# Fulfilling the promise of digital tools to build rangeland resilience

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**The world's rangelands and drylands are undergoing rapid change, and consequently are becoming more difficult to manage. Big data and digital technologies (digital tools) provide land managers with a means to understand and adaptively manage change. An assortment of tools—including standardized field ecosystem monitoring databases; web-accessible maps of vegetation change, production forecasts, and climate risk; sensor networks and virtual fencing; mobile applications to collect and access a variety of data; and new models, interpretive tools, and tool libraries—together provide unprecedented opportunities to detect and direct rangeland change. Accessibility to and manager trust in and knowledge of these tools, however, have failed to keep pace with technological advances. Collaborative adaptive management that involves multiple stakeholders and scientists who learn from management actions is ideally suited to capitalize on an integrated suite of digital tools. Embedding science professionals and experienced technology users in social networks can enhance peer-to-peer learning about digital tools and fulfill their considerable promise.**

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Rangeland managers increasingly face environmental and societal conditions that differ substantially from those on which current management knowledge has been built (Briske *et al.* 2015). Rangelands are projected to either become more arid (aridification) or receive more rainfall and experience higher temperatures (mesification) (Godde *et al.* 2020). Changes in plant species diversity and distribution, forage availability and nutritional value, and wildlife habitat are likely outcomes of climate change in most rangelands (Polley *et al.* 2017). Simultaneously, rangelands are also being converted to more intensive uses, including cropland agriculture, residential development, and energy development (Barral *et al.* 2020). Rangeland fragmentation can affect conditions in remaining rangelands, including biodiversity maintenance, ranching-based livelihoods, and community cohesion (Sayre *et al.* 2013; Reid *et al.* 2014). While coping with high degrees of spatial and temporal variability is inherent to managing extensive rangelands, directional changes in climate and land use exaggerate variability and introduce new, disorienting conditions for managers. Consequently, policy and research communities are developing strategies to build resilience to these changes in rangeland ecosystems and pastoral communities, as exemplified by the UN designating 2026 as the International Year of Rangelands and Pastoralists (Briske and Coppock 2023).

## In a nutshell:

- The current abundance of digital tools and information sources could substantially improve the management of rangelands and drylands in the face of land-use and climate change
- We provide a review of the classes of digital tools and their uses
- These tools, however, are often ineffectively used because their applicability to management is unknown, tool access is limited, and potential users have neither trust in nor technical knowledge of the tools
- Linking digital tools to collaborative adaptive management activities, supported by scientists and technicians embedded in local social networks, could increase the utility of digital tools to support rangeland resilience

In response to the need to track and manage global change, there has been rapid development of large, broad-scale, environmental databases ("big data") and digital technologies to support environmental science and resource management. These typically take the form of web-accessible databases, dashboards, maps, information tools, cloud computing, and mobile applications, many of which are packaged as decision support tools (Farley *et al.* 2018). Big data and digital technologies (hereafter, collectively referred to as "digital tools") are playing increasingly important roles in environmental sustainability (Runting *et al.* 2020). Although environmental science communities tend to emphasize the utility of digital tools for detecting global change phenomena (eg global deforestation; Hansen *et al.* 2013) and to motivate societal concern and international action (Runting *et al.* 2020), the

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potential role of digital tools in individual- and community-based sustainability solutions remains underappreciated and underdeveloped. While data produced by traditional, "normal" science yield—at best—general insights about system behavior that can be incorporated into manager knowledge and decision-making frameworks (Sayre *et al.* 2012), digital tools have the potential to integrate scientific insights and technologies and link them to local contexts and traditional knowledge underpinning day-to-day decisions.

In this paper, we review the classes of digital tools and the rangeland management problems they can address. We then synthesize feedback on several of these tools provided by participants of a recent workshop. We argue that integrating digital tools with management is essential for promoting resilience goals in rangelands undergoing change. We suggest that linking the use of digital tools to social networks and community-based natural resource management will markedly improve the relevance and effectiveness of these tools.

## Types of digital tools available to rangeland managers

Digital tools supporting rangeland management fall into six broad categories. Web links to online tools and resources mentioned in the sections below are provided in Table 1. Although analogs of tools are sometimes unavailable outside of the US, there is usually potential to develop or expand these tools based on available data and technology.

### Point-based monitoring data and tools

Standard measurement protocols and databases for point-based collection of vegetation and surface soil indicators have led to the development of large datasets (Densambuu *et al.* 2018; Oliva *et al.* 2020), many of which are publicly available (Figure 1a). These point data can be linked to context variables for analysis, including the type of soil, topography, climate, and land use, that are available from cloud databases and web tools. For example, the Landscape Data Commons—a data repository and portal—houses standardized data and indicators from more than 85,000 locations across land ownership types in the US (McCord and Pilliod 2022) that can be used for local to national assessments (McCord *et al.* 2022) and as reference datasets for comparison with measurements gathered by land managers. Mobile applications enable not only rapid point data collection and handling but also the ability to link locally

**Table 1. Big data and digital tools used for rangeland management decision making**

| Tool class | Tool type | Description | Examples |
|---|---|---|---|
| Point-based | Assessment and monitoring datasets and tools | Data from standardized methods housed in databases and linked to analysis/visualization tools | www.landscapedatacommons.org; www.landscapetoolbox.org (McCord *et al.* 2022); www.usanpn.org (Gerst *et al.* 2021) |
| Point-based | Data collection and information access apps | Web and mobile apps for recording vegetation, soil, and management data and returning site-specific, value-added information to users | www.landpotential.org (Maynard *et al.* 2022); https://chsapps.usgs.gov/apps/land-treatment-exploration-tool (Pilliod *et al.* 2018) |
| Map-based | Remote-sensing–based vegetation cover and production maps | Web apps serving remotely sensed and modeled data on land cover, vegetation fractional cover, and production from past to present | www.rangelands.app (Allred *et al.* 2022); www.usgs.gov/data/rangeland-condition-monitoring-assessment-and-projection-rcmap-fractional-component-time; www.mrlc.gov/eva (Rigge *et al.* 2021); www.landcart.org (Zhou *et al.* 2020); https://map.geo-rapp.org (Guerschman and Hill 2018); www.longpaddock.qld.gov.au/forage (Zhang and Carter 2018) |
| Map-based | Climate and risk assessment maps | Web apps serving historical and/or forecasted environmental conditions and effects | www.climatetoolbox.org; www.climateengine.com; www.swclimatehub.info/rma/rma-data-viewer.html (Huntington *et al.* 2017; Reyes and Elias 2019) |
| Map-based | Forecast maps | Forecasts of forage production and restoration success relative to long-term averages | https://grasscast.unl.edu (Wardropper *et al.* 2021); www.longpaddock.qld.gov.au/aussiegrass (Pringle *et al.* 2021) |
| Sensor-based | Precision ranching sensor networks and dashboards | Livestock GPS collars, virtual fencing collars, weather stations, and water-level sensors connected to web dashboards and mobile apps | Tools in development or proprietary (Spiegal *et al.* 2020; Boyd *et al.* 2023) |
| Model-based | Model outputs | Web apps or spatial datasets on processes such as soil erosion linked to point or ecological site/state maps | www.landscapedatacommons.org (Williams *et al.* 2016; Edwards *et al.* 2022); https://dss.tucson.ars.ag.gov/rhem (Hernandez *et al.* 2017) |
| Interpretive | Ecological site descriptions and state and transition models | Web-accessible information on reference vegetation, causes of vegetation change, and conservation practices linked to soil maps | https://edit.jornada.nmsu.edu (Bestelmeyer *et al.* 2017); www.landfire.gov (Blankenship *et al.* 2021) |
| Interpretive | Sustainability indicators and benchmarks | Standard indicators representing production, environmental, and well-being attributes of agricultural systems for assessing management trade-offs | Tools in development (Fernández-Giménez *et al.* 2019; Webb *et al.* 2020; Spiegal *et al.* 2022) |
| Library | Tool and information libraries | Web apps to facilitate discovery of tools and information sources matched to need | https://webapps.jornada.nmsu.edu/livestock; www.wocat.net/en (Gonzalez-Roglich *et al.* 2019) |

**Notes:** the list is not exhaustive but represents major types of tools.

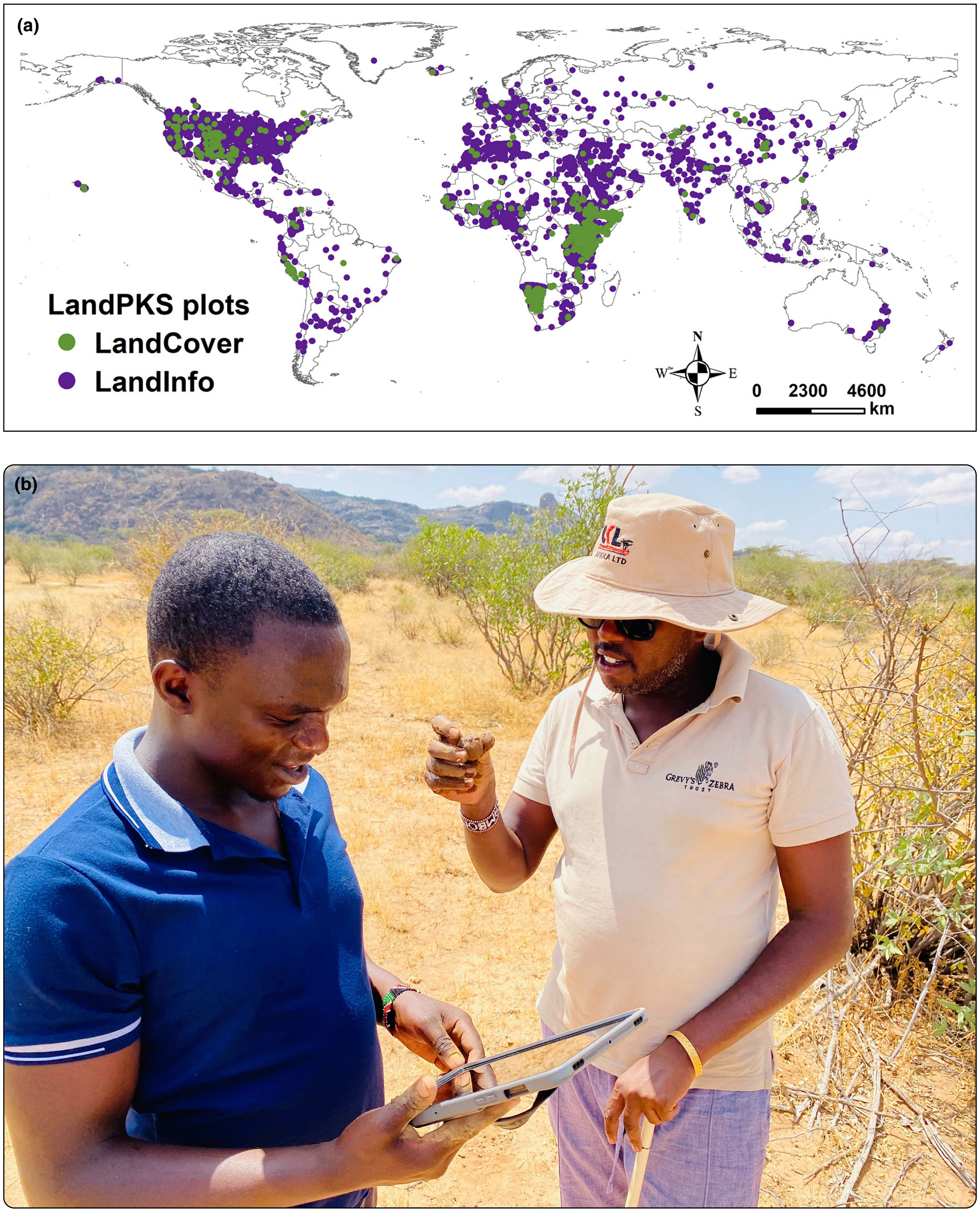


**Figure 1.** (a) Community scientists use the Land Potential Knowledge System (LandPKS) to collect vegetation (LandCover) and soils (LandInfo) data at over 34,000 locations globally. (b) The Grevy's Zebra Trust uses LandPKS as a monitoring tool in its community-based restoration strategy in Kalama Conservancy, Samburu, Kenya. Photo credit: D Kimiti.

collected data with cloud-based data and decision-support tools, such as locally appropriate soil conservation methods (Figure 1b; Maynard *et al*. 2022).

## Mapped data and tools

The abundance of standardized, accessible, point-based vegetation data and indicators (eg bare ground cover) has led to a revolution in the development of remote-sensing–based map tools, in which point data are used to train computational algorithms for estimating vegetation cover and production (Beutel *et al*. 2019; Zhou *et al*. 2020; Rigge *et al*. 2021; Allred *et al*. 2022). For example, the Rangeland Analysis Platform (RAP) is an interactive online tool that uses satellite imagery dating to 1986 as the basis for formulating yearly and spatially continuous estimates of vegetation cover by plant functional group and production at 30-m spatial resolution, which users can query and visualize in web applications. In web applications linked to RAP and similar products, such as Climate Engine, trends in vegetation cover and production over different timescales can be produced, indicating hotspots of vegetation recovery or degradation (Figure 2c; Bestelmeyer *et al.* 2021). Forecasts of forage conditions (Hartman *et al.* 2020; Pringle *et al.* 2021; Wardropper *et al.* 2021) and climate-associated risks and opportunities (Huntington *et al.* 2017; Reyes and Elias 2019) can at last provide land managers with information needed

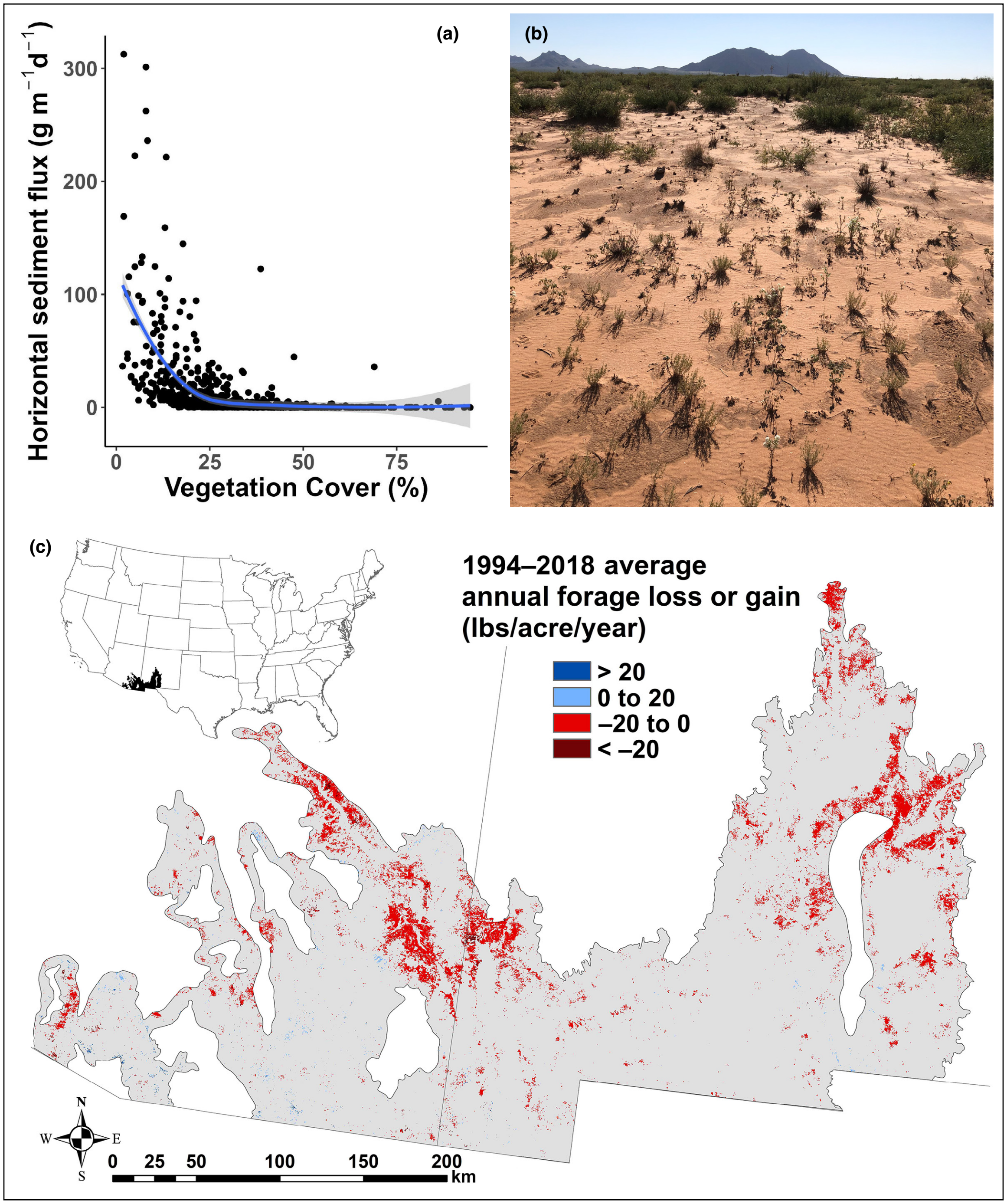


**Figure 2.** (a) In the desert grassland region of the southwestern US, 700 plots from the Landscape Data Commons were used to run the Aeolian Erosion (AERO) wind erosion model to determine thresholds of vegetation cover loss that increase the risk of wind erosion. Black dots denote individual plots, blue line denotes the regression curve, and gray shaded area denotes the 95% confidence interval. (b) An area in New Mexico's Jornada Experimental Range with low vegetation cover and exhibiting evidence of wind erosion. (c) Trends in herbaceous vegetation production from the Rangeland Production Monitoring Service in desert grasslands from 1986 to 2018, showing hotspots of declining vegetation production (red) and smaller areas of production increase (blue) (data from Bestelmeyer *et al.* [2021]).

for short-term and long-term planning. Such dynamic map tools provide not only actionable information on locations in the spaces between monitoring points but also information on landscape patterns needed to understand and manage the impacts of livestock movements, spatial variations in soils and weather, and wildlife habitat.

### Sensor networks

Networked ground-based sensor technologies provide a means to access real-time, local information about livestock, infrastructure, climatic, and vegetation conditions across a management area. Data from livestock tracking collars, remote water-level sensors, weather stations, and PhenoCams (digital cameras that provide indicators of vegetation growth stage) relayed to computer servers by wireless networks can be accessed via web or mobile applications (Spiegal *et al.* 2020; Browning *et al.* 2021). There is also potential for sensor networks to monitor biodiversity and habitat quality as indicators of land health through the use of machine-learning computation to extract species presence and activity data from video and audio recording devices, environmental DNA, radar, and light detection and ranging (lidar) (Besson *et al.* 2022; van Klink *et al.* 2022). Virtual fencing takes this capability even further, allowing ranchers to adjust livestock grazing pressure dynamically using mobile applications to match variability in weather, forage availability, and vegetation condition or fire risk based on the map tools discussed earlier (eg Boyd *et al.* 2023).

### Model-based point and map data

Both point- and map-based estimates of soils, vegetation cover, and vegetation production can be combined with new models to predict and scale-up other processes of management interest, such as soil erosion. For instance, data on bare soil cover, canopy gap distribution, and vegetation height from point-based monitoring sources can be used as inputs in a sediment transport model to produce spatially explicit estimates of dust flux (Figure 2, a and b; Edwards *et al.* 2022). There is also great promise for providing additional indicator data via maps to users, including indicator data pertaining to carbon sequestration potential (Gray *et al.* 2022), ecosystem function such as precipitation use efficiency (the ratio between aboveground net primary production and precipitation; Verón *et al.* 2018), and wildlife habitat quality (Pilliod *et al.* 2022). Notably, the models underpinning indicator maps are ultimately based on distributed and networked long-term experiments conducted at research stations in rangelands throughout the world, such as those within long-term ecological and agricultural research networks.

### Interpretive tools

To make indicator information useful, land managers need tools to interpret point- and map-based indicators and connect those interpretations to decisions. For example, state and transition models (STMs) represent the multiple potential states for a land type and information on the events and practices that cause or prevent shifts between states. Although STMs formerly existed only as collections of written documents, they can now be made machine readable and available via web and mobile applications connected to soil maps (NRCS 2023). STMs can also be linked to quantitative benchmarks that enable field-collected, mapped, and modeled data to be classified to an ecological state and then to management interpretations, such as evaluating the risk of a transition and prioritizing restoration practices (Sato and Lindenmayer 2021; Edwards *et al.* 2022). Databases housing interpretive benchmarks for multiple indicators linked to management practices are needed to base decisions on the multiple ecosystem services provided by rangelands (Power 2010). Such multifactor (sustainability) indicator databases are currently in development (Webb *et al.* 2020; Spiegal *et al.* 2022).

### Tool libraries

Although hundreds of other management tools and technologies that solve specific problems are available (eg for management/restoration techniques and tracking ranch expenses and product markets), matching the right tool with the right problem can be daunting. Tool libraries, such as the Tools for the Beef Industry and the World Overview of Conservation Approaches and Technologies catalogue (Gonzalez-Roglich *et al.* 2019), organize tools and methods to enable users to match them to local context and need, including via mobile applications such as the Land Potential Knowledge System (Maynard *et al.* 2022).

## Barriers to the use of digital tools

The examples presented above illustrate the potential opportunities for using digital tools to assist in adaptive management. However, several societal and technological obstacles must be addressed before these tools can be accessed broadly by the user community. We conducted a day-long workshop at the US Department of Agriculture's (USDA's) Agricultural Research Service Jornada Experimental Range in Las Cruces, New Mexico, in October 2022 to introduce some of these tools and discuss barriers to their practical application. After presenting demonstrations of several digital tools (including digital cover and production maps, monitoring database tools, precision ranching technologies, and mobile applications), we conducted a breakout group session with ~60 participants representing local livestock producers, federal and state agencies, university teaching and extension, conservation and education nonprofits, international development organizations, and tribal governments. Participants were randomly sorted into five groups and a discussion leader was assigned to each group. A facilitator guided participants in discussions about the most important limitations to the use of digital tools. Written statements gathered by the discussion leaders and from verbal reports to all participants were categorized and summarized by the lead author to understand major concerns of stakeholders. We identified three general types of barriers, which echo those found in earlier work (Meredith *et al.* 2021; Wardropper *et al.* 2021; Pearman and Cravens 2022).

First, there are several *accessibility* limitations, including (1) awareness that tools exist, (2) the cost or availability of broadband connectivity or cellular service to be able to use tools, and (3) the complexity of the tool relative to the time available to a manager to learn how to use it (Meredith *et al.* 2021). Overcoming these limitations requires greater investment in communication, training, and demonstrations of tool use, as well as rural broadband and cellular coverage.

Second, use can be limited by a *lack of trust in or acceptance of technologies*. Limited trust can result from a lack of engagement with stakeholder representatives in technology development. The overpromise (or misunderstanding) of applicability and performance by developers and technology enthusiasts can further weaken trust. Without knowledge of how a technology works and without a clear understanding of technological limitations, there may be little trust that tools will provide real solutions. In addition, technical support for tools may diminish over time and tool access may be suspended due to funding limitations or shifting institutional priorities (Pearman and Cravens 2022), creating a further disincentive for managers to invest in tool adoption. Furthermore, participants noted that hesitancy to use certain technologies can be due to the possibility that data may not support hoped-for narratives or create vulnerabilities to their business, requiring a cultural shift in how data are interpreted and used by multiple parties (Meredith *et al.* 2021).

Third, there is insufficient *knowledge of technology applications* to match tools to specific management problems and decision-making processes. In the words of one participant, we must better understand the "ecosystem of need" of managers—including decisions on seasonal herd rotations, long-term planning, monitoring, and government interactions—and match the "ecosystem of technological support" to satisfy those needs. Developers must also consider relationships of tools to institutional (especially government agency) processes, including the incorporation of tools in established agency workflows (eg conservation planning), the availability of tools at relevant spatial and temporal scales, and restrictions on access to data and use of technologies by governments. The term "ecosystem" evokes connections with and interactions among multiple decision processes and tools, but technology developers have seldom addressed such connections. Efforts to design tools responding to the needs of multiple types of users and instituting an iterative, user-feedback–driven approach to modify tools could enhance knowledge sharing and coordinated action across users and reduce tool duplication (Meredith *et al.* 2021; Pearman and Cravens 2022).

## Strategies to fulfill the promise of digital tools

Digital tools have the potential to help address multiple, long-standing problems at the science–management interface (Sayre *et al.* 2012). Solving these problems requires an emphasis on multiple indicators and values over general assertions of environmental health or dysfunction; attention to context dependence over global generalities; adaptation to continual change over maintaining stable conditions; and science production, interpretation, and use by inclusive groups of stakeholders rather than by an exclusive group of experts.

These solutions have been termed a "post-normal" approach to science (Sayre *et al.* 2012) and are embodied by a form of community-based natural resource management known as collaborative adaptive management (CAM). CAM emphasizes feedbacks among monitoring, learning, and management with multiple stakeholders (Fernández-Giménez *et al.* 2019). Structured learning from management actions—especially "multiple-loop" learning—is central to CAM. Multiple-loop learning represents the deepening influence of learning on decision-making processes, including (1) relying on monitoring to understand the effects of management actions that are used to adjust management implementation (single-loop learning); (2) reassessing assumptions and mechanisms of cause–effect relationships captured in formal or "mental" models that might lead to new management approaches (double-loop learning); and (3) revising concepts, values, or ways of governing such that new management objectives (and corresponding approaches) are identified (triple-loop learning) (Fernández-Giménez *et al.* 2019).

Digital tools can support multiple-loop learning in collaborative groups (Figure 3). *Prior knowledge* of management concerns has a large influence on management *objectives*, but objectives can also be informed by data on rangeland health, climate change, woody plant encroachment, land conversion, and other processes made available by digital tools. Objectives, in turn, determine the kinds of indicators that are relevant for adaptive decision making. *Models*, including STMs and process models, can be used to identify management actions that are likely to facilitate progress toward meeting objectives in particular areas. Management *actions* can employ precision ranch technologies and maps of ecosystem states to design, implement, and adjust grazing pressure and restoration efforts. A variety of *monitoring* tools and databases allow evaluation of progress toward objectives based on relevant indicators, and STMs and associated benchmarks can guide *interpretation* of monitoring data. Finally, individual and social *learning* can be enhanced through the use of data visualization tools alongside guidance by scientists to help stakeholders think through the

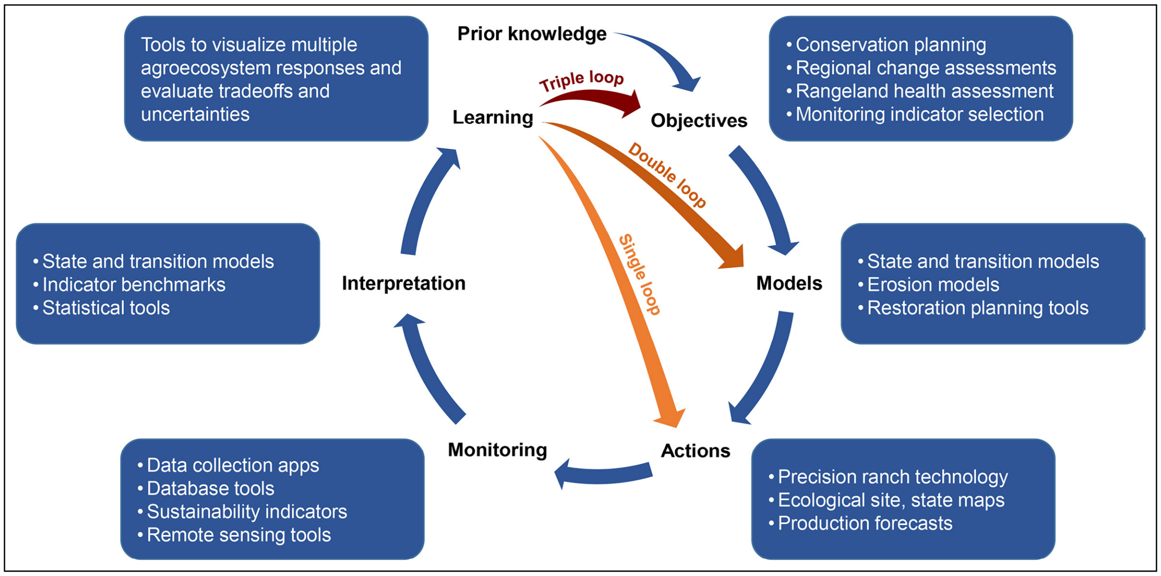


**Figure 3.** Collaborative adaptive management cycle, including single-loop, double-loop, and triple-loop learning pathways, and potential relationships of cycle steps to digital tools.

implications of monitoring results with respect to trade-offs and uncertainties.

## Linking scientists and technologists in social networks

A proven way to enhance rangeland resilience via CAM is to create and support social networks for land managers through community-based organizations (Reid *et al.* 2014). For example, pastoralist community groups are widespread across global rangelands, with varying levels of organization, ranging from highly organized (eg the Malpai Borderlands Group in the US, herder cooperatives in Mongolia) to loosely organized (eg neighboring ranchers who meet occasionally or groups that exchange ideas through social media). For digital tools to augment CAM activities, science professionals (both at research organizations and land management agencies) and experienced technology users must be part of these social networks, making peer-to-peer learning possible. Dedicated professionals can help to overcome the barriers identified earlier, including accessing tools and training, enabling buy-in and trust, and fostering knowledge about which tools perform which functions.

The challenge in linking science and technology professionals to rangeland social networks is ultimately about staffing, time, and strategy. Successful engagement of scientists in social networks takes time and expertise (Wilmer *et al.* 2017), and the cadre of scientists with the skills and time to interact with a growing number of social networks is limited, especially in global rangelands that receive scant attention and investment from decision makers (Sayre *et al.* 2013). Science and technology staffing continues to be based on "normal science" traditions emphasizing the development of general principles and technologies, but there is insufficient capability for upscaling science to users in heterogeneous contexts. Individuals who are trained in knowledge coproduction, and who not only have expertise in digital tools but also have dedicated time for trust-building and sustained engagement with members of social networks, are rare. Furthermore, stakeholders themselves may have limited time to interact with scientists, especially if the benefits of doing so are insubstantial.

Considering the current state of science support as compared with the needs expressed by stakeholders, a radical restructuring of science investments will be required for digital tools and CAM to contribute most effectively to resilience in rangelands (and social–ecological systems more broadly). This restructuring has begun in the US through institutions such as the USDA Climate Hubs that aim to synthesize science, develop tools, and connect these resources directly to users via convening activities and outreach. Increasing local access to knowledge is a clear need (Dinan *et al.* 2021) that Climate Hubs and partnering Agricultural Extension offices can fulfill with increased staff who become part of social networks. Similar opportunities exist in other rangelands of the world where government-supported technical staff (eg extension or land management officers) are embedded in local communities and could be leveraged to advance the use of digital tools and CAM.

Locally embedded science and technology staff could support multiple social networks by (1) engaging with stakeholders to determine community needs and preferred ways of engaging with scientists using digital tools; (2) reducing the time costs of interactions between scientists and stakeholders, and increasing time available to build relationships and trust; (3) identifying combinations of tools that address needs; (4) working with groups to implement CAM steps over suitable time periods (Figure 3); and (5) assisting individuals and groups with integrating digital tools into decision-making and planning activities as well as day-to-day management. Locally embedded science and technology staff can be supported by and work closely with science professionals at federal research laboratories, universities, and agencies serving "boundary spanning" roles (Briske 2012) that iteratively improve the development, effectiveness, and adoption of digital tools. An updated approach to land management science that is built on insights from social science could harness the power of digital tools to enhance rangeland resilience in the decades ahead.

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## Data Availability Statement

No data were collected for this study.

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