Adaptive monitoring for multiscale land management: Lessons learned from the Assessment, Inventory, and Monitoring (AIM) principles

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On the Ground

- The BLM Assessment, Inventory, and Monitoring (AIM) strategy recommends five principles for building multiscale monitoring programs: standardized methods and indicators; data management and stewardship; appropriate sample designs; remote sensing integration; and structured implementation. These principles guide monitoring across public lands.
- We find the AIM principles are sound and worthy of consideration for design and adaptation of rangeland monitoring programs worldwide.
- An emergent principle, standard workflows and analysis frameworks for using data, connects data to land management decision-making and empowers land managers.
- The AIM principles inspire and provide opportunities for the rangeland management community to implement adaptive management.

Keywords: data management, decision-making, design, indicators, public lands, rangeland monitoring.

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Introduction

Land management and natural resource decisions play an increasingly crucial role amidst many simultaneous changes occurring on rangelands globally.[1] Ongoing changes include 1) intensifying and diversifying land uses; 2) expectations of multiple ecosystem services from rangelands; 3) multiscale management objectives; and 4) novel weather, climate, and disturbance patterns and species assemblages. Traditionally, managers attempt to match monitoring efforts to individual issues or management questions on a case-by-case basis to guide rangeland management. Although this approach may provide high-quality data to answer a specific question in an area, it is not robust to the spectrum of changes that land managers are experiencing and it results in inconsistent monitoring efforts across landscapes and land uses. In contrast, rangeland monitoring information is most valuable when collected consistently, through long-term efforts addressing multiple objectives and different scales of land management decisions.[2] This information empowers decision-makers to manage change through adaptive land management.[1] The challenge is to create a flexible, multiscale monitoring program that is both feasible to implement at broad scales and responsive to local-scale management questions.[3,4] In addition, the program must overcome the significant institutional hurdles to establishing and sustaining monitoring,[3,5,6] and adapt through time as new information emerges and questions change ("adaptive monitoring").[7]

The US Department of Interior Bureau of Land Management (BLM) and partners developed a monitoring approach to address the challenges of implementing a multiscale, multiuse adaptive monitoring program. The BLM is responsible for the management of 9.9 million km^2 (245 million acres) of public lands in the United States with a mission to support multiple uses and sustained yield from rangelands.[8] Within a single area, managers must balance land uses including livestock grazing, energy development and reclamation, wildlife habitat needs, and recreation, all while conserving natural, cultural, and historical resources. Cumulatively, BLM administers almost 200 land use plans, manages over 16,000 grazing permits and leases, oversees 177 wild horse and burro herd management areas, and completes approximately 4,000 km^2 (1 million acres) of vegetation treatments per year; 1,500 to 2,000 environmental analyses yearly support BLM work. As an alternative to developing monitoring programs for each specific use, BLM developed the Assessment, Inventory, and Monitoring (AIM) strategy to be implemented agency wide. The goal of the AIM strategy is "to provide the BLM and its partners with the information needed to understand…resource location and abundance, condition, and trend, and to provide a basis for effective adaptive management."[9]

The AIM strategy consists of five principles that guide development of standardized approaches to describing condition and trend of rangeland ecosystems. The five principles include 1) standardized field methods and indicators; 2) data management and stewardship; 3) appropriate sample designs; 4) integration with remote sensing; and 5) structured implementation. Data management and structured implementation were added as principles to those originally proposed[9] as the BLM operationalized the AIM strategy and integrated AIM into decision-making processes. These two principles ensure the collection of meaningful monitoring data to inform management and the timely availability of such information. Collectively, the five principles reflect best practices from the scientific literature[3,7] on adaptive monitoring as well as existing monitoring efforts, such as the Natural Resource Conservation Service (NRCS) National Resources Inventory, the US Environmental Protection Agency's (EPA) National Aquatic Resource Surveys, the US Forest Service (USFS) and BLM PACFISH/INFISH Biological Opinion effectiveness monitoring, and BLM's own assessment and monitoring activities. Putting the principles into practice has required coordinated effort among agency staff, across disciplines (e.g., range, wildlife), and with partner organizations. The AIM program is the sum of these collaborative efforts.

Since AIM's inception in 2011, BLM developed AIM field data collection protocols for uplands, wadeable streams and rivers, and wetlands and riparian areas with a focus on key ecosystem processes.[10–12] AIM data are available at over 30,000 upland locations, 3,000 wadeable stream and river reaches, and 100 wetland and riparian locations from Arizona to Alaska (Fig. 1). These data are integral to producing analysis products and remote sensing models that promote understanding of rangeland condition and trend.[13,14] AIM supports BLM land management across scales, ecosystems, and disciplines (Table 1). For example, AIM data and related products are used to evaluate effectiveness of land use plans, determine wildlife habitat suitability, decide whether land health standards are being achieved in support of land use authorizations, and understand restoration and rehabilitation efficacy. However, data use is uneven across different land uses, disciplines, and offices. Further, there is a need to better communicate AIM data and BLM decision processes with local stakeholders, land users, and the public to facilitate adaptive management across boundaries.[4]

Reflecting on AIM principles can inform rangeland adaptive monitoring efforts worldwide. Our objective is to review implementation of AIM principles, consider lessons learned, and highlight changes over time, in order to refine BLM's AIM program and other multiscale, multiuse adaptive monitoring programs. Additionally, we suggest opportunities for land managers and researchers to co-produce shared knowledge about rangeland health, the foundation of adaptive management.

Principle 1: Standardized field methods and indicators to allow data comparisons throughout BLM and its partners

Status

Standardization makes monitoring more efficient and cost-effective. The AIM program has established standard field methods and indicators for upland rangelands[9,10] and wadeable streams and rivers (Fig. 2).[3,11] A protocol for wetlands and riparian areas, which integrates upland AIM and other wetland protocols, is currently being finalized.[12] Indicators are measured at individual plots or stream reaches, which cover approximately 1 acre in uplands, wetlands, or riparian areas and a minimum of one-tenth of a mile in wadeable streams and rivers. Agency personnel and partners collect these data across BLM (Fig. 1) and apply them to land management decisions (Table 1).

Monitoring efforts rooted in policy ensure collected data serve a purpose and fit within a management framework.[7,15] The AIM standard (core) indicators were selected because they inform BLM policy mandates (Table 1) and describe ecosystem attributes (Fig. 2). The fundamentals of rangeland health[16] are one major policy driver, providing a comprehensive regulatory framework for complying with requirements from the Federal Land Policy and Management Act (FLPMA, the BLM's organic act), the Clean Water Act, and the Endangered Species Act, among others. The fundamentals establish four measures of ecosystem sustainability: watershed function, maintenance of ecological processes, water quality compliance, and sustained habitat for species of management concern (Fig. 2). Under these regulations, BLM and stakeholders developed regional land health standards and related indicators for each of the four fundamentals. AIM provides consistent methods across twelve different states and nineteen sets of standards to address the diversity of indicators described in the land health standards and streamline monitoring and evaluation across public lands.[17]

Standardized field methods and indicators facilitate integration of monitoring efforts within and across management boundaries. Within BLM, standardized methods and indicators support range-wide greater sage grouse (*Centrocercus urophasianus*) habitat analyses and exploration of regional invasive species trends, for example. BLM is also collaborating with USFS, EPA, and NRCS to combine shared monitoring data to increase the precision of indicator estimates for BLM-managed lands and improve our understanding of regional condition and trend. At local scales, quantitative AIM indicators are used alone or in combination with qualitative assessments such as Interpreting Indicators of Rangeland Health and Proper Functioning Condition, providing multiple lines of evidence for decision-making.[18,19]

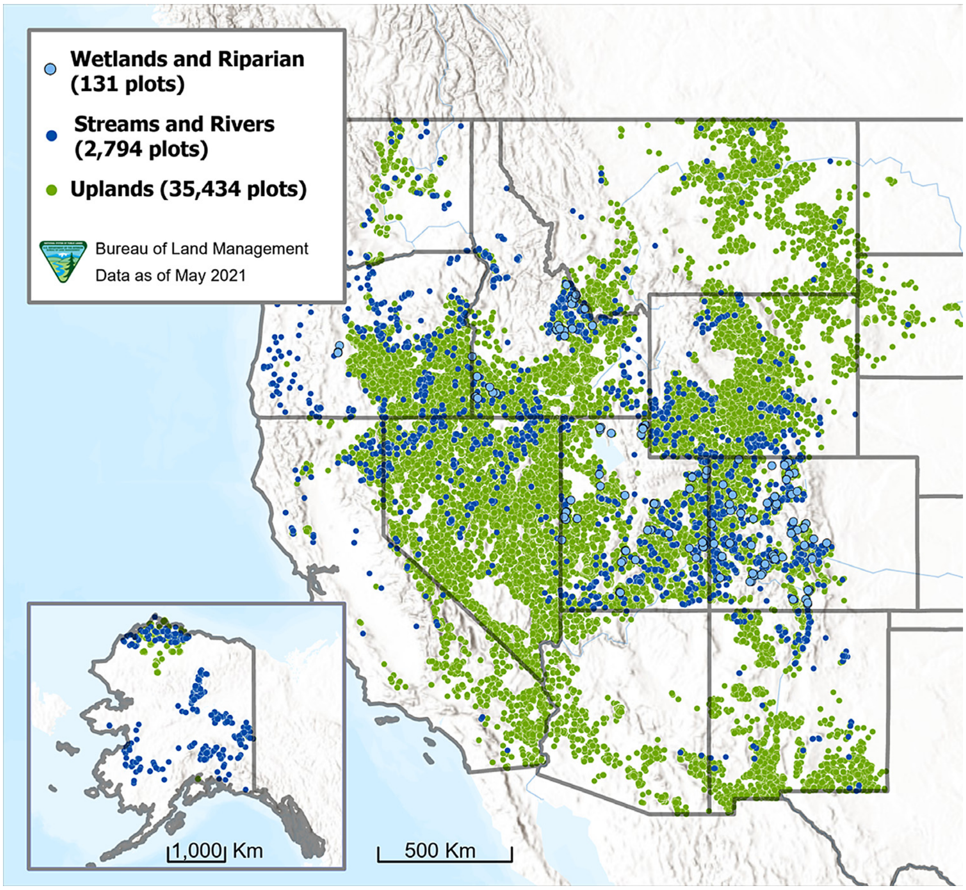

Figure 1. AIM data collection locations on BLM-managed public lands in the western United States and Alaska as of May 2021.

Table 1
Examples of multiscale management decisions required by BLM policy and informed by AIM data

Management decision	Reporting area (scale)	Example policy drivers	AIM-specific technical guidance	Published examples of AIM data use
NEPA compliance	Various	National Environmental Policy and Management Act, Council on Environmental Quality Guidelines	None	Xian et al. 2015,[17,37] Jones et al. 2018[13] (used in unpublished examples)
National inventories	National, state or ecoregion	FLPMA (201a); PRIA (1901b1 and 1903a)	None	Karl et al. 2016,[55] Yu et al. 2020[56]
Land use plan effectiveness	District or field office (greater than ~100,000 ha)	FLPMA; Land Use Planning Handbook; land use plans and amendments; BLM Instruction Memorandum 2016-139	None	Brady et al. 2018[50]
Species of management concern	Watershed or group of watersheds	Biological opinions; land use plans and amendments	Stiver et al. 2015[47]	Herren et al.[57] In press
Land health assessments	Grazing allotment, watershed, wild horse and burro management areas (40-40,000 ha)	43 CFR 4180; Land Health Handbook; State water quality standards	Kachergis et al. 2020[17]	Unpublished examples
Restoration or rehabilitation treatment effectiveness	Individual or groups of treatments (4-400 ha)	Depends on treatment type (e.g., 43 CFR 3809.420)	Reporting templates (unpublished)	Traynor et al. 2020,[58] Barker et al. 2019,[29] Ernst-Brock et al. 2019[30]
Reclamation effectiveness	Individual or groups of treatments (4-400 ha)	43 CFR 3162.5-2	Brady et al. 2018[50]	Di Stefano et al. 2020[59]

Note: AIM data actively supports these management decisions, while technical guidance and published examples are at various stages of development and are critical to long-term success.

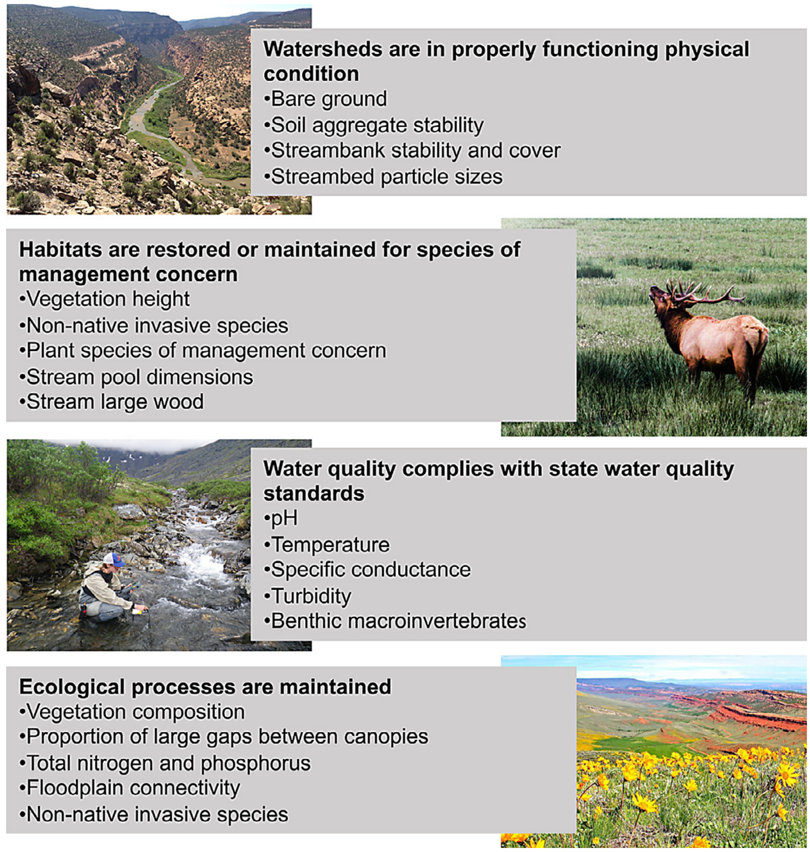

Figure 2. Example AIM indicators for each of the four fundamentals of rangeland health, which is BLM's policy for managing rangelands. The four fundamentals provide a common set of management questions, and the AIM strategy provides a nationally consistent approach to assess the condition and trend of BLM-managed lands. Example AIM indicators are only listed for a single fundamental, but many crosswalk to multiple fundamentals.

Lessons learned and adaptation

Standard methods focused on assessing the condition and trend of indicators related to BLM's fundamentals of land health have been key to AIM's success (Fig. 2). Land health policy and AIM core indicators are broadly applicable across ecosystem types and management objectives and are readily applied to management decisions. Simultaneously, contingent or supplemental methods and indicators provide flexibility to measure locally relevant, unforeseen, or secondary monitoring objectives (e.g., fuel measurements for wildfire fuel reduction treatments[20]). These additional methods and indicators are only used when applicable to a specific ecosystem, land use, or management objective. The combined use of core, contingent, and supplemental methods allows AIM to achieve national consistency, while retaining flexibility to meet information needs at local scales. We recommend this approach to ensure the long-term sustainability of monitoring efforts, which often fail because of disagreement over what to monitor and changes in administrative support.[3,7,21]

Standardized methods and indicators also result in cost-effective and sustainable monitoring implementation for BLM. This principle enables large-scale efficiency by focusing funding and personnel resources on a limited set of monitoring information, making collection and management of that information achievable. For example, regional AIM trainings address core and contingent methods and can effectively communicate protocols and data quality procedures in 1 to 2 weeks. Likewise, a single suite of data collection and management systems support many monitoring efforts. Automated data quality checks ensure data quality before calculating standard indicators used for decision-making (see Principle 2). Our experience establishing methods for uplands and wadeable streams and rivers has informed the development of standardized core and contingent methods for wetlands and riparian areas.[12] When complete, AIM will deliver a comprehensive set of tools for understanding rangeland ecosystem conditions and trends across BLM-managed lands to support decision-making and facilitate adaptive management.

Documentation is a key component of standardized methods and indicators. Specific examples include published field methods guides,[10,11] readily available and peer-reviewed metadata including indicator computations, and quality assurance and quality control procedures.[22,23] AIM data include extensive metadata[24,25] to support a comprehensive understanding of available data, appropriate data applications, and comparisons of field methods and indicator computation for possible data integration among monitoring programs. Thorough documentation ensures that data are findable, accessible, interoperable, and reusable (i.e., FAIR).[26]

Making necessary changes to standard protocols is critical to ensuring the relevance of monitoring data to decision-making and adapting to change.[3,15] Protocol clarifications and updates are considered on an annual basis to improve data quality and to remain consistent with other monitoring programs. As the AIM practitioner base grows and becomes more diverse, we receive increasing requests to modify methods and/or add core methods. The AIM program will benefit from formalizing and broadly communicating our change management process to increase the transparency of how changes are made. Decision factors include the feasibility of requested changes, end users' needs, and the implications for continuity and consistency of AIM data over time.

Principle 2: Data management and stewardship to ensure data quality, accessibility, and use

Status

Electronic data capture and management facilitate monitoring data collection, data quality, accessibility, and interpretation, which increase the value of monitoring data and save monitoring programs time and money.[26,27] AIM data collectors use electronic data capture, quality control, and storage workflows. A centralized, national data management team maintains these workflows, with contributions from many individuals across BLM. Centralized databases store AIM data and facilitate data access and reuse.[26] BLM staff access AIM data alongside other core datasets via web portals. The public can access AIM calculated indicators through the BLM Landscape Approach Data Portal (https://landscape.blm.gov/), and raw data are available upon request.

Comprehensive electronic data capture along with centralized management and data distribution has been critical to the usefulness of AIM data within and beyond BLM. AIM data comply with the Open, Public, Electronic, and Necessary Government Data Act; they are publicly available, in open format, machine-readable, and contain well-formed metadata. Requests for monitoring data reports at the state or national level are accomplished with straightforward database queries and analyses. For example, stakeholders expressed concern about specific grass height management objectives in draft planning documents. We provided them with maps derived from AIM data, which illustrated that grass height nationwide largely meets these height objectives, and their concerns were alleviated. AIM data are shared with partner organizations (e.g., universities, research agencies, and nonprofit organizations) who use the data to improve understanding and management of rangelands including building remote sensing models of fractional cover,[13,28] evaluating postfire vegetation responses,[29] and describing treatment effectiveness.[30]

Lessons learned and adaptation

Electronic data capture and management will continue to facilitate success of AIM and other monitoring programs. Maintaining and improving modern data workflows requires constant adaptation given rapid changes in technology. For example, AIM data collection recently transitioned to a new electronic data capture platform to improve compatibility with BLM enterprise systems, increase efficiency in data collection, and to provide calculated indicators to users more quickly. Changing technologies also create ongoing needs for communication and training for field data collectors.

Determining the appropriate level of investment and sustained support in data management will be critical to AIM and other monitoring programs' future success. Initial investments in AIM data management created data infrastructure and workflows that met short-term needs. However, as yearly data collection expanded, these became challenging to manage. We improved data infrastructure and workflows through increased investment in central data support (about a tenth of the overall budget), which maintains data workflows and facilitates distributed data management activities at state and local levels. Clear two-way communication between the central data management team and state and local data managers (including field data collectors and users) is critical for keeping costs low, data quality high, and data products relevant to decision-making. In response to data user requests, we expanded the data elements which are tracked, especially those related to sample designs, such that the entire monitoring workflow is captured and managed electronically. Investments in data quality as well as data management throughout the BLM are essential to maintain a useful dataset for land management decision-making.[3,31]

Monitoring programs that embrace electronic data capture and management can also contribute informatics leadership and expertise to build standard datasets required for land management decisions. We have helped land managers prioritize and invest in other critical datasets and data systems to support decision-making (e.g., standard core and supplemental indicators and methods). Many efforts are underway to standardize and aggregate key geospatial information, including areas identified for certain uses in land use plans (e.g. motorized travel, energy development), vegetation treatment areas,[32] and surface disturbance and reclamation. Further, these standardized datasets are increasingly integrated into tools to understand condition and trend of AIM indicators and support decision-making (see Emergent Principle). Effective data management places information in the hands of land managers and decision-makers at all levels, and eases data-supported decision-making, thus facilitating adaptive management (Table 1).

Principle 3: Appropriate sample designs to minimize bias and maximize what can be learned from collected data

Status

Appropriate sample designs ensure that collected data adequately address monitoring questions and provide insights at the required scale(s) with known levels of precision and accuracy.[7,33] In the AIM program, appropriate sample designs are identified based on the multiple management and monitoring objectives for an area. AIM sample designs enable rangeland condition estimates at different scales from national or ecoregional to field office, watershed, or smaller areas (Fig. 3).[2,9] The majority of AIM sample designs are based on a Generalized Random Tessellation Stratified (GRTS) approach to locating samples,[34] which ensures a random, spatially balanced sample within an area of interest. Locations are sampled with attention to their order in the design to maintain spatial balance following GRTS principles. With this approach, sample sizes can be expanded or reduced in response to logistical, financial, or personnel limitations and still provide a valid sample of the study area. This allows for flexibility in monitoring while drawing inference to areas of interest with known levels of uncertainty. AIM sample designs support statements such as, "65% of stream kilometers in the Upper Platte River Watershed have minimal departure from regional reference conditions (± 90% confidence interval) for fine sediment" (Fig. 3).

We use three main scales of designs that meet different information needs tied to policy requirements. The monitoring needs and associated designs are frequently nested such that monitoring locations can make inference to many scales, resulting in efficiencies for data collection and use (Table 1; Fig. 3):

1) *National, state, and ecoregional:* Multistate designs enable reporting across BLM-managed lands in the western United States. These are the lowest-intensity designs, meaning that each monitoring location represents a large area or stream length. The results serve as a national inventory required by FLPMA and can also inform broad-scale environmental analyses. Currently, the Landscape Monitoring Framework and the National Lotic AIM Assessment are BLM's national designs for uplands and wadeable streams and rivers, respectively.
2) *BLM districts or field offices:* Administrative designs enable reporting for land use plan effectiveness as required by FLPMA and BLM policy (Table 1; Fig. 3). These are medium intensity designs often stratified by ecosystem types (e.g., shortgrass grassland or sagebrush) to allocate monitoring effort among areas of interest. These designs may also support future land use planning efforts as well as environmental analyses to guide local management actions or decisions.
3) *Local:* Intensifications of broader-scale designs focus on a subset of an administrative or land use planning area. Examples include habitat type, watershed, a grazing allotment for a term permit renewal, or a treatment area to assess restoration effectiveness (Fig. 3). These are necessary when the district or field office design does not contain sufficient samples within a local reporting area and other available datasets are insufficient (e.g., remote sensing products).

Nonrandom targeted design approaches are also used in AIM to address local questions. Targeted monitoring locations, such as key areas in pastures, are purposefully chosen to answer a specific question. For example, a land manager with questions about grazing use impacts may locate monitoring in areas with known grazing intensity to draw a causal link between grazing and rangeland health. Targeted designs thus complement random designs by enabling additional insights. However, unlike random designs, results from targeted monitoring cannot be extrapolated beyond the location sampled, and measures of error can be confounded by spatial autocorrelation.[33] Thus, we flag targeted monitoring locations within AIM data, and encourage documentation of the rationale for selection, so assumptions and potential biases can inform future analyses. Random designs also provide context for targeted monitoring by distinguishing between changes at the local scale and at broader spatial scales.

Lessons learned and adaptation

Statistically valid sample designs are an important tool in the monitoring design toolbox, but land managers require flexibility in design approaches to address their information needs. In 2016, the AIM program shifted terminology from "statistically valid" designs to highlight "appropriate" designs. This shift was driven in part by feedback from AIM practitioners communicating the importance of nonrandom, targeted design approaches for site-specific decisions and questions land managers often face. Supporting multiple design options, including targeted designs, while implementing consistent core methods ensures that national monitoring programs are providing relevant data for both broad-scale and local decision-making.[3] Successfully leveraging multiple design approaches in land management decision-making requires land managers to understand the appropriate uses and constraints of each. We document sample design information in databases and provide training for new monitoring specialists and data collectors regarding different design approaches.

In the future, we will continue to refine approaches to creating, managing, and implementing sample designs to inform multiscale management objectives. Land managers, statisticians, and rangeland scientists all have valuable contributions, so that design improvements are relevant for management as well as statistically valid, appropriate, and robust. Refinements of monitoring design approaches may include sample sufficiency and utility of random designs at various scales; interactions and tradeoffs among multiple overlapping designs; reuse of monitoring locations including targeted and/or historic locations; and approaches for integrating trends and

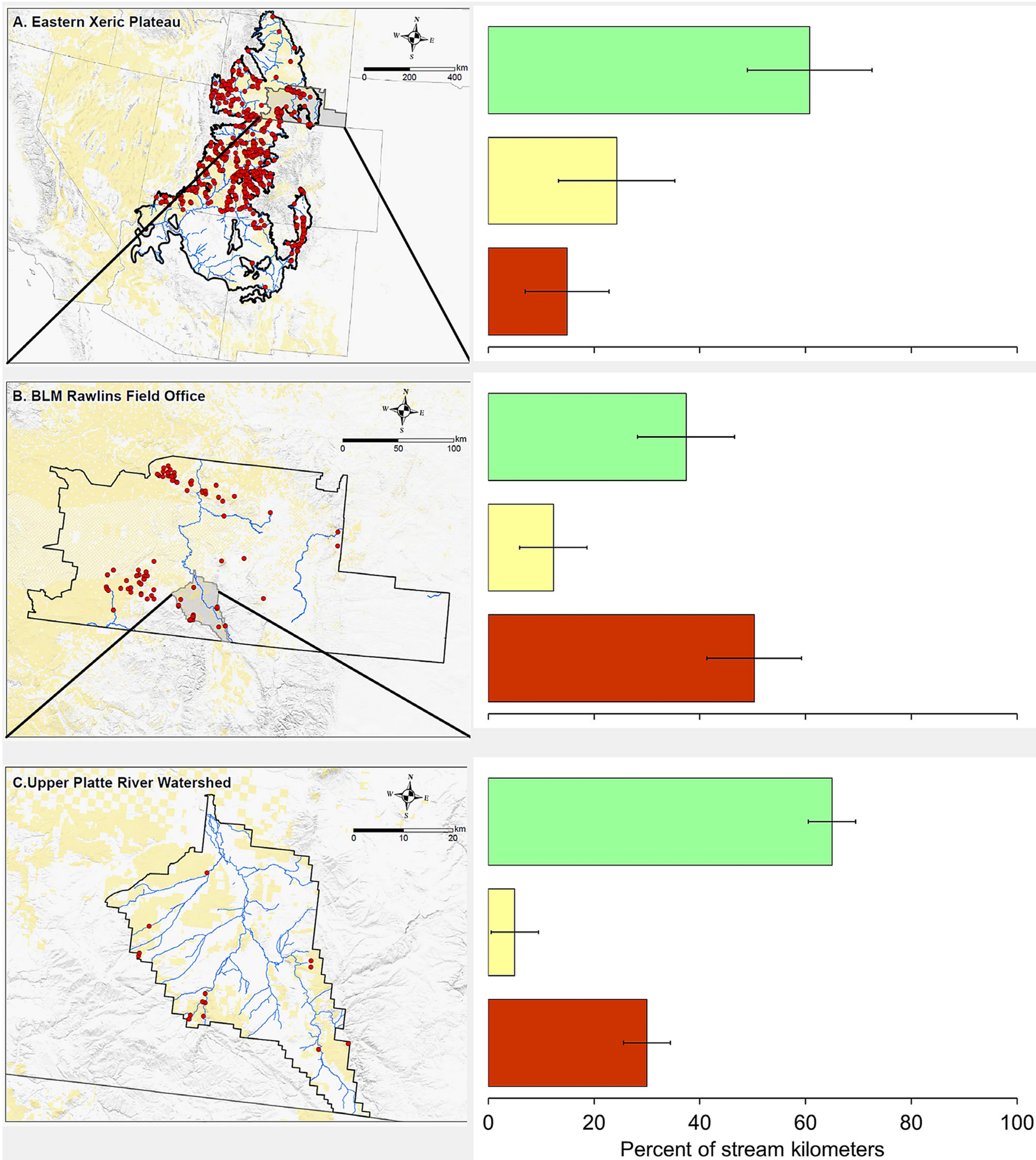

Figure 3. The percent of stream kilometers having minimal (green), moderate (yellow), and major (red) departure from reference conditions (±90% confidence intervals) for percent fine sediment compared among spatially nested reporting areas: A, Eastern xeric basins; B, BLM Rawlins Field Office, Wyoming; and C, Upper Platte River Watershed. The use of standard field methods, statistically valid sample designs, and benchmarks allow data to be integrated among spatial scales and reporting areas. An example quantitative objective for applying data to decision-making is: maintain fine sediment below the 90th percentile (i.e., moderate or minimal departure) of regional reference conditions for small streams in the Eastern Xeric Basin.

causal analyses in addition to condition estimates. BLM land managers are especially interested in trend analysis, and we are incorporating plot revisits to monitor changes in rangeland ecosystems over time and in response to management actions.

Future adaptations to a monitoring design should be informed by multiscale management objectives (e.g., Table 1) to maximize monitoring efficiency and use of data.[15] Therefore, it is imperative that land managers identify objectives and use relevant data, including data collected as part of AIM, to understand the impact of their design decisions on their ability to address objectives. The practices of identifying explicit objectives and using monitoring data to improve our understanding of the system are the basis of adaptive management.[35] Likewise, a cornerstone of an adaptive monitoring program is to modify design approaches when needed to address management objectives (also see McCord and Pilliod, this issue).[3,7]

Principle 4: Integration with remote sensing to optimize sampling and calibrate continuous map products

Status

The last decade has seen a proliferation of remotely sensed products and tools, in part because of the availability and volume of data collected through AIM and similar monitoring efforts.[36] Remote sensing products leverage field data with current and historical imagery to make spatially explicit predictions of core indicator values (e.g., vegetation cover and bare ground) across landscapes. Examples include vegetation classification efforts such as Landfire Existing Vegetation Type and fractional cover products that extend predictions throughout the USGS Landsat satellite record.[13,28,37] Method standardization (Principle 1) and commitment to data quality and management (Principle 2) are key to the success of these efforts (also see Allred et al. and McCord et al., this issue). Remote sensing scientists and land managers have benefitted most recently from innovations in cloud computing and web-based data portals (e.g., Google Earth Engine) that have revolutionized image analysis, data production, and dissemination of rangeland remote sensing information (e.g., climateengine.org, rangelands.app, landcart.org, and https://www.mrlc.gov/rangeland-viewer/).

Remotely sensed products are increasingly used as a line of evidence to support decision-making by BLM and its partners. Broad-scale analyses such as regional Environmental Impact Statements gain insight from detailed information about conditions in areas affected by a land management decision. Remote sensing also supports and integrates with field monitoring efforts, making on-the-ground monitoring more cost-effective and efficient. For example, improved wetland inventory products from remote sensing provide a robust sample frame for accurate wetland sample design and site selection. Likewise, remote sensing products can inform stratification of AIM monitoring designs. Remote sensing helps optimize field sampling while also extending insights across landscapes.

Lessons learned and adaptation

Amidst increasing accessibility of remote sensing information for rangelands, workflows are needed for integrating remote sensing data into management decisions (see Emergent Principle). Land managers and the researchers who develop remote sensing products would benefit from a shared understanding of appropriate uses and drawbacks of these products for decision-making. Considerations for using remote sensing data include spatial scale, spatial resolution, temporal resolution in the context of landscape patterns, and concordance with other datasets.[38] Emerging frameworks for using remote sensing data should include instruction for interpreting model error and uncertainty.[39] Management-science partnerships will continue to be critical for creating meaningful change and leveraging the wealth of imagery available.

Improved integration with decision workflows will inevitably reveal opportunities to create or update remote sensing datasets to support effective decision-making (also see Emergent Principle). Technological advances, including cloud computing and new image and sensor products (e.g., synthetic aperture radar), can increase the pace of development and improve the accuracy of remote sensing to inform land and natural resource management. For example, to date there has been limited growth in mapping stream, river, wetland and riparian indicators using remote sensing, mostly due to challenges with mapping very small areas (pixel size) and water bodies concealed by overhanging vegetation. Improved mapping of land uses and natural disturbances represent additional opportunities for remote sensing to inform decision-making (e.g., BLM postfire mapping, unpublished; disturbance mapping and analysis[40]). Finally, remote sensing provides a landscape-wide opportunity for analytical insights such as models of ecosystem potential[40,41] and causal factor analysis.[42]

Principle 5: Structured implementation to guide monitoring program development, implementation, and management decisions

Status

Although standard methods, data management, appropriate sample designs, and remote sensing are all individually useful principles, structured implementation integrates these principles to support meaningful collection and use of monitoring data. Structured implementation enables practitioners to use AIM to address management questions. Well-defined management and monitoring questions are foundational for adaptive monitoring programs.[7] Management-driven questions optimize application of AIM principles to ensure the necessary data are collected, data are of sufficient quality for a given application, and AIM implementation is cost effective and sustainable. Structured implementation allows AIM to address a diversity of management questions in a consistent and defensible manner.

When a new AIM effort begins, local monitoring leads and their interdisciplinary team step through the key decisions necessary for a successful monitoring effort. We developed a monitoring design worksheet that streamlines and documents the monitoring planning process and provides a framework for adapting monitoring as needed after each field season. Initial steps include specifying management objec-

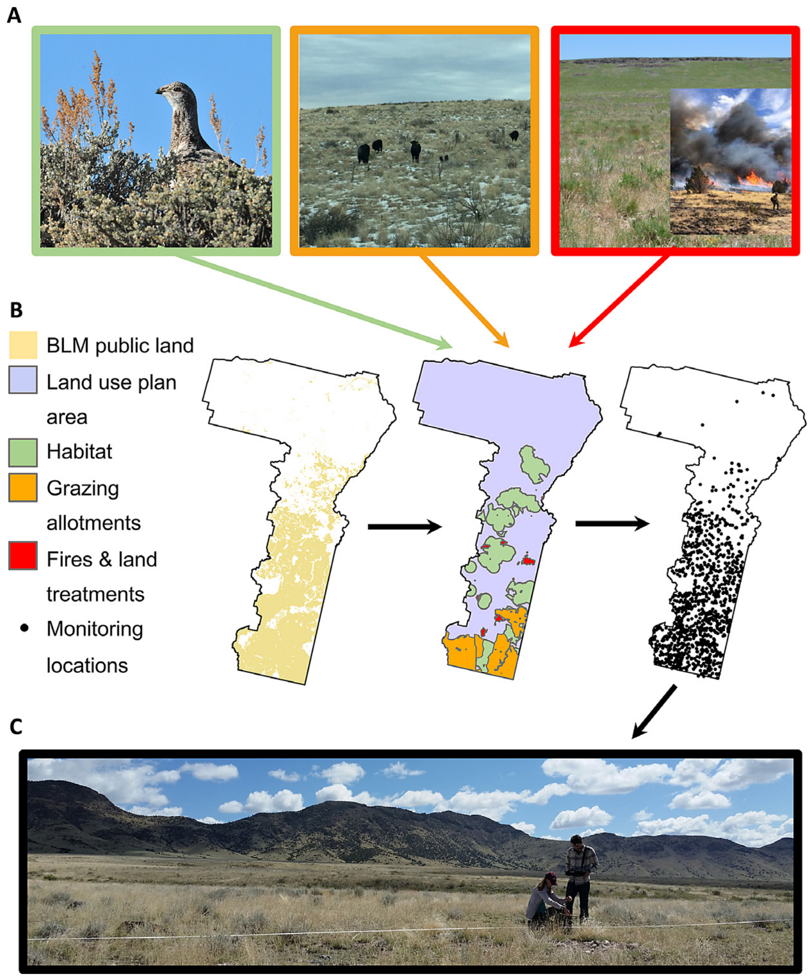

Figure 4. Monitoring design process for Vale District in eastern Oregon. A, Multiscale management questions include land use plan effectiveness, wildlife habitat condition, land health evaluations for grazing permits, and postfire rehabilitation treatment effectiveness. B, Areas relevant to each question are mapped and used to select the appropriate number and distribution of monitoring locations. C, Upland core methods are collected at each monitoring location, with contingent or supplemental methods added depending on the question.

tives and indicators (Fig. 4A), identifying reporting areas, and considering stratification (Fig. 4B). If AIM indicators do not address all identified management objectives, the team may choose supplemental methods and associated indicators to be collected with AIM data. Next, the team develops monitoring objectives and associated benchmarks for the indicators to be collected, providing a framework for data use in decision-making. Management and monitoring objectives, with related spatial information, inform the selection of monitoring locations for a multiyear monitoring plan (Fig. 4C). Finally, the monitoring lead describes a quality assurance and quality control plan to ensure their data meets data quality standards (McCord et al, this issue). This planning process balances monitoring needs with resources, time, and funding, and ensures that management decisions based on AIM data are defensible. Overall, AIM's structured implementation principle provides the necessary support for a step-by-step process of sound adaptive monitoring (McCord and Pilliod, this issue).

AIM implementation is supported by a network of monitoring specialists across BLM and within partner organizations. Monitoring coordinators in state offices manage funding and coordinate AIM efforts within each state to ensure data collection supports interdisciplinary decision-making needs. Monitoring leads at the BLM district or field office oversee AIM monitoring efforts, from design to data management and data use to inform decision-making. Centralized support for field, district, and state office monitoring staff is provided by a technical team at the National Operations Center. The national team leads protocol refinements; training; monitoring design workflows; electronic data capture and storage (including quality control); data visualization and access services; and analysis support. Specialized science partners also contribute to this work. The USDA Agricultural Research Service Jornada Experimental Range, Utah State University's National Aquatic Monitoring Center, and the Colorado Natural Heritage Program support upland, wadeable stream and river, and wetland and riparian workflows, respectively. Numerous research partners also work closely with BLM staff to develop remote sensing products needed for land and natural resource management.

Lessons learned and adaptation

This principle was created to transform the AIM strategy into a program of work that would inform land management decision-making.[43] As AIM continues to adapt, we will refine the implementation process to ensure that AIM is working as efficiently as possible. For example, we recently completed our second revision of the monitoring design worksheet, the standard tool for planning monitoring efforts and sample designs. Likewise, we adopted a standard approach to partnering with outside organizations for data collection as well as training and data management, which has proven beneficial for consistent and successful monitoring implementation. Built-in feedback mechanisms enable frequent re-evaluation of AIM implementation and inform adaptation. Central support staff work closely with monitoring leads at state and local offices to manage AIM efforts. Training and regular program coordination are also key mechanisms for feedback and improvement (see Newingham et al., this issue). The AIM community has highlighted that data use in decision-making, including integration with adaptive management, is a critical area for future improvement. Overcoming this shared challenge of using adaptive monitoring data for adaptive management is increasingly crucial for natural resource managers and communities worldwide amidst ongoing change.

Emergent Principle: Data use through standard workflows and analysis frameworks that empower land managers to make data-supported decisions

Guided by policy, AIM principles, and a support network, AIM data are collected in over three quarters of BLM field offices and are broadly available across public lands (Fig. 1). AIM data are beginning to streamline decision-making with a diversity of published examples available (Table 1). However, informal program feedback reveals that data use lags behind data collection, as frequently occurs in environmental management.[4,44,45] Further, AIM data use is uneven across BLM disciplines and offices, highlighting opportunities for improved integration with land managers' day-to-day decisions. Individual managers choose to adopt an innovation, or not, based on the utility and value of the innovation. Adoption decisions are complex and can be influenced by the individuals' characteristics, their perceptions of the innovation, and their social context.[44,46] To fully support adaptive management amidst ongoing change, the AIM program must connect with practitioners and support the use of AIM data for specific land management decisions. Therefore, we propose a sixth AIM principle: Data use through standard workflows and analysis frameworks that empower land managers to make data-supported decisions.

Land managers use AIM data for decision-making more frequently when they have technical guidance that describes workflows and analysis frameworks for applying data to decisions. Such technical guidance establishes a transparent and evident connection from monitoring data to the specific decisions land managers make daily.[15] For example, the Habitat Assessment Framework[47] facilitates and streamlines greater sage-grouse habitat assessments, providing a process for using AIM and other data to evaluate habitat quality to inform decision-making. Similarly, standard reporting templates that incorporate monitoring information are used to evaluate treatment effectiveness after fires and plan future treatments.[32] When these workflows and analyses have been unclear, however, use of AIM data has lagged. Our experience suggests that perceived complexity, lack of clear advantages to using new data types, and perceived incompatibility with existing decision workflows can be barriers to AIM data use.[46] Many opportunities exist to connect policy and available data with decision-making through development of specific technical guidance (Table 1).

Recent work with land health evaluations in support of land use authorizations, frequently applied to livestock grazing, illustrates a path forward for developing standard workflows and analysis frameworks for decision-making. First, we listened to questions from resource specialists and recognized the need. Next, we studied relevant policy. We convened an interdisciplinary team of monitoring and range experts to understand and document the specific steps for applying AIM data to a land health evaluation and authorization of permitted use, including reference to specific datasets and analysis approaches. We solicited and incorporated feedback. The product, *Guide to Using AIM and LMF Data in Land Health Evaluations and Authorizations of Permitted Uses*,[17] assists practitioners by clearly demonstrating how AIM data can be incorporated as part of multiple lines of evidence into an established decision-making process.[19] It also streamlines decision-making by fostering consistency in the decision workflow and reducing training needs of new staff, thereby saving time and money.

Data analysis is a key component of workflows for using data in decision-making. Quantitative data can provide transparent, consistent, and defensible decision support when they are analyzed within the context of established quantitative objectives and benchmarks for indicators that are important for, and responsive to, management. Scientific literature and policy regarding adaptive management recommend using quantitative monitoring objectives as a standard analysis framework to inform decision-making (e.g., DOI Adaptive Management Technical Guide[35]). Accordingly, the AIM program emphasizes quantitative objectives as part of the structured implementation process (e.g., Fig. 3) and provides additional instructions.[17] The most difficult step is setting benchmarks, or indicator values that define desired conditions and are meaningful for management. Improved interpretive frameworks and tools could greatly facilitate setting benchmarks. For example, frameworks for setting benchmarks based on undisturbed reference sites are broadly used for stream and river ecosystems across agencies.[48] Likewise, Ecological Site Descriptions contain information for setting benchmarks that could be improved with more quantitative AIM indicators and links to ecosystem functions (e.g., benchmarks for canopy

Table 2
Recommendations derived from the AIM principles, which can inform design and adaptation of monitoring efforts worldwide

Principle	Key elements
Principle 1: Standardized field methods and indicators	• Standardize core methods and indicators, but retain flexibility to address local questions (e.g., contingent and supplemental indicators) • Rely upon ecosystem attributes and policy to guide agreement on standard indicators • Choose commonly used methods to provide consistency across management boundaries and enable partnerships in data use • Maintain metadata including indicator calculations • Maintain clear change management processes
Principle 2: Data management and stewardship	• Ensure data are findable, accessible, interoperable, and reusable (i.e., FAIR[26]) • Identify and account for all components of the data workflow, from design to collection to storage • Invest in constant maintenance of data workflows • Leverage the full suite of standard datasets to support rangeland decision-making
Principle 3: Appropriate sample designs	• Tailor design approaches to management and monitoring objectives • Use scalable design approaches when information across different overlapping areas is needed • Use targeted design approaches to answer questions tied to a location • Re-evaluate your design periodically and adapt as appropriate
Principle 4: Integration with remote sensing	• Leverage on-the-ground data to calibrate and validate remote sensing products • Work closely with decision-makers to interpret and integrate remote sensing products into decisions • Use remote sensing products to improve efficiency of on-the-ground monitoring work
Principle 5: Structured implementation	• Develop a structured process for practitioners to use the monitoring program to address multiscale management questions, including local questions • Ensure sufficient technical and logistical support to maintain long-term monitoring • Adapt monitoring efforts when needed
Emergent Principle: Data use through standard workflows	• Develop workflows and analysis frameworks for using data in decision-making • Ground workflows in decision-makers' experiences and policy and include end users in workflow development and refinement • Use quantitative objectives with benchmarks, an analysis framework that is broadly applicable to land management • Workflows and analysis frameworks should foster co-production of knowledge by integrating multiple knowledge types • Consider the full suite of standard datasets that support decision-making, including supplemental indicators, permitted uses, and natural disturbances

gap size to manage wind erosion[49]). Some land managers hesitate to set benchmarks because of limited published and/or place-specific justification for the exact value. Available AIM data can fill this gap by providing a line of evidence to set or update benchmarks. For example, AIM data were used to update benchmarks in Alaska.[50] AIM data are also increasingly used to provide restoration or reclamation objectives after wildfire or other disturbance. Setting benchmarks using AIM data is especially effective when data are first screened to identify AIM plots that represent reference conditions or certain ecological functions.[40,49,50] The AIM program has effectively provided support for decision-making by both communicating to decision-makers about quantitative objectives and providing technical assistance with selecting objectives and benchmarks.

Recognition of this principle empowers the rangeland management community to work together to establish standard workflows and analysis frameworks for using data for management decisions. Co-production of knowledge by a diverse group of stakeholders[45] is a widely recognized mechanism for increasing the salience, credibility, and legitimacy of information for decision-making and therefore its use.[45] Standard workflows describe the decision, a critical first step to co-production,[45,51] and provide a process for stakeholders to work through. In developing analysis frameworks, we recognize the valuable contributions of different knowledge types including historic and qualitative data and scientific, professional, local, and indigenous knowledge. For example, we recommend that benchmarks are set using all available information. Likewise, conclusions about land health should be based on multiple lines of evidence.[17,49,52] AIM data provide information about the current condition of uplands, wadeable streams and rivers, and wetlands and riparian areas, which is consistent across different regions, issues, and stakeholders. AIM data thus provide a critical line of evidence to complement other types of knowledge in decision-making.[45,53]

The AIM program also provides a model for generating and using other datasets needed for decision-making. For instance, supplemental indicators will be necessary for specific management questions (e.g., fuels measurements for fuel reduction treatments[20]). Likewise, geospatial information about land uses such as vegetation treatments and surface disturbance and reclamation will be needed, especially to connect monitoring data to causal factors.[54] Together, we can create and improve these datasets to generate a shared portfolio of information about rangelands (see Principle 1). BLM specialists, land users, researchers, and the public have valuable contributions to make to this work. Standard data, along with standard approaches to using it, can streamline decision-making and inform adaptive management across boundaries into the future. A key challenge will be to collaboratively incorporate new science and technology as it becomes available as part of the adaptive monitoring process.

Conclusions

The AIM principles provide a framework for monitoring programs to meet multiscale information needs for land management in the changing landscapes of rangeland ecosystems and the context of policy requirements. We conclude that the principles are sound and worthy of consideration for design and adaptation of other rangeland monitoring efforts worldwide (Table 2). The AIM principles have become the standard rangeland ecosystem monitoring approach within BLM,[2,9] increasing efficiency of monitoring work, ensuring the quality and utility of data (including remote sensing products), informing defensible decisions, and streamlining processes. Although some principles must be strictly followed for effectiveness (standardization, data management), there is also a need for flexibility in some principles given appropriate rationale and documentation. Land managers require additional datasets beyond rangeland condition for specific decisions, and AIM principles are useful for developing these datasets.

Our vision is to empower land managers to make defensible decisions regarding multiple uses of rangeland ecosystems sustained through time. To achieve this vision, we intend to focus on establishing standard workflows and analysis frameworks for using data in decision-making, a principle that has emerged from our experience. We will continue to emphasize workflows and decisions that are rooted in policy and represent critical day-to-day needs of land managers (Table 1). Additionally, technical guidance, policy, and funding support are critical to ensure that AIM data are useful for land management decisions. Achieving multiple objectives with one monitoring effort is unusual and challenging. The AIM principles and related technical tools enable BLM together with partners to achieve this challenge, while providing a strong business-case to land managers to use these data in decisions.

The AIM goal remains, "to provide the BLM and its partners with the information needed to understand…resource location and abundance, condition, and trend, and to provide a basis for effective adaptive management."[9] This goal will be achieved if the broader rangeland management community participates alongside BLM in a renewed effort to coproduce knowledge about rangeland health, how it is changing, and where to take action.[1] AIM provides a key line of evidence alongside other types of knowledge from remote sensing maps to indigenous and local knowledge. This shared knowledge is necessary to sustain multiple uses of rangelands into the future, which not only aligns with the mission of BLM but also benefits us all.

Declaration of Competing Interest

Sarah McCord is a Guest Editor for this special issue, but was not involved in the handling, review, or decision process for this manuscript. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The content of sponsored issues of Rangelands is handled with the same editorial independence and single-blind peer review as that of regular issues.

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References

1. Bestelmeyer BT, Briske DD. Grand challenges for resilience-based management of rangelands. *Rangel Ecol Manag*. 2012; 65(6):654–663. doi:10.2111/REM-D-12-00072.1.
2. Toevs GR, Taylor JJ, Spurrier CS, MacKinnon C, Bobo MR. *Assessment, Inventory, and Monitoring Strategy: For Integrated Renewable Resources Management*. US Department of Interior, Bureau of Land Management, National Operations Center; 2011 Accessed October 7, 2020 https://www.blm.gov/sites/blm.gov/files/uploads/IB2012-080_att1.pdf.
3. Lindenmayer DB, Likens GE. The science and application of ecological monitoring. *Biol Conserv*. 2010; 143(6):1317–1328. doi:10.1016/j.biocon.2010.02.013.
4. Danielsen F, Burgess ND, Jensen PM, Pirhofer-Walzl K. Environmental monitoring: the scale and speed of implementation varies according to the degree of peoples involvement. *J Appl Ecol*. 2010; 47(6):1166–1168. doi:10.1111/j.1365-2664.2010.01874.x.
5. Waylen KA, Blackstock KL, van Hulst FJ, et al. Policy-driven monitoring and evaluation: does it support adaptive management of socio-ecological systems? *Sci Total Environ*. 2019; 662:373–384. doi:10.1016/j.scitotenv.2018.12.462.
6. Biber E. The challenge of collecting and using environmental monitoring data. *Ecol Soc*. 2013; 18(4). doi:10.5751/ES-06117-180468.

7. Lindenmayer DB, Likens GE. Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends Ecol Evol*. 2009; 24(9):482–486. doi:10.1016/j.tree.2009.03.005.
8. US Department of Interior, Bureau of Land Management (ed). *The Federal Land Policy and Management Act of 1976 as Amended*; 2016:106. Accessed June 29, 2021. https://www.blm.gov/sites/blm.gov/files/AboutUs_LawsandRegs_FLPMA.pdf
9. Toevs GR, Karl JW, Taylor JJ, et al. Consistent indicators and methods and a scalable sample design to meet assessment, inventory, and monitoring information needs across scales. *Rangelands*. 2011; 33(4):14–20. doi:10.2111/1551-501X-33.4.14.
10. Herrick JE, Van Zee JW, McCord SE, Courtright EM, Karl JW, Burkett LM. *Monitoring Manual for Grassland, Shrubland, and Savanna Ecosystems*. 2nd ed. USDA - ARS Jornada Experimental Range; 2018 Vol 1 November 3, 2018 https://wwwlandscapetoolboxorg/manuals/monitoring-manual/ Accessed.
11. Bureau of Land Management. AIM National Aquatic Monitoring Framework: Field Protocol for Wadeable Lotic Systems 2017. Accessed October 7, 2020. https://www.blm.gov/documents/national-office/blm-library/technical-reference/aim-national-aquatic-monitoring-0.
12. Bureau of Land Management. AIM National Lentic Monitoring Framework: Field Protocol for Lentic Riparian-Wetland Systems. 2021. Accessed June 29, 2021. https://aim.landscapetoolbox.org/wp-content/uploads/2021/02/Jan2021DraftLenticAIMProtocol.pdf.
13. Jones MO, Allred BW, Naugle DE, et al. Innovation in rangeland monitoring: annual, 30 m, plant functional type percent cover maps for U.S. rangelands, 1984–2017. *Ecosphere*. 2018; 9(9). doi:10.1002/ecs2.2430.
14. Rigge M, Homer C, Cleeves L, et al. Quantifying western US rangelands as fractional components with multi-resolution remote sensing and in situ data. *Remote Sens*. 2020; 12(3):412. doi:10.3390/rs12030412.
15. Nichols SJ, Barmuta LA, Chessman BC, et al. The imperative need for nationally coordinated bioassessment of rivers and streams. *Mar Freshwater Res*. 2016; 68(4):599–613. doi:10.1071/MF15329.
16. 43 CFR § 4180. *Fundamentals of Rangeland Health, 43 CFR § 4180.1;*2006. Accessed June 29, 2021. https://www.blm.gov/sites/blm.gov/files/uploads/Media_Library_BLM_Policy_h4180-1.pdf
17. Kachergis E, Lepak N, Karl MG, Miller SW, Davidson Z. Guide to Using AIM and LMF Data in Land Health Evaluations and Authorizations of Permitted Uses. US Department of the Interior, Bureau of Land Management, National Operations Center; 2020. Accessed July 28, 2020. https://www.blm.gov/documents/noc/blm-library/technical-note/guide-using-aim-and-lmf-data-land-health-evaluations-and
18. Dickard M, Gonzalez M, Elmore W, et al. Riparian Area Management: Proper Functioning Condition Assessment for Lotic Areas. US Department of the Interior, Bureau of Land Management, National Operations Center; 2015. Accessed July 30, 2021. https://www.blm.gov/documents/national-office/blm-library/technical-reference/riparian-area-management
19. Pellant M, Shaver PL, Pyke DA, et al. Interpreting Indicators of Rangeland Health, Version 5. US Department of the Interior, Bureau of Land Management, National Operations Center; 2020. Access July 30, 2021. https://www.blm.gov/documents/national-office/blm-library/technical-reference/interpreting-indicators-rangeland-health-0
20. Brown JK. Handbook for Inventorying Surface Fuels and Biomass in the Interior West. U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; 1982. Accessed June 29, 2021. https://www.fs.fed.us/rm/pubs_int/int_gtr129.pdf
21. Reynolds JH. An overview of statistical considerations in long-term monitoring. In: Cooper AB, Licht DS, Millspaugh JJ, Gitzen RA, eds. *Design and Analysis of Long-Term Ecological Monitoring Studies*. Cambridge University Press; 2012:23–53.
22. Quality Assurance & Quality Control – Assessment, Inventory, and Monitoring. Assessment, Inventory, and Monitoring support for BLM AIM projects and programs. Accessed June 29, 2021. https://aim.landscapetoolbox.org/quality-assurance-quality-control/
23. McCord SE, Webb NP, Van Zee JW, et al. Provoking a cultural shift in data quality. *BioScience*. 2021; 71(6):647–657. doi:10.1093/biosci/biab020.
24. BLM AIM TerrADat Metadata. Accessed June 29, 2021. https://landscape.blm.gov/geoportal/catalog/search/resource/details.page?uuid=%7BFC25396E-D9BC-40AA-988B-D5BB5F8171DE%7D
25. BLM AIM AquADat Point Metadata. Accessed June 29, 2021. https://landscape.blm.gov/geoportal/catalog/search/resource/details.page?uuid=%7B5C8DD8C9-CA61-14F73-B739-E7792D829006%7D
26. Wilkinson MD, Dumontier M, Aalbersberg IJ, et al. The FAIR Guiding Principles for scientific data management and stewardship. *Sci Data*. 2016; 3. doi:10.1038/sdata.2016.18.
27. Thriemer K, Ley B, Ame SM, et al. Replacing paper data collection forms with electronic data entry in the field: findings from a study of community-acquired bloodstream infections in Pemba, Zanzibar. *BMC Res Notes*. 2012; 5(1):113. doi:10.1186/1756-0500-5-113.
28. Zhou B, Okin GS, Zhang J. Leveraging Google Earth Engine (GEE) and machine learning algorithms to incorporate in situ measurement from different times for rangelands monitoring. *Remote Sens Environ*. 2020; 236. doi:10.1016/j.rse.2019.111521.
29. Barker BS, Pilliod DS, Rigge M, Homer CG. Pre-fire vegetation drives post-fire outcomes in sagebrush ecosystems: evidence from field and remote sensing data. *Ecosphere*. 2019; 10(11):e02929. doi:10.1002/ecs2.2929.
30. Ernst-Brock C, Turner L, Tausch RJ, Leger EA. Long-term vegetation responses to pinyon-juniper woodland reduction treatments in Nevada, USA. *J Environ Manag*. 2019; 242:315–326. doi:10.1016/j.jenvman.2019.04.053.
31. Michener WK. Quality assurance and quality control (QA/QC). In: Recknagel F, Michener WK, eds. *Ecological Informatics: Data Management and Knowledge Discovery*. Springer International Publishing; 2018:55–70.
32. Pilliod DS, Welty JL, Toevs GR. Seventy-five years of vegetation treatments on public rangelands in the Great Basin of North America. *Rangelands*. 2017; 39(1):1–9. doi:10.1016/j.rala.2016.12.001.
33. McDonald T. Spatial sampling designs for long-term ecological monitoring. In: Cooper AB, Licht DS, Millspaugh JJ, Gitzen RA, eds. *Design and Analysis of Long-Term Ecological Monitoring Studies*. Cambridge University Press; 2012:101–125.
34. Stevens DL, Olsen AR. Spatially balanced sampling of natural resources. *J Am Stat Assoc*. 2004; 99(465):262–278. doi:10.1198/016214504000000250.
35. Williams BK, Szaro RC, Shapiro CD. *Adaptive Management: The U.S. Department of the Interior Technical Guide*. U.S. Department of the Interior; 2009:84.
36. Jones MO, Naugle DE, Twidwell D, Uden DR, Maestas JD, Allred BW. Beyond inventories: emergence of a

new era in rangeland monitoring. *Rangel Ecol Manag*. 2020; 73(5):577–583. doi:10.1016/j.rama.2020.06.009.
37. Xian G, Homer C, Rigge M, Shi H, Meyer D. Characterization of shrubland ecosystem components as continuous fields in the northwest United States. *Remote Sens Environ*. 2015; 168:286–300. doi:10.1016/j.rse.2015.07.014.
38. Allred BW, Creutzburg MK, Carlson JC, et al. Guiding principles for using satellite-derived maps in rangeland management. *Rangelands*. 2022. doi:10.1016/j.rala.2021.09.004.
39. McCord SE, Buenemann M, Karl JW, Browning DM, Hadley BC. Integrating remotely sensed imagery and existing multiscale field data to derive rangeland indicators: application of Bayesian additive regression trees. *Rangel Ecol Manag*. 2017; 70(5):644–655. doi:10.1016/j.rama.2017.02.004.
40. Nauman TW, Duniway MC, Villarreal ML, Poitras TB. Disturbance automated reference toolset (DART): assessing patterns in ecological recovery from energy development on the Colorado Plateau. *Sci Total Environ*. 2017; 584-585:476–488. doi:10.1016/j.scitotenv.2017.01.034.
41. Rigge MB, Homer CG, Shi H, Wylie B. Departures of rangeland fractional component cover and land cover from Landsat-based ecological potential in Wyoming USA. *Rangel Ecol Manag*. 2020; 73(6):856–870. doi:10.1016/j.rama.2020.03.009.
42. Wood DJA, Seipel T, Irvine KM, Rew LJ, Stoy PC. Fire and development influences on sagebrush community plant groups across a climate gradient in northern Nevada. *Ecosphere*. 2019; 10(12):e02990. doi:10.1002/ecs2.2990.
43. Taylor JJ, Kachergis E, Toevs GR, et al. AIM-Monitoring: A Component of the BLM Assessment, Inventory, and Monitoring Strategy. US Department of the Interior, Bureau of Land Management, National Operations Center; 2014. Accessed June 29, 2021. https://gis.blm.gov/AIMDownload/Docs/TN_445.pdf
44. Marshall NA, Gordon IJ, Ash AJ. The reluctance of resource-users to adopt seasonal climate forecasts to enhance resilience to climate variability on the rangelands. *Clim Change*. 2011; 107(3):511–529. doi:10.1007/s10584-010-9962-y.
45. Cash DW, Clark WC, Alcock F, et al. Knowledge systems for sustainable development. *Proc Natl Acad Sci U S A*. 2003; 100(14):8086–8091. doi:10.1073/pnas.1231332100.
46. Rogers EM. *Diffusion of Innovations*. 4th ed. Simon and Schuster; 2010.
47. Stiver S, Rinkes E, Naugle D, Makela P, Nance D, Karl J. Sage-grouse habitat assessment framework: multiscale habitat assessment tool. *Bureau of Land Management and Western Association of Fish and Wildlife Agencies Technical Reference*. 2015:6710–6711. Accessed June 29, 2021. https://www.ntc.blm.gov/krc/uploads/923/TR_6710-01_HAF.pdf .
48. Hawkins CP, Olson JR, Hill RA. The reference condition: predicting benchmarks for ecological and water-quality assessments. *J North Am Benthol Soc*. 2010; 29(1):312–343. doi:10.1899/09-092.1.
49. Webb NP, Kachergis E, Miller SW, et al. Indicators and benchmarks for wind erosion monitoring, assessment and management. *Ecol Indic*. 2020; 110. doi:10.1016/j.ecolind.2019.105881.
50. Brady C, Varner M, Post J, Miller SW, Cappuccio N. *Developing Quantifiable Management Objectives from Reference Conditions for Wadeable Streams in the Eastern Interior Field Office*. Alaska: US Department of the Interior, Bureau of Land Management; 2018:27.
51. Beier P, Hansen LJ, Helbrecht L, Behar D. A how-to guide for coproduction of actionable science. *Conserv Lett*. 2017; 10(3):288–296. doi:10.1111/conl.12300.
52. Coates PS, Prochazka BG, O'Donnell MS, et al. *Range-Wide Greater Sage-Grouse Hierarchical Monitoring Framework—Implications for Defining Population Boundaries, Trend Estimation, and a Targeted Annual Warning System*. US Geological Survey; 2021:243.
53. Meadow AM, Ferguson DB, Guido Z, Horangic A, Owen G, Wall T. Moving toward the deliberate coproduction of climate science knowledge. *Weather Clim Soc*. 2015; 7(2):179–191. doi:10.1175/WCAS-D-14-00050.1.
54. Pilliod DS, Welty JL, Jeffries MI. USGS Land Treatment Digital Library Data Release: A centralized archive for land treatment tabular and spatial data (ver. 3.0, November 2020); 2019. doi:10.5066/P98OBOLS.
55. Karl MG, Kachergis E, Karl JW. *Rangeland Resource Assessment—2011*. Bureau of Land Management; 2016:96.
56. Yu CL, Li J, Karl MG, Krueger TJ. Obtaining a balanced area sample for the Bureau of Land Management Rangeland Survey. *JABES*. 2020; 25(2):250–275. doi:10.1007/s13253-020-00392-5.
57. Herren V, Kachergis E, Titolo A, et al. Greater sage-grouse plan implementation: rangewide monitoring report for 2015–2020. US Department of the Interior, Bureau of Land Management, Denver, CO; 2021.
58. Traynor ACE, Karl JW, Davidson ZM. Using Assessment, Inventory, and Monitoring data for evaluating rangeland treatment effects in Northern New Mexico. *Rangelands*. 2020; 42(4):117–129. doi:10.1016/j.rala.2020.06.001.
59. Di Stéfano S, Karl JW, Bailey DW, Hale S. Evaluation of the automated reference toolset as a method to select reference plots for oil and gas reclamation on Colorado Plateau rangelands. *J Environ Manag*. 2020; 265. doi:10.1016/j.jenvman.2020.110578.

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