

Quantifying Aspects of Rangeland Health at Watershed Scales in Colorado Using Remotely Sensed Data Products

Authors: Kleist, Nathan J., Domschke, Christopher T., Litschert, S.E., Seim, J. Hunter, and Carter, Sarah K.

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Quantifying aspects of rangeland health at watershed scales in Colorado using remotely sensed data products

By Nathan J. Kleist, Christopher T. Domschke, S.E. Litschert, J. Hunter Seim, and Sarah K. Carter

On the Ground

- During grazing permit renewals, the Bureau of Land Management assesses land health using indicators typically measured using field-based data collected from individual sites within grazing allotments. However, agency guidance suggests assessments be completed at larger spatial scales.
- We explored how the current generation of remotely sensed data products could be used to quantify aspects of land health at watershed scales in Colorado to provide broad spatial and temporal context for the land health assessment process.
- We found multiple indicators could be quantified using these data products and were relevant to land health standards.
- Within focal watersheds, bare ground cover decreased over the past 30 years, while annual herbaceous cover has increased over the last 10 years. Vegetation productivity was variable over time, but interannual fluctuations were consistent across watersheds.
- Remotely sensed data products can help resource managers understand how current conditions relate to broad spatial and temporal trends in the region and could provide another line of evidence for the land health assessment process. They may also identify target areas where management strategies, such as eradication of invasive annual grasses, should be focused, and could help resource managers communicate complex issues to the public.

Keywords: Bureau of Land Management, Remote sensing, Rangeland health, Landscape approach, Landscape metrics, Monitoring.

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Introduction

In the United States, about 27% of the country's total land area is public land managed by the federal government. Of the agencies managing federal public lands, the Bureau of Land Management (BLM) manages the largest area, approximately 989,017 km² (244,391,312 acres), or roughly 10.8% of the country.¹ The BLM manages these lands for multiple resources, uses, and values (Federal Land Policy and Management Act of 1976 Title I, 43 USC § 1701), and about 627,263 km² (155,000,000 acres), or 63%, of BLM-managed lands are permitted for livestock grazing.² Lands permitted for livestock grazing must also meet the four fundamentals of rangeland health: watershed function, ecological processes, water quality, and habitats for special status species (Fundamentals of Rangeland Health, 43 CFR § 4180.1).

The BLM land health assessment (LHA) process is a required component of the permitting process for livestock grazing on BLM lands. Livestock grazing permits can be controversial and are subject to legal challenges—highlighting the importance of a rigorous LHA process.^{3–5} LHAs are guided by state- or regional-level land health standards (developed under the federal Fundamentals of Rangeland Health) and are conducted in three main phases: assessment, evaluation, and determination (Fig. S1).⁶ During the assessment phase, BLM estimates the status of ecosystem structures, functions, and processes within a specified geographic area using qualitative indicators measured with field-based data. Upland and riparian standards are often assessed, respectively, using the protocols defined in *Interpreting Indicators of Rangeland Health*⁷ and a Proper Functioning Condition assessment.⁸ Additionally, both upland and riparian assessments are frequently informed by data collected as part of the BLM's Assessment, Inventory and Monitoring program.⁹ In the evaluation phase, BLM staff interpret findings from the assessment to evaluate the degree of achievement of land health standards.⁶ A key component of the evaluation phase is consideration of relevant reference conditions for each standard,

Table 1

Colorado land health standards and indicators we identified as being relevant and feasible to assess at watershed scales and the remotely sensed data products we used to quantify each indicator

Indicator	Relevant metric(s)	Remotely sensed data products
Upland soils standard: Upland soils exhibit infiltration and permeability rates appropriate to soil type, climate, landform, and geologic processes. Adequate soil infiltration and permeability allows for the accumulation of soil moisture necessary for optimal plant growth and vigor and minimizes surface runoff.		
Canopy and ground cover are appropriate	Bare ground cover	RCMAP Fractional Component Time-Series Across the Western U.S. 1985-2020
There are vigorous, desirable plants	Upland vegetation productivity	eMODIS: Time-integrated NDVI
Riparian standard: Riparian systems are associated with both running and standing water to function properly and have the ability to recover from major disturbances such as fire, severe grazing, or 100-year floods. Riparian vegetation captures sediment, and provides forage, habitat, and biodiversity. Water quality is improved or maintained. Stable soils store and release water slowly.		
Vigorous, desirable plants are present	Riparian vegetation productivity	eMODIS: Time-integrated NDVI
Native and other desirable species standard: Healthy, productive plant and animal communities of native and other desirable species are maintained at viable population levels commensurate with the species and habitat's potential. Plants and animals at both the community and population level are productive, resilient, diverse, vigorous, and able to reproduce and sustain natural fluctuations and ecological processes.		
Noxious weeds and undesirable species are minimal in the overall plant community	Annual herbaceous cover	RCMAP Fractional Component Time-Series Across the Western U.S. 1985-2020
Native plant and animal communities are spatially distributed across the landscape with a density, composition, and frequency of species suitable to ensure reproductive capability and sustainability	Amount and patch sizes of priority vegetation communities	LANDFIRE EVT (pinyon-juniper [EVT: 7016, 7102] and riparian-wetland [EVT: 7942, 7943, 7944, 9011, 9017, 9019, 9021, 9022, 9327, 9329, 9519, 9827, 9829])
Landscapes exhibit connectivity of habitat or presence of corridors to prevent habitat fragmentation	Distance between patches of priority vegetation communities	LANDFIRE EVT (pinyon-juniper and riparian-wetland)
Photosynthetic activity is evident throughout the growing season	Vegetation productivity	eMODIS: Time-integrated NDVI
Diversity and density of plant and animal species are in balance with habitat/landscape potential and exhibit resilience to human activities.	Vegetation type diversity	LANDFIRE EVT

eMODIS indicates Moderate Resolution Imaging Spectroradiometer satellite imagery; LANDFIRE EVT, LANDFIRE Existing Vegetation Type Ecological System; NDVI, normalized difference vegetation index; RCMAP, Rangeland Condition Monitoring Assessment and Projection.

which provide context for understanding the rate, direction, and magnitude of change for different indicators at the site. A number of reference conditions may be relevant to land health on BLM-managed rangelands, including pre-European settlement conditions, desired conditions, or conditions that may be attainable given the current landscape.¹⁰⁻¹³ The evaluation phase may also evaluate factors that may have prevented achievement of a standard. In the determination phase, if one or more standards are not met, a finding is made that livestock grazing on public lands is or is not a significant factor in failing to achieve the standards.⁶ Factors other than grazing may be identified as a causal factor for a standard not being met.

We focused our study of the land health assessment process in Colorado where there are 31,565 km² (7,800,000 acres) of rangelands, about 11% of the total area of the state, managed for grazing by the BLM under the Colorado Standards for Public Land Health.¹⁴ Bureau of Land Management guidance suggests LHAs be performed at the scale of fifth-level watersheds (hereafter, watersheds), which have a mean size of 545.1 km² (134,695 acres) in Colorado. However, because BLM makes decisions on grazing permits within allotments, current LHA processes are typically focused on grazing allotments, which average 18.15 km² (4,486 acres) in Colorado.⁶

Data collected within individual allotments provide important information about the effects of grazing but may not be adequate to assess all standards. For example, the Colorado native and other desirable species standard (see Table 1) includes indicators of habitat connectivity and the spatial distribution of species across landscapes. Resource managers can use remotely sensed data products, which were designed to provide information at broad spatial and temporal scales, to fully assess such indicators and provide important context for allotment-scale LHA processes.

Project goals and objectives

Here, we take advantage of recent advances in rangeland monitoring¹⁵ to provide BLM with a set of landscape-scale results that complement traditional field-based LHA methods by providing valuable spatial and temporal context. Our overarching goal was to work with BLM staff at state and field office levels to explore how remotely sensed data products could be analyzed within and across watersheds and over time to complement current land health processes. We had two objectives: 1) identify Colorado land health standards and indicators amenable to quantification at watershed scales using remotely sensed data products, and 2) quantify metrics providing spatial and temporal context for land health

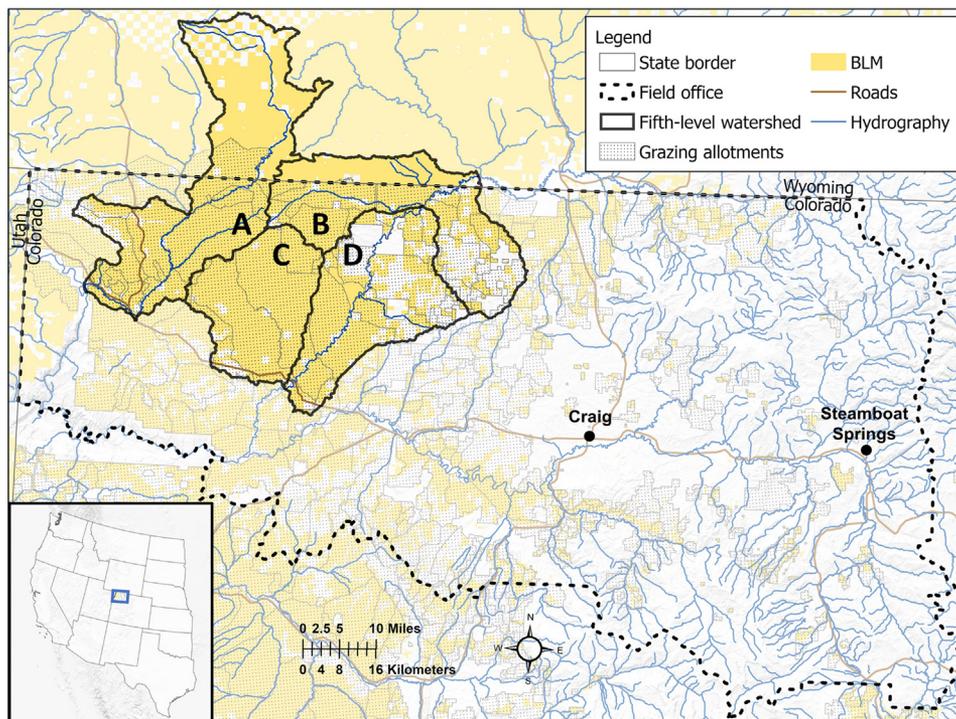


Figure 1. The Little Snake Field Office in northwest Colorado with Bureau of Land Management (BLM) managed lands, cattle grazing allotments, and a contiguous group of watersheds (A, Shell Creek; B, Powder Wash; C, Sand Wash; D, Greasewood Gulch). The blue rectangle on the inset of the western United States shows the map extent.

assessments conducted at the scale of individual livestock grazing allotments.¹⁶

Methods

Study area

We worked with BLM to identify watersheds for this study containing large tracts of contiguous BLM-administered lands permitted for grazing. We selected four watersheds within the Little Snake Field Office—Shell Creek, Powder Wash, Sand Wash, and Greasewood Gulch watersheds—located in northwestern Colorado (Fig. 1). The field office includes 17,000 km² (4.2 million acres) of federal, state, county, and private lands, of which approximately 5,261 km² (1.3 million acres) are administered by the BLM.¹⁷

Identifying land health standards and indicators amenable to quantification at watershed scales using remotely sensed data products

To meet our first objective, we undertook two tasks simultaneously. We worked with BLM to review standards and indicators for attributes that could be quantified at watershed scales, and we identified remotely sensed data products that provided relevant information for each. We required remotely sensed data products be publicly available, peer reviewed as

of January 2021, spatially explicit, and had an accuracy assessment to ensure data were defensible and suitable for use at broader spatial scales, such as watersheds and BLM field offices. After our review of the standards and indicators and remotely sensed data products, we held a series of meetings with BLM field, state, and national office staff to gather further input on the applicability of remotely sensed data to the land health assessment process. We focused this study on vegetation community and soil indicators, and thus did not consider indicators under the special status species or water quality standards. We suggest the datasets we selected for use in this case study be considered as examples of those available; we did not attempt to perform an exhaustive review of all remotely sensed data products.

Colorado upland soil standard—The upland soil standard is focused on appropriate soil function resulting in optimal plant growth and vigor (see Table 1). The ground cover indicator from this standard can be assessed using the bare ground cover at a site,⁷ which is typically measured through ocular estimates, point-intercept samples, and rangeland trend time series photographs providing data on ground cover at representative sample sites within grazing allotments.¹⁸ We selected the Rangeland Condition Monitoring Assessment and Projection (RCMAP) Fractional Component Time-Series Across the Western U.S. 1985–2020 Bare Ground data (hereafter, bare ground component) to quantify the percent bare ground for a watershed (Table 1).^{19,20} We also included

Daymet annual total precipitation data to provide further context for bare ground trends in our study area.²¹

Another indicator within the upland soil standard describes plant vigor, which can be assessed at landscape scales using indices derived from remotely sensed data like the normalized difference vegetation index (NDVI).²² We selected eMODIS Phenological Metrics Time-Integrated NDVI (TIN) from 2001 to 2020, as a measure of vegetation productivity for the entire duration of the growing season.^{23,24} The eMODIS TIN is a phenological metric derived from MODIS (Moderate Resolution Imaging Spectroradiometer) satellite imagery calculated by identifying the start and end dates for each year's growing season and integrating NDVI values for the duration of that time period. The TIN represents the canopy photosynthetic activity for the growing season. There are other productivity data available at finer temporal and spatial scales.²⁵ We selected eMODIS TIN because it incorporates annual synthesis of MODIS satellite data across growing seasons into a peer-reviewed data product.

We defined the boundaries of the uplands using a Colorado River Basin valley bottoms spatial layer from the CO-RIP dataset.²⁶ A key point is that the CO-RIP polygon data we chose represents the maximum extent of riparian corridors (hereafter, valley bottoms), not areas identified as having riparian vegetation. Valley bottoms are useful for exploring temporal fluctuations in riparian vegetation,²⁷ and we used the inverse of the valley bottoms to delineate uplands. We then quantified the mean annual TIN within the uplands of each watershed.

Colorado riparian standard—This standard is focused on overall riparian ecosystem function. The vigorous, desirable plants indicator under this standard can be informed by a measure of riparian vegetation productivity. For this metric, we quantified the TIN from 2001 to 2020 within the valley bottoms from the CO-RIP dataset.²⁶

Colorado native and other desirable species standard—The native and other desirable species standard describes plant and animal populations and communities that are “productive, resilient, diverse, vigorous” and “able to sustain natural fluctuations.” We restricted our assessment to vegetation for this standard. The noxious weeds indicator within this standard states these plants should be minimal. After conversations with BLM, we concentrated our approach for this indicator on exotic annual grasses. We used RCMAP Fractional Component Time-Series Across the Western U.S. 1985–2020 Annual Herbaceous data (hereafter, annual herbaceous component) to provide broad-scale spatial data for this indicator from 1985 to 2020. The RCMAP annual herbaceous component layers only include annual grasses and forbs. Although native annual grasses and forbs do occur in the study area, the layers are primarily representative of invasive species.²⁸ We also included wildfire perimeters from the Monitoring Trends in Burn Severity dataset²⁹ and quantified wildfires as percent

of watershed burned to provide some relevant context for annual grass spread.

The native and other desirable species standard also describes indicators of landscape pattern including the spatial distribution and density of native plants and habitat connectivity. To understand the types of native vegetation communities BLM would typically assess for these indicators, we sought additional input from staff in the Little Snake Field Office and the Colorado State Office, and reviewed the most recent Resource Management Plan for the Little Snake Field Office.¹⁷ Several vegetation communities were indicated as priorities for management; we selected pinyon-juniper and riparian-wetland for our assessment.

We used LANDFIRE Existing Vegetation Type (EVT) Ecological System codes to represent priority vegetation communities. LANDFIRE EVTs represent groups of plant community types that tend to co-occur within similar landscapes, and BLM feedback suggested EVTs had an appropriate level of thematic detail to specify the vegetation types comprising these communities and adequately represented on-the-ground vegetation (Table 1).^{30,31} For pinyon-juniper, we included all LANDFIRE EVTs containing both ‘pinyon’ and ‘juniper’ in the EVT name and occurred within the study area. Although we refer to these habitat types as pinyon-juniper, within the Little Snake Field Office, these are primarily juniper (*Juniperus spp.*). For riparian-wetland, we included all vegetation types containing the words “riparian,” “wetland,” or “marsh” in the EVT group name.

We calculated total area, patch sizes, and distances between patches of vegetation communities following methods previously published by Carter et al.³² The area and patch size distribution of priority vegetation communities provided data relevant to the spatial distribution of the native plants indicator, while data on distances between patches of the same vegetation type provided relevant information for the habitat connectivity indicator.

The native and desirable species standard also included an indicator for growing season photosynthetic activity. We used the same data here, eMODIS TIN, that we used for the plant vigor indicators from the upland soils and riparian systems standards. However, here, we calculated mean TIN across full watersheds rather than restricting assessment to uplands or valley bottoms.

For the plant diversity indicator, we calculated the number of natural LANDFIRE EVTs within 500 m (0.31 miles) of a focal cell. Because this indicator falls under the Colorado native and other desirable species standard, we excluded developed, agricultural, or other disturbed EVTs to quantify a metric of native vegetation community diversity. Our choice of a 1 km² (247.11 acres) moving window was based on previously published methods³² developed together with BLM. The description of the plant diversity indicator suggested a species-level measure of diversity, but we could find no remotely sensed data with the thematic detail needed to analyze species diversity at a watershed scale, although there is potential in this area of research.³³

Quantify metrics providing spatial and temporal context for land health assessments

We performed all analyses in R version 4.1.2,³⁴ with the exception of the moving-window analysis for the calculation of natural LANDFIRE EVT diversity, which was completed in ArcGIS Pro 2.9.³⁵

We used functions from the R packages “sf”³⁶ and “terra”³⁷ to crop and mask time-series raster data to watersheds. We also cropped and masked eMODIS TIN rasters to the valley bottom and upland areas of each watershed, as defined by the CO-RIP dataset. We removed any raster cells outside the valid range (0-100) of each dataset. We converted raster data to data frames and used functions in the R package “dplyr”³⁸ to clean the data and calculate mean annual values for each dataset. We also present maps of the slope and P value for pixel change trends published by RCMAP (Fig. S2). When quantifying the RCMAP annual herbaceous component, we adapted five invasion categories (Invasion free, 0%; Trace, 1-10%; Mild, 11-25%; Moderate, 26-50%; and Dominated, >50%) linked to suggested management strategies.^{39,40}

We used LANDFIRE EVTs to define pinyon-juniper and riparian-wetland vegetation communities and quantified patch metrics within four areas of interest based on scale and jurisdiction: 1) all lands in the field office, 2) BLM-managed lands in the field office, 3) all lands in watersheds, and 4) BLM-managed lands in watersheds. First, we used the function `st_intersect` in the “sf”³⁶ package to create BLM land ownership polygons for the field office and watersheds. Before calculating patches, we cropped the LANDFIRE raster to a 15 km (9.3 mile) buffer around the field office polygon to ensure no patches were artificially truncated by watershed, field office, or jurisdiction boundaries. We removed raster cells that were not pinyon-juniper or riparian-wetland EVTs by classifying them as null values.

For pinyon-juniper communities, which often occur in large swaths across the landscape, we required pixel adjacency in at least one of eight directions to be considered part of the same patch. We used the function `get_patches` from the R package “landscapemetrics”⁴¹ to delineate contiguous patches of pinyon-juniper. We converted the pinyon-juniper patch raster data to polygons using the function `as.polygons` from the “terra”³⁷ R package, calculated the size of each patch, and, following BLM input, removed patches < 4,500 m² (1.11 acres) to focus the assessment on larger, more contiguous patches more likely to be accurately represented by the LANDFIRE dataset.

Riparian-wetland vegetation generally occurs in smaller, more linear patches than upland types, like pinyon-juniper. We used a “cluster” method where all pixels within 90 m of the focal pixel were assigned to the same patch. This method was based on a previously published study on BLM lands in which the author’s visually examined imagery and associated LANDFIRE riparian-wetland pixels along small streams are typical of BLM administered lands.³² We converted the riparian-wetland community EVT raster to polygons, and used the R package “sf”³⁶ to draw 45 m (148 feet)

buffers around riparian-wetland vegetation. We combined overlapping and adjacent cell buffers such that each resulting feature identified the location of a “cluster” patch of riparian-wetland vegetation. We calculated patch sizes and removed patches <1,800 m² (0.44 acres).

We calculated nearest neighbor distances for pinyon-juniper and riparian-wetland patches with the function `st_nn` from the R package “nngeo.”⁴² We assigned all patches to size and distance classes and quantified the total area of each of the classes within each of the areas of interest. We calculated the percent of each vegetation community assigned to each size and distance class. Note the total area of each patch contained by the area of interest and the true size of the patch, unconstrained by jurisdictional boundaries, are different values. Thus, a very large patch may only take up a small area within the boundary of a given area of interest.

We calculated vegetation type diversity by reclassifying the LANDFIRE EVT raster to remove developed, agricultural, and other disturbed EVTs. We used the Spatial Analyst Focal Statistics tool in ArcGIS Pro to count the number of unique, naturally occurring EVTs within 500 m (1,640 feet) of a focal pixel using a moving window.³² We loaded the output raster into R and used “terra” functions to crop and mask it to the watersheds. Finally, we assigned values to five richness classes to demonstrate one approach to visualizing these results. All figures were constructed using the R package “ggplot2,”⁴³ and all maps were created in ArcGIS Pro.³⁵

Results

Identify land health standards and indicators amenable to quantification at watershed scales using remotely sensed data products

We finalized a set of eight indicators from three Colorado standards and quantified them with remotely sensed data products at watershed scales (Table 1).

Quantify metrics providing spatial and temporal context for land health assessments

Colorado upland soils standard—The annual mean percent bare ground cover from 1985 to 2020 ranged from 67% to 71% with a mean of 68% in Shell Creek, 49% to 54% with a mean of 50% in Powder Wash, 49% to 58% with a mean of 52% in Greasewood Gulch, and 63% to 71% with a mean of 65% in Sand Wash (Figs. 2 and S2). The years 1989 to 1992 were the four highest estimates of percent bare ground for all watersheds. Of the most recent 10 years of data, the mean percent bare ground cover was below the range established by the earliest 10 years of available data in 2011 in Powder Wash and 2011 and 2017 in Greasewood Gulch.

In upland areas, the mean growing season TIN from 2001 to 2020 ranged from 5 to 20 with a mean of 11 in Shell Creek, 7 to 31 with a mean of 17 in Powder Wash, 6 to 28 with a

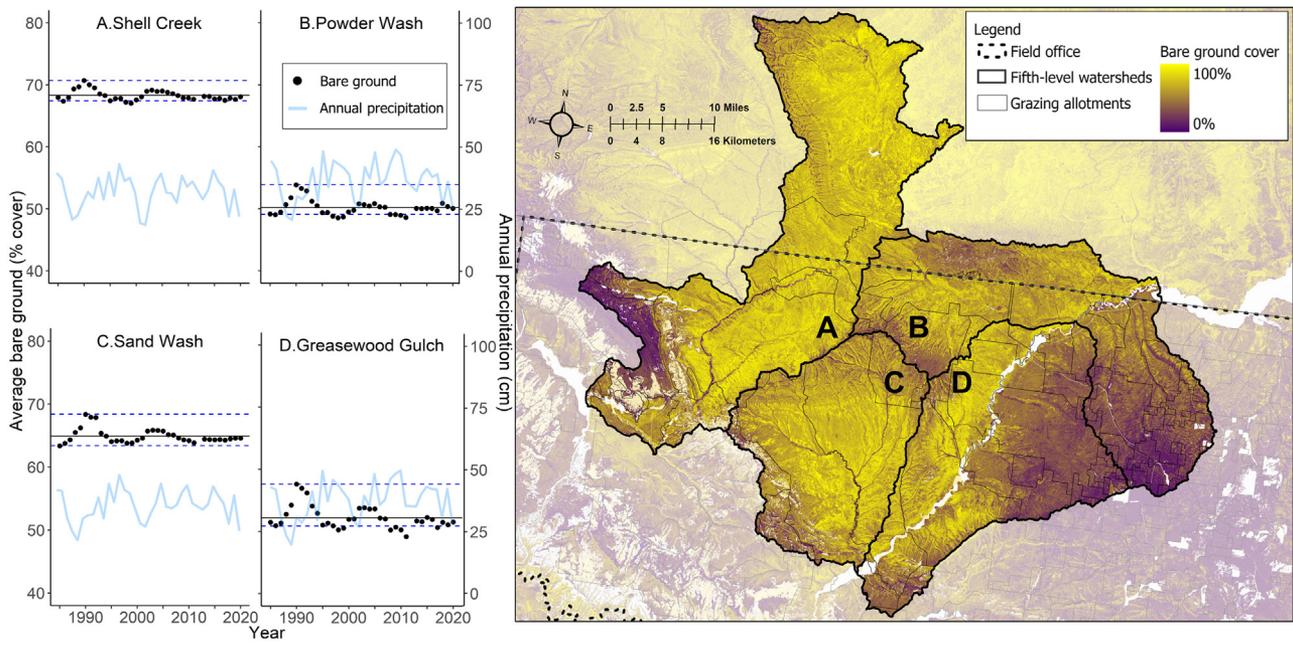


Figure 2. Trends in mean bare ground cover from 1985 to 2020 (left) and a map of 2020 bare ground cover (right) in a group of fifth-level watersheds in northwestern Colorado, USA. Black dots are annual means, and the horizontal gray dashed lines show the range established by the first ten years of data. The light blue line is the mean of the annual total precipitation in each pixel for each watershed.

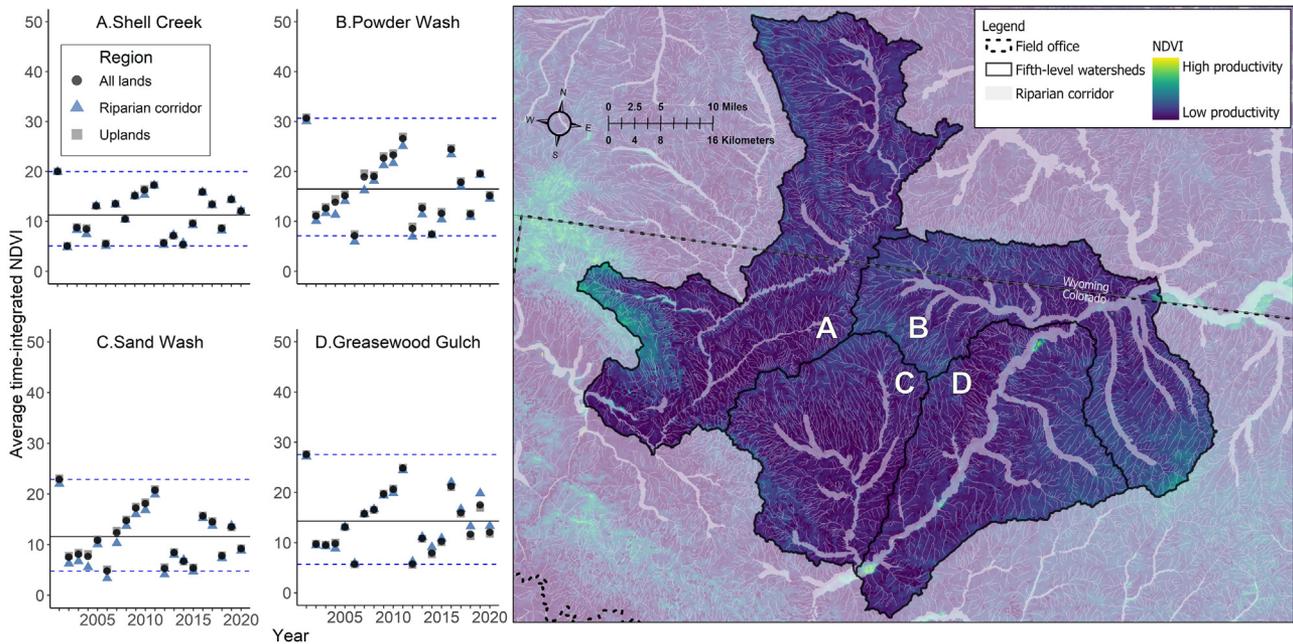


Figure 3. Annual growing season vegetation productivity from 2001–2020 (left), and a map of 2020 time-integrated (TIN) normalized difference vegetation index (NDVI) overlaid within the valley bottoms of a group of 5th-level watersheds in northwestern Colorado (right). In the figure on the left, black circles are annual means across all lands, light blue triangles are annual means in the riparian corridor (i.e., valley bottoms), and gray squares are annual means in the uplands (inverse of riparian corridor). The horizontal blue dashed lines show the range established by the first 10 years of data, and the solid black lines show the mean of all years, both shown here using TIN values from all lands.

mean of 14 in Greasewood Gulch, and 5 to 23 with a mean of 12 in Sand Wash (Fig. 3).

Colorado riparian standard—The mean TIN for the 2001 to 2020 growing seasons ranged from 5 to 20 with a mean of 11 in Shell Creek, 6 to 30 with a mean of 15 in Powder Wash, 6 to 27 with a mean of 15 in Greasewood Gulch, and 3 to 22 with a mean of 11 in Sand Wash (Fig. 3).

Colorado native and other desirable species standard—Results for the noxious weeds indicator show from 1985 to 2020 the invasion categories with the highest percent cover in each watershed were “Invasion free” in Shell Creek and Powder Wash and “Trace” in Greasewood Gulch and Sand Wash (Figs. 4 and S2). Of the most recent 10 years, the mean percent of the watershed in the “Mild” invasion category from 2013 to 2020 in Powder Wash and Greasewood Gulch was above the

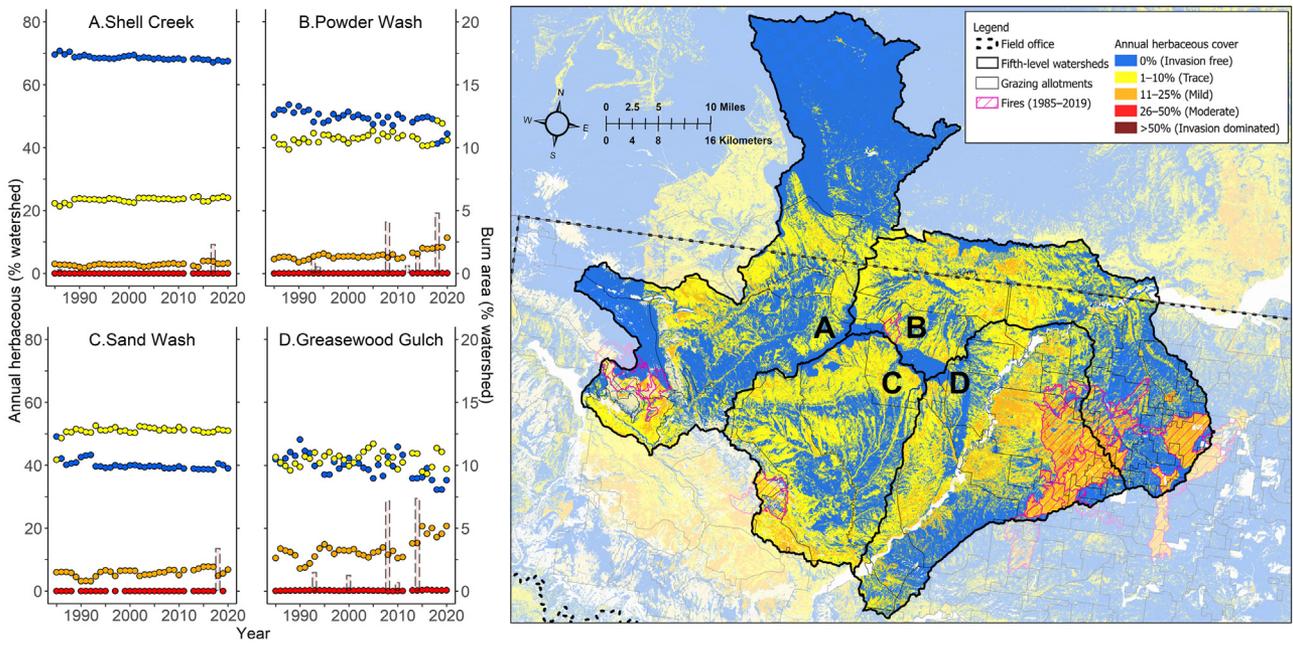


Figure 4. The right panel shows a 2020 map of annual herbaceous vegetation across a group of fifth-level watersheds in northwestern Colorado. The invasion categories colors for each panel are defined in the map legend. The colored dots on the left panel show the annual percent of each watershed in four invasion categories from 1985 to 2020, and the light pink bars show the percent of each watershed burned in wildfires.

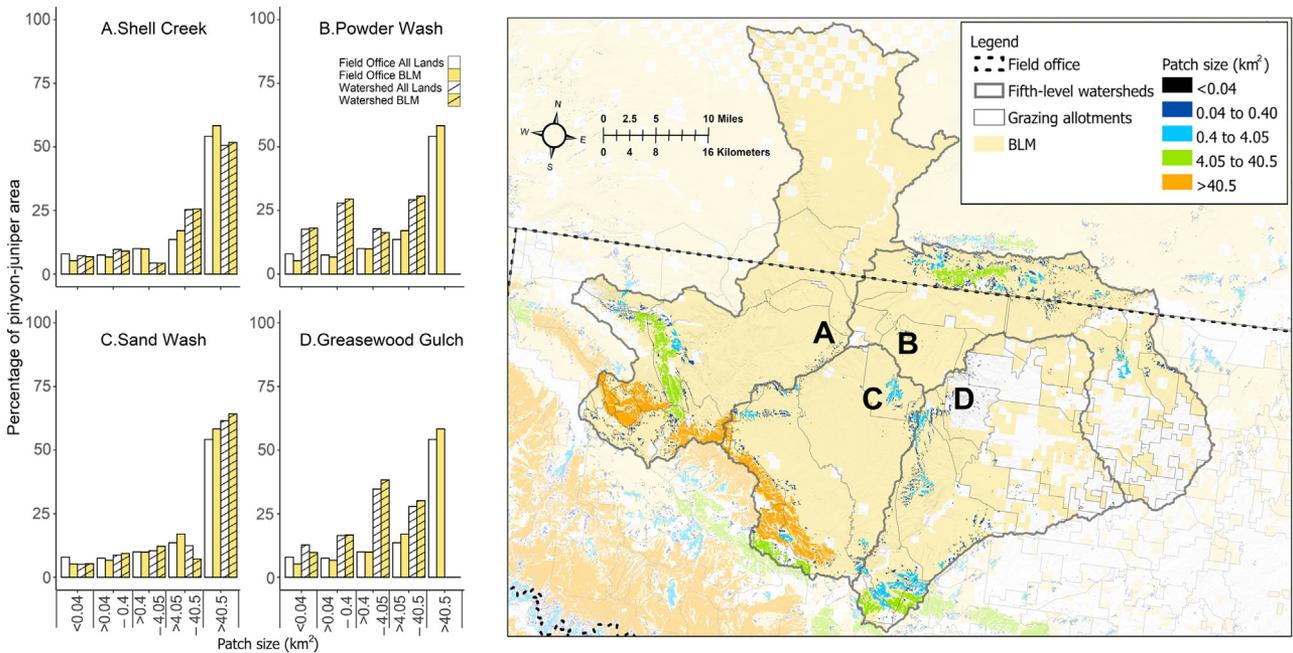


Figure 5. Pinyon-juniper patch size classes across a group of fifth-level watersheds in northwestern Colorado (right), and the mean percent of the watershed and field office belonging to each jurisdiction and patch size class as defined in the map legend (left). Small groups of pinyon-juniper vegetation cover <5 pixels ($4,500 \text{ m}^2$ [1.1 acres]) did not meet our criteria for a patch. However, the size-class percentages presented above were calculated based on the total amount of a vegetation type, and thus the bars for a given area of interest will not equal 100. Approximately 7% of the total area of pinyon-juniper from all lands and 3% from Bureau of Land Management (BLM) lands across the field office were not included in patches.

range established by the earliest 10 years. Additionally, $<0.5\%$ of the watershed in Powder Wash and Greasewood Gulch was in the "Moderate" invasion category in each of the last 10 years.

Results for the spatial distribution of native plants indicator show pinyon-juniper cover was highest in the western

portion of the field office (Fig. S3). There were an estimated $1,575 \text{ km}^2$ ($389,191$ acres) of pinyon-juniper on all lands and 986 km^2 ($243,646$ acres) on BLM lands (Table S1). Patches of pinyon-juniper were present in Shell Creek and Sand Wash across all five size classes but did not occur in patches $>40.5 \text{ km}^2$ ($10,000$ acres) in Powder Wash and Greasewood Gulch

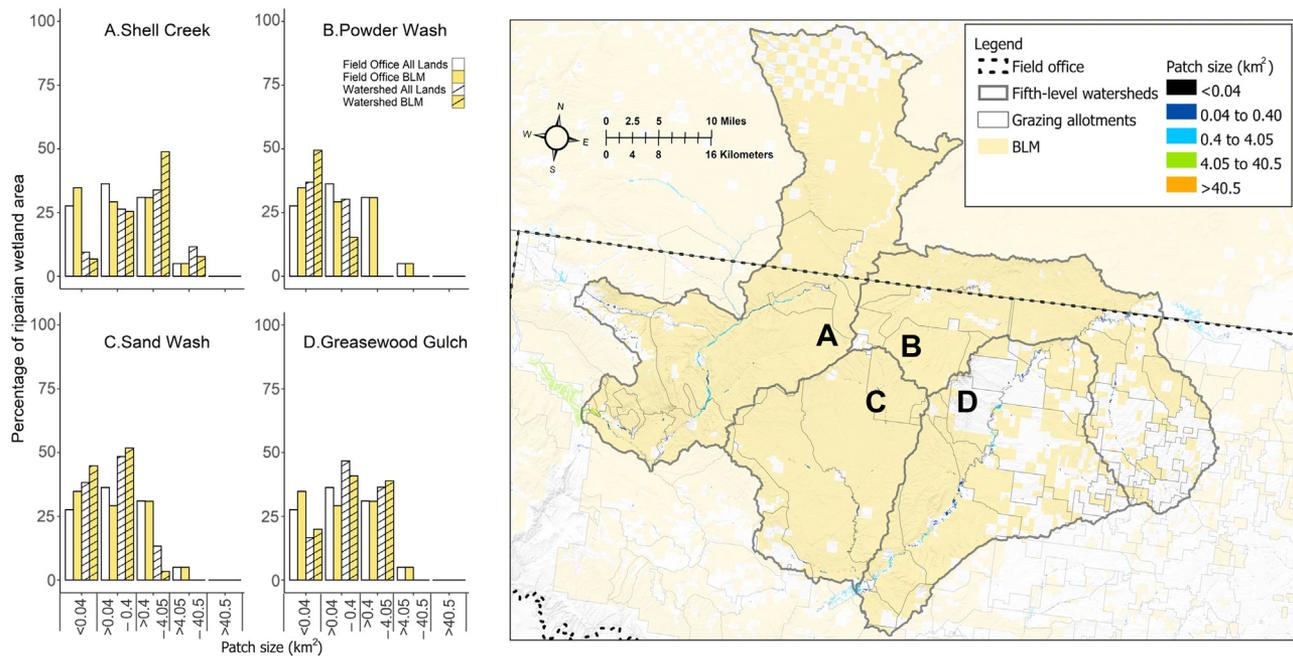


Figure 6. Riparian-wetland patch size classes across a group of fifth-level watersheds in northwestern Colorado (right), and the mean percent of the watershed and field office belonging to each jurisdiction and patch size class as defined in the map legend (left). Small groups <2 pixels ($1,800 \text{ m}^2$ [0.44 acres]) did not meet our criteria for a riparian-wetland patch. However, the size-class percentages presented above were calculated based on the total amount of a vegetation type, and thus the bars for a given area of interest will not equal 100. Across the field office, approximately 4% of the total area of riparian-wetland vegetation on all lands and 14% on Bureau of Land Management (BLM) lands was not included in patches.

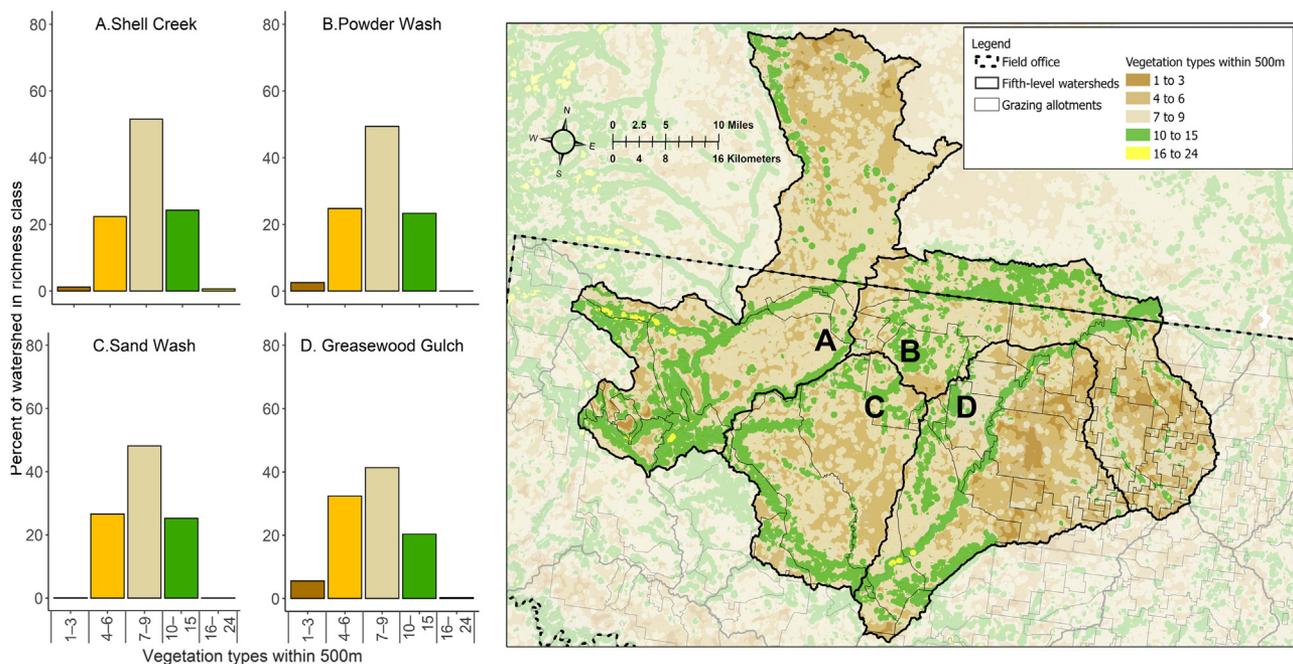


Figure 7. A map of vegetation class richness represented by the number of naturally occurring LANDFIRE existing vegetation types within a 500 m (0.31 miles) radius, across a group of fifth-level watersheds in northwestern Colorado (right). A bar graph depicting the percent of each watershed in five vegetation richness classes (left).

(Fig. 5). At the field-office scale, most pinyon-juniper occurred in patches $>40.5 \text{ km}^2$ (10,000 acres), and both Shell Creek and Sand Wash closely followed this trend. However, Greasewood Gulch and Powder Wash had the highest percent of pinyon-juniper in medium sized patches ($>0.4\text{--}4.05 \text{ km}^2$ [100–1,000 acres]). Patch size distribution patterns were

similar for all lands and BLM-managed lands in all analysis areas.

Riparian-wetland vegetation occurred mostly in the eastern portion of the field office, and there were 373 km^2 (92,170 acres) on all lands and 25 km^2 (6,178 acres) on BLM lands (Table S1; Fig. S3). There were no riparian-wetland patches

in the largest size class (>40.5 km² [10,000 acres]) in either the field office or watersheds (Fig. 6). At the field office scale, most riparian-wetland patches were equally distributed across the three smallest size classes. In watersheds, riparian-wetland patches were mostly in the two smallest size classes, with the exception of Shell Creek, which had a higher percentage of riparian-wetland vegetation types in medium-sized patches.

The results for the habitat connectivity indicator show that, across all areas of interest, >90% of pinyon-juniper patches were within 100 m (0.06 miles) of another patch. Few (1-4%) patches were within 100 to 500 m (0.06-0.31 miles) of the nearest patch, and <1% were >500 m (0.31 miles) from another patch (Fig. S4). Across all areas of interest, most riparian-wetland patches were within 500 m (0.31 miles) of another patch (Fig. S5).

The growing season photosynthetic activity indicator results show the mean TIN during the 2001 to 2020 growing seasons ranged from 5 to 20 with a mean of 11 in Shell Creek, 7 to 31 with a mean of 16 in Powder Wash, 6 to 28 with a mean of 14 in Greasewood Gulch, and 5 to 23 with a mean of 12 in Sand Wash (Fig. 3).

The results for the native plant diversity indicator show >40% of the area of each watershed has 7 to 9 different naturally occurring vegetation types within 500 m (0.31 miles) (Fig. 7). Shell Creek, Powder Wash, and Sand Wash have 4 to 6 naturally occurring vegetation types in 22% to 27% of their total area and 10 to 15 naturally occurring vegetation types in 23% to 26% of their total area. Thirty-eight percent of the total area of Greasewood Gulch had six or fewer naturally occurring vegetation types within 500 m (0.31 miles).

Discussion

We worked with BLM staff to provide remotely sensed data and analyses to inform land health standards and indicators at watershed scales in Colorado. We selected a subset of data from three remotely sensed products and quantified results to be applied to eight indicators across three land health standards. We sought to provide BLM field staff with a set of quantitative, watershed-scale results to broadly illustrate how remotely sensed data can complement the field data typically used to assess land health and inform livestock grazing decisions on public lands.

Identifying land health standards and indicators amenable to quantification at watershed scales using remotely sensed data products

There is increasing emphasis on managing public lands at landscape scales (e.g., DOI policy [604 DM 1]). We examined existing standards and indicators in Colorado using this landscape-level lens and found multiple standards and indicators had meaningful and relevant interpretations at watershed levels—despite the fact they are most often applied at the scale of individual grazing allotments. Others have also come to this conclusion. For example, standards and indica-

tors from across the BLM directly reference landscape patterns, and the BLM in Oregon recently completed a pilot study exploring how threat-based models can be used to facilitate a landscape-scale approach to LHAs.⁴⁴ Additionally, a survey of university and federal rangeland science experts identified remotely sensed data as one of the best ways to prioritize rangeland monitoring,⁴⁵ and Carter et al. have recently developed a framework for applying a core set of five landscape indicators to land health.³²

The remotely sensed data products we identified as informative for the LHA process are also widely used in other broad-scale ecological analyses in the western United States. For example, the RCMAP annual herbaceous component was used by a cheatgrass working group as a data source in a common spatial map created to guide strategic actions, such as cross-boundary regional planning of cheatgrass control efforts.⁴⁶ LANDFIRE EVT_s were recently used to map the extent of pinyon-juniper woodlands as part of an effort to characterize total aboveground biomass of pinyon-juniper ecosystems across the Great Basin.⁴⁷

Quantify metrics providing spatial and temporal context for land health assessments

Upland soils standard—We calculated temporal trends in annual mean bare ground cover (Fig. 2) and TIN (Fig. 3) across four watersheds to provide information relevant to two indicators from the upland soils standard.

Trends in bare ground cover were similar across watersheds, with bare ground cover peaking around 1990 and decreasing in the 30 years since (Fig. 2). However, the westernmost pair of watersheds consistently had more bare ground than the easternmost. A look at precipitation trends in the region shows years of low total precipitation seemed to correspond with higher means of bare ground cover, but mean annual totals of precipitation are similar across watersheds. This indicates another broad-scale factor, such as soil type, may contribute to observed differences across watersheds. It is worth noting the RCMAP bare ground component includes exposed rock,²⁸ which may also influence results. Monitoring bare ground cover at watershed-scales can help provide important information about the system's response to short-term droughts (1-2 years), which may lead to increases in bare ground cover that can become more extensive with prolonged drought.⁷ Bare ground cover data may also be linked to factors such as dust to create benchmarks to help manage exposure,⁴⁸ and has been identified as an important tool for monitoring rangeland condition by federal rangeland experts.⁴⁵

We used TIN as a proxy for plant vigor, as NDVI has been found to be strongly correlated to vegetation productivity,⁴⁹ especially at low values.⁵⁰ We found TIN values across the uplands, valley bottoms (riparian corridors), and all lands were nearly identical (Fig. 3), and thus we combine our discussion of these results here. We found all four watersheds had relatively low growing season TIN and similar temporal trends in TIN from 2001 to 2020. Long-term means below a TIN of 20 for all watersheds indicate low vegetation cover across

the region, which is likely a signal of the arid to semiarid shrub steppe habitats of the Wyoming Basin ecoregion.⁵¹ In all four watersheds, temporal trends showed a general pattern of annual increases, interrupted by large declines during the drought years of 2002 and 2012 recorded across the western United States. The pattern of rapid decreases in this measure of NDVI followed by gradual annual gains indicates drought years could have lasting effects on vegetation productivity in these systems.⁵² TIN values within the valley bottoms were almost identical, within watersheds, to results for uplands (Fig. S3). This indicates areas delineated as valley bottoms have similar productivity in this region as uplands. It is possible the broad extent of valley bottoms, identified using CO-RIP, may have increased the similarity of the upland and riparian values.

Riparian standard—We calculated temporal trends in annual mean TIN in valley bottoms (Fig. 3) across four watersheds to provide information relevant to one indicator from the riparian standard. See the discussion of TIN results above, in the preceding paragraph.

Native and other desirable species standard—For this standard, we were able to quantify metrics relevant to five indicators (Table 1). The percent of each watershed in different invasion categories³⁹ was relevant to the noxious weeds indicator. Shell Creek had the highest percentage of "Invasion free" (0%) cover across all years, which indicates maintenance of long-term stable conditions (Fig. 4). The other watersheds had more variable trends over time. Notably, there was a trend toward higher cover of "Mild" and lower cover of "Invasion free" areas in the easternmost pair of watersheds, Greasewood Gulch and Powder Wash.

Managers can use these trends to better understand how disturbances like wildfires, at a specific point in time, may have contributed to invasion. For example, in this study, large wildfires occurred in 2008 and 2014 along the easternmost border of Greasewood Gulch and Powder Wash (Fig. 4).²⁹ In 2015, >5% of Greasewood Gulch was added to the "Mild" invasion category—the largest such increase seen in the 35 year span of data—and it is possible this heightened pace of invasion could be linked to the recent wildfire. As invasion progresses, these systems may lose ecosystem function and could be at increasingly higher risk of wildfire due to the accumulation of fine fuels. Both factors could push the system past the threshold of self-recovery and into a new ecological state.⁴⁰

The invasion categories can also be linked to appropriate management strategies,^{39,40} which essentially provide resource managers with a mapped estimate of where invasive plant management could be most appropriate. For example, areas where cover of the "Trace" invasion category is increasing could be a focus for early detection and eradication efforts, which have a high chance of success and low cost and effort. Areas in the "Mild" invasion category still have a high recovery potential, but management efforts, including eradication, would be higher cost and effort.

To provide information for the spatial distribution of native plants indicator, we quantified the amount (Table S1; Fig.

S3) and patch sizes of pinyon-juniper (Fig. 4) and riparian-wetland habitat types (Fig. 6). We found pinyon-juniper cover in Shell Creek and Sand Wash occurred primarily in patches >40.5 km² (10,000 acres), which more closely resembled the overall pattern for the field office than the pattern in the nearby Powder Wash and Greasewood Gulch watersheds. This could be influenced by the proximity of the southern portions of these watersheds to the Colorado Plateau ecoregion, which is characterized by extensive pinyon-juniper cover.⁵¹ Patches of riparian-wetland communities were generally equally distributed among patch size categories <4.05 km² (1,000 acres) across watersheds and in the field office, indicating similar structure of these communities across the region.

We calculated temporal trends in annual mean TIN (Fig. 3) to provide information for the photosynthetic activity indicator. See the discussion of TIN results above in the third paragraph of the Upland soils standard section of the Discussion.

We also quantified the diversity of natural vegetation types to inform the plant diversity indicator (Fig. 7). Across all watersheds, areas with moderate local diversity (7-9) were most common, but some noticeable pockets of very high diversity (16-24) were found in Shell Creek and Greasewood Gulch. These results provide information useful for land health and may also help resource managers identify areas that could be valuable contributors to local plant diversity.

Limitations

We have presented a case study demonstrating how results from remotely sensed data products could be applied to the LHA process in Colorado. We expect this approach would apply to BLM LHAs in other western locations, but there may be questions related to other state or regional land health standards and indicators or other available remotely sensed products warranting further consideration.

Similar to LANDFIRE, the National Land Cover Database (NLCD)⁵³ is a categorical land cover raster, but NLCD has more coarse thematic detail than LANDFIRE (16 vegetation classes compared with over 500 classes, respectively). However, we note the higher thematic detail of LANDFIRE appears tied to decreased accuracy.³¹ If assessment of broad vegetation classes, such as evergreen forest, is adequate, rather than specific vegetation communities, such as pinyon-juniper woodland, the use of NLCD should be considered. The NLCD data also provide the ability to monitor change in land cover patterns over time (2001-2019), as they include updates to previous years with each new data release. We are not aware of a remotely sensed dataset allowing comparison of patch characteristics over time with the thematic detail needed for these vegetation communities. Other sources of data that could be used for land health are the fractional vegetation cover products from the Rangeland Analysis Platform and the Landscape Cover Analysis and Reporting

Tools,^{54,55} which span a similar time frame as the RCMAP products and include most of the same vegetation types.

A recent BLM technical note provides an evaluation of available fractional vegetation cover products, including RCMAP, Rangeland Analysis Platform, and Landscape Cover Analysis and Reporting Tools.⁵⁶ The BLM technical note provides a general overview of strengths and weaknesses of each product as well as an independent assessment of error. Aspects of our results may be impacted by the published error rates associated with each dataset. For example, we note the published error rate for the RCMAP annual herbaceous component suggests some potential membership uncertainty between pixels categorized as Invasion free and Trace.²⁸ However, our purpose was to demonstrate how resource managers can use maps, so we chose to map Invasion free pixels separately from Trace because of their ecological importance to monitoring the spread of invasive species. In the context of managing for land health, fractional vegetation cover products provide information that can help identify priority areas for assessing landscape management intervention or determine where additional sampling efforts may be beneficial. Although low error rates in the data are beneficial, at appropriate scales, remotely sensed data provide valuable information reflecting real landscape heterogeneity even when error rates are considered.¹⁶

Researchers may also need to consider how best to represent reference conditions for their particular region and application, especially given the lack of spatially explicit data on ecological site potential in many regions.¹² Here, we used the initial 10 years of data as a starting point, which BLM found to be useful and relevant, but other approaches and time periods could be used. We used nearest neighbor distances as a simple measure of structural connectivity for managers to consider during LHA processes. However, resource managers may want to incorporate complementary analyses on corridors or functional connectivity for priority species, as discussed by Carter et al.³² Finally, our approach is meant to be as straightforward as possible, but for BLM staff to use these methods on a regular basis, they will need to calculate the indicators themselves, likely through a semi-automated user interface they can easily access and use. Staff also need accessible frameworks that allow them to efficiently consider these remotely sensed indicators together with species-level data collected at individual field sites (e.g., BLM Assessment Inventory and Monitoring data).

Conclusion

BLM is constantly striving to better understand the ecological condition of public lands and to communicate those conditions to the public. Land health standards were developed to provide the public and public land managers with a clear picture of the ecological health of public lands and to help inform land management decisions. To ensure the accuracy and usefulness of the end product (i.e., BLM LHAs), it is important to obtain data from as many sources as possible.

To date, the use of remotely sensed data products in LHA remains inconsistent but is rapidly gaining momentum.

The framework we present here can provide an additional line of evidence for assessing land health standards by highlighting long-term spatial and temporal trends to help field staff better contextualize site-based assessments. Such an approach could be useful in the absence of mapped data on reference conditions, and when applied at a watershed-scale, may help identify causal factors negatively affecting land health not isolated to a single allotment. For example, if conditions on one allotment are trending differently than other nearby allotments over time, that could present justification for BLM to explore causal factors related to conditions on that allotment. The maps and visualizations of recent historical trends can also help BLM communicate the broader spatial context for current conditions to members of the public and other stakeholders, and the spatially explicit time-series trends for bare ground and annual herbaceous cover were of particular interest to BLM staff.

We did not seek to formally identify factors causing or contributing to current conditions here, but some drivers are indicated by the data. For example, BLM field staff report this region experienced a drought in 2012, and region-wide reductions in growing season TIN were recorded that year along with some smaller increases to bare ground. Although such large drops in vegetation productivity from one year to the next may seem out of the ordinary, the growing season TIN of all four focal watersheds has remained within the range established by the first 10 years of data, indicating these fluctuations have been stable across the time period of the data. Collaborating with BLM on the development of practical methods to relate reference conditions to broad-scale data, and correlating those data with drivers of change, will be critical to further adoption of broad-scale data use in the land health process and could be a beneficial next step.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: None.

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Supplementary materials

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Authors are from: U.S. Geological Survey, Fort Collins Science Center, Fort Collins, CO 80526–8118F, USA; Bureau of Land Management, Colorado State Office, Lakerwood, CO 80215, USA; Bureau of Land Management, National Operations Center, Denver Federal Center, Denver, CO 80225–0047, USA; Bureau of Land Management, Little Snake Field Office, Craig, CO 81625, USA