black points; sites with high summary scores are shown with arrows indicating higher ecological condition (i.e., arrows pointing right), sites with low summary scores are shown with arrows indicating lower ecological condition (i.e., arrows pointing left).

In comparing suitability ratings with ratings for use-related disturbance and reported stock use levels, we identified four meadows-of-concern (Table 3-3). Meadows-of-concern are those sites with low to moderate suitability, high disturbance and high to very high stock use, including: Castle Camp (#20), Miller Lake- North (#38), Smedberg Lake (#44) and Tilden Lake- South (#46). We identified nine meadows of potential concern: Emeric Lake (#6), Merced Lake- East #9, Merced Lake- Shore #10, Benson Lake #19, Hook Lake (#32), Matterhorn Canyon #36, Miller Lake- South (#39), Tilden-North (#45), and Upper Lyell- North (#49). In addition, we note that one site, Upper Lyell- North, is within 5% of the meadow of concern rating due to disturbance score that falls just short of high rating. We also note two meadows with high suitability ratings that had no reported use: Merced Lake- West (#11) and Paradise (#40).

Table 3-3. Ratings for suitability, meadows-of-concern, disturbance score, and stock use (with crosswalk to site ID for Figure 3-9). Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Dark shading indicates meadows-of-concern, and light shading indicates meadows of potential concern. Bold font indicates meadows within 5% of meadow of concern rating, and italicized meadows are within 5% of a lower suitability rating.

ID #	Site Name	Suitab. Rating	Disturb. Score Rating	Stock Use Rating	ID#	Site Name	Suitability Rating	Disturb. Score Rating	Stock Use Rating
1	Babcock Lake	Mod	Low	Mod	28	Elizabeth Lake	Mod	Mod	None
2	*Doc Moyle's- East*	*High*	*Mod*	*Mod*	29	Grace Meadow	Mod	Mod	None
3	Doc Moyle's- West	Low	Mod	Mod	30	Grace- North	Mod	Mod	None
4	E Sunrise Lake	Mod	Mod	Mod	31	Harden Lake	Mod	Mod	Low
5	Echo Lake	Mod	Low	None	32	Hook Lake	Mod	Mod	High
6	Emeric Lake	Mod	Mod	High	33	José's Camp	Mod	Mod	Mod
7	Long Meadow	Mod	Mod	None	34	Lower Kerrick	Mod	Mod	Mod
8	Matthes Lake	Mod	Low	None	35	Lower Lyell	Mod	Mod	None
9	Merced Lk.- East	Mod	Mod	V.High	36	Matterhorn Cyn	Mod	Mod	V.High
10	Merced Lk.- Shore	Low	High	None	37	Middle Lyell	Mod	Mod	None
11	Merced Lk.- West	High	Mod	*None*	38	Miller Lake-	Mod	High	High
12	Red Peak- North	Low	Low	None	39	Miller Lake-	Mod	Mod	High
13	Red Peak- South	Mod	Low	None	40	Paradise	High	Mod	Low
14	Snow Flat	Mod	Mod	None	41	Rock Island Pass	Mod	Mod	Mod
15	Triple Peak- North	Mod	Low	None	42	Rodgers Meadow	Mod	Mod	Low
16	Triple Peak- South	Mod	Mod	None	43	S of Matterhorn	Mod	Low	None
17	Turner Lake	Mod	Low	None	44	Smedberg Lake	Low	High	High
18	Washburn Lake	Low	Mod	Mod	45	Tilden- North	Mod	Mod	V.High
19	Benson Lake	High	High	V.High	46	Tilden- South	Mod	High	V.High
20	Castle Camp	Mod	High	V.High	47	Twin Lakes	Low	Mod	Mod
21	Cold Canyon	High	Mod	High	48	Upper Kerrick	Mod	Mod	Mod
22	Cold Cyn- North	Mod	Mod	None	**49**	**Upper Lyell-**	**Mod**	**Mod**	**V.High**
23	Dog Lake	Mod	Mod	None	50	*Upper Lyell-*	*High*	*Mod*	*V.High*
24	Dog Lake- East	Mod	Low	None	*51*	*Upper Slide*	*High*	*Low*	*Low*
25	Dorothy Lake	Mod	Mod	Mod	52	W of Tilden	Mod	Mod	None
26	E of Gaylor Pit	Mod	Mod	None	53	Wilma Lake	Mod	Mod	Mod
27	Elbow Hill	Mod	Mod	None					

4. Discussion

4.1 Use of metrics and summary scores to prioritize monitoring

We evaluated data for multiple metrics from 53 high elevation wilderness meadows in Yosemite National Park, and ranked sites in terms of four assessment categories: meadow and streambank ecological condition (i.e., stream channels were surveyed at 19 of the 53 sites), vulnerability to disturbance, and use-related disturbance. Using PCA and simple linear regression we evaluated correlation among the contributing metrics for assessment categories such that some metrics were eliminated from calculation of summary scores. However, correlation among metrics can also help to justify and prioritize indicators for monitoring. Results for streambank ecological condition indicated that streambank stability, vegetation biomass, and upland species cover were strongly correlated to PC1; and linear regression results support a positive relationship between streambank stability and vegetation biomass, and a negative relationship between streambank stability and upland species cover. Managers seeking to efficiently quantify streambank stability could choose to monitor metrics for either streambank stability, vegetation biomass, or upland species cover, or all three. Similarly, PCA results for use-related disturbance metrics depicted correlation among informal trails, roll pits, trampled area, and fire-rings; linear regression results indicated significant positive relationships for pairwise combination of these metrics. These results suggest that these disturbance features co-occur, whereby overnight use by pack stock groups may facilitate meadow fire-rings, and stock use can produce multiple disturbance features (e.g., informal trails, roll pits, trampled areas, and hoof punching). Therefore, managers seeking to monitor use-related disturbance could choose to monitor informal trails only.

However, the evaluation of single metrics alone may fail to capture the unique environmental context of some sites, and may be insufficient to identify causal factors (Karr and Chu 1997). For instance, PCA results for use-related disturbance indicated general orthogonality among formal trails and other use-related disturbance metrics, suggesting that areal extent of formal trails within a site is not a good indicator for the likelihood of other disturbance features. Rather other factors, such as the presence or vicinity of campsites, could be investigated for potential relationships to the occurrence of use-related disturbance features. In addition, monitoring schemes that include reference sites may be necessary for identifying causal mechanisms related to use levels. Furthermore, evidence for specific ecological effects associated with certain disturbance metrics other than informal trails, such as features that lead to increased bare ground, the formation of headcuts, or channelized erosion, may warrant the inclusion of these metrics within monitoring protocols regardless of correlation.

Site rankings by summary score for each assessment category facilitate comparing conditions of each site relative to others in the sample pool. These ranks can help to identify meadows that may warrant more intensive monitoring, site-specific research, or targeted management actions (i.e., use-restriction, restoration, or other). Inspection of observed values for sites by each metric may warrant additional site-specific examination due to atypical outlying values for a single metric, if this metric is of concern. For example, high upland species cover at Middle Lyell or high values for disturbance features at Benson Lake (informal trails, roll pits, and meadow fire-rings), and Smedberg Lake (trampled area) may warrant further monitoring at these sites to ensure that disturbance does not result in unacceptable impacts to ecological condition. In this manner, monitoring activities could be tailored to address site-specific information, and management actions can be targeted to improve ecological condition.

4.2 Relationships among scores, reported stock use levels, and disturbance

We used model selection based on AICc analysis to explore parsimonious relationships among scores for meadow and streambank ecological condition, vulnerability, disturbance, and reported stock use. In addition we explored relationships for bare ground cover, and for streambank stability, with vulnerability, disturbance, and reported stock use. We focused on very basic and simplistic models to test *a priori* assumptions and to detect the potential for simple relationships within very complex systems. Additional in-depth analyses that stratify data for these sites based on hydrogeomorphic type, vegetation community, landscape position, elevation, or other parameters could be used to explore more complex relationships for meadow response to use (by both human and stock) and use-related disturbance that may exist among these sites. Such analyses could provide additional insight for improved site-specific monitoring and management.

We have the most confidence in model selection results for the bare ground cover data set, which indicated the top four ranked models to predict bare ground cover at these sites as a function of site vulnerability to disturbance and the density of stock use (i.e., level of stock use per unit area; stocking rate). The best model, maximum stock use per unit area by vulnerability, was roughly 1.4 times more likely to show a better fit than the next highest ranked model; this indicates that the highest stocking rates at these sites shows the closest relationship to bare ground cover. In general, these relationships could be made more robust by data collection at more sites with moderate and high use levels; given these data met the assumptions for linear regression (normality, and non-constant variance), we would expect this same relationship. Moreover, our results corroborate conclusions by others who evaluated pack stock grazing and reported reduced productivity, vegetation cover, and increased bare soil (Olson-Rutz et al. 1996b, Stohlgren et al. 1989, Cole et al. 2004), and reduced standing biomass (Olson-Rutz et al. 1996a, Cole et al. 2004). Despite the fact that most study sites received low to moderate levels of use, our results support those by Cole et al. (2004) who reported effects from pack stock grazing at modest intensity levels. Overall, these results support the use of bare soil as a monitoring indicator for meadows.

Model selection results also suggest that the effect of informal trails on streambank stability is greater at drier sites (i.e., streambanks with greater upland species cover). Data for these analyses are based on a relatively small sample size (n= 19) and show minor concern, especially at low values, for fit to a normal distribution suggesting a potential non-linear relationship. Given the relatively low sample size, data collection at additional sites would help to verify these reported relationships and likely reduce the range of the confidence intervals around the coefficient. Our reported confidence interval encompassed zero, but is biased towards negative values. Nonetheless, this finding is consistent with Trimble and Mendel (1995) who attributed decreased bank stability to livestock activity, and with Micheli and Kirchner (2002a) who reported that streambanks lacking wet meadow vegetation are roughly ten times more susceptible to erosion than streambanks with wet meadow vegetation. Overall, these results support the use of streambank stability for meadow streams as a monitoring indicator for the biological values described by the draft Merced and Tuolumne Wild and Scenic River Plans (NPS 2013a; NPS 2013b).

Results of model selection for meadow ecological condition and streambank ecological condition must be tempered by concerns regarding the fit of the best model to normal distributions and potential non-constant variance. In light of these concerns, exploration of data transformations and/or the fit of these data to non-linear models would be appropriate. Though somewhat inconclusive (i.e., r^2 value of 0.22, and due to concerns mentioned above), the best model to predict meadow ecological condition was the negative relationship to elevation. We note that our assessment of meadow ecological condition includes metrics such as total vegetation cover, bare ground cover, and litter depth that largely reflect attributes related to site productivity. Decreased ecological condition score with increased elevation is therefore consistent with Ratliff (1985) and Ratliff et al. (1987), who described meadow productivity decreasing as elevation increases for Sierra Nevada meadows. Ultimately, this relationship suggests that future analyses or monitoring to evaluate meadow ecological condition may benefit from stratifying sites based on elevation. The best model to predict streambank ecological condition was the interaction of use-related disturbance by vulnerability to disturbance; in addition to concerns described above, this result is further limited due to a relatively small sample size. Nonetheless, this interaction suggests that the overall effect of disturbance is reduced at more vulnerable sites. Although counterintuitive, this effect may be explained by considering that site vulnerability is predominantly influenced by metrics that reflect site wetness (i.e., four of the seven metrics that comprise summary scores for vulnerability to disturbance are streambank area, lakeshore area, pond area, and wet meadow area [which we double-weighted]). Micheli and Kirchner (2002b) reported that streambank strength and failure mechanics are correlated with vegetation density indicators, including stem counts, standing biomass per unit area, and the ratio of root mass to soil mass. It is therefore plausible, that use-related disturbance at wetter sites has a lower overall effect upon streambank ecological conditions than at drier sites due to compensation by factors such as higher vegetation density at wet sites.

Overall, for these results, relatively low r-square values (i.e., ranging from 0.22 to 0.48 for the best models), low sample size for the streambank data sets, as well as concerns regarding assumptions for linear regression, preclude strong inference. Nonetheless, we anticipate that the parameters and interactions described by these simple relationships would likely be valid components of more complex models seeking to quantify potential meadow response to stock use level or use-related disturbance. Furthermore, as the park improves stock use tracking and reporting, more accurate stock use numbers for future studies may help validate these conclusions.

4.3 Management context: suitability for use and meadows-of-concern

The biplot of ecological condition scores vs. vulnerability scores illustrates one way to interpret the results of this study in an applied management context, for the purpose of stratifying sites in terms of their relative suitability for use by pack stock. Our suggested delineations classify six sites as having low suitability for use; these are all the sites with high vulnerability to disturbance and may therefore have the greatest relative risk for use-related declines in ecological condition. The vast majority of sites (40) were classed as having moderate suitability for use ratings, and primarily included meadows with moderate ecological condition and vulnerability to disturbance ratings. We included sites with low ecological condition in the moderate suitability, to emphasize the need to investigate causes for the low condition and to facilitate improvement at these sites possibly through management actions. For example, future research might assess whether low values for ecological condition metrics are a consequence of limitations inherent to the environmental context of a site, or due to historic and/or current use-related disturbances. Seven sites classified as having high suitability are those with the lowest relative risk of decline from use-related disturbance. These sites have low vulnerability, and are therefore less susceptible to undesirable effects on meadow condition from low levels of use-related disturbance. In addition, these sites have relatively high ecological condition that could buffer against minor or short-term impacts.

Our examination of suitability ratings in conjunction with ratings for disturbance score and use levels identified four meadows-of-concern . These sites exhibited low to moderate suitability ratings and had high disturbance and use levels. These sites may be at relatively greater risk for decline in condition under current use patterns, and include Castle Camp, Miller Lake- North, Smedberg Lake, and Tilden Lake- South. They may warrant greater consideration for additional investigation and monitoring, and may be candidates for management actions to improve ecological condition or regulate use. In addition, we identified nine sites as potential meadows-of-concern , because they had low to moderate suitability, and have either high disturbance *or* high use. We also included one site with high suitability but also high disturbance and very high stock use. These sites are: Emeric Lake, Merced Lake- East, Merced Lake- Shore, Benson Lake, Hook Lake, Matterhorn Canyon, Miller Lake- South, Tilden- North and Upper Lyell- North. If use patterns or use-related disturbance change slightly, meadows –of-potential-concern could shift into the meadows-of-concern category.

We also noted two sites rated as high suitability that had no reported use, Merced Lake- West and Paradise. Their high suitability rating suggests that these sites may have greater relative capability to absorb use-related disturbance without exhibiting undesirable levels of diminished ecological condition. However, Merced Lake- West site was closed to free-range grazing approximately 20 years ago (Mark Fincher, NPS Yosemite Wilderness Division, pers. comm., 2013) due to excessive use and deteriorating conditions (Sharsmith 1961). This emphasizes the need to consider the history of use and management at these sites and underscores the importance of followup monitoring for any site receiving high amounts of use, regardless of its suitability.

We acknowledge two notable challenges regarding the use of summary scores and our approach to suggest suitability-for-use ratings. These include: 1) delineation of category divisions for summary scores and interpretation of the suitability-for-use regions, and 2) incorporating streambank ecological condition into a quantification of overall meadow ecological condition.

Our suggested suitability ratings are based on the 10^{th} and 90^{th} percentiles of summary scores and were driven by both professional judgement and apparent natural breaks that appeared relatively consistently across each data set. Divisions based on the highest and lowest 10% of scores is a conservative approach, that identifies few sites at both ends of the range and 80% of sites as moderate. This type of classification approach for low and high ratings conveys relative rank within the sample pool. Nonetheless, an effective management approach could be based on site-specific objectives and by considering the continuous nature of site rankings, rather than as discrete categories. This is a particularly important consideration for meadows on the border of lower suitability categories. For instance, we noted three sites, Doc Moyle's- East, Upper Lyell- South, and Upper Slide, that are rated as high suitability for use but are within 5% of the division to moderate suitability. Decline in meadow ecological conditions at Doc Moyle's- East, or increased vulnerability to disturbance at Upper Lyell- South and Upper Slide, could shift these sites to moderate suitability for use; this type of shift at Upper Lyell- South would qualify it as a potential meadow of concern.

Our approach to suggest site suitability for use was based primarily on meadow ecological condition by vulnerability, and was only qualitatively informed by streambank conditions because of the difficulty to quantitatively compare sites with and without defined stream channels. Nonetheless, it is plausible to speculate that degradation of streambank conditions may be equally, or perhaps more important in determining overall conditions and suitability for use at meadows with perennial streams; evaluations of Tuolumne Meadows by Cooper et al. (2006), Loehide et al. (2009), and NPS (2010), reported that meadow ecosystem dependence on depth to groundwater can be at least partially influenced by surface channel conditions. Similarly, Norton et al. (2011) reported that meadow degradation corresponds with channel widening. In this respect, it may be a justifiable priority to also monitor conditions at sites with defined channels, and especially those sites with low summary scores for streambank ecological condition, such as Middle Lyell and Upper Lyell- South.

4.4 Research needs and study limitations

It is important to emphasize that our assessments stem from single point-in-time surveys for these 53 meadows that were not randomly selected. Therefore, caution should be exercised in extrapolating the results of this study. On-going monitoring efforts at selected sites could augment this approach by incorporating additional data to better represent the natural ranges of variability of these metrics; such efforts could compare with conditions at strategic reference or sentinel sites. However, given the widespread distribution of past grazing and use across the park landscape (Snyder 2003), reference sites that may facilitate pairwise comparisons to sites with use have not yet been identified. Nonetheless, by identifying natural ranges of variability, our approach to suggest sites with low and high condition would be better informed. Such information could be valuable to develop site-specific, quantifiable objectives that facilitate conservation and/or recovery (see Science Advisory Board 2002). On-going monitoring would facilitate the evaluation of ecosystem trends, in terms of meadow resiliency to disturbance, and would supplement our approximation of ecological condition and vulnerability to disturbance.

Monitoring the amount of use is important to identify sites at risk for use-related decline, and can help prioritize sites for monitoring when resources and staffing are limited. Monitoring meadow condition over time is important to ensure that management action are triggered if condition trends decline below desired thresholds. In addition, research to evaluate the natural range of variation and potential effects of repeated (i.e., annual) disturbance at these sites is important to inform relationships between ecological condition and disturbance.

Resiliency (see Kauffman et al. 1997) likely determines important ecological aspects such as longevity of disturbance features and potential effects of disturbance to meadow ecology and hydrology. Although meadow resiliency has not been investigated for these sites, it is plausible that single or isolated disturbance from infrequent use may be relatively short-lived and could produce few long-lasting or detrimental effects on meadow condition. Conversely, use-related disturbance metrics may increase suddenly from one year of high use, or when meadows are more susceptible (i.e., sites with extensive seasonal and/or perennially wet soils), and may yield long-term ecological effects. Targeted monitoring or research studies could be appropriate for such scenarios, and facilitate important insight on meadow resilience to use-related disturbances and for input to state and transition models or other analyses of potential ecosystem trends. Important questions centered on resilience of meadows are appropriate for trampled wetlands, grazed areas, creek crossings or other disturbances to potentially sensitive meadow components.

Data for reported stock use levels, as well as use-related disturbance scores, were strongly right-skewed, in that the majority of sites had low values for these categories, while few sites had high values. For example, 23 sites had no reported use, and 5 had very high use levels. A potential bias induced by skewed data is that most of the sites are clustered near the origin and have little range of spread, while the few sites positioned farther along the x-axis can have a strong effect on the observed relationships. In addition, potential inaccuracies for reported stock use numbers can affect the strength of the model selection findings in this report. Roughly half the sites in this data set have varying levels of uncertainty regarding their reported and actual pack stock use. Park management at Yosemite is improving methods for stock use reporting and tracking (i.e., record keeping); this effort will help to improve the precision and accuracy of future studies that evaluate potential stock use-related effects.

Similarly, the lack of information on human foot traffic at these sites as a potential covariate may also be problematic for the results of these analyses. Hiking traffic can result in many trampling impacts (Price 1985). For instance, we observed and recorded extensive evidence of foot traffic at some sites with no reported stock use, including Merced Lake-Shore (adjacent to a High Sierra Camp) and Elizabeth Lake (a major day-hiking destination from Tuolumne Meadows). Although we focused on stock use, in part because of available records quantifying such use, it is important to acknowledge that these sites are also used by humans and may receive extensive foot traffic in some cases.

In addition, the behavior patterns of free-range pack stock at these sites have not been investigated; such studies have potential to further refine our understanding of stock use at these sites and the occurrence of use-related disturbance features. For example, spatial analyses of actual use behavior could identify preferred locations where stock either forage, loaf, or rest, and could facilitate a risk assessment for sites based on the potential overlap of stock use with sensitive meadow resources. Such information could be especially helpful to understand relationships of use-related disturbance and ecological conditions where sites have a large spatial extent, high ecological heterogenity (or patchiness), or where sites are relatively close to one another.

5.0 Conclusion

The results of this study present tools that could be used to guide and prioritize future efforts to monitor and manage meadows in Yosemite. Tools that group and prioritize sites for management consideration are useful and commonly used in conservation planning (Margules and Pressey 2000, Pressey and Cowling 2001, Noss et al. 2002), but it is important to acknowledge their inherent limitations and realize they are insufficient to replace the pragmatism and experience of resource managers (Pressey and Cowling 2001). Although meadows can be categorized to facilitate evaluation and general understanding, each remains distinct in terms of its ecological potential (Science Advisory Board 2002), site history and exposure to use, and hydrogeomorphic context (Weixelman et al. 2011). Some sites may be inherently limited in the level of ecological condition that can be achieved, even if all use-related disturbances are eliminated. Site-specific management prescriptions regarding meadow use could appropriately combine inference from these results with results from other studies. Other metrics currently in development, such as plant functional groups (USFS rangeland program) and hydrologic vulnerability using spectral reflectance data (USGS Yosemite Field Station), to refine our use of seral state for meadow ecological condition scores and wet and dry area for vulnerability to disturbance scores.

Managers are encouraged to scrutinize this approach. Given that natural divisions within ecological data sets are often subtle and asymmetric, alternative approaches to categorize these data sets exist. Our hope is that this approach and suggested ratings will help inform the development of a comprehensive framework for meadow management. Such a comprehensive approach could also consider ecosystem trends and resiliency, and site-specific concerns such as the presence of special status or rare species, sensitive habitats, archeological sites, and the potential for use-type conflicts.

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Appendix A. Study component protocols

Gridpoint Plot Collection

Before our initial field visit, we generated plot locations on a grid across each meadow in ArcMap 9.3.2 software. Grid spacing was 20m, 25m, or 30m depending on meadow size, with small meadows receiving the tighter spacing to increase sample size. We located each plot with Trimble Juno GPS units and re-logged its coordinates if adequate satellite reception was available. We then established a temporary 5x5m square plot and used the GPS data dictionary to record data on vegetation canopy cover, dominant plant species, substrate characteristics, and other metrics (Table A-1). We recorded most data as ocular estimates of cover class (Table A-2). To improve consistency among observers, we thoroughly trained field staff in visualizing cover and calibrated them at the start of each new meadow. In addition, the same staff collected all gridpoint data throughout the field season, which further minimized observer bias.

If a gridpoint was located in a non-meadow area[3], observers either relocated it by pacing 5m directly away from the non-meadow location or rejected the plot if relocating it did not resolve the situation. Observers recorded the plant association in rejected plots, if possible, so that some information was retained from those areas. In large meadows where gridpoints exceeded 90 plots, plant association only was recorded at odd-numbered plots due to time constraints.

Table A-1. Data collected at each gridpoint plot.

Data Field	Definition
Total vegetation	Total cover of all vascular vegetation in the plot (could not exceed 100%, does not account for layered vegetation). Desiccated or senesced vegetation at the end of the season was visualized in its fully alive condition.
Graminoid cover[1]	Total cover of all grasses, sedges, and rushes
Forb cover[1]	Total cover of all non-graminoid herbaceous species
Subshrub cover[1]	Total cover of all shrub species with height generally less than 0.5m at maturity
Shrub cover[1]	Total cover of all shrub species with height generally greater than 0.5m at maturity
Fern / allies cover[1]	Total cover of all fern and fern ally species
# Seedling/saplings[1]	Stem count of trees less than 2m in height that are rooted in the plot.
Dominant species (up to 3)	Up to three dominant species and their cover were recorded at each plot. Dominant 1 was the species with the greatest cover. Dominant 2 and Dominant 3 were recorded if they had at least half the relative cover of Dominant 1.
Other species [1] (up to 3)	Up to three other common species (with less than half the relative cover of Dominant Species 1) were recorded. These were recorded in decreasing order of cover, but no cover value was recorded.
Association name	The vegetation community of the plot and surrounding area (10m in any direction) was assigned a name from the Yosemite floristic classification (Moore and Johnson 2011). This field characterized a larger area than the 5x5m plot, to minimize the effect of plots falling on an anomalous concentration of a particular species.

[3] Criteria included: in a creek or forest, on the transition between two distinct plant communities, on rocks or wood that were greater than 10% cover, tree or shrub cover greater than 25%, or on a meadow border with significant needle cast from surrounding forest

Table A-1. Data collected at each gridpoint plot.

Data Field	Definition
Association comments	If the community did not fit any of the association names from the Yosemite floristic classification (Moore and Johnson 2011), a new name and comment was recorded in this field.

Table A-1 (continued). Data collected at each gridpoint plot.

Data Field	Definition
Moss	Cover of all moss in the plot. Cover for dormant moss was estimated in a fully green condition.
Bare ground	Cover of all bare ground was included in this estimate. Gravel (less than 2cm diameter) was included in bare ground. If bare ground was covered by water, we included an estimate of the bare ground under water.
Litter	Ground-level plant material that was dead before the current year's growing season, either detached or present in the form of thatch (in perennial graminoid communities). If litter was covered by water, we included underwater litter in the estimate.
Water	Cover of all standing or flowing water (regardless of depth) at the time of plot collection.
Burrow	Cover of all burrow holes and excavation tailings.
# Burrow holes	All small mammal burrow entrances (recent or old), were counted in the plot.
Manure	Cover of pack stock manure (fresh or old).
Hoof punches	Cover of distinguishable hoof marks >1cm deep, which break through the root mat in vegetated
Hoof prints	Cover of distinguishable hoof prints <1cm deep that do not break through the root mat were
Grazed vegetation	Cover of vegetation that had been grazed, regardless of residual height.
Soil moisture[1]	Moisture rating for soil surface (top 2cm) of "inundated", "saturated", "moist", or "dry"
Litter depth	Distance from the soil surface to the surface of the litter/thatch, measured at two randomly selected locations in the plot. Random locations were selected by tossing a pin flag over the shoulder from plot center.
Vegetation height[2]	Distance from soil surface to the top level of dominant herbaceous canopy (generally vegetative structures, not inflorescences) measured at the two randomly-selected locations in the plot.

[1] These fields were added for meadows visited in 2010 or later; they were not recorded for 2008 meadows.
[2] For 2008 meadows, vegetation height of the highest part of a dominant species plant (usually a floral structure) was measured. Therefore, vegetation heights are not comparable between meadows surveyed in in 2008 vs. 2010-2011 sampling efforts.

Table A-2. Cover class breaks for gridpoint plot data.

Cover Class	Percent Cover
T	Trace (<1%)
P	Present 1-5%
1a	6-10%
1b	11-15%
02	16-25%
03	26-35%
04	36-45%
5a[1]	46-50%
5b[1]	51-55%
06	56-65%
07	66-75%
08	76-85%
09	86-95%

10	96-100%
[1]5a and 5b cover classes provide estimates for slightly less than half, and slightly more than half of 100% cover.	

We downloaded gridpoint plot data from the GPS units and exported them to ArcMap, Microsoft Access, and Microsoft Excel for summary and analysis. We converted cover class data to numerical values (using the midpoint of each cover class) for metrics where mean values per meadow were of interest (as in vegetation cover or bare ground). We derived spatial extent of other metrics (e.g. conifer encroachment, small mammal burrowing or pack stock disturbance) by calculating the proportion of plots containing these features of interest.

Mapping and Quantifying Anthropogenic Disturbance

We performed a census through systematic coverage of all meadows to record human and pack stock disturbance and other features relevant for meadow characterization (Table A-3). We performed this census by walking the entire meadow area in parallel transects approximately 25m apart. Certain features (such as informal trails, manure, or hoof punching) outside the meadow boundary but within 25m were included because of their potential effects on adjacent meadow areas. We mapped all features with Juno ST GPS units and collected data corresponding to each feature with the GPS data dictionary. We recorded wildlife observations in field notes for each meadow except in the case of special status amphibian species Yosemite toad (*Bufo canorus*) and mountain yellow legged frog (*Rana muscosa*), which we mapped with GPS points.

We exported mapped features using Pathfinder Office software to create shapefiles in ArcMap 10 and edited line and area features in a standardized way to correct for outlying vertices. We displayed these features on maps of each meadow in addition to vegetation communities from gridpoint plots or early season wet soils. We summarized data by feature type and divided by meadow area to normalize for meadow size, allowing for more accurate comparison among meadows.

Table A-3. Mapped anthropogenic disturbance and other features.

Feature Name	Feature Type	Definition
Bare ground	Area	Area at least $10m^2$ with <25% vegetation cover (<15% cover in *Carex filifolia* communities). Attributed with "completely barren," "mostly barren," or <25% vegetation. Also attributed with possible cause, such as "alluvial deposits," "mammal burrows," "human," "stock", or "unknown".
Headcut	Point	A sudden change in elevation or knickpoint at the leading edge of a gully. Headcuts are observed where sheet flow occurs above the headcut (and more hydric vegetation is supported) and flow is channeled below the headcut (where vegetation communities are more xeric due to the lowered water table).
Pond	Area	Area at least $10m^2$ that has standing water for most of the growing season and observable "banks". Amphibian presence and range of water depth on the survey date were recorded. Ponds large and permanent enough to be mapped using DOQQ imagery were not mapped in the field.
Informal Trail	Line	All social trails (not formal hiking trails) at least 7m long were mapped with line features according to the Yosemite National Park protocol for informal trails mapping (Yosemite National Park 2009).
Fire ring	Point	Usually circular arrangement of rocks with fire scarring on the interior surfaces. No distinction was made between fire rings showing current use and old rings.

Table A-3. Mapped anthropogenic disturbance and other features.

Feature Name	Feature Type	Definition
Stock Camp	Area	The perimeter of the camp (area showing impact from tents, pack stock holding areas, etc) was mapped. Stock camps were mapped outside the 25m meadow buffer, only for display on site maps.
Roll pit	Area	A defined area of disturbed bare ground at least $10m^2$ with a dished appearance, created by pack stock.
Manure	Point	Pack stock manure was attributed with density (piles per $25m^2$), either "single," low (2 piles)", "medium (3-4 piles)," or "high (5+ piles)".
Hoof punches	Point	Any distinguishable hoof marks >1cm deep, penetrating the root mat in vegetated areas. Hoof punches were attributed with the same density values as manure, and surrounding plant community was recorded.
Trampling	Area	Areas at least $10m^2$ with often overlapping hoof punches that are less than 0.5m apart. Soils usually have a churned appearance. Surrounding plant community was recorded.
Grazed area	Area	Areas at least $10m^2$ that have vegetation continuously grazed to <5cm in height. Areas where vegetation was taller than 5cm but had been continuously grazed, as was the case for species such as *Carex vesicaria* (inflated sedge) and *Carex utriculata* (bladder sedge), were also mapped. Plant community was recorded.

Stream monitoring (MIM)

We used procedures described in Multiple Indicator Monitoring (MIM) of Stream Channels and Streamside Vegetation (Burton et al. 2011) to survey nineteen meadow sites during 2008-2011. Surveys were conducted in August and September, after stream levels had receded to base flow and during the peak period of stock use. Brief description of the monitoring protocol is provided below; detailed information on this protocol can be found in the technical reference (Burton et al. 2011).

Criteria defined in Burton et al. (2011) recommends protocol application on wadeable, low-gradient, alluvial channels with well-developed channel banks (dominated by meadow or riparian vegetation, and having well developed scour lines at base flow). We assessed each site for its suitability to implement the MIM protocol. Minor exceptions from the authors recommended application included: 1) small areas of channels were occasionally un-wadable due to pool depth; and, 2) surveyed streams included intermittent channels with well defined scour lines. A variety of methods were used to overcome challenges from pool depth, including ocular estimation of data, relocation of sample points and/or transect.

Site selection was prioritized as those that receive pack stock use and would be sensitive to management actions. A designated monitoring area (DMA) was established at each site, in areas with homogenous physical characteristics, and vegetation composition and structure. After stratification, we selected and delineated a DMA at each site by following guidelines detailed in Burton et al. (2011). DMA length was proportional to average channel width across the meadow complex. Minimum requirements for a DMA for any stream channel with a mean width equal to, or less than, 5m was 110m in length. For channels averaging greater than 5 meters in width, we calculated DMA length to be 20 times the average channel width. The DMA starting point was randomly chosen within the DMA, whereby we implemented the systematic, random-stratified sample design to obtain data on vegetation plot composition and structure in relation to the physical characteristics of the stream channel.

Table A-4. Multiple Indicator Monitoring (MIM) metrics for subalpine meadow stream assessments.

Indicator Name	Metric Type	Description/Use
Woody Species Use	short-term	Used to monitor the severity of livestock grazing (adapted from U.S. Bureau of Land Management 1996a). Woody species use is a percent estimate of the extent of browse (terminal bud removal) on current season's growth of available woody plants (up to 2m in height and within 2 m of the greenline.
Stubble Height	short-term	Measures residual height of forage species preferred by stock. Approximate height of the key herbaceous forage species was recorded within 5 cm (2 in) of sampling frame handle. If more than one key species was present, only that closest to the handle was selected. Stubble height is recorded regardless of whether or not grazing is evident.
Steambank Alteration	short-term	Used to measure presence and absence of stock at the site and provides an easily comparable quantification of current use severity. Alteration must be from the current grazing season, identifiable as being made by a horse or a mule. Hoof punches of deer or people are not counted. The number of hoof prints at each plot is counted (up to 5).
Greenline Composition	long-term	Used to characterize the vegetation of the riparian corridor. Composition is given as percent foliar cover of each constituent in the sample plot that covers at least 10% of plot area. Constituents include vascular plants, anchored wood, or embedded rock. Wood and rock must be greater than 15 cm (6 in) in diameter. Species names are recorded for all vascular plants. Areas of understory and overstory are counted separately. Cover of bare ground, litter, and non-vascular plants are not included.
Woody Species Height Class	long-term	Used to calculate woody biomass production and shading of the water in the stream channel. Can also be used to monitor changes in establishment of woody plant species over time. Height classes for woody species were recorded for all plants rooted within or having foliar cover above the sampling plot. Height class delineations as defined in Burton et al. (2011).
Stream Bank Stability and Cover	long-term	Summarizes streambank stability at each plot. Takes bank type into consideration (erosional or depositional), amount vegetation present (covered or uncovered), and the presence of active erosion features (fracture, slump, slough, eroding, or absent). Depositional plots were those where clay, silt, sand, or gravel, were actively being deposited by the stream, often at channel margins adjacent to the greenline. "Covered" plots were those with at least 50% of the area between the greenline and the scour line supported with perennial vegetation, large rock, or embedded wood. "Stable" plots were those with no erosion features present.
Greenline to Greenline Width (GGW)	long-term	Measures width of the channel by using the greenline to define the channel margins. GGW is often synonymous with bankfull width, as the greenline is typically at or near bankfull stage. GGW is measured perpendicular to flow at every sample plot. GGW is an effective measure of large or rapid increases in stream width that may be the result of local disturbances and channel instability.
Substrate	long-term	Estimates bed particle size distribution useful in indicating the condition of and monitoring trends in the energy balance of the stream. At every other plot, 10 bed particles are selected at evenly spaced intervals across the active channel, providing a sample size of at least 200 (10 particles at each of 20 transects) for each stream.

Vegetation sampling methods used a double Daubenmire quadrat frame (40 X 100 cm) at regularly spaced intervals (adjusted according to DMA length) along each bank. Sampling intervals provided at least 80 plots per DMA. We recorded woody species use and height in larger plots (40 x 200 cm) expanding outward from each quadrat location. Physical channel characteristics were obtained from cross-sections established at each quadrat location. At each cross-section, we measured channel width. At every other cross-section, we measured streambed substrate size by randomly selecting 10 particles at evenly-spaced intervals across the channel.

We collected spatial data using Trimble Juno GPS units, including meadow-stream complex and DMA end-point locations. These data were processed using Trimble TerraSync Software. Tabular data that included vegetation composition, structure, and use, as well as physical cross-section data, were entered directly into Microsoft Excel worksheets provided by Burton et al. (2011).

Following collection, data analyses were conducted using data analysis modules provided by Burton et al. (2011). Using the observed physical and vegetation data, 25 indicators were generated for each site. Of the 25 indicators, we determined that 13 were most relevant to summarize hydrologic and ecological conditions at these subalpine stream sites (Table 5). Condition indicators were then assigned categorical condition rating classes based on the criteria in Burton et al. (2011) (Tables 6 and 7).

In addition to the suite of indicators provided by the MIM protocol, we recorded the frequency and severity of headcut erosion features due to their ability to alter site hydrology and subsequently affect the majority of other metrics and indices. This addition was made between 2009 and 2010 survey seasons, and thus was not recorded for the Matterhorn Canyon and Upper Lyell-South sites. We estimated headcut severity by assessing width, depth, and length of observed headcuts within the DMA, and classified severity into low, moderate and high ratings. Low-severity headcuts were less than 1m long/wide/deep, moderate-severity headcuts were generally about 3m long/wide/deep. High-severity headcuts would be greater than 3m long/wide/deep, but we did not encounter headcuts of this severity at any site.

Table A-5. MIM condition indicators for subalpine meadow stream assessments (from Burton et al. 2011).

Stream Survey Metric	Indicator Type	Description/Measure
Site Ecological Status Rating	Rating	Weighted average of ecological status ratings for all species at the site. Dominant plants are double weighted. Ecological status is calculated using plant successional status ratings (Weixelman & Zamudio 2001) and Winward's Riparian Capability Groups.
Site Wetland Rating	Rating	Weighted average of wetland ratings for all species at the site as computed using the Wetland Indicator Status of Reed (1996).
Site Winward Greenline Stability	Rating	Weighted average of Winward stability ratings for all species at the site. Dominant plants are double weighted.
Plant Diversity	Index	Measure of species richness at the site. Species richness is calculated by multiplying the number of plant species by average species composition of the plots divided by standard deviation of relative plant species composition.
Biomass Index	Index	Measure of vegetation density on the greenline at the site.
Percent Woody	Proportion	Percentage of plots containing woody plants. Woody plants include shrubs, sub-shrubs, and rhizomatous woody species, such as willows.
% Rhizomatous Woody	Proportion	Percentage of woody plants that are rhizomatous woody species, such as willows.
Percent Hydric	Proportion	Percentage of plots containing hydric plants, including willows, *Carex* and other water-loving plants.
Percent Hydric Herbaceous	Proportion	Percentage of plots containing herbaceous hydric plants (i.e., excluding woody species).
Mean Alteration	Proportion	Arithmetic mean of plot alteration values (for all plots on the survey reach).
Mean Woody Use	Proportion	Arithmetic mean of percent woody use (for all plots on the survey reach).
Percent Stable	Proportion	Percent of total plots classified as “stable” (i.e., those with no active erosion). Stream bank stability is a composite index of the following bank characteristics: type (erosional or depositional), vegetative cover (uncovered=<50%, covered=>50%), and observed erosion feature frequency (fracture, slump block, slough, erosion, or absent). Sites with lower stability values have a combination of these indicators.
Percent Bank Cover	Proportion	Percent of total plots classified as “covered” (i.e., those that have more than 50% vegetation cover from the plot to the scour line).

Table A-6. MIM Indicator Condition classes (scale of 0-100) for meadow stream assessments (from Burton et al. 2011).

Ecological Status Rating	Ecological Status Classification	Site Wetland Rating	Site Wetland Classification	Vegetation Biomass Index	Vegetation Biomass Classification
0-15	Very Early	0-15 (UPL, UPL+)	Very poor	<10	Very Low
16-40	Early	16-40 (FACU- , FACU, FACU+)	Poor	10 - 20	Low
41-60	Mid	41-60 (FAC-, FAC, FAC+)	Fair	20 - 30	Moderate
61-85	Late	61-85 (FACW-, FACW, FACW+)	Good	30 - 40	High
86+	(PNC) Potential Natural Community	86+ (OBL-, OBL)	Very Good	>40	Very High

Table A-7. MIM Rating and Index Condition classes (scale of 0-10) for meadow stream assessments (from Burton et al. 2011).

Modified Winward Greenline Stability Rating	Winward Stability Classification	Plant Diversity Index	Plant Diversity Classification	Shade Index	Shade Classification
<4	Low	<1	Very Low	<.5	Very Low
5-6	Mid	1-2	Low	.5-0.99	Low
>8	High	3-4	Moderate	1-1.99	Moderate
		5-6	High	2-3.99	High
		>6	Very High	>4	Very High

Appendix B. Vegetation cover and bare soil correction factor

Table B-1. Mean vegetation and bare ground cover per plot, sorted by most common vegetation types, for meadows sampled in 2008 and 2010-2011. The mean difference (bottom right) are the values for the correction factor that were applied to 2008 cover values to correct for differences in ocular estimate methods between years.

	2008			2010-2011			Difference	
Plant Association	**#plots**	**Veg %cover**	**Bare %cover**	**#plots**	**Veg %cover**	**Bare %cover**	**Veg %cover**	**Bare %cover**
Calamagrostis breweri/ Vaccinium caespitosum	408	71.0	7.0	154	51.6	12.2	19.4	-5.2
Ptilagrostis kingii	269	76.9	7.9	89	56.0	9.9	20.9	-2.0
Calamagrostis breweri/ Oreostemma alpigenum	214	68.9	9.1	111	49.5	15.3	19.4	-6.2
Deschampsia cespitosa	182	72.6	7.8	93	52.1	14.8	20.5	-7.0
Carex filifolia	144	56.1	28.9	88	34.8	40.7	21.3	-11.8
Carex vesicaria- C. utriculata	93	69.1	10.0	280	47.6	16.6	21.5	-6.6
Calamagrosts breweri	75	70.0	12.0	26	39.4	25.8	30.6	-13.8
Carex scopulorum	56	70.2	10.8	30	50.3	15.6	19.9	-4.8
Oreostemma alpigenum	54	66.0	12.0	24	47.1	24.1	18.9	-12.1
Deschampsia cespitosa- Polygonum bistortoides	49	78.4	5.5	35	58.2	12.7	20.2	-7.2
Vaccinium caespitosum	15	68.7	12.5	37	52.5	19.2	16.2	-6.7
						Mean difference	**20.8**	**-7.6**

Appendix C. Values and relativized scores for assessment metrics

Table C-1. Metric values, by site, for metrics used in meadow ecological condition scores. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation highlighted in grey and with bold font. Bolded site names are those sites surveyed in 2008 with corrected percent cover values for vegetation cover and bare ground.

Site Name	Total Vegetation Cover (%)			Bare ground cover (%)			Early seral vegetation		Late seral vegetation		Litter depth		
	Mean	StdDev	Score	Mean	StdDev	Score	%Comp	Score	%Comp	Score	Mean (cm)	StdDev	Score
1-Babcock Lake	51.0	14.9	84%	14.4	18.6	61%	15.0%	47%	76.6%	77%	1.6	2.4	48%
2-Doc Moyle's- East	50.9	14.1	84%	8.4	12.1	77%	7.4%	74%	84.9%	85%	3.0	2.3	91%
3-Doc Moyle's- West	49.0	14.0	81%	13.9	13.4	62%	8.3%	71%	89.3%	89%	3.2	2.9	98%
4-E Sunrise Lake	56.1	13.6	92%	15.9	10.2	57%	14.2%	50%	82.9%	83%	1.1	1.2	32%
5-Echo Lake	60.0	10.3	99%	14.9	11.4	60%	9.1%	68%	87.4%	87%	1.9	2.7	59%
6-Emeric Lake	48.9	14.5	80%	18.5	21.6	50%	19.2%	33%	77.5%	78%	1.0	1.1	30%
7-Long Meadow	54.1	11.1	89%	17.9	11.4	51%	15.7%	45%	83.0%	83%	1.2	1.4	36%
8-Matthes Lake	47.0	11.7	77%	11.9	8.1	68%	25.0%	86%	74.4%	88%	1.3	0.9	39%
9-Merced Lake- East	37.3	9.3	61%	**36.9**	21.5	0%	0.0%	100%	**100.0%**	100%	2.8	2.0	84%
10-Merced Lake- Shore	52.8	15.0	87%	6.1	10.2	83%	3.5%	88%	93.4%	93%	3.0	2.4	90%
11-Merced Lake- West	55.2	21.0	91%	1.9	2.5	95%	0.0%	100%	78.8%	79%	7.9	14.7	100%
12-Red Peak- North	48.9	19.2	81%	17.2	22.5	53%	4.2%	85%	89.3%	89%	2.5	3.0	76%
13-Red Peak- South	60.2	13.7	99%	4.1	10.8	89%	19.4%	32%	75.6%	76%	2.7	3.1	82%
14-Snow Flat	45.3	9.6	75%	11.2	6.1	70%	27.4%	3%	63.6%	64%	1.5	1.2	46%
15-Triple Peak- North	57.7	14.8	95%	12.7	13.5	65%	19.4%	32%	70.8%	71%	1.2	1.0	36%
16-Triple Peak- South	54.0	13.2	89%	9.4	14.2	75%	14.7%	48%	76.1%	76%	1.8	1.9	55%
17-Turner Lake	54.9	11.8	90%	10.9	14.6	70%	20.7%	27%	71.4%	71%	1.6	2.2	48%
18-Washburn Lake	57.4	19.6	95%	9.3	11.1	75%	0.0%	100%	98.2%	98%	2.7	2.1	82%
19-Benson Lake	58.1	10.0	96%	13.8	12.7	62%	4.2%	85%	95.8%	96%	2.7	2.5	81%
20-Castle Camp	54.5	18.5	90%	22.2	17.1	40%	5.3%	81%	82.0%	82%	2.7	2.7	82%
21-Cold Canyon	51.6	15.4	85%	24.3	18.2	34%	6.1%	78%	83.0%	83%	2.1	2.5	63%
22-Cold Canyon- North	41.4	9.4	68%	15.4	19.4	58%	2.7%	90%	87.1%	87%	1.0	1.0	30%
23-Dog Lake	43.6	14.9	72%	14.9	7.3	60%	14.8%	48%	76.8%	77%	1.3	1.5	39%
24-Dog Lake East	44.0	8.2	72%	13.8	6.8	62%	23.0%	19%	70.6%	71%	1.5	0.8	47%
25-Dorothy Lake	46.1	14.8	76%	20.6	13.8	44%	13.1%	54%	75.5%	75%	0.9	1.4	26%
26-E of Gaylor Pit	50.3	15.7	83%	18.5	12.6	50%	11.6%	59%	78.4%	78%	2.1	1.5	62%
27-Elbow Hill	45.4	7.7	75%	30.8	15.6	16%	18.7%	34%	40.6%	41%	1.2	1.2	35%

Table C-1 (continued). Metric values, by site, for metrics used in meadow ecological condition scores. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation highlighted in grey and with bold font. Bolded site names are those sites surveyed in 2008 with corrected percent cover values for vegetation cover and bare ground.

Site Name	Total Vegetation Cover (%)			Bare ground cover (%)			Early seral vegetation		Late seral vegetation		Litter depth		
	Mean	StdDev	Score	Mean	StdDev	Score	%Comp	Score	%Comp	Score	Mean (cm)	StdDev	Score
28-Elizabeth Lake	53.5	14.8	88%	11.6	4.9	68%	16.0%	43%	81.9%	82%	1.2	1.1	36%
29-Grace Meadows	53.1	14.1	87%	19.5	15.4	47%	17.1%	40%	69.7%	70%	1.1	1.1	32%
30-Grace North	49.4	11.3	81%	21.9	12.5	41%	4.4%	84%	74.3%	74%	0.7	0.9	22%
31-Harden Lake	50.8	11.6	84%	9.6	8.3	74%	1.4%	95%	46.3%	46%	**3.3**	3.3	100%
32-Hook Lake	51.6	13.3	85%	21.1	13.9	43%	15.4%	46%	74.7%	75%	2.4	3.4	72%
33-José's Camp	**60.7**	14.3	100%	13.9	12.8	62%	2.5%	91%	86.5%	87%	0.9	1.3	28%
34-Lower Kerrick	46.1	13.0	76%	28.9	19.4	22%	0.6%	98%	92.4%	92%	0.9	1.2	28%
35-Lower Lyell	37.4	17.6	62%	31.7	16.9	14%	12.7%	55%	59.8%	60%	1.4	2.0	41%
36-Matterhorn Canyon	55.7	15.3	92%	18.8	16.9	49%	5.7%	80%	86.4%	86%	1.9	2.8	57%
37-Middle Lyell	42.5	14.5	70%	27.5	17.7	25%	4.0%	12%	87.5%	74%	1.4	2.0	44%
38-Miller Lake-North	45.9	13.1	76%	20.6	12.8	44%	21.6%	24%	74.1%	74%	2.7	2.8	81%
39-Miller Lake-South	40.5	15.0	67%	21.0	14.1	43%	14.2%	50%	83.0%	83%	2.2	2.0	65%
40-Paradise	55.1	11.5	91%	10.9	12.5	70%	1.9%	93%	86.3%	86%	2.8	2.4	84%
41-Rock Island Pass	47.0	13.0	77%	26.2	18.2	29%	1.0%	96%	80.9%	81%	0.5	0.5	16%
42-Rodgers Meadow	43.7	10.9	72%	28.9	19.3	22%	22.9%	19%	66.7%	67%	1.2	1.7	37%
43-S of Matterhorn	49.4	11.8	81%	17.1	13.0	54%	7.1%	75%	70.4%	70%	2.4	3.0	73%
44-Smedberg Lake	52.6	13.1	87%	17.8	11.9	52%	**28.4%**	0%	70.9%	71%	1.9	2.8	59%
45-Tilden Lake- North	50.8	11.9	84%	20.7	14.6	44%	14.9%	48%	80.2%	80%	1.8	2.7	55%
46-Tilden Lake- South	56.8	10.2	94%	16.5	11.1	55%	24.0%	15%	70.6%	71%	1.6	1.7	48%
47-Twin Lakes	44.6	16.4	73%	16.7	15.8	55%	5.5%	81%	85.2%	85%	1.2	1.1	36%
48-Upper Kerrick	46.3	14.9	76%	20.2	11.6	45%	20.5%	28%	75.2%	75%	1.3	2.2	39%
49-Upper Lyell- North	53.3	14.8	88%	15.3	10.3	58%	12.0%	58%	63.3%	63%	2.4	2.6	73%
50-Upper Lyell- South	49.8	27.4	82%	16.2	13.2	56%	13.5%	52%	71.4%	71%	2.2	1.9	67%
51-Upper Slide	42.5	16.7	70%	23.1	17.4	37%	1.6%	95%	95.1%	95%	1.2	2.0	35%
52-W of Tilden	56.4	11.5	93%	14.5	7.3	61%	5.5%	81%	80.2%	80%	2.7	3.0	82%
53-Wilma Lake	40.4	17.7	67%	17.6	20.7	52%	0.0%	100%	84.0%	84%	2.3	2.1	69%

Table C-2. Values and relativized scores for metrics used in ecological condition of meadow streams. Maximum value used for score calculations are highlighted in grey and with bold font. Only meadows with stream survey data are included in this table.

	Site Name	Ecological Status	Score Ecol. status	%UPL and FACU species	Score %UPL and FACU	Veg. Biomass Index	Score Biomass Index	Bank Stability	Score Bank Stability	Shade Index	Score Shade Index
Merced Watershed	3-Doc Moyle's-West	**100**	100%	0.1	99%	71	68%	88	88%	0	0%
	6-Emeric Lake	88	88%	2.4	84%	61	59%	81	81%	0.01	14%
	12-Red Peak-North	**100**	100%	2.7	82%	76	73%	93	93%	0.03	42%
	16-Triple Peak-South	**100**	100%	1.8	88%	70	67%	54	54%	0	0%
	17-Turner Lake	**100**	100%	1.4	90%	75	72%	84	84%	**0.07**	100%
Tuolumne Watershed	20-Castle Camp	**100**	100%	8.5	43%	60	58%	81	81%	0.01	14%
	21-Cold Canyon	87	87%	11.4	24%	72	69%	85	85%	0.06	85%
	26-E of Gaylor Pit	81	81%	6.3	58%	87	84%	78	78%	0	0%
	29-Grace Meadow	85	85%	0.8	95%	96	92%	98	98%	0.01	14%
	34-Lower Kerrick	**100**	100%	3.3	78%	88	85%	80	80%	0.01	14%
	36-Matterhorn Canyon	97	97%	6.2	59%	78	75%	45	45%	0.02	29%
	37-Middle Lyell	73	73%	28.6	0%	66	63%	52	52%	0	0%
	42-Rodgers Meadow	89	89%	0.2	99%	82	79%	98	98%	0.03	42%
	44-Smedberg Lake	99	99%	4.7	69%	84	81%	91	91%	0.01	14%
	47-Twin Lakes	98	98%	1.4	91%	72	69%	92	92%	0.05	71%
	49-Upper Lyell-North	**100**	100%	6.4	57%	66	63%	61	61%	0	0%
	50-Upper Lyell-South	94	94%	**15.0**	0%	41	39%	43	43%	0	0%
	51-Upper Slide	**100**	100%	0.2	99%	**104**	100%	**100**	100%	0.02	28%
	52-W of Tilden	**100**	100%	4.6	69%	91	88%	85	85%	0.01	14%

Table C-3. Values and relativized scores for metrics contributing to vulnerability to use. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation are highlighted in grey and with bold font.

Site Name	Elevation		Slope		Streambank		Ponds		Lakeshore		Perennial wet		Dry meadow	
	(m)	Score	(%)	Score	%area	Score	%area	Score	%area	Score	OBL	Score	%UPL	Score
1-Babcock Lake	2738	89%	1.6	16%	0.0	0%	6.1	61%	0.0	0%	32.9	34%	5.4	10%
2-Doc Moyle's-East	2845	93%	2.1	22%	3.5	65%	0.3	3%	0.0	0%	58.2	60%	12.9	23%
3-Doc Moyle's-West	2836	92%	2.8	30%	4.5	85%	12.0	100%	0.0	0%	72.1	74%	0.0	0%
4-E Sunrise Lake	2873	94%	8.2	85%	0.1	2%	0.5	5%	1.3	64%	16.0	16%	11.2	20%
5-Echo Lake	2852	93%	5.3	55%	2.8	52%	0.0	0%	0.7	34%	8.8	9%	29.3	52%
6-Emeric Lake	2846	93%	3.0	31%	1.4	27%	0.0	0%	0.7	35%	24.6	25%	22.6	41%
7-Long Meadow	2896	94%	4.3	45%	2.1	39%	0.1	1%	0.0	0%	13.5	14%	10.7	19%
8-Matthes Lake	2938	96%	3.6	38%	1.3	25%	2.3	23%	0.5	23%	30.5	31%	9.9	18%
9-Merced Lake-East	2231	73%	1.3	14%	0.0	0%	0.0	0%	0.0	0%	**97.6**	100%	0.0	0%
10-Merced Lake-Shore	2195	71%	4.3	45%	1.3	24%	0.0	0%	**2.1**	100%	75.4	77%	0.0	0%
11-Merced Lake-West	2215	72%	2.8	29%	0.0	0%	0.0	0%	0.0	0%	89.9	92%	0.0	0%
12-Red Peak-North	2858	93%	2.7	28%	4.4	82%	8.5	86%	0.0	0%	57.3	59%	7.8	14%
13-Red Peak-South	2894	94%	6.8	71%	2.3	43%	5.2	52%	0.0	0%	32.4	33%	24.6	44%
14-Snow Flat	2670	87%	1.3	13%	1.5	28%	0.1	1%	0.0	0%	33.8	35%	8.7	16%
15-Triple Peak-North	2749	89%	2.3	24%	3.5	65%	0.5	5%	0.0	0%	16.7	17%	14.4	26%
16-Triple Peak-South	2762	90%	2.1	22%	5.3	100%	0.0	0%	0.0	0%	18.9	19%	27.1	49%
17-Turner Lake	2909	95%	3.4	35%	4.5	85%	0.3	3%	0.6	29%	36.6	38%	9.7	17%
18-Washburn Lake	2318	75%	4.5	46%	3.8	71%	0.5	5%	3.0	100%	86.7	89%	0.9	2%
19-Benson Lake	2316	75%	1.9	20%	0.0	0%	6.8	68%	0.0	0%	38.7	40%	0.0	0%
20-Castle Camp	2673	87%	3.0	31%	4.3	81%	1.0	10%	0.0	0%	21.3	22%	7.0	13%
21-Cold Canyon	2652	86%	1.6	17%	1.4	26%	1.6	16%	0.0	0%	8.4	9%	24.5	44%
22-Cold Canyon-North	2658	87%	3.2	33%	3.2	59%	0.2	2%	0.0	0%	7.0	7%	17.0	30%
23-Dog Lake	2795	91%	1.8	19%	1.1	21%	0.0	0%	1.9	92%	10.2	10%	27.4	49%

Table C-3. Values and relativized scores for metrics contributing to vulnerability to use. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation are highlighted in grey and with bold font.

Site Name	Elevation		Slope		Streambank		Ponds		Lakeshore		Perennial wet		Dry meadow	
	(m)	Score	(%)	Score	%area	Score	%area	Score	%area	Score	OBL	Score	%UPL	Score
24-Dog Lake East	2816	92%	1.6	17%	4.0	76%	0.0	0%	0.0	0%	11.0	11%	**55.8**	100%
25-Dorothy Lake	2865	93%	2.9	30%	0.0	0%	3.0	30%	1.4	66%	14.9	15%	6.0	11%
26-E of Gaylor Pit	2841	92%	2.4	25%	3.4	65%	0.3	3%	0.0	0%	2.5	3%	37.9	68%
27-Elbow Hill	2658	87%	1.6	17%	0.1	2%	0.7	7%	0.0	0%	41.5	42%	7.2	13%
28-Elizabeth Lake	2890	94%	3.1	32%	3.1	57%	0.0	0%	0.6	29%	23.0	24%	14.7	26%
29-Grace Meadows	2646	86%	2.6	27%	2.1	40%	1.5	15%	0.0	0%	23.3	24%	16.3	29%
30-Grace North	2658	87%	7.7	80%	1.3	24%	0.0	0%	0.0	0%	24.1	25%	0.0	0%
31-Harden Lake	2280	74%	2.4	25%	0.0	0%	0.1	1%	0.0	0%	61.4	63%	0.0	0%
32-Hook Lake	2865	93%	2.9	30%	0.0	0%	1.1	12%	0.0	0%	26.1	27%	20.2	36%
33-José's Camp	2755	90%	6.2	65%	2.7	50%	1.9	19%	0.0	0%	5.7	6%	9.7	17%
34-Lower Kerrick	2560	83%	3.6	38%	1.7	32%	0.2	3%	0.0	0%	6.0	6%	53.3	96%
35-Lower Lyell	2658	87%	2.6	27%	1.1	20%	0.0	0%	0.0	0%	1.3	1%	43.0	77%
36-Matterhorn Canyon	2569	84%	3.3	34%	3.0	57%	0.3	3%	0.0	0%	11.2	11%	36.3	65%
37-Middle Lyell	2719	89%	3.7	38%	3.0	56%	4.3	43%	0.0	0%	14.9	15%	21.0	38%
38-Miller Lake-North	2887	94%	8.5	89%	0.7	13%	1.3	13%	0.6	29%	24.9	26%	14.5	26%
39-Miller Lake-South	2896	94%	7.1	74%	0.5	9%	7.4	75%	0.6	30%	21.0	22%	22.7	41%
40-Paradise	2341	76%	3.2	33%	1.8	34%	2.9	29%	0.0	0%	30.5	31%	2.8	5%
41-Rock Island Pass	**3072**	100%	**9.6**	100%	0.0	0%	0.0	0%	0.0	0%	1.4	1%	22.2	40%
42-Rodgers Meadow	2670	87%	3.0	31%	2.3	43%	**9.9**	100%	0.0	0%	35.3	36%	12.1	22%
43-S of Matterhorn	2579	84%	5.4	56%	0.0	0%	2.1	21%	0.0	0%	61.5	63%	0.0	0%
44-Smedberg Lake	2810	91%	3.3	34%	3.9	73%	1.1	11%	1.6	76%	43.3	44%	20.6	37%
45-Tilden Lake-North	2731	89%	3.8	39%	3.4	63%	1.0	10%	0.8	38%	11.6	12%	33.5	60%
46-Tilden Lake-South	2713	88%	8.7	90%	1.3	25%	0.3	3%	1.9	94%	26.6	27%	3.0	5%
47-Twin Lakes	2719	89%	5.5	57%	**7.7**	100%	2.6	26%	1.4	68%	31.3	32%	10.3	19%
48-Upper Kerrick	2835	92%	2.4	25%	1.6	30%	3.3	33%	0.0	0%	25.4	26%	14.2	25%

Table C-3. Values and relativized scores for metrics contributing to vulnerability to use. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation are highlighted in grey and with bold font.

Site Name	Elevation		Slope		Streambank		Ponds		Lakeshore		Perennial wet		Dry meadow	
	(m)	Score	(%)	Score	%area	Score	%area	Score	%area	Score	OBL	Score	%UPL	Score
49-Upper Lyell-North	2734	89%	3.2	33%	2.7	51%	0.0	0%	0.0	0%	2.8	3%	27.9	50%
50-Upper Lyell-South	2734	89%	1.9	20%	2.8	52%	0.8	8%	0.0	0%	14.0	14%	14.4	26%
51-Upper Slide	2792	91%	4.1	43%	1.5	29%	0.9	9%	0.0	0%	6.1	6%	20.8	37%
52-W of Tilden	2542	83%	3.2	33%	2.9	54%	0.0	0%	0.0	0%	17.7	18%	34.9	63%
53-Wilma Lake	2422	79%	1.9	20%	1.9	36%	0.0	0%	3.1	100%	47.2	48%	0.0	0%

Table C-4. Values and relativized scores for use-related disturbance metrics. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation score are highlighted in grey and with bold font.

Site Name	Formal trails		Informal trails		Fire rings		Trampling		Roll pits	
	%Area	Score	%Area	Score	Points/Ha	Score	%Area	Score	%Area	Score
1-Babcock Lake	0.0	0%	0.0	0%	0.48	47%	1.4	21%	0.00	0%
2-Doc Moyle's- East	0.0	0%	0.0	1%	0.15	15%	0.0	0%	0.00	0%
3-Doc Moyle's- West	0.0	0%	0.0	1%	0.36	34%	1.7	25%	0.00	0%
4-E Sunrise Lake	0.0	0%	0.4	11%	**1.04**	100%	0.0	0%	0.00	0%
5-Echo Lake	0.0	0%	0.0	0%	0.14	14%	0.0	0%	0.00	0%
6-Emeric Lake	0.1	5%	0.2	7%	0.21	20%	0.6	9%	0.06	26%
7-Long Meadow	0.2	10%	0.0	0%	0.05	5%	0.1	2%	0.00	0%
8-Matthes Lake	0.0	0%	0.0	0%	0.00	0%	0.0	3%	0.00	0%
9-Merced Lake- East	0.0	0%	0.7	20%	0.00	0%	4.4	65%	0.09	40%
10-Merced Lake- Shore	0.4	16%	1.0	29%	0.00	0%	0.4	6%	0.00	0%
11-Merced Lake- West	0.9	38%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
12-Red Peak- North	0.0	0%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
13-Red Peak- South	0.0	0%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
14-Snow Flat	0.5	20%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
15-Triple Peak- North	0.0	0%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
16-Triple Peak- South	1.3	55%	0.0	0%	0.51	49%	0.0	0%	0.00	0%
17-Turner	0.0	0%	0.0	0%	0.24	23%	0.0	0%	0.00	0%
18-Washburn	1.2	51%	0.3	8%	0.36	35%	0.0	0%	0.00	0%

Table C-4 (continued). Values and relativized scores for use-related disturbance metrics. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation score are highlighted in grey and with bold font.

Site Name	Formal trails		Informal trails		Fire rings		Trampling		Roll pits	
	%Area	Score	%Area	Score	Points/Ha	Score	%Area	Score	%Area	Score
19-Benson	0.0	0%	**3.3**	100%	3.08	100%	**6.8**	100%	0.39	100%
20-Castle Camp	1.4	60%	0.7	20%	0.69	66%	1.5	23%	0.07	32%
21-Cold Canyon	0.4	18%	0.0	0%	0.13	12%	0.2	3%	0.01	6%
22-Cold Canyon-North	1.3	56%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
23-Dog Lake	0.0	0%	0.2	7%	0.00	0%	1.5	22%	0.00	0%
24-Dog Lake East	0.0	0%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
25-Dorothy Lake	1.0	43%	0.5	15%	0.25	24%	1.1	16%	0.00	0%
26-E of Gaylor Pit	0.7	30%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
27-Elbow Hill	1.3	57%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
28-Elizabeth Lake	0.2	10%	0.0	0%	0.00	0%	0.1	1%	0.00	0%
29-Grace Meadows	0.8	34%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
30-Grace North	2.1	93%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
31-Harden Lake	0.8	33%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
32-Hook Lake	0.6	28%	0.2	7%	0.00	0%	1.2	18%	0.13	55%
33-José's Camp	0.0	0%	0.3	8%	0.24	23%	0.0	0%	0.00	0%
34-Lower Kerrick	0.6	28%	0.0	0%	0.16	15%	0.1	1%	0.01	6%

Table C-4 (continued). Values and relativized scores for use-related disturbance metrics. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation score are highlighted in grey and with bold font.

Site Name	Formal trails		Informal trails		Fire rings		Trampling		Roll pits	
	%Area	Score	%Area	Score	Points/Ha	Score	%Area	Score	%Area	Score
35-Lower Lyell	0.4	19%	0.3	10%	0.14	14%	0.0	0%	0.00	0%
36-Matterhorn Canyon	0.5	23%	0.5	15%	0.10	9%	3.9	57%	0.17	75%
37-Middle Lyell	0.6	28%	0.0	0%	0.16	16%	0.2	0%	0.00	0%
38-Miller Lake-North	2.5	100%	0.2	6%	0.24	23%	0.0	0%	0.04	18%
39-Miller Lake-South	0.0	0%	1.1	33%	0.27	26%	3.5	51%	0.09	38%
40-Paradise	1.1	47%	0.0	0%	0.18	17%	0.0	0%	0.00	0%
41-Rock Island Pass	0.6	26%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
42-Rodgers Meadow	0.7	30%	0.0	0%	0.06	6%	0.0	0%	0.00	0%
43-S of Matterhorn	0.0	0%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
44-Smedberg Lake	**2.3**	100%	1.0	29%	0.50	48%	14.5	100%	0.10	43%
45-Tilden Lake- North	0.0	0%	0.9	27%	0.13	12%	1.3	19%	0.00	0%
46-Tilden Lake- South	1.2	52%	0.8	25%	0.29	28%	4.7	69%	**0.23**	100%
47-Twin Lakes	0.0	0%	0.1	2%	0.39	38%	5.1	76%	0.00	0%
48-Upper Kerrick	0.5	20%	0.0	0%	0.05	4%	0.1	2%	0.01	4%
49-Upper Lyell- North	0.7	29%	0.4	12%	0.25	24%	0.5	8%	0.01	5%
50-Upper Lyell- South	0.4	17%	0.8	24%	0.42	41%	0.8	12%	0.10	45%

Table C-4 (continued). Values and relativized scores for use-related disturbance metrics. Sites are organized alphabetical within watersheds, sites 1-18 are within the Merced, and sites 19-53 are within the Tuolumne. Maximum value used for score calculation score are highlighted in grey and with bold font.

Site Name	Formal trails		Informal trails		Fire rings		Trampling		Roll pits	
	%Area	**Score**	**%Area**	**Score**	**Points/Ha**	**Score**	**%Area**	**Score**	**%Area**	**Score**
51-Upper Slide	0.0	0%	0.0	0%	0.22	21%	0.0	0%	0.00	0%
52-W of Tilden	0.9	41%	0.0	0%	0.00	0%	0.0	0%	0.00	0%
53-Wilma Lake	1.4	60%	0.0	1%	0.51	50%	0.0	0%	0.00	0%

Appendix D. Results of simple linear regression for metrics within each assessment category

Table D-1. Linear regression results for pairwise comparisons of metrics within each assessment category (outliers included**)**; P-values are shown below and left of the diagonal, estimated regression coefficients for slope are shown above and right of the diagonal. Results with a p-value less than 0.05 are indicated with bold font and grey highlight.

Meadow Ecological Condition							
	PercBG	TotVegCvr	EarlSer	LateSer	LitDpth		
PercBG		**-0.5033**			**-0.0697**		
TotVegCvr	**0.0000**						
EarlSer	0.6906	0.8795		**-0.7565**	**-0.0415**		
LateSer	0.5034	0.4745	**0.0000**				
LitDpth	**0.0010**	0.1043	**0.0253**	0.4811			
Streambank Ecological Condition							
	EcolStat	FacUpl_S	VegBiom	ShadInd	StrmStab		
EcolStat		**-0.5070**					
FacUpl_S	**0.0072**		**-0.9879**		**-1.6008**		
VegBiom	0.8330	**0.0429**			**0.7600**		
ShadInd	0.5860	0.3571	0.6687		**335.7328**		
StrmStab	0.5663	**0.0062**	**0.0062**	**0.0978**			
Vulnerability to Disturbance							
	Elev	Slope	StrmArea	LakeArea	PondArea	OBL	FacUpl_M
Elev		**0.0030**				**-0.0663**	**0.0231**
Slope	**0.0275**						
StrmArea	0.1431	0.3516					
LakeArea	0.2639	0.1649	0.6211			**7.1221**	**-3.9966**
PondArea	0.3485	0.9241	0.6610	0.1976			**-1.1879**
OBL	**0.0000**	0.2221	0.5128	**0.0893**	0.1509		**-0.3773**
FacUpl_M	**0.0113**	0.6001	0.1158	**0.0994**	**0.0840**	**0.0000**	
Use-Related Disturbance							
	FrmTrl	InfTrl	Tramp	RollPit	FireRing		
FrmTrl							
InfTrl	0.7350		**2.2881**	**0.0009**	**0.5827**		
Tramp	0.1732	**0.0000**		**0.0002**	**0.0764**		
RollPit	0.8707	**0.0000**	**0.0000**		**428.1729**		
FireRing	0.7644	**0.0000**	**0.0022**	**0.0000**			

Table D-2. Linear regression results for pairwise comparisons of metrics within each assessment category (outliers excluded); P-values are shown below and left of the diagonal, estimated regression coefficients for slope are shown above and right of the diagonal. Results with a p-value less than 0.05 are indicated with bold font and grey highlight.

Meadow Ecological Condition							
	PercBG	TotVegCvr	EarlSer	LateSer	LitDpth		
PercBG		**-0.5033**			**-0.0361**		
TotVegCvr	**0.0000**						
EarlSer	0.6906	0.8795		**-0.6857**	**-0.0228**		
LateSer	0.7891	0.6945	**0.0000**				
LitDpth	**0.0178**	0.1478	**0.0724**	0.4794			
Streambank Ecological Condition							
	EcolStat	FacUpl_S	VegBiom	ShadInd	StrmStab		
EcolStat							
FacUpl_S	0.5029		**-2.0808**		**-2.4878**		
VegBiom	0.8330	**0.0110**			**0.7600**		
ShadInd	0.5860	0.6885	0.6687		**335.7328**		
StrmStab	0.5663	**0.0109**	**0.0062**	**0.0978**			
Vulnerability to Disturbance							
	Elev	Slope	StrmArea	LakeArea	PondArea	OBL	FacUpl_M
Elev		**0.0030**				**-0.0663**	**0.0231**
Slope	**0.0275**			**0.0886**			
StrmArea	0.1122	0.1283					**2.5776**
LakeArea	0.5809	**0.0271**	0.3994				
PondArea	0.4947	0.8926	0.5282	0.3969			
OBL	**0.0000**	0.2221	0.4378	0.7801	0.5540		**-0.3773**
FacUpl _M	**0.0113**	0.6001	**0.0458**	0.4556	0.1920	**0.0000**	
Use-Related Disturbance							
	FrmTrl	InfTrl	Tramp	RollPit	FireRing		
FrmTrl							
InfTrl	0.6369		**1.5500**	**0.0005**	**0.1374**		
Tramp	0.1809	**0.0012**		**0.0002**	**0.1614**		
RollPit	0.2583	**0.0019**	**0.0000**				
FireRing	0.7644	**0.0792**	**0.0000**	0.3558			

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