Prioritizing science efforts to inform decision making on public lands

Sarah K Carter[1*], Travis S Haby[2], Jennifer K Meineke[1], Alison C Foster[1], Laine E McCall[3], Leigh D Espy[4], Megan A Gilbert[5], Jeffrey E Herrick[6], and Karen L Prentice[5]

Public land management agencies in the US are committed to using science-informed decision making, but there has been little research on the types and topics of science that managers need most to inform their decisions. We used the National Environmental Policy Act to identify four types of science information needed for making decisions relevant to public lands: (1) data on resources of concern, (2) scientific studies relevant to potential effects of proposed actions, (3) methods for quantifying potential effects of proposed actions, and (4) effective mitigation measures. We then used this framework to analyze 70 Environmental Assessments completed by the Bureau of Land Management in Colorado. Commonly proposed actions were oil and gas development, livestock grazing, land transactions, and recreation. Commonly analyzed resources included terrestrial wildlife, protected birds, vegetation, and soils. Focusing research efforts on the intersection of these resources and actions, and on developing and evaluating the effectiveness of mitigation measures to protect these resources, could strengthen the science foundation for public lands decision making.

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Public lands managed by four federal agencies – the Bureau of Land Management (BLM), US Forest Service, US Fish and Wildlife Service, and National Park Service – comprise more than 26% of land area within the US (Figure 1; CRS 2020). Every year, each of these federal agencies must make hundreds to thousands of formal planning and management decisions that balance diverse resource uses and values. Those decisions are complex and regularly litigated (Ruple and Race 2020).

For public lands to be managed sustainably and for public lands decisions to withstand litigation, those decisions need to be informed by the best available science (Sullivan *et al*. 2006). In recognition of this, the US Government and federal public land management agencies have recently reaffirmed the importance of using the best available science and data to inform their decisions (eg Kitchell *et al*. 2015; Executive Memorandum 2021a). Furthermore, foundational environmental laws in the US, such as the Endangered Species Act (ESA, 16 USC §§1531-1544) and the National Environmental Policy Act (NEPA, 42 USC §§4321 et seq), mandate consideration of science. The ESA requires that species determinations be made on the basis of the "best scientific and commercial data available" (16 USC §1533[b][1][A]). NEPA is particularly noteworthy because of its breadth: it requires that environmental impacts of all proposed "major federal actions significantly affecting the quality of the human environment" (eg renewal of a grazing permit, development of a land-use plan) be assessed (42 USC §4332[C]) and that natural and social sciences be considered in that assessment (42 USC §4332[A]).

However, relatively few studies have focused on identifying the types and topics of science information that resource managers need most (but see Davis *et al*. 2013; Matzek *et al*. 2015), and decisions made by land-use planners and resource managers often rely primarily on information other than published science (eg unpublished reports, expert opinion; Pullin *et al*. 2003; Dilling and Lemos 2011; Archie *et al*. 2014).

Hereafter, we refer to science broadly as "science information", which includes factual inputs, data, models, analyses, technical information, and scientific assessments (OMB 2004). We use science or scientific studies to refer specifically to the rigorous standardized collection of information using the scientific process (Sullivan *et al*. 2006).

There are several potential reasons for the observed lack of reliance on science information in decision making. Among them is the fact that scientists often focus on topics that are not relevant to land managers (Fazey *et al*. 2005; McNie 2007; Cvitanovic *et al*. 2014). Scientists also may not conduct studies at the spatial scales needed to inform public lands decisions (Archie *et al*. 2014; Kemp *et al*. 2015; Carter *et al*. 2020b) and may produce products that are not tailored for use in existing decision processes (Dilling and Lemos 2011). As a result, there is increasing interest in strategies and mechanisms to bridge the gap between science and management on public lands, including providing clear agency guidance and support for science use, strengthening long-term science–management partnerships, fostering coproduction of science with land

[1]US Geological Survey, Fort Collins Science Center, Fort Collins, CO [*](skcarter@usgs.gov); [2]Bureau of Land Management, National Operations Center, Denver, CO; [3]Contractor with the US Geological Survey, Fort Collins Science Center, Fort Collins, CO; [4]Bureau of Land Management, Eastern States Office, Falls Church, VA; [5]Bureau of Land Management, Headquarters, Lakewood, CO; [6]US Department of Agriculture – Agricultural Research Service, Range Management Research Unit, Jornada Experimental Range, Las Cruces, NM

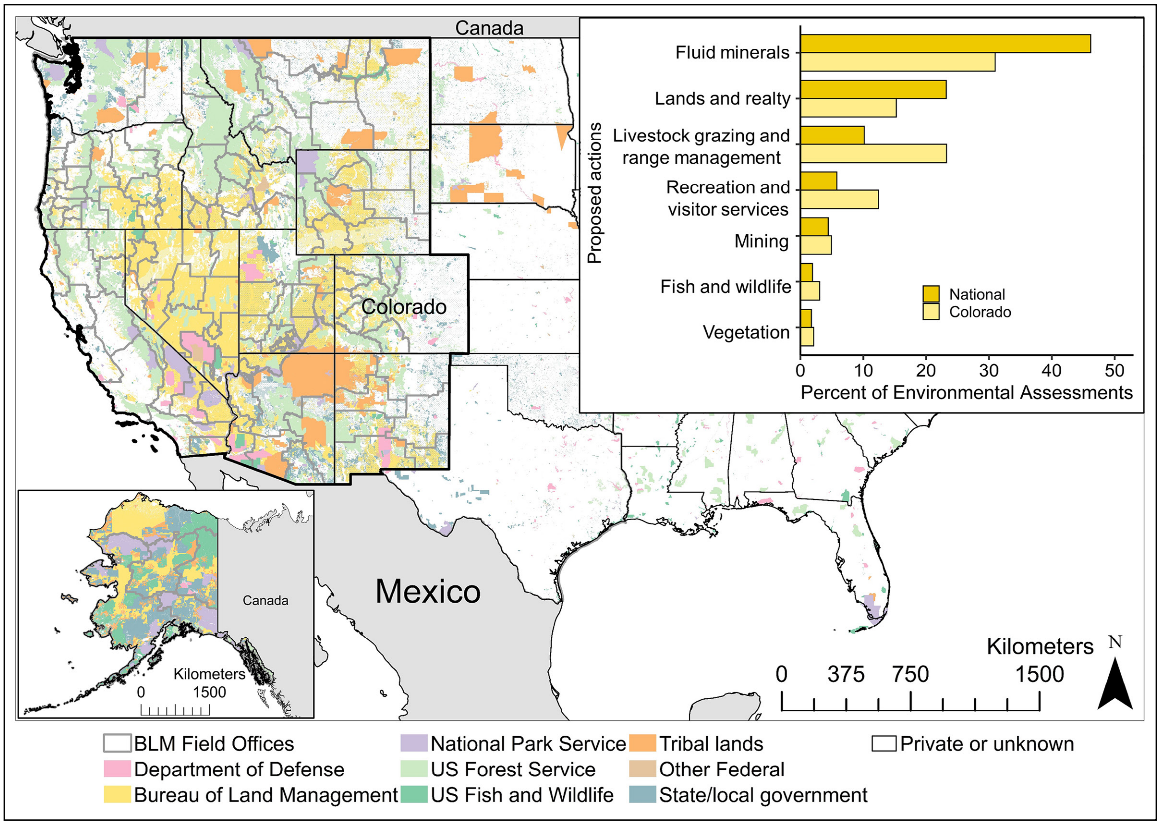

Figure 1. Distribution and jurisdiction of public lands in the continental US, including boundaries for Bureau of Land Management (BLM) Field Offices in western states (within bold black outline) and Alaska (lower-left inset) (BLM 2021). Most BLM management decisions are made at Field Office levels. Upper-right inset: categories of proposed actions analyzed in BLM Environmental Assessments completed in Colorado (n = 426) and nationally (n = 5741) from 2015 to 2019. Categories of proposed actions constituting <2% of the total are not shown.

managers, and developing landscape models to support agency NEPA analyses (Archie *et al.* 2014; Kemp *et al.* 2015; Carter *et al.* 2020b).

BLM and the US Geological Survey (USGS) initiated this current study, with the goal of identifying the types and topics of science information that could strengthen the foundation for science-based decision making on US public lands. We had two objectives: (1) to develop a framework for understanding the core types of science information that directly align with the needs of public land managers, and (2) to use that framework to identify key topics – combinations of actions and resources – for which science information is needed to inform public lands decisions.

Methods

A framework for understanding the types of science information needed

To develop this framework, we (led by our BLM coauthors, who collectively have more than six decades of experience managing public lands and implementing NEPA) first considered the processes that public land managers must follow when making management decisions. On the basis of their experience and knowledge of the diverse activities that BLM conducts, these coauthors determined that the most commonly applied decision processes in BLM are driven by NEPA. Accordingly, we examined NEPA itself and BLM's handbook for implementing NEPA (BLM 2008) to identify the specific information needed to conduct each major step in NEPA analyses (see Results section) and developed a framework to represent both. Because of NEPA's broad applicability, NEPA analyses are often conducted in conjunction with another substantive management action or decision process. Therefore, our framework generally reflects the needs of those processes (eg permitting, land-use planning) as well. Finally, we shared the framework with scientists and managers from multiple federal agencies for feedback and refinement.

Topics for which science information is needed

We then used the framework to analyze public lands decisions. We analyzed BLM decisions because this agency is responsible for managing the largest area of US public lands, representing 10.8% of the country (CRS 2020). We selected Colorado as our primary study area because of its diverse resources and ecological landscapes, and because the frequency distribution of proposed actions in the state is similar to that of the nation as a whole (Figure 1). In addition, BLM Colorado staff were available to work with USGS as part of a coproduction partnership to develop sampling and analysis methods.

We first identified all Environmental Assessments (EAs) that were complete and available on BLM's E-Planning website (https://www.blm.gov/programs/planning-and-nepa/eplanning) for the period 2015–2019. Next, we quantified how frequently different types of proposed actions occurred across all decisions in both Colorado and the nation. We adopted the categories for proposed actions used by the BLM, with one exception: we combined "Livestock grazing" and "Rangeland management" into a single category. While "Livestock grazing" EAs typically assess proposed grazing actions/permits and "Rangeland management" EAs might assess construction of fences or watering facilities, in practice the two labels may be used interchangeably and are often implemented jointly.

We randomly sampled ten EAs from each category of proposed action with at least ten completed EAs, and ten EAs from all other categories combined, for a total of 70 sampled EAs (Figure 1; WebTable 1). For each sampled EA, we recorded the resources analyzed using BLM's list of resource categories, with minor clarifications. We considered a resource to be analyzed when there was a header for that resource and at least one sentence in that section about its analysis.

We then identified (1) how frequently analysis sections for different resources included one or more data citations, and (2) the resources for which we most often found citations of publicly available data establishing the baseline presence or condition of the resource (note that data may also be referenced in the agency's full project record, which we did not analyze). We also recorded (3) how frequently potential direct, indirect, and cumulative effects were quantified for different resources, and (4) the resources for which we most often found clear, comprehensive, and quantitative effects analyses (See WebPanel 1 for detailed methods). We note that NEPA does not require quantification of potential effects – analyses may be qualitative. Rather, we used quantification as an indicator that relevant data, scientific studies, and analysis methods for that resource were available and accessible to managers, facilitating quantification of potential effects.

Finally, we identified whether EAs recommended or required one or more mitigation actions (often referred to as mitigation measures, best management practices, or permit conditions or stipulations) intended to minimize adverse impacts of the proposed action on a resource. We coded mitigation actions based on the resource(s) they were meant to protect or, when that was unclear, what they were meant to prevent (eg contamination from hazardous materials).

Three USGS ecologists coded the EAs after multiple practice and consultation sessions with BLM staff who had expertise and NEPA analysis experience with the actions and resources considered in the EAs to establish clear understanding, repeatability, and coding consistency. When coding questions arose, the ecologists discussed and decided on them together using negotiated agreement (Garrison *et al*. 2006).

Results

A framework for understanding the types of science information needed

The framework we developed consists of four core types of science information that relate directly to steps in NEPA analyses and are thus needed to inform management decisions for public lands: data, scientific studies, analysis methods, and mitigation actions (Figure 2).

A foundational step in NEPA analyses is to describe the affected environment (BLM 2008). The affected environment section describes resource locations, conditions, and trends; past, present, and reasonably foreseeable future resource uses; ecological and physical processes; and human communities. Accordingly, managers need quality data (ie resource inventories, assessments, monitoring data, and predictive models) across large areal extents to use as the basis for this section.

Another core step in NEPA analyses is identifying what "issues" – points of disagreement, debate, or dispute with a proposed action based on an anticipated environmental impact (BLM 2008) – have the potential for "significant" impacts as defined by the Council on Environmental Quality (40 CFR §1501.3[b]). For simplicity, we refer to issues as conflicts between a specific action and resource. Managers need access

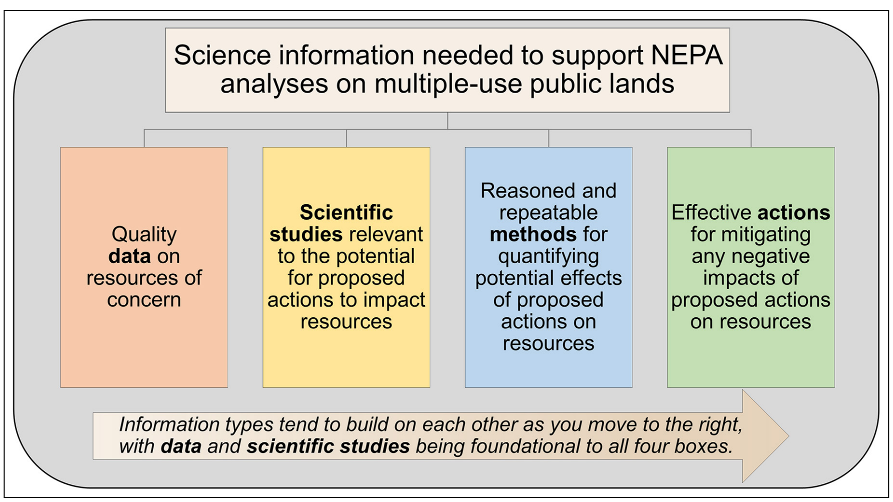

Figure 2. Four categories of science information (colored rectangles) underpin National Environmental Policy Act (NEPA) analyses on federally managed public lands. As one moves from left to right in the framework, the types of science information needed build on each other (for example, both quality resource *data* and relevant *scientific studies* are necessary to develop and apply reasoned and repeatable *methods* to analyze potential effects of proposed actions on resources of concern).

to relevant, up-to-date scientific studies on commonly analyzed issues to help determine the likelihood of specific proposed actions impacting resources of concern.

Once managers determine that a proposed action may impact a resource, NEPA requires assessment of those potential effects. Three types of effects are considered: direct effects are caused by the action and occur at the same time and place; indirect effects are caused by the action but are removed in time or space; and cumulative effects result from the proposed action together with other past, present, and reasonably foreseeable future actions. Managers need reasoned and repeatable methods and models, along with the data and scientific studies required to apply the methods and populate the models, to understand the nature (eg behavioral avoidance, mortality), intensity (eg number of animals), and spatial and temporal extent of likely effects.

A final aspect of public lands decisions is mitigation to avoid, minimize, or compensate for any potential adverse impacts of a proposed action (BLM 2008). To comply with a major purpose of NEPA – reducing the negative environmental consequences of proposed actions (42 USC §4321) – public land managers need mitigation measures that studies have shown to be effective.

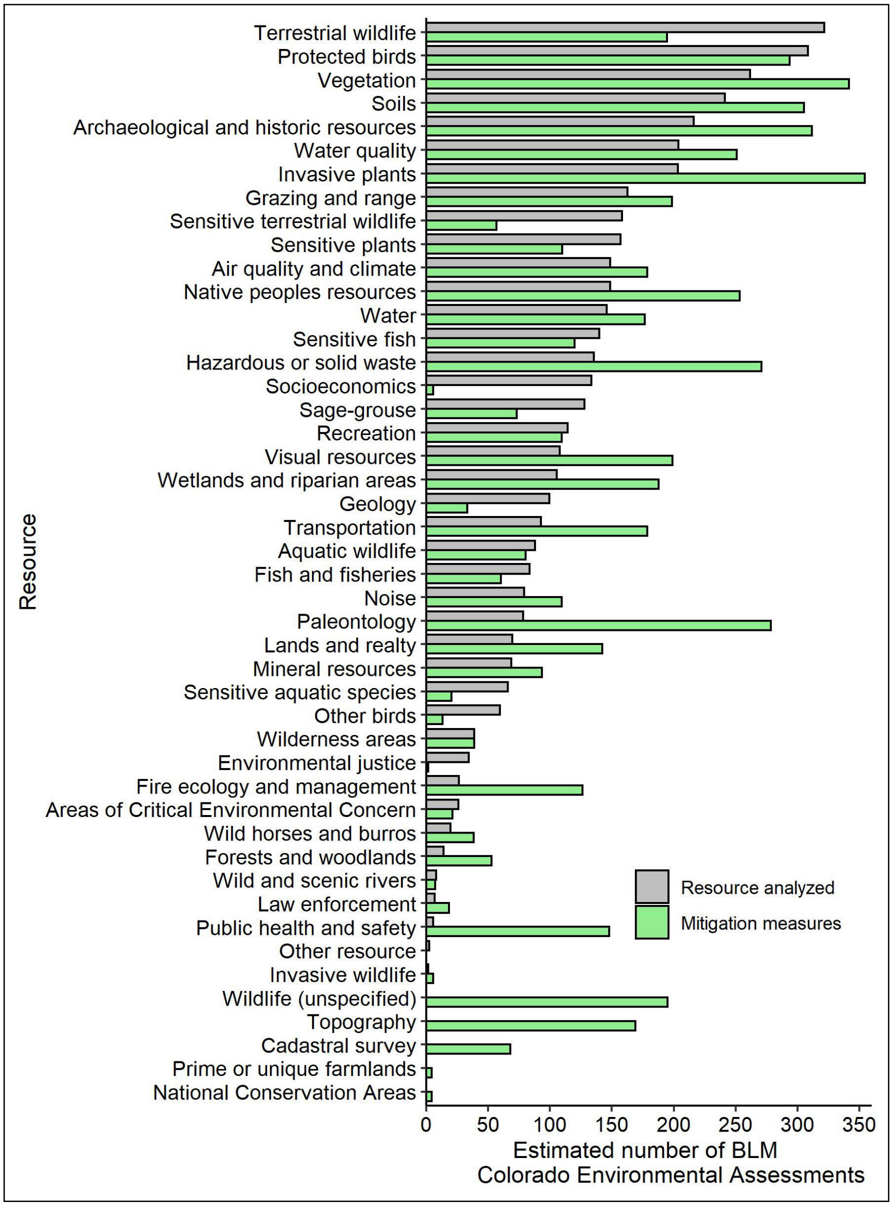

Figure 3. Estimated total number of times individual resources were analyzed (gray bars) and mitigated for (green bars) in Environmental Assessments (EAs) completed by the Bureau of Land Management (BLM) in Colorado from 2015 to 2019, based on our stratified random sample of 70 EAs. Note that mitigation measures (ie actions to mitigate adverse impacts of the proposed action on the resource) are regularly included for resources not formally analyzed in an EA.

Topics for which science information is needed

Data on the presence and condition of resources of concern

Resources most frequently analyzed in the sampled Colorado EAs were terrestrial wildlife (typically big game, excluding sensitive/listed species, 75% of EAs), protected birds (72%), vegetation (61%), soils (57%), archaeological and historic resources (51%), water quality (48%), and invasive plants (48%) (Figure 3). Data were cited in 29% of 721 analysis sections. Publicly available datasets were most commonly cited for soils, socioeconomics, air quality and climate, water, and geology.

Scientific studies relevant to the potential for proposed actions to impact resources

Categories of actions most commonly proposed in BLM Colorado EAs were "Fluid minerals" development (primarily petroleum and natural gas infrastructure: eg construction of pipelines, drilling of new wells, applications for permits to drill; proposed in 31% of EAs), "Livestock grazing and range management" (eg renewal of grazing permits, construction of livestock watering facilities; 23% of EAs), "Lands and realty" (eg land transfers, issuance of rights-of-way permits; 15% of EAs), and "Recreation" (eg construction of new trails, issuance of special event permits; 12% of EAs) (Figure 1). The top "issues" in Colorado included potential impacts to terrestrial wildlife and to protected birds from actions in the "Fluid minerals", "Livestock grazing and range management", "Recreation", and "Fish and wildlife" categories (WebFigure 1). The frequency distribution of categories of actions varied by state, with "Fluid minerals" development being the category of action most frequently proposed across multiple states (WebFigure 2).

Methods for quantifying potential effects of proposed actions

We found that relatively few resource analysis sections quantified direct, indirect, and cumulative effects (29%, 13%, and 10%, respectively). Resources for which we found examples of clear, comprehensive, quantitative analyses for all three types of potential effects – direct, indirect, and cumulative – were air quality and climate, terrestrial wildlife, and protected birds.

Effective mitigation actions

Mitigation measures were most often included to address invasive plants and to protect vegetation, archaeological and historic resources, soils, and protected birds (Figure 3). Mitigation measures were least often included (<5% of times analyzed) for environmental justice and socioeconomics (Figure 3).

Discussion

In the western US, public lands provide resources, uses, and values ranging from archaeological sites to energy development. Because management decisions often involve deciding which activities to allow, and accepting the associated trade-offs, decision making on public lands is complex. Laws and policies require the use of science in public lands decisions (Sullivan *et al*. 2006), and managers believe strongly in the value of science for informing those decisions (Kemp *et al*. 2015; White *et al*. 2019). However, managers' time is limited, and they often do not have easy access to the science products they most need (Archie *et al*. 2014; White *et al*. 2019). Scientists can develop and share actionable science (Beier *et al*. 2017) to help inform decisions. However, a precursor to doing so effectively is for scientists to better understand the types and topics of science information needed by federal land managers.

A framework for understanding the types of science information needed

We developed and applied a framework to identify the topics for which quality resource data, scientific studies about impacts, methods for analyzing potential impacts of proposed actions, and development and testing of effective mitigation measures may be most needed. To better understand how and to what extent their existing science projects and products can help inform key steps in public lands decision processes, scientists can use this framework to evaluate their own research programs. For example, scientists often focus almost exclusively on the data and scientific studies categories, and may be unaware of the considerable need for methods and models to quantify different types of potential impacts of proposed actions on resources, and for mitigation actions that have been field-tested for effectiveness. Science providers can also use the framework to organize science information for sharing with public land managers.

Issues that are particularly important for the scientific community to address are those for which research results may conflict or the science may be dated (BLM 2008), along with issues affected by changing populations, ecological and physical processes (eg wildfire and climate), and land uses. Managers also highly value science that can inform decisions about topics for which there is low public consensus (White *et al*. 2019).

Data on the presence and condition of resources of concern

Quality resource data provide the foundation for environmental analyses. Using and citing publicly available data is not required by NEPA but helps build trust and understanding with stakeholders in land-use planning processes (Sayer *et al*. 2013). In Colorado, terrestrial wildlife (eg mule deer [*Odocoileus hemionus*]) was the most commonly analyzed resource in BLM EAs, highlighting the importance of having current, publicly available spatial data on the presence and condition of big game populations and habitats (eg CPW 2020; Kauffman *et al*. 2020). For many other resources, publicly available data were cited infrequently (eg in one of 33 invasive plant sections). Conducting surveys, as well as developing and sharing decision-quality habitat models (Sofaer *et al*. 2019), for invasive plants and other species of management concern could broaden and strengthen the basis for determining which resources are likely present and therefore need to be considered in decisions.

Scientific studies relevant to the potential for proposed actions to impact resources

Substantial development of traditional (oil, natural gas) and renewable (wind, solar, geothermal) energy sources occurs on US public lands and can affect many resources (Allred *et al*. 2015). We found that terrestrial wildlife, protected birds, and rare fish are often a concern for proposed energy development, highlighting the need for continued efforts to understand the impacts of energy infrastructure on these species. Greater sage-grouse (*Centrocercus urophasianus*) embody this conflict. The wealth of research undertaken to inform a listing decision for the species (US DOI 2015) led BLM to request development of an online, searchable annotated bibliography (https://apps.usgs.gov/science-for-resource-managers) and science synthesis (Hanser *et al*. 2018). Science syntheses in general are highly valued by managers (Seavy and Howell 2010), as are digital products that help managers easily find and access relevant science and aid in the comprehension of its core implications (Davis *et al*. 2013). Targeted development of similar products for other topics may help land managers locate and use relevant science in their decisions.

Methods for quantifying potential effects of proposed actions

We used quantification of potential effects of proposed actions (which is not required by NEPA) as an indicator that managers had clear, science-based methods to follow and the building blocks needed to apply those methods and models: high-quality, easily accessible data, and scientific studies about how specific types of actions affect different resources. We found relatively few quantitative effects analyses, suggesting a need for scientists to develop such methods and models, to help ensure that both are readily available to and used by managers, and to document them through peer-reviewed, open-access publications to increase credibility, defensibility, and transparency (Matzek *et al.* 2015; Sofaer *et al.* 2019).

We found the largest number of clear, comprehensive, and quantitative effects analyses for air quality and climate and for terrestrial wildlife. In 2013, BLM Colorado began a concerted effort to develop a standardized process for analyzing air quality, with the resulting reports (eg Vijayaraghavan *et al.* 2017) now frequently cited in BLM air-quality analyses. Recent studies have also addressed the impacts of energy development on mule deer, including how oil and gas well density affect deer presence, behavior, and demography (eg Hall *et al.* 2020; Northrup *et al.* 2021). Similar initiatives focused on other commonly analyzed resources could strengthen analyses of environmental effects on public lands.

Cumulative effects of proposed actions have landscape-level implications for the future condition of public lands (eg Carter *et al.* 2020b) and are frequently litigated (Adelman and Glicksman 2018). The few resources for which we found clear, comprehensive, quantitative analyses of potential cumulative effects suggest a need for clear guidance and step-by-step methods to help staff analyze cumulative effects for all resources. Efforts to monitor development at landscape levels (eg Carr and Leinwand 2020) and research the levels of development that may significantly impact species of concern (eg Carter *et al.* 2020a) could inform such analyses.

Effective mitigation actions

Mitigation actions required by public land managers need to be effective and scientifically defensible. Invasive plant mitigation measures, for instance, typically require specific practices intended to limit the introduction and spread of invasive species during ground-disturbing activities. However, agency capacity to monitor implementation and evaluate the effectiveness of such measures is limited. As such, the scientific community has an important opportunity to partner with public land managers to evaluate to what extent measures currently relied on to protect different resources are being employed and are proving to be effective, and to refine or develop new measures when needed. Advancing environmental justice is a current national priority (Executive Memorandum 2021b) but was a topic infrequently analyzed and mitigated in our study, highlighting the need for an improved understanding of the potential adverse impacts of proposed actions on communities of color and low-income communities and for identifying measures that may help mitigate those effects.

Our study has limitations, including that we focused on decisions made on lands managed by a single agency within a single state. However, actions proposed for BLM lands in Colorado are diverse and encompass the range of actions likely to occur on other public lands (see WebFigure 2). Resources in Colorado are similarly diverse. We selected our study timeframe to encompass multiple political administrations, which can influence public lands activities and analyses (eg Executive Memorandum 2021b). Our framework was developed with a single law (NEPA) as its foundation, but also reflects the information needs of many other public lands processes (eg Section 7 Consultations under the ESA, 16 USC §1536). Furthermore, NEPA applies broadly to federal lands and actions (with many US states and other nations having similar laws) and has remained largely unaltered for more than 50 years (recent changes to the implementing regulations for NEPA do not affect our framework or findings).

Conclusion

We encourage scientists to use our framework and findings in three ways. The first is broad: to see their research in a new light – through a lens of public lands decision making. Second, at an individual level, we hope scientists in and beyond Colorado can use our framework, together with the issues we found to be most commonly analyzed (WebFigure 1) and the different types and numbers of actions proposed on BLM lands in other states (WebFigure 2), to consider how their own research projects and findings may be relevant to public lands decision making in their area. Notably, research does not have to involve the exact species or location to be helpful; managers can apply science information they deem relevant to the issue being analyzed and state any associated assumptions or limitations (BLM 2008). Finally, we hope our analysis can also help scientists consider new research directions and efforts to fill key knowledge gaps that could strengthen the science foundation for public lands decision making in their area.

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Data Availability Statement

Data used here were retrieved from the Bureau of Land Management E-Planning database, available at www.blm.gov/programs/planning-and-nepa/eplanning. A complete list of the documents from this database that were analyzed is provided in WebTable 1.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.2672/suppinfo