# Leveraging Rangeland Monitoring Data for Wildlife: From Concept to Practice

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# Leveraging rangeland monitoring data for wildlife: From concept to practice

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**On the Ground**

- Available rangeland data, from field-measured plots to remotely sensed landscapes, provide much needed information for mapping and modeling wildlife habitats.
- Better integration of wildlife habitat characteristics into rangeland monitoring schemes is needed for most rangeland wildlife species at varying spatial and temporal scales.
- Here, we aim to stimulate use of and inspire ideas about rangeland monitoring data in the context of wildlife habitat modeling and species conservation.

**Keywords:** Habitat, Modeling, Mapping, Remote sensing, Species conservation.

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## Introduction

A fundamental goal of contemporary rangeland management in the United States is to conserve biodiversity while maintaining livestock production and other land uses.[1,2] America's rangelands are home to diverse flora and fauna, with over 3,000 vertebrate species occurring in rangelands in the western United States.[3] Managing rangelands for wildlife requires an understanding of a species' habitat requirements and how populations may respond to changes in habitat. However, a common limitation in rangeland monitoring is that wildlife habitat is rarely measured systematically or consistently through time, except for a few high-profile species, like greater sage-grouse (*Centrocercus urophasianus*),[4] within selected areas. Monitoring the conditions and trends of soil and vegetation, however, has been a standard practice in rangelands for decades, and these metrics, even if not collected explicitly in the context of wildlife habitat monitoring, could be useful for modeling wildlife-habitat relationships and species conservation planning.[5] The challenge is to translate monitoring data collected for a different purpose into meaningful parameters for assessing the condition of habitats, with the ultimate goal of implementing timely and appropriate management responses.[6]

We highlight this process as a "challenge" due to the complexity of the ecology of wildlife species. For many species, resource needs change through time and may vary across different spatial scales. Individual animals have distinct diel, seasonal, and annual patterns of habitat use and selection, and habitats used for foraging, accessing water, finding mates, and surviving winter may not occur in the same location and may occur over different spatial extents. For example, greater sage-grouse select different habitat characteristics for breeding (i.e., open spaces for leks), nesting, early and late brood rearing, foraging, and wintering.[7] Thus, the availability, size, patchiness, and spatial arrangement of specific habitats across landscapes of varying spatial scales are important considerations of wildlife managers and landowners.[8] Further, dispersing or migrating individuals may pass through areas considered to be marginal habitat, but these areas also are important for populations because they can influence survival, fecundity, and gene flow.[9] Some mule deer (*Odocoileus hemionus*) populations in Wyoming, for example, migrate over 240 km (~150 miles) and pass through areas of high stress for individuals to access critical resources.[10] Finally, habitat relationships can also vary throughout the range of a species because of genetic and environmental variation, and adaptation to local conditions.

Careful environmental measurements, collected as part of a monitoring program, may characterize habitat attributes but still do a relatively poor job of predicting animal use if they are not directly related to habitat functional properties. Functional properties of habitat are the link between habitat attributes and how and why an animal uses those habitat resources; they define how a habitat attribute (e.g., canopy cover) affects an individual's survival and reproduction. For example, a habitat attribute such as shrub canopy can provide several functions: concealment from predators, protection from environmental conditions, or a substrate for nesting. Translating measurements of habitat attributes into meaningful information about their functional properties for wildlife is important but challenging. This process, which usually involves demographic and geospatial models, also requires an understanding of the ecology of the target wildlife species.[11] Applying these approaches to multiple species simultaneously, such as species assemblages and communities, adds additional complexity and is arguably untenable and impractical for wildlife management and decision-making. Thus, most habitat assessments are limited to the species level, although capacity for multispecies habitat assessments is advancing.[12] In some cases, umbrella species concepts are used, whereby habitat assessments for one species are implied to be representative or helpful for a suite of species sharing similar habitat associations and life histories.[13,14]

Whereas a monitoring program should start with a conceptual model and clear objectives,[15] the capacity of a monitoring program to characterize the physical and functional properties of wildlife habitat depends on the amount and quality of relevant data.[16] Data sources range from field-measured variables to those derived from remote sensing (e.g., sensors deployed on aircraft, unmanned aircraft systems [UAS or drones], and satellites; Fig. 1). These data can be collected for a specific purpose, such as during a research project, or mined from other sources, such as monitoring and remote sensing programs. These latter sources of information are attractive for wildlife applications because of their potential availability across a broad range of locations, spatial scales, and time periods, as well as low cost.[17] Using these types of data for modeling wildlife habitat is becoming more common, as monitoring and remote sensing data are increasingly organized, centralized, standardized, and accessible. Rapid advances in technology and computational power have also facilitated use of these data for progressively sophisticated habitat models.[18,19] We do offer a word of caution, however: data mining can be fraught with inferential problems and successful application will ultimately depend on an understanding of the original sampling design and recognition of the assumptions in model-based inference.[20]

Rangeland monitoring, when done well, provides the requisite information for decisions about livestock forage production and utilization, and assessments of rangeland health. There is less certainty, however, about whether these data also provide the requisite information needed for wildlife habitat management and whether these data are sufficient for modeling, mapping, and assessing wildlife habitat for decision-making. We explore these important issues in the spirit of facilitating adaptive rangeland monitoring (sensu Lindenmayer and Likens 2009)[15] for the next generation of rangeland specialists. We emphasize the use of existing rangeland monitoring data collected by public agencies for characterizing and modeling wildlife habitat. Our goal is not to dwell on deficiencies of past monitoring programs or misuse of monitoring data, but instead to think anew about the environmental data traditionally collected during rangeland monitoring and how it can be used for wildlife conservation by the next generation of rangeland resource managers.

To avoid confusion, we emphasize that this paper is an examination of how comprehensive monitoring of vegetation and soils in rangelands could be better used for wildlife habitat assessments and not about the (equally important) topic of monitoring wildlife populations, indicator species, or population responses to management actions. We recognize these approaches may be more useful in the context of monitoring for conservation planning and less useful for evaluating the success of management actions (effectiveness monitoring), but both are needed to achieve tangible conservation outcomes. We discuss opportunities for modifications to existing rangeland monitoring protocols that could improve their utility for wildlife habitat modeling. Like many monitoring papers before us, we emphasize the importance of standard protocols, sampling design, inference, and scale, as well as the need for consistent financial support and proper data stewardship. Our paper draws mostly from examples and experiences in the western United States because that is where most of the comprehensive rangeland monitoring data in the US were, and are, collected, especially on public lands.

## Brief history of rangeland monitoring with implications for wildlife

An assessment of the historical and contemporary challenges associated with planning and implementing objective-based rangeland monitoring has been covered elsewhere,[21,22] but a brief description of the data typically collected during rangeland monitoring is important context for wildlife. Most rangeland monitoring focuses on observable and easily measurable components of vegetation. Initial efforts to monitor vegetation on rangelands focused on estimating herbaceous production and specific use of that production by livestock.[21,23] The practice of measuring other characteristics of vegetation, such as species or functional group composition, canopy cover, and height, has increased through time and is now common practice in North American rangelands (Table 1). For public rangeland managers in the United States, most of these attributes were intended for local decision-making, such as determinations for rangeland health and forage availability for stocking rates and permitting.[24] Thus, most rangeland monitoring used plot-based measurements, usually with intended inference for a pasture or grazing allotment. A transition from qualitative to quantitative assessments, combined with efforts to standardize monitoring for greater inference across private and public rangelands in the United States, started in the 1970s when the Bureau of Land Management (BLM) initiated the Soil and Vegetation Inventory Method.[25] The Natural Resources Conservation Service

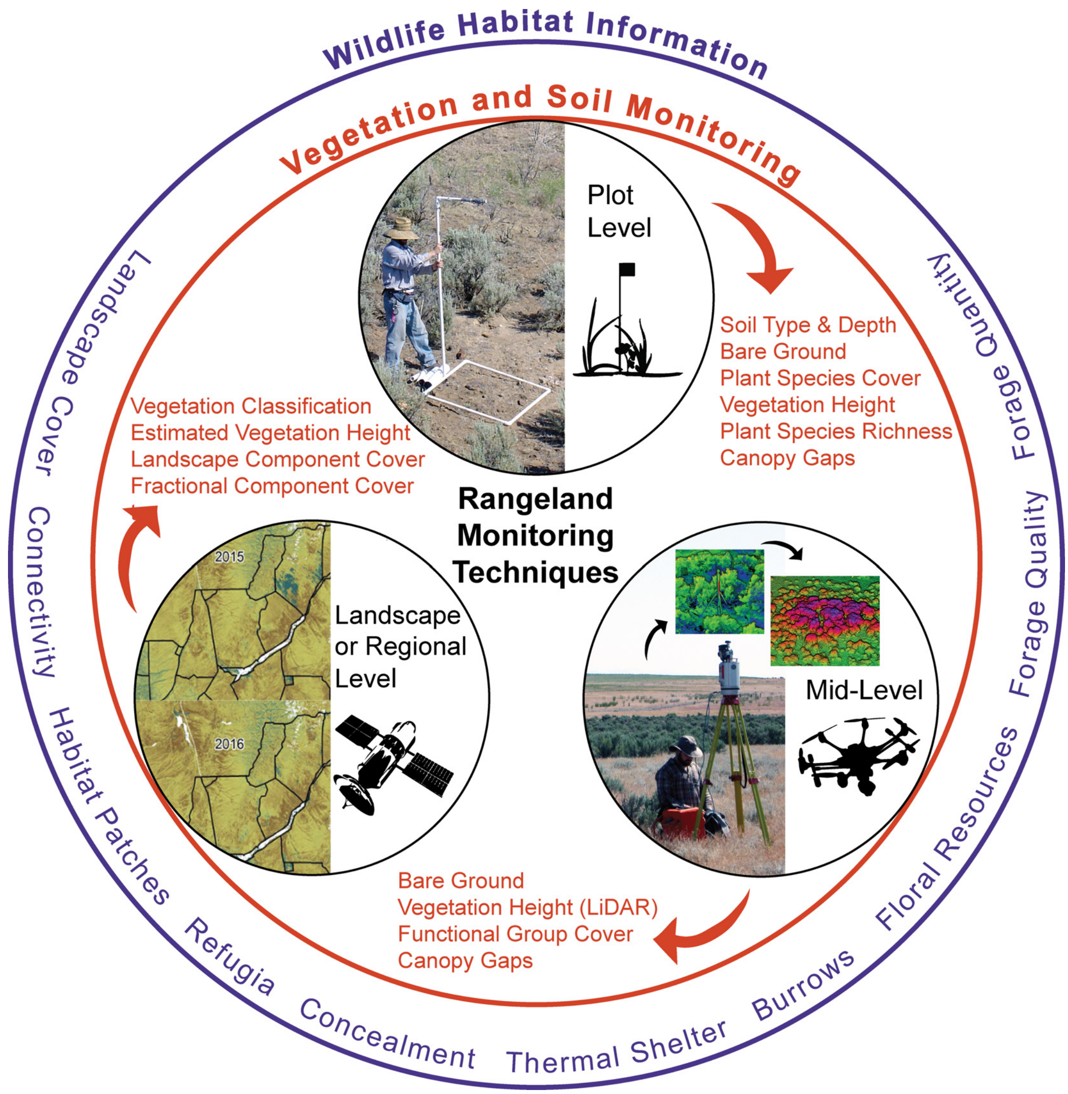


**Figure 1.** The inner circle depicts attributes of vegetation and soil captured during typical rangeland monitoring. The monitoring techniques span multiple spatial scales, which may share information. Most field monitoring is conducted at the plot-level. The mid-level has been difficult for wildlife biologists to map in the past, but is important for individual animal habitat selection, home ranges, and activity areas. The landscape level is somewhat undefined, but could represent a pasture, allotment, or larger spatial extent. The outer ring lists the information these vegetation and soil metrics provide for wildlife habitat.

**Table 1**
Vegetation and soil indicators measured during typical rangeland monitoring and examples of wildlife habitat attributes or functional properties that can be derived directly or indirectly from monitoring data.

| Indicator | Method | Measure | Wildlife habitat properties |
|---|---|---|---|
| Bare ground | Line-point intercept (LPI), Grid-point intercept (GPI) | Percentage of points hitting bare ground | Viewsheds, movement paths, basking areas, burrow sites |
| Vegetation composition | LPI, GPI | Percentage of points hitting plant species or functional groups (% foliar cover) | Concealment, viewsheds, forage, nesting sites, thermal shelter |
| Vegetation height or Vertical density | Height at selected points along a transect or belt, or within a quadrat | Height of tallest leaf or stem, Visual obstruction | Concealment, viewsheds, forage, nesting sites, thermal shelter, mobility |
| Plant species of management concern | Line-point intercept, supplemented with plot-level inventory | Species detection (detected/not detected) | Specialist forage (e.g., pollinators) |
| Abundance of invasive plant species | Line-point intercept, supplemented with plot-level inventory | Species detection (detected/not detected) | Potential degradation of habitat |
| Intercanopy gaps | Canopy gap intercept | Proportion of a line covered by large gaps between plant canopies | Concealment, viewsheds, movement paths, basking areas, thermal shelter |
| Soil stability | Soil aggregate stability | Soil sample's stability when exposed to rapid wetting | Plant communities, burrow sites |

(NRCS) followed with adaptations to the National Resources Inventory (NRI) in 1995.[26] In 2011, the BLM implemented the Assessment Inventory and Monitoring (AIM) Program.[27]

In the United States, rangeland management on public lands is entwined with species habitat conservation because of federal mandates, especially the Federal Land Policy and Management Act of 1976, which states public lands are to be managed in a manner that "will provide food and habitat for fish and wildlife and domestic animals" (Section 102(a)(8) of Public Law 94-579). The word *habitat* is not defined in the mandate and is often used loosely, but Krausman and Morrison[28] recently urged practitioners to clarify its definition as "the resources and conditions present in an area that produce occupancy, which may include survival and reproduction by a given organism." They point out that habitat is always organism specific but is comprised of more than vegetation. Habitats encompass all parts of the biosphere, including biotic (e.g., vegetation, other animals), edaphic (i.e., related to soils), topographic, and climatic components. Simplistically, habitat is the biotic and abiotic environment an animal needs to meet its basic requirements of food, water, refuge, and space. For practicality, however, complex (i.e., multivariate) attributes of wildlife habitat are often simplified into somewhat ambiguous descriptive terms, such as composition, structure, and quality.[28] These synthetic attributes of species habitat require definition so they can be measured, enumerated, reproduced, and communicated.

The use and importance of vegetation monitoring data for wildlife have changed through time with socioeconomic values. For wildlife, the early focus of monitoring data was identification of forage preferences by wild ungulates for specific rangeland plant species.[23] Mapping of potential rangeland vegetation types in the 1960s was also a critical step toward estimating the spatial distribution of wildlife habitats.[29,30] Publication of the Robel pole method of evaluating visual obstruction at locations used by the greater prairie chicken (*Tympanuchus cupido*) was an important development in quantifying rangeland wildlife habitat attributes because it correlated herbaceous production with the height of vegetation obscuring wildlife locations.[31] Furthermore, this seminal paper recognized the important role of structure (i.e., physiognomy) in quantifying wildlife habitat as compared with solely focusing on plant species composition (i.e., floristics).[32] To better represent wildlife habitat structure, some protocols switched to measuring vegetation in horizontal layers.[33] These approaches also characterized ground surface conditions, such as bare ground and litter, as well as information about subsurface structure and composition (e.g., soil horizons). The AIM and NRI programs today capture elements of habitat structure through measurements of canopy gap and height.[26,34]

During the 1980s the concept of spatial scale was brought forward as integral in interpreting habitat selection by wildlife.[35] Scientists recognized animals were selecting habitats based on properties that varied across spatial scales, sometimes hierarchically. This coincided with increased awareness of the importance of longer temporal scales for wildlife, such as seasonal and annual patterns of habitat use.[36] Arguably, since the concept of scale gained attention, most rangeland data collection and analysis for wildlife have been at the microhabitat or patch scale, usually representing only a small portion of a home range or animal's activity area. However, contemporary applications of rangeland wildlife data often incorporate multiple spatial and temporal scales. Today's use of rangeland vegetation monitoring data increasingly focuses on multiscale applications, including previously unfathomable models of landscapes, states, and regions over years to decades, owing to advancements in remote sensing and geographic information systems (GIS) (Fig. 1).[37,38] However, while landscape- or regional-level remote sensing data are now becoming incorporated into rangeland monitoring efforts,[39] mid-level monitoring (see Fig. 1) is in an early research phase in spite of its recognized importance.[40,41]

Finally, there are notable differences among US natural resource agencies in the aim of their wildlife monitoring, which can create a disconnect between habitat data and population data. Agencies managing wildlife population data are not necessarily the same agencies monitoring habitat. For example, state agencies manage wildlife in the public trust and thus tend to focus on monitoring the health and size of populations, particularly of game species. Classic examples include annual grouse lek counts and composition of big game populations.[42,43] Some federal and tribal natural resource agencies and private organizations also monitor wildlife, contributing important information on nongame species. For example, the USGS and Canadian Wildlife Service manage the North American Breeding Bird Survey with broad external partnerships, and the US Fish and Wildlife Service promotes planning and coordination of wildlife monitoring both within and outside of the National Refuge System with federal, state, and other partners. Much of the habitat monitoring data, on the other hand, comes from different sources. Federal agencies charged with managing public lands often have vegetation or habitat monitoring programs or, as in the case of NRCS, support habitat monitoring on state, tribal, and private lands. Thus, there is a need for better connections between habitat data and wildlife population data collected as part of monitoring programs, often by different agencies.[4] Developing explicit linkages between habitat management and wildlife conservation objectives, help address concerns raised by some biologists about the usefulness of relying solely on habitat relationships for wildlife conservation.[44]

## Rangeland monitoring metrics with applications for wildlife

Of the soil and vegetation indicators typically measured during rangeland monitoring (Table 1), ground and canopy cover are the most widely used for wildlife habitat evaluations.[45] Cover is a particularly important attribute for understanding habitat relationships of rangeland wildlife because it can reflect both vegetation structure and composition.[46] Height of vegetation is also important for wildlife for both concealment and visibility (or viewshed), and is an important attribute of habitat structure strongly associated with foraging, nesting, thermoregulation, and other wildlife functions.[47,48] For example, vegetation height and structure are especially important for niche partitioning among grassland birds, although they are often measured inconsistently.[32,49] Measuring habitat structure consistently is tricky and often resorts to estimating visual obstruction of rangeland vegetation around animal locations using cover boards or cover poles calibrated for target species.[50] Comparisons of habitat assessment methods designed specifically for sage-grouse against core, standardized monitoring methods, such as those used by AIM and NRI, found there was value in using AIM data for assessing grouse habitat despite differences in the way height was measured.[48]

Soil type, depth, and stability are important for burrowing animals and ultimately influence species distributions of some fossorial and semifossorial animals.[51] Further, the interaction between soil type and burrowing mammals, like prairie dogs (*Cynomys* spp.), can also influence vegetation composition and structure, and subsequently, wildlife communities.[52] Soil characteristics also influence plant communities and thus habitat quality for herbivores.[53,54]

Monitoring the characteristics, quality (nutrients, allelochemicals), and distribution of forage plants is a crucial aspect of evaluating habitat for herbivores, but is rare in most rangeland monitoring protocols.[55] Foodscapes, as they are now called, can be measured on the ground, but remote sensing will likely be the predominant way to monitor changes in foodscapes through time.[56] This may be a particular area of growth for mid-scale monitoring efforts, such as at the scale of an animal's home range, using sensors mounted on UAS or other devices (Fig. 1).

The spatial variability of environmental conditions across a landscape has garnered considerable attention from wildlife biologists because of the observed relationships between habitat heterogeneity and species diversity.[57] This has important implications for wildlife if management actions (e.g., prescribed fire, targeted grazing, restoration) can be used to increase habitat heterogeneity.[58] For example, a study in the Tallgrass Prairie Preserve in north-central Oklahoma concluded managers could use dormant-season prescribed fire to influence the spring and summer grazing behavior of cattle and promote a shifting mosaic of vegetation structural types that maintained the greatest grassland bird diversity as well as agricultural productivity.[59] The concept that spatial and temporal habitat heterogeneity maximizes biodiversity has been applied on rangelands worldwide,[60] but not without some controversy.[61] Rangeland monitoring programs have been slow to capture and quantify this relationship, although remote sensing products will be particularly useful for this application.[62,63]

The process of combining plot-measured and remotely-sensed monitoring data to develop spatially explicit habitat maps for wildlife species is an important advancement for adaptive monitoring of rangelands. We demonstrate this process in a conceptual diagram using the mountain plover (*Charadrius montanus*) as an example (Fig. 2). Starting at the lower left panel of the figure, field data collectors measure vegetation and bare ground cover using point-intercept (note the pin flag) and quadrats, and habitat structure using height and visual obstruction (note the Robel pole)[31] of vegetation. Using information from previous studies,[64] researchers formulate hypotheses about nesting habitat requirements of mountain plover. These plot data are then combined with remotely sensed vegetation cover data and nest location information to generate predictive models of breeding habitat suitability that are spatially explicit. Repeat measurements through time allow users to map how habitat suitability changes through time or in response to disturbance or land management.[58] The utility of these maps to predict habitat quality is greatly improved with the addition of animal locations for model validation, testing, and refinement. The predictive power of these types of models can be further improved by relating habitat with population demography, measures such as to survival, recruitment, fecundity, and population growth rates. New monitoring data may refine the models as methods adapt and improve, a key step in the adaptive monitoring framework (see McCord and Pilliod,[65] this issue).

## Examples of leveraging rangeland monitoring data for wildlife

Several of the vegetation and soil variables described above have been collected for decades as part of US public rangeland monitoring protocols, but rarely are these data used for wildlife habitat modeling or assessments. For instance, the BLM, which manages about 12% (99.4 million hectares [245.7 million acres]) of the total land area of the United States, has a long tradition of collecting cover, frequency, and production data at established plots.[45] Use of these data for longitudinal assessments of wildlife habitat, particularly across broad spatial scales, has been hampered by inconsistencies in methods of data collection across space and time.[66] There are also challenges of integrating federal monitoring datasets with state, tribal, and private monitoring efforts. Oftentimes it is difficult to know what formal or informal monitoring is occurring in a region simply because of a lack of communication and coordination. Monitoring invasive plants is a good example of formal monitoring providing useful ancillary or supplemental information even though it has a separate, specific purpose. Informal monitoring by public or private entities is often not recognized by traditional scientific processes and yet can also provide additional sources of information. Increasing awareness of and access to these alternative sources of information, however, is crucial for their utility to comprehensive monitoring programs.

We know of only two contemporary soil and vegetation monitoring programs in US rangelands that provide crucial and broad geographic coverage of data on rangeland condition, and these programs could have broad importance for wildlife habitat monitoring: BLM's AIM Program (https://aim.landscapetoolbox.org/) and NRCS's NRI

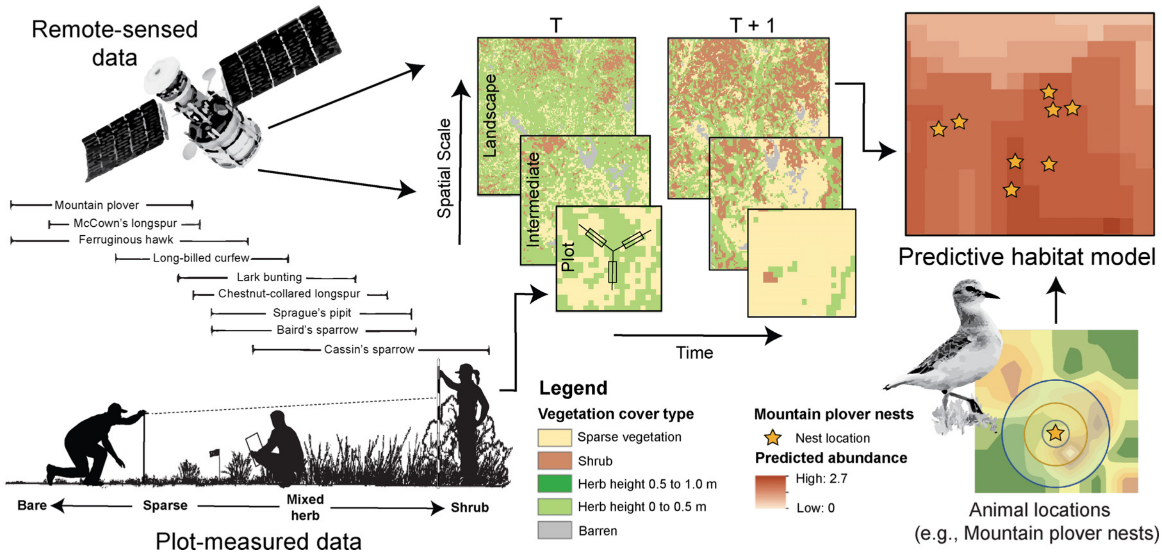


**Figure 2.** Conceptual diagram of the process of combining plot-measured and remote-sensed monitoring data to develop spatially explicit habitat maps for wildlife species of interest. Repeat measurements through time allow users to map habitat changes. The utility of these maps to predict habitat quality is greatly improved with the addition of animal locations for model validation, testing, and refinement. For example, mountain plover *(Charadrius montanus)* nesting habitat, which is generally associated with short sparse vegetation, is monitored at the plot scale. These data can be combined with remote sensing of vegetation cover at intermediate or landscape levels and nest location information to generate predictive habitat models (of breeding habitat suitability, for example). From an adaptive monitoring perspective, consider the entire process as iterative that improves as new information becomes available and monitoring data or methods adapt and improve. The panel in the lower left was modified from Knopf[64] and Derner et al.[58]

Program (https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/technical/nra/nri/).[67,68] Neither of these programs were designed specifically to capture habitat attributes for wildlife, although wildlife is identified as an important component of biotic integrity, one of three key attributes evaluated to determine ecosystem function.[68] To date, AIM and NRI data have rarely been used in wildlife habitat assessments. But one of the first descriptions of potential uses of AIM data in the literature was in the context of greater sage-grouse conservation due to the unprecedented threats of wildfire to sage-grouse habitat and the sagebrush ecosystem.[69] More recently, scientists leveraged the AIM protocol to evaluate restoration treatments aimed at improving big game winter habitat and providing sagebrush cover for sagebrush obligate species.[70] Most of the uses of AIM data, however, have been for validating remote sensing products or evaluating soil conditions and plant communities rather than modeling wildlife habitat, although some of the remote sensing products could eventually be used for landscape-level wildlife habitat assessments.[71]

Leveraging rangeland monitoring data for wildlife management can be further improved by explicitly integrating both wildlife and rangeland goals into monitoring programs. For example, the Utah Division of Wildlife Resources (UDWR) implemented a range trend monitoring program (https://wildlife.utah.gov/range-trends.html) in 1982 with the explicit objective of informing not only UDWR biologists, but also the private landowners and public agency personnel who are tasked with managing wildlife habitat. The UDWR range trend program monitors vegetation condition in permanently marked key areas at about 600 sites, primarily on winter ranges used by mule deer and elk (*Cervus canadensis*). Selected sites within different UDWR regions are monitored each summer, so the entire state is covered every 5 years. Each site is photographed and monitored to count deer and elk pellet groups, and vegetation measurements are taken along transects covering a 30 m x 150 m area and include: ocular estimates of plant and ground cover; nested frequency; woody canopy cover via line-intercept; shrub density, utilization, and health; and tree densities. These data can be used by UDWR for wildlife management plans, and by federal agencies for allotment management plans and to identify where to target habitat improvement efforts.

Notably, the UDWR range trend monitoring protocol also has been used to monitor habitat improvement projects. The Utah Watershed Restoration Initiative (WRI; https://wri.utah.gov/wri/), a partnership with UDWR and other state and federal agencies, sponsors rangeland improvement projects, and pre- and post-treatment monitoring of a subset of those sites has been included within the UDWR range trend sampling rotation. Those WRI data, which are publicly available, have been used to contrast the effectiveness of different vegetation treatment methods, as well as examine invasive species responses, potential mechanisms driving the success (or failure) of those treatments across different habitats, and cost-effectiveness of treatments.[72,73,74] Moreover, although the UDWR rangeland studies originally targeted big game habitat, the data have also been used to inform management of other wildlife species. For example, Riginos et al. used these data to examine effects of fire on vegetation cover relative to habitat guidelines for greater sage-grouse.[75] Guidelines were gleaned from both BLM standards at the state level and range-wide recommendations.

Because of the large proportion of federal land ownership in the West, at least some level of monitoring—even if not with wildlife habitat as an explicit objective—is occurring on millions of acres and has been integral to wildlife research and conservation efforts. For example, vegetation monitoring data have been incorporated into several wildlife conservation initiatives: the Wyoming Migration Initiative focuses on migratory ungulates (https://migrationinitiative.org/); ongoing efforts to develop an ecosystem-wide conservation strategy for sagebrush landscapes (Sagebrush Conservation Initiative, https://wafwa.org/iniatives/sci); and numerous regional and state collaboratives focused on greater sage-grouse. For example, the Wyoming Landscape Conservation Initiative (https://www.wlci.gov/) aims to assess and enhance habitat throughout southwestern Wyoming for a suite of wildlife species, incorporating ungulates as well as greater sage-grouse, sagebrush songbirds, herpetofauna, and other mammals.

Although federal rangelands in the western United States have long been subject to monitoring of vegetation trends, more recent efforts on private lands have resulted in increasingly comprehensive monitoring of rangelands, as well as greater similarity in protocols and data types between federal and private lands.[67] Incorporating more consistent methods on nonfederally managed lands will be extremely important, for example, within the Great Plains where most rangelands are located on private or state lands, with a scattering of federal holdings (e.g., in US Forest Service national grasslands and US Fish and Wildlife Service national refuges).[76] As a result, this region has less temporal and spatial coverage of standardized vegetation monitoring data compared with western landscapes, which can make application of vegetation monitoring data to wildlife management challenging. NRI data may be available on some of these private lands and could be useful for wildlife applications.[30] Some monitoring has also occurred on private lands enrolled in the Conservation Reserve Program (CRP), which may help fill some of these data gaps.[77] One example where this monitoring was directly focused on upland wildlife is CP-33, which targets habitat buffers for upland gamebirds. The national CP-33 monitoring program included vegetation monitoring on enrolled lands throughout much of the Midwest, including grasslands in the eastern Great Plains.[78] Vegetation surveys were designed to specifically target northern bobwhite (*Colinus virginianus*) while also benefiting other upland birds.[79] In this example, vegetation monitoring was designed directly to align with wildlife goals. Future efforts to standardize these methods across land ownerships as well as considerations of the spatial arrangement of the CRP fields on the landscape will be important for evaluating their potential benefit for the many imperiled wildlife species in this region.

## Next generation of adaptive rangeland monitoring for wildlife

New tools in remote sensing are enabling adaptive monitoring in part by addressing both spatial and temporal data limitations and facilitating coproduction among scientists and practitioners.[80] For example, the Multi-Resolution Land Characteristics (MRLC; https://www.mrlc.gov/) consortium is a group of federal agencies that coordinate and generate consistent and relevant land cover information at the national scale. MRLC hosts rangeland cover and condition data from various sources, including from the National Land Cover Database (NLCD) and Rangeland Condition Monitoring Assessment and Projection (RCMAP) time series[81]. These products provide relatively fine-scale (30-m), wall-to-wall remotely sensed data that are publicly accessible and useful for monitoring because they have been captured systematically dating back to the mid-1980s.[39] These products help remedy some of the temporal and methodological limitations to tracking changes in wildlife habitats over time and across different spatial scales. Approaches could even be applied retrospectively, such as to determine whether historical changes in land cover may partly explain why species are declining in a region (e.g., grassland birds of the eastern Great Plains).[82]

While these new remote sensing tools provide meaningful wildlife habitat information at the landscape or regional level, there is less clarity on how to monitor wildlife habitats at the intermediate or mid-level.[83] Mid-level ground surface and vegetation data are often collected by airborne light detection and ranging (LiDAR), ground-based terrestrial laser scanning (TLS), or other types of sensors, sometimes attached to UAS (Fig. 1).[17] This scale of data could provide crucial information about composition, structure, and quality of habitat at meaningful scales (e.g., home range) for many species, especially because the fine grain of the data (i.e., down to decimeters) allows for novel habitat characterizations. Some argue this is the frontier of wildlife habitat monitoring and modeling,[84] such as for assessing thermal heterogeneity of wildlife habitat,[41] foodscapes,[56] and cover from predators, recently coined "fearscapes."[85] Standardization and application of these mid-level data for wildlife and integration with existing monitoring programs needs more attention.[62]

In addition to the need for greater spatial and temporal consistency in monitoring methods and coverage, lack of accessibility of rangeland monitoring data can preclude its application to wildlife habitat conservation efforts. Researchers in state, academic or nonprofit institutions may not know about or be able to access the diversity of data collected across rangelands because there is no central repository or index for these data. The Climate Engine (http://climateengine.org/) allows access to remotely-sensed climatic and vegetation data (based on Landsat) and can be used to obtain within-year data or annual data spanning the past 35 years. The relatively new Rangeland Analysis Platform (RAP; https://rangelands.app/) combines satellite imagery with thousands of on-the-ground vegetation measurements from the AIM and NRI programs to model a number of land surface variables including cover of herbaceous vegetation, shrubs, trees, and bare ground extending back to 1984.[86] However, knowledge of many of these data products is only obtained through collaborative networks, resulting in insular data use and precluding cross-pollination among disciplines and regions.[87] This issue has the potential to stifle important progress and adaptive monitoring.

Fully integrating modern remotely sensed rangeland data resources into wildlife habitat management will require coordination between the researchers responsible for the creation of models and the managers who use these models as decision support tools in structured decision-making processes.[88,89] For the current and next generation of rangeland managers, this will require increased communication and strengthening of relationships with wildlife and rangeland researchers and remote sensing developers for effective coproduction of relevant, defensible tools, products, and information.[87,90] Communication and coordination with local and regional managers early in the research process can improve the utility and application of scientific findings and outcomes. As stated by Merkle et al.[91]:

*In most cases, the development of a collaborative research-management framework is a result of individual managers and researchers increasing communication and building trust, and institutions creating opportunities and rewards for enhancing working relationships that lead to collectively producing and integrating research into management decisions (p. 1,649).*

## Ten ways to improve connections between vegetation monitoring and wildlife

1. Improve monitoring objectives for wildlife, especially implicit linkages among measured attributes of habitats, their functional properties for wildlife, and meaningful population-level responses (e.g., increased fecundity, recruitment, juvenile and adult survival, population growth). Twenty-five years ago, Reed Noss[92] pointed out, "In any monitoring program, particular attention should be paid to specifying the questions that monitoring is intended to answer and validating the relationships between indicators and the components of biodiversity they represent."(p. 355) This message is still meaningful and needed.
2. Build bridges between land management agencies (e.g., BLM, USFS) and wildlife-focused entities (i.e., state and tribal wildlife agencies, USFWS, nongovernmental organizations) to identify habitat monitoring needs tied to wildlife conservation objectives and develop plans to address these needs within existing rangeland vegetation monitoring protocols, where possible. Land managers and scientists could commit to collaborative processes using effectiveness monitoring in decision making to address rangeland health and wildlife conservation objectives.[93] This may also include systematic conservation planning for the spatial prioritization of wildlife conservation within economic constraints.[88] For example, Toombs and Roberts[94] suggested "increasing the emphasis of NRCS conservation programs and financial assistance on maintaining or increasing compositional and structural heterogeneity of vegetation, rather than [strictly] on livestock distribution, could be an approach that unifies livestock production and wildlife habitat objectives." (p. 351) The "Working Lands for Wildlife" frameworks released by the NRCS in 2020 may in the future provide a hub for bringing together priorities and datasets in both the Great Plains and sagebrush steppe (https://wlfw.rangelands.app).
3. Facilitate coordination of soil and vegetation monitoring efforts within and across organizations and evaluate where adjustments can be made to increase comparability and maximize utility for wildlife habitat; make this a priority within agencies and designate individuals to drive the monitoring program and maintain coordination. Examples of this integration have been tested with NRI and Forest Inventory and Analysis programs in Minnesota and Oregon providing an opportunity for lessons learned and paths forward.[95,96]
4. Provide funding for initial efforts to coordinate field-based soil and vegetation monitoring for wildlife applications across agencies and institutions after first determining objectives to be accomplished by different conservation strategies or management actions or developing a conceptual model of the system to be monitored. Then provide annual funding for data sharing, curation, and coordination. This may include cost-benefit analyses to increase accountability and return on investment for achieving rangeland health and wildlife conservation objectives.
5. Facilitate coordination, provide funding for, and continue to support remote sensing applications, especially as relevant for wildlife habitat modeling and mapping. Improving coordination and standardization of mid-level data sources, such as UAS and TLS, with existing monitoring programs will be particularly important to move newer remote sensing platforms from research to application.[62]
6. Continue working to integrate vegetation monitoring data into threat management approaches (e.g., resistance and resilience), especially focusing on applying these approaches at mid- and landscape-scales as data become available.[97]
7. Make better connections between Ecological Site Descriptions (ESDs) and wildlife habitat. An additional opportunity for monitoring rangeland wildlife habitats lies in applications of information from ESDs, which classify land types according to soils and other physical and biotic factors.[98] Quantifying biodiversity metrics associated with ESDs is already underway.[99]
8. Continue to fill existing gaps in our knowledge of soil properties in certain regions as well as at finer spatial resolutions; both may be necessary for evaluating habitat selection by individual animals and across extents needed for modeling species distributions. Existing monitoring protocols include some soil parameters (e.g., soil aggregate stability), but this remains a fruitful area for collaboration among rangeland scientists, wildlife ecologists, and soil scientists.
9. Improve integration of existing rangeland resource tools, such as the Land Treatment Exploration Tool (http://usgs.gov/ltet), into decision-making and decision support tools for wildlife. This may require some additional funding to ensure compatibility and improve functionality and ac-

cessibility to multiple users. Ultimately, however, this integration will increase efficiency, reduce redundancy, and improve implementation, especially with proper end-user training.

10. Promote the continued development and accessibility of repositories for soil and vegetation monitoring data derived from plot-level field monitoring efforts and mid- to landscape-level remote sensing. Data accessibility and management are a growing focus for scientific research globally, especially when projects are supported by public funds. The wealth of existing rangeland monitoring data should be maintained in perpetuity through a carefully coordinated and federally supported network. The Landscape Data Portal (https://landscape.blm.gov) provides a good example of a repository for geospatial data, maps, models, and reports associated with BLM lands.

## A vision for better integration of wildlife habitat needs into rangeland monitoring

A strategy or roadmap for how to improve integration of wildlife information needs into rangeland monitoring programs is overdue. Our presentation of 10 ways to facilitate and support this effort, described above, is a start. Taking such an approach will create new opportunities for wildlife research but, more importantly, it could improve wildlife management through generation of organized, accessible information for timely decision making. We emphasize that this process will benefit from multistakeholder communication, flexibility, and adaptability. Because of the unavoidable reality of limited resources needed to address massive information needs (for thousands of species), the process will need to begin with identifying the most important wildlife conservation problems and then use adaptive monitoring and conservation science to address well-articulated objectives. A key component in this process will also be identifying the most relevant spatial scales of inquiry, and successfully integrating multiple data sources across those scales in analyses. This is one of the most important breakthroughs in wildlife science over the past two decades. We can now go beyond plot-level microhabitat assessments and integrate information across multiple spatial scales that we know are an important part of wildlife habitat selection. Institutional priorities and workflows will need to incorporate these priorities to increase coordination among field-measured and sensor-derived monitoring to enhance data comparability. We should be careful, however, that a science perspective does not interfere with collaborative conservation. The science should be adapted to address the most important conservation problems instead of adapting rangeland and wildlife objectives to take advantage of increasingly available data. Ideally, these efforts and products would allow for change through time and before-after-control-impact type analyses for documenting and solving these top conservation problems.

Some wildlife biologists argue that monitoring habitat is no substitute for documenting population responses to management actions.[45] We are not suggesting that modeling habitat relationships is a substitute for evaluating population change in relation to land management or environmental perturbation. We are suggesting that using available rangeland vegetation monitoring data for modeling wildlife habitats could complement population studies and provide useful information for wildlife habitat conservation and management. Unfortunately, population field studies are expensive, difficult, and rarely sustained over longer time periods, which is unlikely to change. Some biologists suggest monitoring occupancy might be a less expensive solution.[100] Innovative technologies, such as single species and species-assemblage detection using environmental DNA in water, snow, soil, air, and plant substrates, may be a game changer for wildlife occupancy monitoring.[101] Overall, we are optimistic about forthcoming, technological improvements of our ability to understand the implicit linkages between habitat characteristics that can be measured and monitored and population or community responses to anthropogenic and environmental change.

In conclusion, our vision for the future is that new developments and applications of rangeland monitoring, particularly in the realm of standardized field methods and remote sensing data, will be more and more important to wildlife habitat monitoring and management efforts. Properly funded and curated highly accessible repositories for these data will ensure practitioners with a wide variety of backgrounds can access and apply these datasets to manage and conserve rangeland wildlife habitats throughout the next century. Tangible conservation outcomes will depend on how effectively monitoring information is used and embedded in a collaborative decision-making process.

## Declaration of Competing Interest

D.S.P is a guest editor for this Special Issue but was not involved with the review or decision process for this manuscript. 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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