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Big data and digital tools to support adaptive rangeland management

Webb, N[1]; McCord, S[1]; Bestelmeyer, B[1]; Herrick, J; Edwards, B; Houdeshell, CA; Kachergis, E

[1] USDA-ARS Jornada Experimental Range, Las Cruces, NM, USA; [2] USDA-NRCS Resource Inventory and Assessment Division, CEAP-Grazing Lands, Davis, CA, USA; [3] Bureau of Land Management, National Operations Center, Lakewood, CO, USA

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Abstract

There is a growing thirst for data and digital tools to support adaptive rangeland management. Over the last two decades, adoption of standardized field monitoring methods has enabled unprecedented data collection across rangelands globally. Monitoring capability has been boosted by an explosion of remote sensing products and models that can leverage field datasets and cloud computing to extend predictions across space and time and produce new indicators of rangeland health. Integrating these datasets with decision-support tools has the potential to support the development of new knowledge systems and place data and interpretive tools in the hands of managers in the field. Here, we review examples of recent developments that are transforming how pastoralists, extensionists, scientists, and agencies make decisions about rangeland use and management. These developments leverage new perspectives on data quality, data harmonization and aggregation tools, models that produce new integrative indicators, standard frameworks for describing land potential, and applications of benchmarks to make objective and actionable decisions supporting adaptive land management. These improvements can dramatically simplify rangeland monitoring and assessment, in both developed and developing world contexts, in addition to increasing the decision-making value of rangeland monitoring.

Introduction

The world has now passed 1.5°C warming. As the climate continues to change, pastoralists and rangeland managers must adapt to novel growing conditions often exacerbated by interacting effects of invasive species, wildfire, drought, soil erosion and changing social and economic conditions. In this time of environmental change, monitoring the status, condition and trend of land health attributes is of critical importance for identifying threats, understanding risks, and anticipating change in rangeland ecosystem services and the sustainability of enterprises – and adaptively managing them. Monitoring land health indicators provides a means for pastoralists and other rangeland managers to objectively assess different attributes and the function of landscapes, whether they are changing, where, when and why changes are occurring, and evaluate the outcomes of management actions. Recent integration of large-scale monitoring datasets with digital tools for interpreting land health indicators offers new opportunities to develop approaches that provide pastoralists and other range managers with information and knowledge to simplify adaptive management decisions. Here, we review examples of big data and digital tools that are successfully transforming management decision-making on rangelands. We synthesize lessons learned from these developments that could support opportunities for new research, adaptive management approaches and international collaboration.

Standardize and upscale monitoring methods

Monitoring methods standardization has provided a foundation for using indicators to assess the status, condition and trend of ecological attributes that are important for understanding and adaptively managing rangelands. In the United States, the *Monitoring Manual for Grassland, Shrubland and Savannah Ecosystems* was developed collaboratively with rangeland scientists and managers to provide standardized methods for collecting data that can be used to describe soil and site stability, hydrologic function, the biotic integrity of landscapes, and derive other indicators of, for example, wildlife habitat suitability and biodiversity (Herrick et al. 2018). The standard methods include line-point intercept (LPI), which enables estimation of the fractional cover of vegetation by species and other ground cover elements, a vegetation height estimation method, the canopy gap intercept method which enables quantification of bare ground connectivity, and a method for conducting species inventory. Extensive training and observer calibration programs, supported by rigorous data quality assurance and quality control (QA&QC) approaches (McCord et al., 2021) and statistically valid sampling frameworks (Toevs et al., 2011; Stauffer et al. 2022), have enabled implementation of the standard monitoring methods by producers, land management agencies and research institutions at over 100,000 locations across privately and publicly owned and managed grazing lands in the United States since 2004. Similar standard methods have been developed and implemented elsewhere around the world, providing comparable opportunities for adaptive management informed by globally standardized land health indicators (Oliva et al. 2016; Tokmakoff et al. 2020; Dashbal et al. 2023). Recognizing the significant costs associated with implementing large-scale monitoring, the Land Potential Knowledge System (LandPKS) mobile applications (https://landpotential.org/ [Accessed 22 01 2025]) were developed to provide globally accessible and compatible field-based monitoring technologies (Herrick et al., 2017).

Harmonize monitoring data and models

A major challenge to the findability, accessibility, interoperability and reusability of large-scale monitoring datasets is that different monitoring programs tend to develop and use their own data collection tools and formats and data management systems. In the United States, the Database for Inventory, Monitoring and Assessment (DIMA) (Courtright and Van Zee 2011), Vegetation GIS Data System (VGS) and ESRI-based Survey123 apps, for example, are all used for data collection among users following Herrick et al. (2018). While data collection formats have been optimized to reduce errors in the field, they are not typically analysis friendly (McCord et al. 2023). Furthermore, databases and data management systems have tended to exist in isolation among user groups. Monitoring data may be collected and managed separately by different organizations and government entities, while cross-tenure management is not uncommon. Consequently, inference from indicator assessments has often been restricted to specific land use and tenure and the ability to make cross-scale assessments has been limited.

The Landscape Data Commons (https://landscapedatacommons.org [Accessed 15 01 2025]) uses modern cyberinfrastructure to harmonize and aggregate monitoring data, enabling unprecedented access to standardized monitoring data and calculated land health indicators (McCord et al., 2023). Open-source code and toolsets enable data harmonization and standardized indicator calculation (McCord et al. 2022), ingestion of raw monitoring data into staging and production databases, and data access through a web portal and application programming interface (API) – which are open to users globally. During data harmonization, a set of 58 common grazing land indicators are calculated that can be used to assess land health, prioritize land for restoration and rehabilitation, and assess outcomes of conservation practices and whether land use and management objectives are being met. A Rangeland Indicator Calculator (https://jornada-data.shinyapps.io/rangeland-indicator-calculator/ [Accessed 15 01 2025]) enables users to query or upload data and grouping variables to produce custom indicators of management interest.

Concurrent management for multiple ecosystem services, which is typical for rangelands, requires a broad set of indicators and the ability to assess their interactive responses to drought, climate change and disturbances, in addition to responses to management practices sought to improve the sustainability of rangeland social-ecological systems. Harmonizing and aggregating monitoring datasets has provided opportunities for the scientific community to develop, in partnership with pastoralists and managers, new indicators that can broaden data use in decision making, and to develop predictive models that extend the kinds of quantitative indicators available to users (e.g., wind and water erosion) and their spatial and temporal coverage through remote sensing applications (Jones et al. 2018; Allred et al. 2020). The Rangeland Hydrology and Erosion Model (RHEM) (Hernandez et al. 2017) and Aeolian EROsion (AERO) model (Edwards et al. 2022) were developed for standard monitoring data applications. Running the models on aggregated monitoring datasets has enabled public release of quantitative erosion indicators that are interpretable alongside other indicators of land health and biodiversity – transforming how soil erosion can be considered in management decisions across watersheds and airsheds (Webb et al. 2017). For example, AERO has been used to assess how invasive annual grasses can accelerate and suppress sediment transport across rangeland wind erosion hotspots depending on wildfire interactions (Tremino et al. 2024). Such models also present new opportunities to evaluate relationships between land degradation processes and the ecological dynamics of rangelands, with identification of critical eco-geomorphic thresholds providing a basis for identifying early warning indicators of ecological state change (Webb et al. 2024) and insights into where and why restoration practices are/are not likely to be successful (Schaeffer et al. 2025).

Data analysis and interpretation frameworks to build a shared understanding of ecosystems

Collecting standardized monitoring data provides a foundation for using data to inform adaptive management. However, interpreting data in a reproducible (and defensible) way can be challenging. Setting and applying benchmarks has emerged as a practical way that managers can interpret big indicator datasets and make objective and actionable decisions about rangeland management (Webb et al. 2020). Benchmarks have been defined as indicator values or ranges of values that establish goals for resource conditions, such as land health (Kachergis et al. 2020). Benchmarks can simplify data applications in adaptive management to 1) make land health assessments to determine whether objectives, standards, or regulations are being met; 2) identify and prioritize land for restoration treatments; 3) assess the efficacy of conservation practices, restoration, reclamation, and rehabilitation; and 4) compare management strategies to inform adoption of new management approaches (Webb et al. 2024).

A critical consideration for setting land use and management goals, and selecting management practices, is how effective they are likely to be given the land potential and ecological dynamics of a site. Using information about land potential is an effective way of establishing realistic benchmarks that reflect local ecosystem dynamics – including responses to drought, climate change, disturbances and management. Land potential describes the potential productivity, degradation resistance and resilience of sites as influenced by soil properties, climate and landscape position (Herrick et al. 2013). Ecological states represent contrasting land conditions as influenced by land management and climate variations interacting with land potential. Benchmarks can be established for monitored indicators by identifying indicator values that represent desirable ecological state characteristics. Benchmarks can also be set based on knowledge of thresholds between states at which certain processes, for example soil erosion, impact ecosystem function and result in state change. Collaborative benchmark setting involving natural resource managers, scientists and pastoralists has been an effective way of engaging managers (often for the first time) in exercises to interpret indicator datasets and think critically about their use to inform management on-the-ground. These activities have been supported by development of the Ecosystem Dynamics Interpretive Tool (https://edit.jornada.nmsu.edu/ [Accessed 15 01 2025]) and State Transition Classifier (https://webapps.jornada.nmsu.edu/transition-classifier/ [Accessed 15 01 2025]), which provides a global framework for developing and sharing state-and-transition models (STMs) (Bestelmeyer et al. 2016). Producing quantitative STMs, and establishing indicator value ranges for states and transitions, has become a major research interest to support big data interpretation in decision making to meet land use and sustainable development goals, avoid, reduce and reverse land degradation, and minimize spending on practices that are unlikely to be effective or have undesirable outcomes (Heller et al. 2022; Duniway pers. comment.).

Discussion: Big data-informed adaptive rangeland management

Building accessible knowledge systems from big data and digital tools is already having impact on management decisions, pastoralists livelihoods, and management outcomes on rangelands. Further improving data access will enable more insights that can increase capacity to adopt adaptive management approaches to avoid, reduce and reverse land degradation and support sustainability and planned transformation of rangeland social-ecological systems in the context of drought and climate change. By linking big monitoring datasets with models and interpretive tools that support applications of land potential concepts and benchmarks, simple workflows can be developed that enable pastoralists to prioritize actions based on their management objectives, local knowledge and data. One successful example is the Land Treatment Exploration Tool (https://www.usgs.gov/apps/land-treatment-exploration-tool/ [Accessed 16 01 2025]), which provides a one-stop-shop for managers to access historical land treatment data, monitoring indicators and erosion predictions from the Landscape Data Commons, remote sensing data on vegetation cover, and drought forecasts to plan rangeland restoration and rehabilitation. With such tools in hand, managers can use data to help identify resilient land and management options that support resilience, identify land at risk of degradation and loss of ecosystem function, and apply that knowledge to assess landscapes, learn from their condition and the outcomes of management actions, and adjust management where and when needed to meet land use and management goals. Early identification of where there are risks or threats to the status, condition and trend of rangelands can support identification of land use and management approaches that are sensitive to the drivers of ecological state transitions and assist pastoralists and other rangeland managers in anticipating and preparing for more systemic impacts of climate change.

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