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Guiding principles for using satellite-derived maps in rangeland management

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On the Ground

- Rangeland management has entered a new era with the accessibility and advancement of satellite-derived maps.
- Maps provide a comprehensive view of rangelands in space and time, and challenge us to think critically about natural variability.
- Here, we advance the practice of using satellite-derived maps with four guiding principles designed to increase end user confidence and thereby accessibility of these data for decision-making.

Keywords: heterogeneity, mapping, monitoring, remote sensing.

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Satellite remote sensing and rangelands

In 1975 the National Aeronautics and Space Administration held "the first comprehensive symposium on the practical application of Earth resources survey data" to discuss uses of the Landsat 1 satellite mission.[1] Leading the Agriculture session were four papers on rangeland management and monitoring, all concluding that "LANDSAT color composite images do provide a means for monitoring changes in range condition."[2] Thus the pursuit to map rangelands using satellites began, and the ensuing decades saw numerous advances, innovations, products, and techniques.[3–11] This pursuit still continues after 45 years, but recent advancements have catapulted the discipline into a new era, in which broad-scale mapping is operational and a working reality.[12] Previous limitations of data, access to remotely sensed imagery, and computational resources are disappearing. The reduction of technological barriers has created opportunities to develop consistent maps that span broad geographies and time periods, expanding their use and application.

The value provided by satellite-derived maps is two-fold. First, they efficiently provide data across space and through time. This includes "filling in the gaps" in locations and time periods that traditional, plot-based sampling has not captured, or will ever capture due to logistical and resource constraints. The data provided by maps are not necessarily more or less accurate, or better or worse than plot-based data. Rather, they are complementary and have the advantage and efficiency of representing every location through time, providing a more complete view of the landscape. Such a perspective allows management to adapt to the changes that are occurring on the landscape. The second—and more important—value provided by satellite-derived maps is that they can change the way we think about rangelands. Because maps provide a landscape and temporal view that captures heterogeneity and variation, maps help us think about, understand, and incorporate spatial and temporal dynamics into management actions and decisions; a perspective that has been largely absent in the profession.[13,14]

Given the discipline's 45+ years' pursuit of mapping rangelands, much has been written, discussed, predicted, and promised. Unfortunately, many of those predictions and promises have been overly ambitious, delayed, or simply inaccurate. Furthermore, relatively little emphasis has been placed on training natural resource managers in how to properly use and "think" about satellite-derived maps, especially when compared with education investments made in traditional plot-level sampling and monitoring (e.g., plant identification, plot-level inventory). Such failings have resulted in unmet expectations, frustration, and often an erosion of trust by end users.

Table 1
Key questions asked within a typical rangeland management decision-making framework and the potential utility and role of maps

Key Questions	Planning Step	Potential Utility and Role of Maps*
Where are we now?	Inventory and assessment	**High utility**. Maps efficiently provide data through space and time. Practicality of maps goes up with broader geographic and temporal extents.
Where do we want to be?	Goals	**Moderate utility**. Goal setting is inherently a qualitative process, but maps may help managers set realistic goals by providing landscape context.
How do we get there?	Strategy and prioritization	**High utility**. Maps can provide crucial spatial data needed to inform where and when to act.
What needs to change and when?	Objectives	**Moderate-to-high utility**. Maps can aid in establishing quantifiable targets for management. Maps may also inform how quickly change needs to happen, or areas that need special attention. Practicality of maps goes up with broader geographic and temporal extents.
What are we going to do?	Implementation	**Low-to-moderate utility**. The role and utility of maps is more limited during project-level implementation where local knowledge and data are most important. However, maps may be helpful for anticipating the degree of management intervention that may be required, and where efforts can make the biggest difference. Practicality of maps goes up with broader geographic and temporal extents.
How will we know when we get there?	Monitoring	**High utility**. Maps allow managers to track and quantify progress toward goals and objectives at multiple spatial and temporal scales. Practicality of maps goes up with the amount of monitoring required.

Note: Defining the role of maps early in the process helps make the most efficient use of these tools, recognizing that utility will vary.

* Utility at each step depends upon the specific attribute of management interest (e.g., functional groups, species, cover, production) relative to what the available maps provide, scale of management unit, and whether the level of map error is acceptable for the decisions being made.

We, as developers and users of broad-scale, operational maps, wish to rebuild trust in satellite-derived maps to capitalize on current and coming advancements. Therefore, we offer four guiding principles to help users think critically about and better understand the use of maps in rangeland management: 1) use maps within a decision-making framework; 2) use maps to better understand and embrace landscape variability; 3) keep error in perspective; and 4) think critically about contradictions. We hope readers consider these as principles rather than a checklist, prescription, or rule set on how to use maps. Rather, these core concepts are useful to contemplate, discuss, and integrate into situations where maps are or could be used. Furthermore, we encourage users to think critically about the utility of maps, as each situation will be different. These principles are not exhaustive and may be added to or modified as the profession, scholarship, and technology advance.

Principle 1. Use maps within a decision-making framework

Maps supply an abundance of data, providing a spatial and temporal perspective unparalleled by other sources. It is critical to remember, however, maps themselves (as well as all other data) are used to inform decisions, but do not actually make decisions. The number of recently produced maps, their increased accessibility and ease of use, and their overall popularity creates an invitation—temptation even—to apply them without thinking through a decision-making framework beforehand. This often leads to an inefficient, inaccurate, or inappropriate use of maps as a tool.

Before using maps, start with clear objectives centered on the desired management actions or decisions and not the maps themselves. Identify or develop a decision-making framework that allows critical thinking and input from multiple data sources. Outline the different contributions that maps and other data provide relative to the decision (e.g., Table 1; Box 1). Maps are one tool in the toolbox and should not be used as the only line of evidence or source of information. Consider the strengths and limitations of maps (discussed further below) relative to the objectives. Some maps are applicable to a wide range of questions or uses, and other maps are more specific. Different tools are better suited to inform

Box 1
Using maps for strategic planning: Idaho cheatgrass challenge example

In Idaho, the Natural Resources Conservation Service (NRCS) and partners are implementing the "Cheatgrass Challenge" to reduce the threat of invasive annual grasses. Statewide partners integrated maps of annual grasses into their decision-making framework, first during the inventory and assessment planning step to determine current conditions of the land, and then during the strategy and prioritization step to establish a new proactive, rather than reactive, spatial course of action (Fig. 1). Local experts determined maps were useful in identifying coarse regions for prioritized management including 1) defending core areas of low annual grass infestation, 2) growing core areas (directional arrows) through restoration, and 3) mitigating impacts in areas of moderate-to-high cover of annual grasses. Partners rightly resisted the temptation to define overly precise, hard spatial boundaries on maps. Instead, greater emphasis was placed on the map's value to provide local experts with landscape and statewide scale context of the problem. With broad-scale maps providing spatial guidance, the Cheatgrass Challenge enlists community-based land managers in determining specific project areas and tactics for management using local knowledge, maps, and data. Following implementation, maps are used in the monitoring step to track change through time and inform adaptive management. This example illustrates how satellite-derived maps can be combined with local knowledge and data at different stages in a decision-making framework, yielding an improved management model than would have been possible with only one or the other.

different questions, and maps will not be the best tool for every management application and scale. When in the initial stage of determining how maps (and other data sources) may fit within the decision-making framework, set aside initial judgments of error (see guiding principles 3 and 4) and instead focus on the management objectives and decision-making process. This will help in maintaining a landscape-wide and management-centered perspective (Principle 2).

Principle 2. Use maps to better understand and embrace landscape variability

Rangeland management occurs on landscapes. Although obvious, it is important to remember the landscapes managed are spatially and temporally heterogeneous; that is, they are not uniform but vary across space and through time. This is true for small and large management units alike (i.e., from quarter-quarter section pastures to large public land holdings). It is this full range of landscape variability (or heterogeneity) that is managed for ecosystem goods and services.[16]

Since the beginning, the range profession has wrestled with how to inventory, monitor, and quantify the heterogeneity that is managed. Numerous methods and programs have been developed and implemented to measure rangelands, far too many to list here. Yet, the profession's legacy and the constraints of traditional sampling have limited advancement. West[13] stated it best, "The range profession has put so much of its training efforts into identification of plant species, sampling within plots, and application of conventional statistical analysis that it hasn't had the background to examine other possible ways of answering the questions really being asked."

Traditional plot-level methods attempt to capture and represent heterogeneity through a sampling approach, defined by the number, size, and distribution of plots spread across the landscape and through time. Statistical reductions of plot data (e.g., averages of data across space or through time), however, can remove spatial or temporal contextual information—the landscape is reduced to a statistically correct, but unrealistic representation of mean condition or variability in condition (Figs. 2 and 3). In other cases, the concept of "representative sites" is used to find a single point for data collection within an area, under the assumption that there is little or no meaningful heterogeneity in the area. When we look out across landscapes, we do not see uniform, "average," or "representative" areas. Nor do we see discontinuous chunks of the landscape broken up by plot locations. What we see and what is managed is continuous heterogeneity and variation. We are not stating that plot sampling and statistical reductions are not advantageous or useful, nor are we commenting on their use in experimental or statistical comparison; they will continue to be needed for many applications. Rather, we are simply stating such conditions do not represent the heterogeneity that is being managed and suggest this heterogeneity is an important component of rangeland management. "Average" or "representative" condition assessments do not capture or characterize landscape variability that may be important (Fig. 3).

Box 2
Using maps to inform local management

One of the primary advantages of satellite-derived maps is they can be used at multiple scales, from broader level planning to local management. Due to the nature of scientific literature, examples of broader level applications and analyses abound, and local level examples are less common. We provide three brief real-world scenarios to help readers consider how maps may be used in local management.

Scenario 1: Filling data gaps

In a discussion of future grazing opportunities on public lands, a discrepancy in the amount of data collected between public and private land was identified as a limitation to discussions of grazing management with a permittee. Using data from satellite-derived maps, personal knowledge of the landscape, and the available on-the-ground data, the group was able to fill in the missing gaps and provide a more complete view across ownership boundaries. Satellite-derived data were considered an estimate, and through consultation with the permittee and other colleagues, a more complete picture of both privately and publicly owned management units was obtained.

Scenario 2: Facilitating evaluations of management outcomes

The increased accessibility of satellite-derived maps has removed barriers for many groups. Landowners, who may or may not have the resources for data collection, are able to easily see estimates and trends of their rangeland resources. One group of landowners were particularly interested in how management actions were affecting their lands and used maps to visualize how recent changes in grazing management led to both desirable and undesirable outcomes in rangeland resources. The maps facilitated discussion and provided new insights and perspectives by providing both data and a landscape context of management outcomes.

Scenario 3: Streamlining data collection

Satellite-derived maps can be used prior to field data collection to streamline and prioritize a condition assessment across large landscapes.[17] A group of managers used maps alongside plot data and expert knowledge to help evaluate available information, identify known data gaps or discrepancies, and plan efficient data collection in the next field season. Maps helped identify areas with greater heterogeneity and complexity where increased data collection may be needed.

Unlike traditional plot-level sampling, satellite-derived maps provide a more spatially comprehensive and temporally continuous view of the heterogeneity that we manage (Fig. 2). Due to familiarity and habit, or the need to reduce complexity, users may still choose to summarize maps by averaging or other statistical reductions, following the legacy of plot data. Complex spatial patterns may be distilled into groupings that represent the degree of variability across the landscape (Fig. 3). But to use maps effectively and to take advantage of all the information they provide, it may be necessary to change how we think about and use data in management. Instead of averaging away, discarding, or ignoring heterogeneity, we may consider incorporating it into our management frameworks and strategies (Fig. 3).[14] When heterogeneity is embraced, maps provide an opportunity to use landscape-wide data to address management questions relating to the distribution and magnitude of heterogeneity across the landscape (e.g., Box 2).

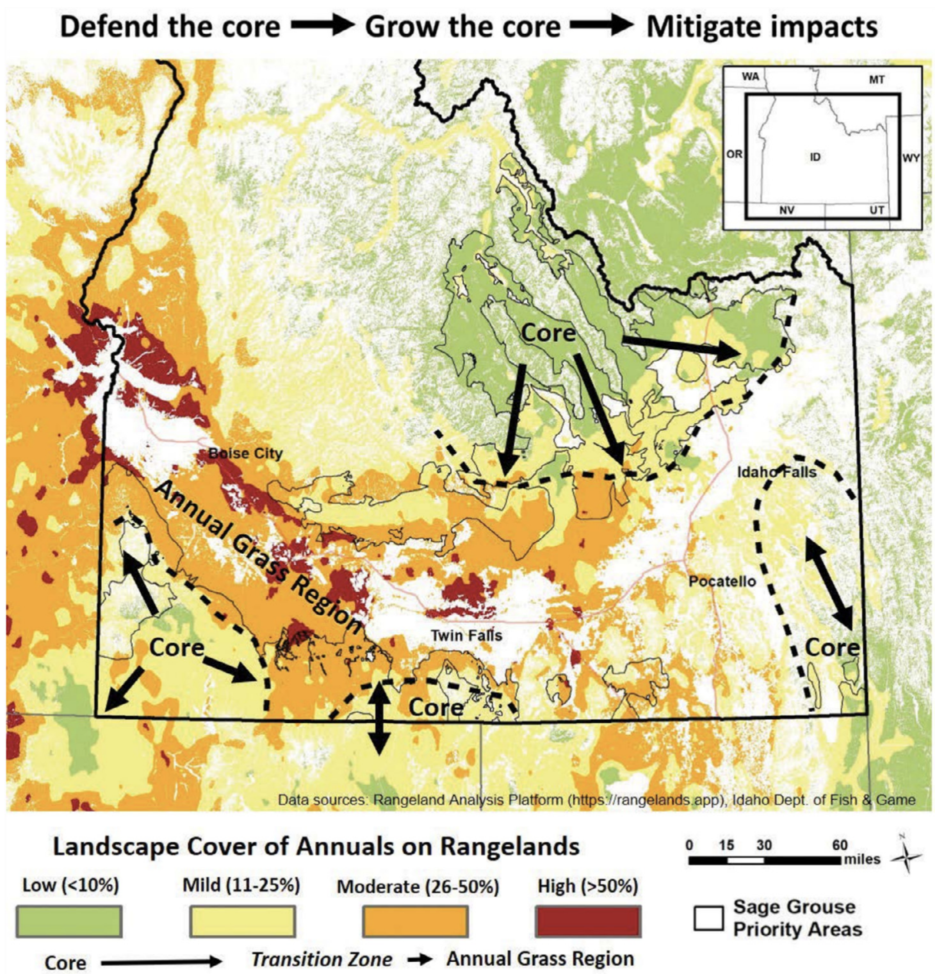

Figure 1. The Idaho Cheatgrass Challenge used satellite-derived maps to help distinguish core areas with relatively low amounts of exotic annual grasses at a landscape scale from regions more heavily invaded. Dashed lines represent approximate transition zones between regions. Delineation of these regions facilitated adoption of a spatial strategy for management (arrows): 1) defend the core, 2) grow the core, and 3) mitigate impacts. Figure from the Idaho Cheatgrass Challenge.[15]

Principle 3. Keep error in perspective

With the increased number of maps and ease of accessibility, user trust in map products can be lost quickly without maintaining the proper perspective on error. Newer maps generally have lower error and greater accuracy than previous generations of maps, but for many users a barrier to their adoption is the perception that the error is too high, the error is unknown for a specific geographic area, or a user with in-depth knowledge of a particular place deems a map to be inaccurate. The wide coverage and ease of use of these maps makes it easier to engage in pedantic fault finding (i.e., nitpicking), where the usefulness or quality of a map is judged based on the perception of accuracy in a handful of locations familiar to the user. Instead of something to be avoided or feared, error is an inevitable part of any type of measurement that warrants understanding and consideration within the decision-making framework. In this section, we provide a big picture view of accuracy and error to help users approach maps with a broader perspective.

In rangeland management we often fail to consider error, perhaps due to the difficulty in error quantification with traditional field sampling methods. But unlike traditional sampling, maps often quantify and report error. This difference can produce the impression that satellite-derived maps contain error whereas field measurements do not. Although sometimes overlooked or ignored, error is unavoidable when measuring rangelands, regardless of the method used. In traditional plot-level sampling, error can be interjected in many ways during rangeland measurements, including in recording data, identifying plant and wildlife species or classifying soil characteristics, or misinterpreting procedures. Error can also be introduced before or after measuring rangelands when determining the number of sampling plots, sampling method, sampling locations, data aggregation or summarization methodology, and so on. All measurements performed—all data collected—contain error.

Error concepts in scientific papers can appear intimidating, and there are often multiple ways of measuring map error. Error in satellite-derived maps comes from a variety of sources,

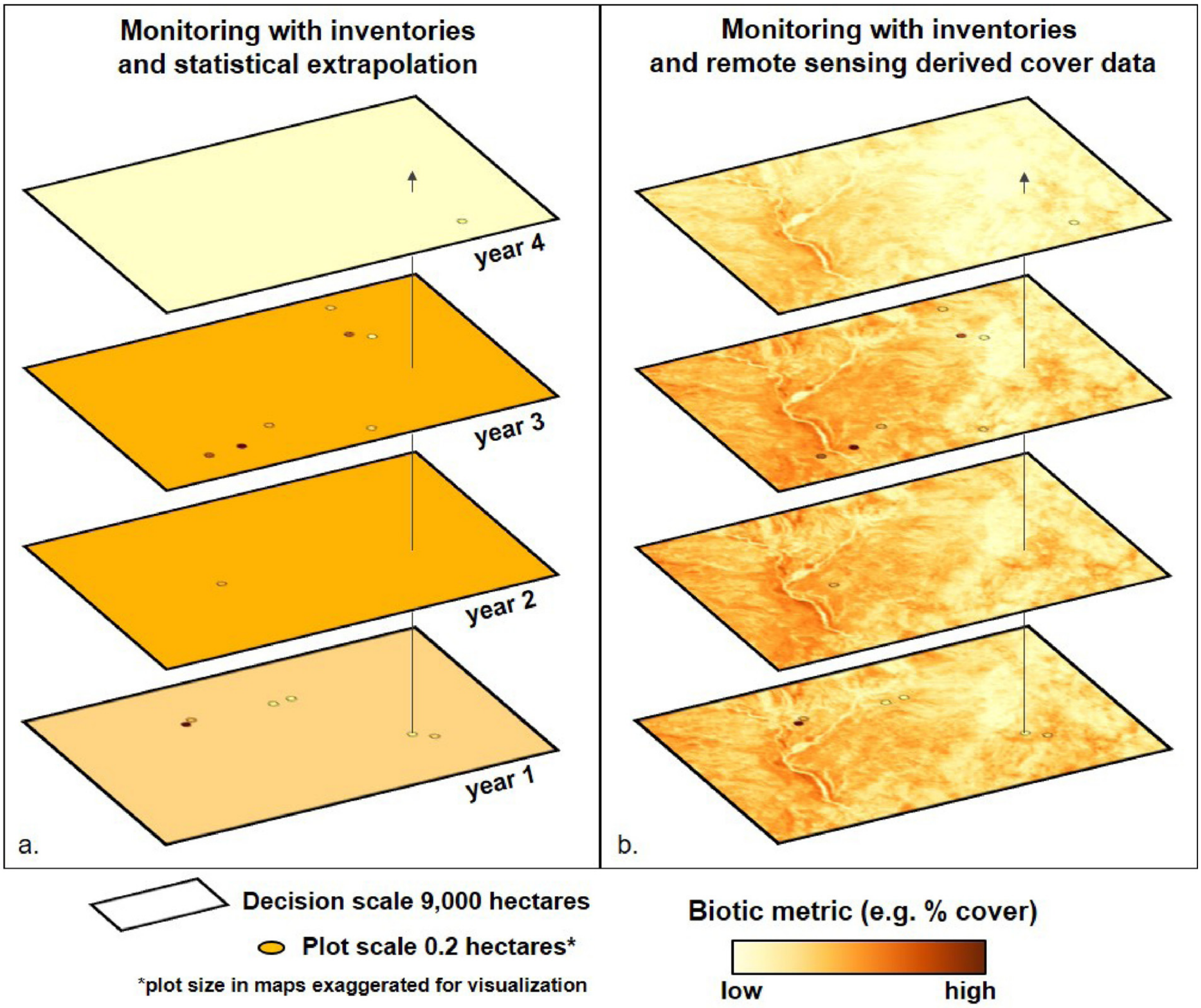

Figure 2. Examples of monitoring 9,000 hectares (approx. 22,000 acres) of rangeland in the western United States over 4 years using A, inventories and statistical extrapolation versus B, inventories coupled with remote sensing-derived data. Actual Bureau of Land Management Assessment, Inventory, and Monitoring plots and their measured percent vegetation cover are shown for each year. A, Solid colors within the decision scale boundary are extrapolated values (mean percent cover of inventories for that year). B, Color gradients within the decision scale boundary are percent cover values provided by continuous land cover data. The arrow represents single plot location unmeasured by inventories through time but with data provided annually through remote sensing-derived monitoring data. Not shown are errors associated with both monitoring methods that must be considered. Figure from Jones et al.[12]

including satellite sensors sensitivity, satellite data transfer and storage, satellite data pre- and post-processing, model input data, or the model itself. Map error is commonly calculated as the difference between a single on-the-ground measurement and its corresponding map value. Multiple errors are then aggregated or summarized to produce a map error metric (e.g., accuracy for categorical maps; root mean square error for continuous maps). This error metric represents the overall or average accuracy of the map. For example, a categorical map (e.g., a land cover map of rangeland, forest, urban, etc.) with an accuracy of 90% means 90% of the time the categories from on-the-ground measurements align with map values. A continuous map (e.g., rangeland production with continuous values) with an error of 10% means on average, across the range of on-the-ground measurements used, map values are within ±10% of on-the-ground values. Although helpful, these commonly used error estimation approaches also have limitations, including the unknown errors associated with the on-the-ground measurements used for comparison, the use of one field location to evaluate a map pixel that may include considerable heterogeneity, and error in the location of field plots or map pixels. Further, it is important for map users to also understand estimates of map error are not analogous to the typical error and distribution of error taught in basic statistics courses (i.e., independent and randomly distributed; Fig. 4). For most maps, the prediction of a categorical class or continuous variable will reflect real landscape heterogeneity, despite containing error (Fig. 4A), and be useful for decision-making.

On a practical level, it is good practice to weigh map error against the value provided by the map's representation of heterogeneity across the landscape (Box 3). Although map error may appear unacceptably high in some circumstances it is important to consider map error in the context of the

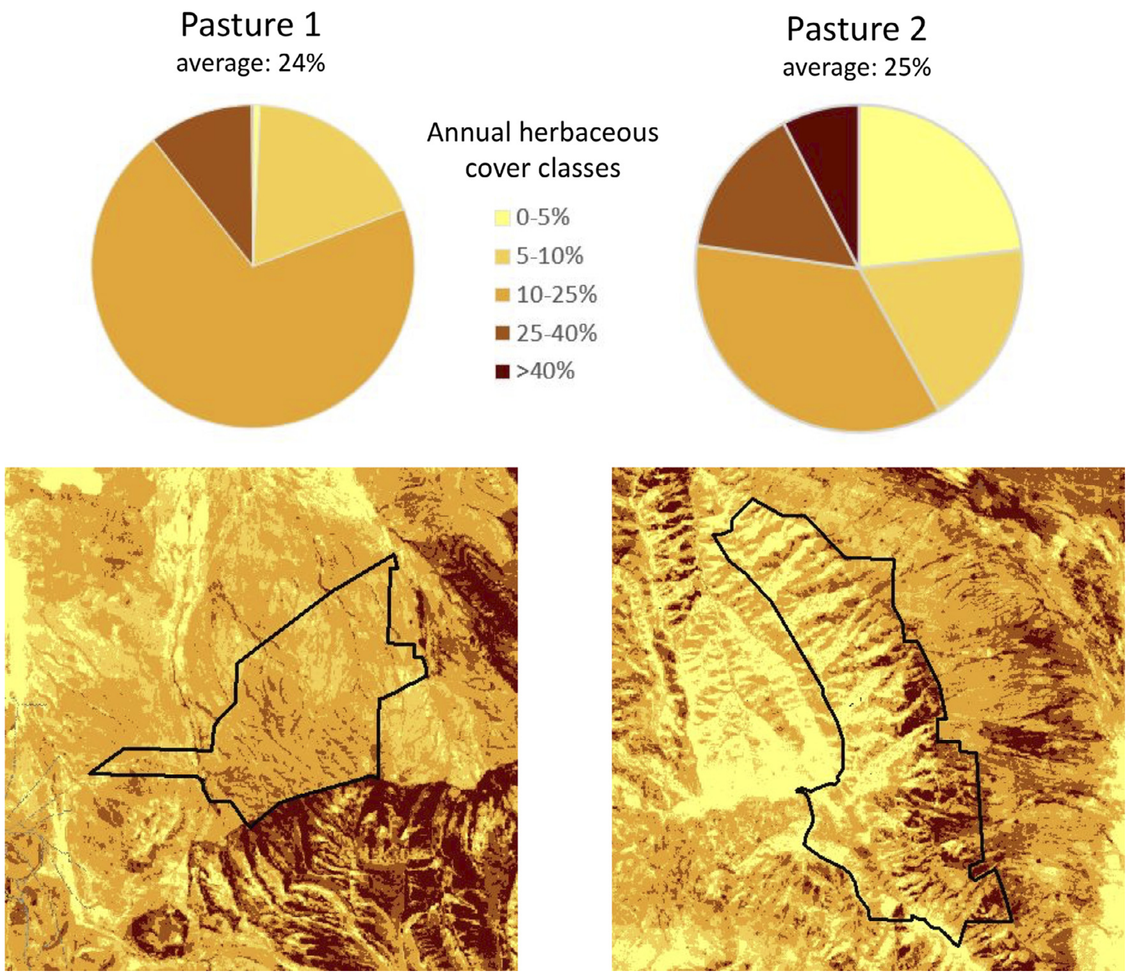

Figure 3. Maps of annual herbaceous cover for two pastures (outlined in black) that have nearly identical averages but very different distributions. Averaging data (from maps or plots) can produce an unrealistic representation, particularly when there is a high level of heterogeneity as in pasture 2. Summarizing the distribution of values across each pasture as shown in the pie charts incorporates heterogeneity into management and provides valuable information about the distribution and severity of annual grass invasion in these two landscapes.

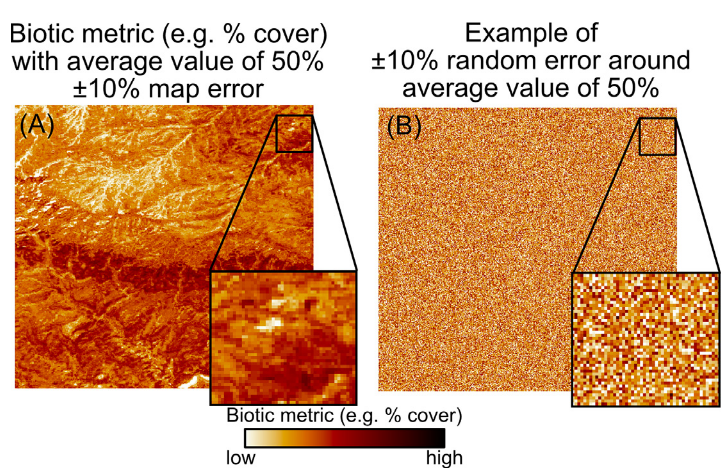

Figure 4. Example demonstrating the difference between a map with error that contains information on landscape heterogeneity (map A) and a hypothetical map with the same mean value and error, but with random error (map B). Despite the 10% error, the map on the left shows patterns in spatially contiguous areas of high and low values based on the topography and landscape.[18,19] In contrast, the map on the right is a spatial depiction of how we often assume error is distributed (independent and random) with typical plot-based estimates (e.g., Fig. 2A).

Box 3

Using multiple maps: Western Governors' Association invasive annual grass toolkit example

In 2019, the Western Governors' Association (WGA) and the US Department of Agriculture agreed "to pursue an effort to meaningfully address the large-scale infestation of invasive annual grasses on western forests and rangelands."[20] Recognizing the potential role of satellite-derived maps in this effort, WGA sought to provide western states with a data layer and strategy to help guide management. Their efforts, however, quickly presented a challenge: there were three readily available maps for the western United States that would be helpful, so which should they choose? All three map products provided valuable contributions to knowledge on the condition of the land, but there were differences in vegetation estimates (from slight to vast) among them. Rather than simply picking one map or discarding all maps together, WGA enlisted the help of the map developers in devising a solution to these data contradictions. The end result was a new map (WGA Toolkit; https://rangelands.app/cheatgrass/) that appropriately combined all three individual maps. In this way, the weight of evidence drawn from all three maps was used to estimate conditions on the ground while minimizing contradictions. While such an outcome may not be possible or desirable for every application, this effort demonstrates an innovative way to critically think about how best to leverage available data without becoming paralyzed by data contradictions.

decisions that are being made and the alternative information sources. How much error is acceptable given my management question or objective? Are lower-error data sources available for the needed information? Even areas with a high density of field plots may not capture the overall landscape heterogeneity, especially considering statistically rigorous plot sample sizes are often logistically infeasible due to resource constraints. Rangelands are diverse landscapes and for many management decisions, high accuracy or low error are not needed to come to an actionable conclusion. For example, some questions that illustrate where a wider margin of error may be acceptable include: Is the watershed functioning at an acceptable level? What are the major threats to rangeland health in an area and how widespread are they? Where are the areas of greatest need for management intervention? Where should field work be prioritized? Is the area changing through time, by how much, and where? The efficiency of maps in providing information and characterizing landscape heterogeneity, even with error, may prove much more useful than initially thought. When implemented in an appropriate framework (Principle 1), error may be well within the margin needed to answer the question of interest, particularly across broader scales.

An excessive focus and lack of perspective on error may lead the user away from a valuable information source. As with all other data, error should not stand in the way of using maps in management. Rather, it is important to understand error and integrate it into the decision-making process. This should not be done by asking "is there any error?" (the answer is always "yes"), but rather, "Is the level or type of error acceptable for the decision being made?" It is unrealistic to expect maps to be acceptable for every use case in rangeland management. If low error is necessary, then satellite-derived maps may not be the right tool, may need to be improved or replaced with a better map, or may only be useful during a limited stage of the process. The decision framework (Principle 1) can guide the acceptability and use of maps, not the error in and of itself.

Principle 4. Think critically about contradictions

As maps become more commonly used in rangeland management, users will inevitably be faced with contradictions. At some point or another, maps will contradict: 1) our own world view, 2) other data sources, or 3) other maps. These contradictions can be difficult to navigate and may make decision-making more complex. When contradictions occur, it is important to step back and consider the various sources of information relative to the decision being made (refer back to Principle 1). Some leading questions to approach this situation could include:

- What other information do I have in this area? Do I have plot data I can compare to the maps? How many plots are needed relative to the size of the area? Are plot data representative of the whole area or are sites biased (e.g., placed in more productive areas)? Can I collect new plot data or photos? Will a visit to the site help?
- How reliable is my existing information? What proportion of the area have I seen in person? How spatially or temporally representative are the data? Does the spatial scale of my question match the available information? How does the map compare to recent aerial imagery?
- Has anything significantly changed that would affect the reliability of some data sources? (e.g., has some of the data been collected pre- and post-disturbance?)
- How large is the contradiction? Is it a matter of degrees or is it vastly different? Would I come to a different conclusion if I used a different source of data? How would I approach this if two different plot datasets contradicted each other?
- What do others think? Do others have more information or data to contribute? Can I get a group together for a discussion?

Maps can be at first criticized, disparaged, or removed entirely from the decision-making process because they are unfamiliar. Due to the geographic extent and abundance of data available in maps, users can zoom in on any pixel in the landscape and determine the pixel is mapped incorrectly. Doing so, however, ignores the many advantages and efficiencies maps provide. We caution readers not to "throw the baby out with the bath water" but instead to think critically about and understand contradictions may arise when using them.

When maps contradict our own perspective, we question both the maps and our perspective. As with all data, the maps may very well contain enough error that they are unacceptable for a particular application. But our own perspective may also be biased or incomplete. Quite often, we do not truly know a landscape as well as we think we do. Furthermore, every piece of land has a complex history influenced by human uses, disturbance, weather and climate, and other factors. We may know a few key or often visited sites, but our personal knowledge of the land is incomplete (which is the very reason we collect data). Question the map and the perspective, but do not discard either. Use what is helpful, do not use what is not helpful, and adjust perspective if needed. In addition to our own perspective, maps will contradict other data sources and maps. The situation of maps contradicting each other has become more prevalent in recent years, as the number of map products has increased dramatically. When this happens, we may quickly think it is a "zero sum game" and must choose one or the other, or we must use all available maps. We advise thinking carefully and critically about the data and maps. It may be found they are not as contradicting as originally thought, or they represent different domains or perspectives. The questions listed previously may stimulate thought and discussion when data sources and maps contradict one another. Moreover, multiple satellite-derived maps can be used to advance consensus in analysis and decision-making, not to promote error-driven infighting among users or within the rangeland profession (e.g., Box 3). Similar to climate models and research—where outputs and results are seldom equal—multiple maps provide multiple lines of evidence to identify and confirm general concurrences that will ultimately aid and help in future management. Although potentially desired, there is no prescribed procedure or rule set for reconciling contradictions. The decision-making framework (Principle 1) will provide guidance on appropriate map usage and how to approach contradictions.

Principles and future advancements

Satellite remote sensing methods continue to advance, providing higher spatial, temporal, and spectral resolution measures resulting in more detailed and robust maps of rangelands. The principles presented here, however, stand on their own and remain applicable and adaptable to future mapping and monitoring efforts. Their adaptability stems from considering all four guiding principles collectively and not as individual items in a checklist. For example, as spatial resolution becomes finer, it is tempting to examine spatial variability at hyper-resolutions. The principle of embracing landscape variability, however, must be juxtaposed with the principles of decision-making, error, and contradictions. Focusing on variability at very fine scales (e.g., sub-meter sized pixels), while perhaps valuable for a very local and specific objective, may not contribute useful information to the objectives set within the decision-making framework, can introduce a new level of error in map interpretation, and may amplify rather than clarify contradictions between field data and mapped values. Invoking the principles collectively serves as a foundation to guide adaptive monitoring and management, irrespective of the tools or technology available.

Conclusions

Although recent advancements in satellite remote sensing of rangelands have produced many operational maps[18,21–25] there has been little guidance on how to effectively incorporate maps into management decisions and thought processes. We wish to advance the practice of using maps by providing the four guiding principles outlined above. We urge map users to challenge their own paradigms and incorporate spatial and temporal perspectives that are enabled and facilitated with maps. We also urge map developers to provide resources and support in assisting map users in learning how to use satellite-derived maps in management. We hope these principles will help users approach maps with more confidence and flexibility—using them when and where they are appropriate and helpful, while recognizing that they are not a panacea. These guidelines are not specific to any individual map or product, and we hope they will remain applicable as the field of remote sensing advances and maps are increasingly used to more effectively manage large, heterogeneous rangelands.

Declaration of Competing Interest

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