PERSPECTIVE

Bridging the research-management gap: landscape science in practice on public lands in the western United States

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Abstract

Context Landscape science relies on foundational concepts of landscape ecology and seeks to understand the physical, biological, and human components of ecosystems to support land management decision-making. Incorporating landscape science into land management decisions, however, remains challenging. Many lands in the western United States are federally owned and managed for multiple uses, including recreation, conservation, and energy development.

Objective We argue for stronger integration of landscape science into the management of these public lands.

Methods We open by outlining the relevance of landscape science for public land planning, management, and environmental effects analysis, including pertinent laws and policies. We identify challenges to integrating landscape science into public land

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management, including the multijurisdictional nature and complicated spatial pattern of public lands, the capacity of agencies to identify and fill landscape science needs, and perceptions about the meaning of landscape approaches to management.

Results We provide several recent examples related to landscape monitoring, restoration, reclamation, and conservation in which landscape science products were developed specifically to support decision-making.

Conclusions We close by highlighting three actions—elevating the importance of science-management partnerships dedicated to coproducing actionable landscape science products, identifying where landscape science could foster efficiencies in the land-use planning process, and developing scenario-based landscape models for shrublands—that could improve landscape science support for public land planners and managers.

Introduction

Landscape science relies on foundational concepts of landscape ecology (Wu 2013) and seeks to understand the physical, biological, and human components of ecosystems to support the decision-making needs of land managers (Robinson and Carson 2013). Land use planning requires the ability to put large quantities of disparate information into context in order to make durable management decisions. Landscape science can provide needed context for the often abundant site-specific data available to land managers. Recent reviews of resource management plans for public lands suggest that foundational concepts in landscape

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ecology are present in plans, but that public lands planning, management, and monitoring could benefit from more explicit incorporation of landscape science, data, and objectives (Trammell et al. 2018).

Such gaps between research and management have been documented in many fields, including ecology and conservation (Turner et al. 2002; Darling 2015; Walsh et al. 2015; Toomey et al. 2017). Researchers may not focus studies on the questions managers most need answered (Fazey et al. 2005), and managers may not use available research in their decisions (Pullin and Knight 2005; Cook et al. 2010; Cvitanovic et al. 2014; Kemp et al. 2015). Research that is not readily accessible, that is complex or technical and not translated into decision-relevant terms so that it can be readily applied by managers, or that is conducted at scales inappropriate to the decision at hand, all pose challenges to managers.

We argue for efforts to more strongly incorporate landscape science into public land management. We begin by outlining the relevance of landscape science for public land management and known challenges facing such an effort. We then present examples of several recent attempts to bridge the landscape science-management gap on public lands. Our examples focus primarily on landscape level applications of research to management of grasslands and shrublands, which comprise many public lands in the western U.S. We close by proposing three actions that could further the integration and use of landscape science in public land management.

The relevance of landscape science for public land management in the U.S.

In the western U.S., public lands constitute the backbone of many conservation efforts, are home to significant historical and cultural sites, provide diverse recreation opportunities, and furnish important renewable and non-renewable sources of energy, among many other uses and values (e.g., Aycrigg et al. 2013; Copeland et al. 2017a). Management mandates, environmental laws, and agency policies that govern public lands clearly reference landscape concepts, and the vast and disconnected area of U.S. public lands underscores the need for landscape science and perspectives to inform public land management.

The high-level management objectives and resource uses allowed on federal public lands vary by management agency and land designation, often including energy and resource extraction, water provision, recreation, wildlife conservation, and livestock grazing (e.g., Federal Land Policy and Management Act of 1976 [43 USC §1701], Multiple-Use Sustained-Yield Act of 1960 [16 USC §528], National Park Service Organic Act of 1916 [54 USC §100101]). Some uses are incompatible with each other and with mandates to maintain and restore renewable natural resources and values. Specific land uses, therefore, are best targeted across heterogeneous landscapes according to inherent suitability, compatibility with other uses and values, demand from stakeholders, and resource sustainability goals. Such targeting can be informed by spatial mapping and analysis of sensitive resources and of restoration and reclamation potential across landscapes.

Foundational environmental laws support inclusion of multi-scale and cross-jurisdictional data and analyses in public lands decision-making. The National Environmental Policy Act (NEPA) of 1969 requires federal agencies to examine all proposed actions on federal lands that may significantly affect the environment. Evaluating potential indirect and cumulative effects of development, in particular, involves considering potential environmental effects at spatial and temporal scales beyond those of individual actions (40 CFR 1508.7). The Endangered Species Act of 1973 (ESA) is a second foundational environmental law that often applies to proposed development actions on public lands. The ESA was intended to conserve ecosystems upon which listed species depend and usually requires designation of critical habitat regardless of the entity with jurisdiction over the land being designated (50 CFR 424). Such designations need to rely on landscape level analyses and data to adequately protect many species. Conservation efforts may also seek to protect species and their habitats before reaching the point at which listing under the ESA is warranted. For example, landscape-level analyses were a critical component of a recent multi-stakeholder effort to protect greater sage-grouse (*Centrocercus urophasianus*) and sagebrush habitats across the western U.S. (Bureau of Land Management and U.S. Forest Service 2014; Bureau of Land Management 2015; Stiver et al. 2015).

Landscape perspectives feature prominently in public land policies and guidance as well. The U.S. Department of the Interior (DOI) seeks to 'Enhance conservation stewardship whereby all levels of government and private landowners work cooperatively together in an atmosphere of mutual respect to achieve shared natural resource management goals across landscapes' (DOI undated). The Bureau of Land Management (BLM) has directed its staff to "incorporate appropriately-scaled metrics in monitoring plans that clearly indicate if landscape and habitat conditions are trending toward, or away from, desired outcomes" (BLM 2018). The National Park Service and U.S. Forest Service now organize their monitoring and, in the case of the U.S. Forest Service, their planning (36 CFR 219 [2012]), around the concept of ecological integrity, which requires identifying the natural range of variability of multiple ecological indicators across large spatial and temporal extents (Wurtzebach and Schultz 2016; Carter et al. 2019).

Finally, the large extent and complicated mosaic of public lands in the West showcase the need for broad spatial and temporal perspectives in planning and management. About 60% of the western U.S. is public land managed by federal, state, and local agencies (Fig. 1), and the spatial configuration of these lands varies. Some are large, clearly defined blocks (e.g., many national parks and forests), whereas others (notably lands managed by BLM) consist of many non-contiguous small blocks interspersed with other public and private lands (e.g., the checkerboard land ownership pattern that resulted from federal land grants to railroad companies). Management decisions made at the level of individual sites (e.g., permitting of individual well pads) that do not consider the size and location of other developments and resources present across the landscape (e.g., roads, well pads, pipelines, wildlife migration corridors) can fragment and degrade large areas of wildlife habitat on public lands. The landscapes surrounding public lands provide the social, political, and ecological contexts in which those lands are managed, constraining both the ability of managers to implement actions and the potential of those actions to achieve desired outcomes (e.g., Hansen and DeFries 2007, Radeloff et al 2010). For example, efforts to manage wildfires and control invasive species across checkerboard areas of federally managed rangelands must include the support of
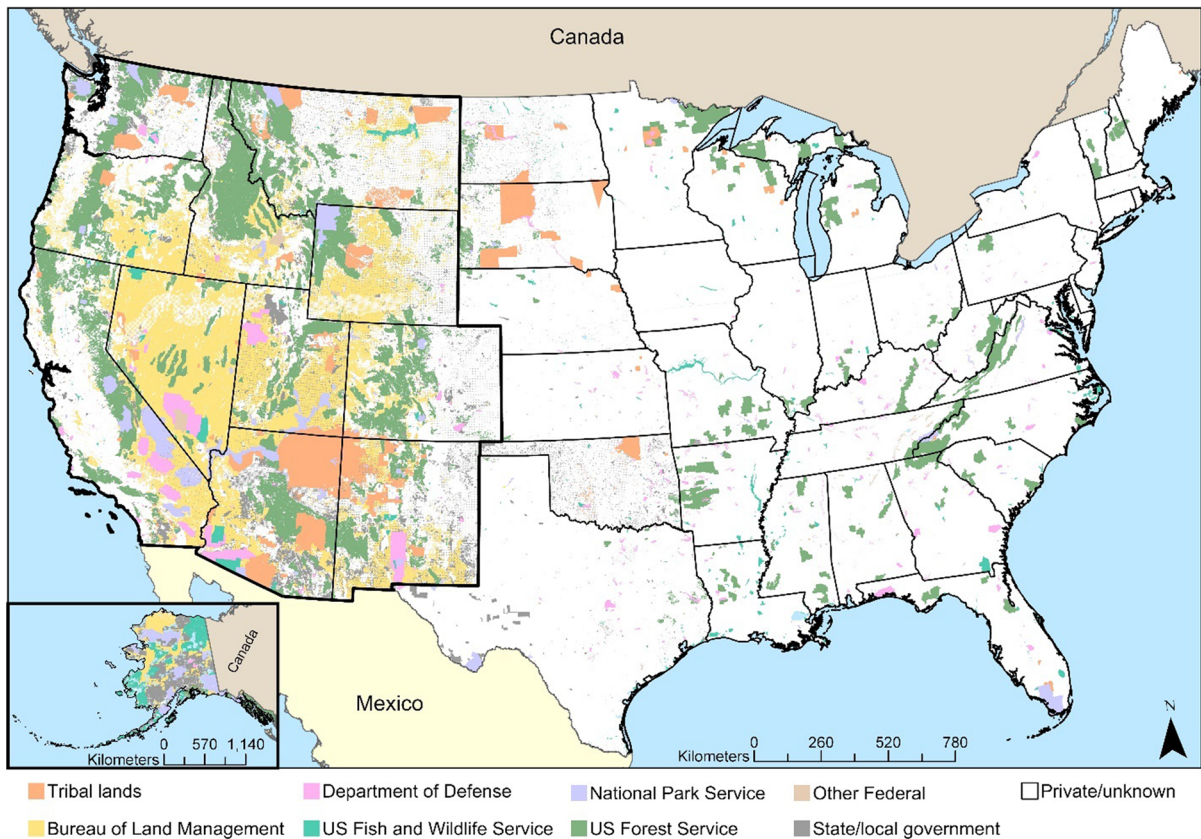
Fig. 1 Distribution and jurisdiction of public lands in the contiguous United States and in Alaska (inset, BLM 2019). In this paper, we refer to the states outlined in the thick black line (including Alaska) as the Western U.S

and actions by other private and public landowners to be successful (DOI 2015).

Challenges to integrating landscape science and landscape management on public lands

Public land managers face challenges in managing at landscape levels and using landscape science despite the legal and policy foundation for both. Challenges include the multijurisdictional nature of public lands, agency capacity to identify and scientists' ability to address landscape science needs for public lands decision-making, and public perceptions about landscape approaches to resource management. Landscapes often include multiple jurisdictions whose agencies have divergent missions, priorities, and data sources. Agencies may also differ in their processes for implementing different environmental laws. All of these differences can lead to conflicts when public

lands managed by different agencies with different mandates occur in close proximity.

Managers may also have difficulty identifying, funding, and using landscape science. Resource management agencies may focus on hiring staff with the specific expertise needed to support field operations (e.g., processing grazing permits), potentially leading to few field staff that have a background in landscape ecology (Trammell et al. 2018). Resource managers in some fields may perceive landscape science as only peripherally relevant to the resources they manage (e.g., cultural or historical sites). Resource managers also may not receive approval to attend training and conferences to maintain their professional literacy in emerging science topics. As a result, managers who received their education and training prior to the emergence of landscape science as a field of study may not have the training, or see the need, to identify and prioritize landscape science needs. When science needs for informing management decisions are
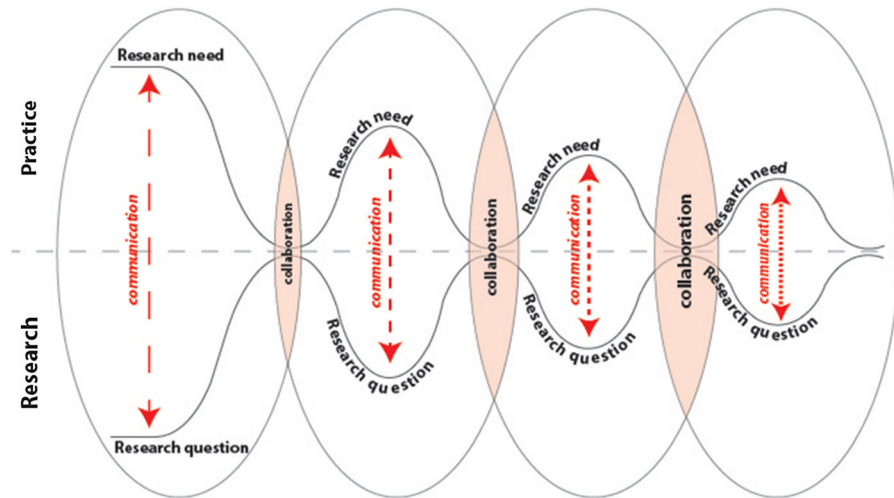
Fig. 2 Conceptualization of the work of science-management partnerships to address problems or challenges (represented by the large ovals) relevant to both scientists and resource managers over time. The dashed line represents the conceptual boundary between science and resource management. Moving from left to right across the figure illustrates increasingly close collaborative problem solving efforts that can occur over time accompanied by greater communication, collaboration, and understanding. Ferguson et al. (2014), used with permission

identified, they may not be novel enough to generate significant interest from major science funders. Management agencies may not prioritize funding for filling landscape science and data gaps or may favor site-based projects that can be completed in a single year over landscape-level projects that require multiple years of funding for implementation. Agency decision processes may also be less established for landscape-level projects. Agencies may lack mechanisms for helping scientists understand the types and topics of science that could be readily incorporated into existing agency decision processes, the degree of certainty in science products needed to reduce management risks to acceptable levels, and the time frame in which science information is needed to improve decision outcomes; and scientists may be unable to produce the desired products in the necessary timeframe. Further, time spent by scientific staff engaging with public land managers to understand these issues and assist with efforts like land-use planning is often undervalued in performance evaluations (Dilling and Lemos 2011; Beier et al. 2017). These challenges, coupled with a long tradition of and political emphasis on site-specific data, often lead to agencies that lack experience and motivation to use landscape science and data.

The application of landscape science in land use planning may also be challenged by perceptions about how landscape level land management may potentially conflict with local land uses and priorities. For example, in 2016 BLM worked to update its land-use planning process to include, among many other things, a requirement to consider landscape level information in the planning process (81 FR 89,580). More than two hundred of the comments submitted in response to the proposed regulation by various organizations, businesses, local and state governments, individuals, and members of Congress (Regulations.gov 2016, two excerpts from these comments are included below) addressed landscapes specifically and illustrate several key challenges that contributed to the regulation being nullified (131 STAT. 76). First is the lack of a clear understanding of the definition of landscape, whether there can be multiple landscapes and scales considered, and the potential implications of both for increasing the size of land-use planning areas such that they might cross field office, district office, or even state boundaries. Second is a perception that landscape-level data and analyses may preclude or override the use of local and site-specific information and plans and devalue the expertise of local land managers and members of the public. Third is a concern that landscape level analyses will complicate and delay the planning process and fail to provide the detailed information that local planners need. These

perceptions and concerns are embodied in comment excerpts such as "… it is unclear how moving to a landscape approach will allow for the detailed planning on the land that is required to inform local managers for adequate decision making." Fourth is a perception that consideration of landscape perspectives and data "… strips away the authority and expertise of local land managers". Such challenges can influence managers and subsequently prevent planners from using landscape science and data, potentially resulting in isolated planning decisions that do not adequately consider or quantify potential environmental impacts across the landscape.

Applying landscape science to public land management

Despite the challenges described above, the importance of landscape-level management has been recognized by resource managers for years (Lidicker 1995; Liu and Taylor 2002). We present below several examples of landscape science products designed to support management needs on western public lands. For each example, we outline the problem identified by public land managers, the research conducted and science or data products produced, and the ways in which the products have been or could be used to inform public land management.

Example 1: monitoring landscapes, hydrology, and climate around national parks

Problem

The NPS Inventory and Monitoring Program facilitates integration of natural resource monitoring into park management by applying standardized monitoring protocols (Oakley et al. 2003; Fancy et al. 2009) across 32 regional monitoring networks. Most networks identified land cover, vegetation, surface hydrology, and weather and climate as key ecosystem drivers that affect park resource conditions. However, designing and implementing monitoring protocols within each network was determined to be unsustainable within the program's resources, and a nationally standardized approach to meeting local monitoring objectives related to park environmental settings was implemented instead. Challenges to landscape

monitoring in NPS include balancing similar data needs across parks of varying sizes (0.3–534,000 ha), the diversity of management priorities and jurisdictions around parks, and the many ways in which parks want to use landscape data to support their scientific, planning, and civic engagement efforts.

Research and products

In 2018, the NPS Inventory and Monitoring Program identified a suite of metrics that act as surrogates for ecological drivers that influence park resource condition, ecological processes, and conservation context. In 2019, NPS began implementation of a Park Environmental Settings monitoring protocol to calculate and report on these metrics (DeVivo et al. 2018). This effort evolved from the NPScape program which delivered landscape-level data, standardized analytical methods, visualization tools, guidance on interpreting results, and park example case studies to assist NPS Inventory and Monitoring networks with integrating landscape dynamics information into park management and planning (Bennetts et al. 2012; Monahan et al. 2012; Monahan et al. 2013; NPS 2013). The nationwide Environmental Settings Monitoring Protocol expands the scope of the original NPScape program to include analyzing other significant drivers of park resources, reporting data at additional scales (such as watersheds), defining monitoring objectives to assess changes in parameters over time, and establishing a framework to integrate landscape dynamics data into planning and management.

Informing management

Successful implementation of the nationwide monitoring protocol will require close coordination and partnerships among many units within NPS. To facilitate use of landscape dynamics data by park staff, the metrics will be calculated centrally and made available to all staff via existing NPS planning tools already used by park managers. Integration of landscape dynamics data into resource management and planning will be facilitated or assisted by monitoring staff who conduct other monitoring efforts at the scale of four to seventeen parks, have an understanding of park management issues and technical capacity, have access to other local monitoring data, and have responsibility for assisting with the integration of

inventory and monitoring data into park decision-making. Application examples may include transportation planning, identifying linkages between habitats fragmented by forest change or road development, exploring relationships between fluctuations in daily streamflow and changes in fish diversity, stream bank erosion, or riparian health observed by park staff, and the use of historical and forecasted climate data to inform controlled burns and invasive species treatments. A science collaboration between an NPS monitoring network and the U.S. Geological Survey (Andrews et al. 2018) used similar landscape and historic climate data to help managers better understand climate-driven effects on water availability in their park. As the nationwide protocol proceeds, the audience for the metrics may expand to other stakeholders like state and local governments, tribes, and non-governmental organizations.

Example 2: restoring arid and semi-arid landscapes

Problem

Ecological restoration across large landscapes in dryland regions is a recognized challenge (Oldfield and Olwell 2015). The prevailing dry conditions of western public lands often do not support plant establishment, and restoration succeeds primarily during unusual wet periods or in portions of a landscape with suitable soils and microclimates (Brabec et al. 2016; Copeland et al. 2017b; Shriver et al. 2018). As temperatures rise and weather variability increases, the frequency of these unusual favorable events supporting dryland plant establishment may decline (Petrie et al. 2017). Anticipating shifts in suitability for any given location is further complicated by variable projections for long-term precipitation patterns, which introduce uncertainty in identifying appropriate species or genotypes for future restoration projects.

Research and products

Research into contemporary drought patterns and twenty-first century drought trajectories can help inform restoration strategies that minimize drought constraints and maximize long-term suitability (Bradford et al. 2018). Results suggest that adaptive and flexible seeding strategies may help address the high

variability in plant establishment and that long-lead (e.g., multi-month) forecasts currently have sufficient skill to provide useful resource management information (Hardegree et al. 2018; Hagger et al. 2018). For example, in big sagebrush ecosystems where plant establishment is related to short-term temperature, snowpack, and spring soil moisture conditions, the probability of successful big sagebrush establishment can be enhanced by seeding in multiple consecutive years (Shriver et al. 2018) or by leveraging seasonal weather forecasts (e.g., forecasts of snowpack, Kapnick et al. 2018) to target seeding during favorable years. Long-term restoration success may be maximized by using propagules from species or genotypes that are adapted to establish and survive in hotter, drier conditions (Butterfield et al. 2016).

Informing management

Current work is focused on improving landscape-level assessments of dryland resistance and resilience (Bradford et al. 2019) and integrating results into decision support tools for managers. Several tools have emerged that help managers identify appropriate seed sources by assessing the long-term climate trajectories within seed zones [e.g., the Seedlot Selection Tool designed to help forest managers match seedlots with planting sites based on climate information (https://seedlotselectiontool.org/sst/), the Climate Distance Mapper tool designed to help resource managers match seed sources with restoration sites (https://usgs-werc-shinytools.shinyapps.io/Climate_Distance_Mapper/), and a tool to aid sampling efforts along climate gradients for an area of interest (https://seedmapper.shinyapps.io/climpart/)]. Additional tools in development will quantify future ecological drought at a given location (Bradford and Andrews 2018) and assess the probability of a planned restoration treatment avoiding drought-induced mortality. The Land Treatment Exploration Tool (Pilliod et al. 2018) identifies past land uses, disturbances, and treatments near proposed restoration projects to help managers understand what restoration methods and seed mixes are more likely to be successful. In combination, these findings and tools can help resource managers maximize the efficacy and long-term effectiveness of restoration efforts across heterogeneous landscapes.

Example 3: landscape considerations
for reclamation

Problem

Reclamation of severely disturbed land is usually
confined to specific sites, but the cumulative effects of
some actions have landscape level implications.
Energy development on U.S. public lands is a good
example. About 3 million hectares of land was cleared
for oil and gas development between 2000 and 2012 in
the central U.S. and Canada (Allred et al. 2015). This
development, particularly where highly concentrated,
has led to concerns about cumulative effects on other
resources, notably wildlife habitat, air quality, and
aesthetics (Allred et al. 2015; Buse et al. 2019). The
type and scale of information needed to inform
mitigation of such impacts vary. Broad-scale infor-
mation is needed during larger planning processes
(e.g., development of land-use plans for BLM field
offices), whereas very fine scale spatial data on
specific resources is needed at the implementation
level to minimize construction and operational
impacts and increase the likelihood of subsequent
reclamation succeeding.

Research and products

New tools and data products have been developed to
address some of these information needs, including an
analysis of reclamation success across spatial and
temporal scales (Nauman et al. 2017), fine scale
information on soils that can be used to predict soil
vulnerability to erosion and challenges to reclamation
(Nauman et al. accepted), and new land classification
concepts suitable for organizing and spatially convey-
ing reclamation potential and best management prac-
tices (Duniway et al. 2016) that can be mapped with
greater spatial resolution and in places without current
soil surveys (Maynard et al. 2019).

Informing management

Planning for energy exploration and development
currently relies on Natural Resources Conservation
Service soil survey maps, which often have limited
spatial and thematic detail. USGS and others have
developed new predictive soil maps that can facilitate
a more informed decision process at both broad and

fine scales. For example, better spatial information on
soil types that are more difficult to reclaim and pose
high risk of accelerated erosion by wind or water if
reclamation fails can be used in planning and siting
processes to minimize some deleterious impacts of
energy exploration and development through avoid-
ance. These same maps can also be used in planning
reclamation actions, including estimating reclamation
costs based on the occurrence of challenging soil
properties (e.g., salinity). New online tools will also
allow agency and industry staff to conduct initial
assessments of the status of reclaimed well pads based
on remote sensing indicators and machine-learning
selected reference sites (Nauman et al. 2017). The
ultimate goal is to capture and synthesize information
on potential development impacts to resources, effects
on other users, and where and how reclamation has
succeeded, and to make this information available in a
spatially explicit framework to inform future planning
and reclamation actions (Duniway et al. 2016).

Example 4: multi-scale management of sage-
grouse

Problem

Animals select for resources across spatial scales, with
choices first made at broader scales (Boyce 2006;
Aldridge et al. 2012). Often we understand local niche
conditions required by species (e.g., nesting habitat for
sage-grouse [*Centrocercus* spp.], Hagen et al. 2007),
but research over the past decade has recognized the
importance of assessing landscape-level resource
requirements as well (Aldridge and Boyce 2007; Fedy
et al. 2014; Kirol et al. 2015). Considering how
resource availability affects individual fitness is par-
ticularly important when landscapes are modified at
faster rates than species can respond, such as with
energy development and sage-grouse, resulting in
ecological traps and population declines (Aldridge and
Boyce 2007; Kirol et al. 2015).

Research and products

Recent studies have focused on sagebrush restoration
that benefits sage-grouse, identifying patch sizes of
sagebrush to plant, how and where to plant them (Pyke
et al. 2015), and broader landscape configurations that
may be required before birds will use restored systems

(Aldridge and Boyce 2007; Kirol et al. 2015). Other studies have elucidated differences in resource selection across scales for Gunnison sage-grouse (*C. minimus*, Aldridge et al. 2012): hens with broods initially select habitats that contain large landscapes of moderate sagebrush cover for protection, but within those landscapes select for smaller patches of lower sagebrush cover that provide access to forage forbs (C.L. Aldridge, unpublished data).

Informing management

Scientists and managers have leveraged insights from this research to develop a hierarchical framework that agencies can use to monitor greater sage-grouse (BLM and U.S. Forest Service 2014) that addresses broad- and mid-scales, and a framework that agencies can use to assess sage-grouse habitat (Stiver et al. 2015) which identifies specific assessment methods and metrics at scales from rangewide to individual sites. These products and approaches are being applied rangewide to assess population changes (Coates et al. 2017; Edmunds et al 2018a, b; O'Donnell et al. 2019), and to evaluate sage-grouse population responses to temporally varying vegetation characteristics (see Rigge et al. 2019), climate, fire, cheatgrass invasion, and energy development to inform future management actions within the sage-grouse range.

Example 5: identifying and protecting migratory corridors for big game

Problem

Significant areas of big game summer range, critical winter range, and seasonal migration corridors occur on public lands, where there is increasing pressure to develop energy sources and expand recreational opportunities (Lendrum et al. 2012; BLM 2018). Population declines in some species and locations further contribute to the need to understand how energy development affects big game and to map big game migration corridors to inform future permitting and mitigation actions.

Research and products

Recent research documented that mule deer avoid winter habitat and alter their behavior in areas with more intense drilling activities and infrastructure by detouring from established migration routes, increasing movement rates, and reducing time spent at stopover sites to rest and feed (Sawyer et al. 2013; Wyckoff et al. 2018). These behavioral changes may reduce their ability to track peak plant nutrition during spring migration (Lendrum et al. 2012). New approaches for identifying migration corridors (Sawyer et al. 2009) have been developed into an online mapping tool (Gage Cartographics LLC and Wyoming Migration Initiative 2017) that is now being taught to state and federal wildlife managers in workshops across the west.

Informing management

As a result of these findings and tools, new energy fields are being designed to include lower densities of well pads and roads, and agencies are requiring reduced disturbance within seasonal big game ranges and migration routes on public lands. Managers are using migration data to identify locations where movements are being impeded by fences and roads, so that those fences can be removed or modified, and problematic road locations can be prioritized for underpass or overpass construction. Managers are also targeting herbicide treatments and other habitat improvement projects to increase the nutritional value of forage at stopover sites.

In addition to these management applications, the recent increase in research on big game migration (e.g., an average of 1, 4, and 8 articles were published annually in the 1990s, 2000s, and 2010s, respectively, on mule deer migration according to a Web of Science topic search conducted 12/31/2019) has also corresponded with key policy and funding actions on the topic. In 2018, DOI directed its bureaus to work with western states to improve the quality of big-game winter range and migration corridor habitat (DOI 2018), and subsequently awarded $2.1 million in grants to state and local partners for projects protecting migration corridors (Streater 2019). Congress then introduced bills (H.R. 2795 and S. 1499) in May 2019 to establish a National Wildlife Corridor System on federal lands and create a grant program to fund conservation projects on state, tribal and private lands to facilitate wildlife movement. The corridor movement continues to gain political momentum with a Senate transportation bill (S. 2302) introduced in July

2019 that would provide $250 million for a nationwide pilot program to reduce wildlife-vehicle collisions and build wildlife crossings.

Strengthening integration of landscape science and management on western public lands

Public land managers often must balance competing goals for resource protection and use, insufficient or conflicting local information, uncertainty in the quality or interpretation of information, and variable time frames in which decisions (and their consequences) occur (Bennetts et al. 2016). While there is a strong legal and policy foundation for considering landscape science in public land management, managers face key challenges in attempting to use landscape science and perspectives in their decisions. We acknowledge that these challenges, particularly public perceptions, are hard to overcome. Adding to these challenges are timing and political factors that can result in limited windows of opportunity for integrating science into policy and management (Brunckhorst et al. 2017; Rose et al. 2017). However, we contend, based on our collective experience and the examples above, that tangible steps can be taken now to promote the integration of landscape science into public lands decision-making, including providing stronger support for long term science-management partnerships, analyzing land use planning processes for places where landscape science is currently missing and could enable efficiencies in the process, and developing models for non-forested landscapes that facilitate comprehensive and repeatable NEPA analyses.

Elevating the importance of science-management partnerships dedicated to producing actionable landscape science products

We suggest that agencies work to elevate the role of partnerships among landscape scientists and land managers, boundary organizations, and knowledge brokers in public lands planning and management. Managing data across different spatial scales or organizational levels will require intentionally creating new positions and processes within administrative agencies for effective knowledge management and integration (Wurtzebach et al. 2019). Individuals will need to be hired into positions specifically designed to share knowledge and translate it for management application within and among agencies. Boundary organizations—groups that specifically work to connect science and management communities—also play a critical role (Cash et al. 2006). For a better chance of success, science-management teams should be comprised of management agency representatives and researchers with dedicated funding to design and carry out research programs that address the long-term, multi-scale problems that increasingly confront public land managers. Partnerships can occur at the level of agencies (e.g., USGS contributes scientific expertise to resource management agencies within DOI) or much smaller units. Partnerships can also span public–private interests, such as the Landscape Conservation Cooperatives that provide science capacity for meeting shared natural and cultural resource priorities across public and private lands (Jacobson and Haubold 2014). Long-term commitment and ongoing investment are required for such efforts to succeed (Prager 2010). Relationships need to be established, impediments to working together identified and addressed, and agency decision-processes evaluated for landscape science integration opportunities. While multi-year funding opportunities that require collaboration between managers and scientists can facilitate the formation and success of such partnerships (Cash et al. 2006; Schultz et al. 2019), the short time period within which many planning and management decisions must be made will continue to pose challenges for science-management partnerships that seek to provide landscape science that is used to inform land-use planning and management actions.

Long-term partnerships enable ongoing commitments to coproducing landscape science products that meet the needs of public land managers. Coproduction, in which scientists and managers collaborate to produce actionable science products (Meadows et al. 2015; Beier et al. 2017), holds strong promise as a mechanism for increasing manager understanding and ownership of science products, and for producing science that is tailored to existing decision processes and used to inform policy and management actions (Jasanoff and Wynne 1998; Lemos and Morehouse 2005; Cook et al. 2013; van Kerkhoff and Lebel 2015). Ongoing communication and shared learning between scientists and managers are crucial to coproduction, and usually continue throughout the life of projects. Coproduction partnerships that span multiple tasks

and projects can enable more integrated, collaborative problem solving over time by researchers and managers (Fig. 2, Ferguson et al. 2014).

Identifying where landscape science use could create efficiencies in land-use planning

A critical next step is for public land planners and managers to work with landscape scientists to evaluate their decision processes and identify specific places where landscape information may be lacking and could create efficiencies or strengthen decisions. We suggest three starting points. (1) Increasing the availability of data on species, resources, and uses that are collected and mapped consistently across broad extents could provide stakeholders with a clearer understanding of current patterns of resources, uses, and concerns across a landscape. For example, BLM and NRCS now use similar methods and metrics to monitor public and private rangelands across the U.S. (Herrick et al. 2010; Toevs et al. 2011). Such data can help promote stronger stakeholder engagement, inform agency planning timelines, and establish a foundation of public trust in the planning process. (2) Landscape analyses that map locations across broad areas where reclamation success might be maximized (see Example 3), or where conflicts between potential land uses and sensitive natural or cultural resources could be minimized, can help developers target subsequent individual proposed actions and enable efficiencies in those individual permitting decisions. For example, the Desert Renewable Energy Conservation Plan established focus areas for siting renewable energy development across the southern California desert by identifying where renewable energy potential was high and conservation concerns could be minimized (BLM 2016). This analysis provided a framework for streamlining subsequent permitting decisions for individual energy projects. Non-regulatory landscape strategies such as the Southeast Conservation Adaptation Strategy (Southeast Conservation Adaptation Strategy 2019) and West-wide Crucial Habitat Assessment Tool (State Wildlife Agencies of the Western United States 2019) could similarly help target individual conservation projects. (3) Periodically quantifying landscape metrics for planning areas could enable monitoring of the effects of management actions at the scales at which those actions are conducted (e.g., field offices, states).

For example, BLM uses mid-scale indicators for monitoring the effects of land-use decisions on greater sage-grouse habitat, and is developing indicators for the amount and distribution of priority vegetation types to help quantify existing Land Health Standards (43 CFR §4180.1), set vegetation management objectives in land-use plans, and monitor progress toward meeting those objectives over time.

Developing and using landscape models to support NEPA analyses

Developing and regularly using landscape models in NEPA analyses could greatly advance the transparency and defensibility of agency analyses of potential indirect and cumulative effects of different development scenarios. Models such as LANDIS II allow users to simulate scenarios of forest disturbance and harvest and to visualize the impacts on forest resources (Scheller et al. 2007). Developing similar models for grassland and shrubland landscapes that can accommodate the variety of disturbance types commonly permitted on public lands could help inform planning in many western landscapes. State-and-transition simulation models are moving us in that direction (Ford et al. 2019) and RMLANDS has been used to simulate the dynamics of non-forested systems (Cushman and McGarigal 2019). Considering multiple affected resources in these models would help public land managers better understand the vulnerability of human communities to different management scenarios. USGS has piloted methods for conducting such assessments (Jenni et al. 2018), which could serve as a starting point. Visualization of modeled scenarios and outcomes could help managers better engage and work with stakeholders, through truly collaborative public meetings, to develop a shared understanding of the potential impacts of alternative management decisions on public lands. Static maps, lengthy written analysis, and encyclopedic appendices which are currently common in public lands planning documents do little to help the average stakeholder understand the complexity of land-use decisions.

Primary considerations in developing landscape models for informing public land management include developing new datasets and indices to quantify how the American public uses lands and how stakeholders may be affected by changes in public land management prescriptions. Public Participatory Geographic

Information System methods coupled with social science survey research have the potential to create geospatial data that reflect current human use and value of public lands (Brown and Weber 2011) and can be easily integrated into landscape models to better understand how behavioral use of public lands would change under different management scenarios. Social vulnerability indices (Flanagan et al. 2011) use socioeconomic, demographic, and public health data to identify sensitive human populations that may be less likely to respond to and recover from changes on the natural landscape resulting from human caused events including energy development, mineral extraction, or grazing; or from natural events such as hurricanes, wildfires, and earthquakes (Cutter and Finch 2008).

Benefits that may be achieved through these three actions include improving the transparency and durability of public lands decisions and minimizing the legal risks that can arise when agencies do not coordinate across boundaries to consider the cumulative effects of proposed actions or make different decisions solely because of political boundaries. The examples above, and numerous others, illustrate the successes that can be achieved when scientists and managers commit to working together to produce and use actionable landscape science and data. We believe that these benefits warrant continued efforts to more strongly integrate landscape science into public lands decision-making.

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