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Linking biophysical models and public preferences for ecosystem service assessments: a case study for the Southern Rocky Mountains

Kenneth J. Bagstad · James M. Reed ·
Darius J. Semmens · Benson C. Sherrouse ·
Austin Troy

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Abstract Through extensive research, ecosystem services have been mapped using both survey-based and biophysical approaches, but comparative mapping of public values and those quantified using models has been lacking. In this paper, we mapped hot and cold spots for perceived and modeled ecosystem services by synthesizing results from a social-values mapping study of residents living near the Pike–San Isabel National Forest (PSI), located in the Southern Rocky Mountains, with corresponding biophysically modeled ecosystem services. Social-value maps for the PSI were developed using the Social Values for Ecosystem Services tool, providing statistically modeled continuous value surfaces for 12 value types, including aesthetic, biodiversity, and life-sustaining values. Biophysically modeled maps of carbon sequestration and storage, scenic viewsheds, sediment regulation,

and water yield were generated using the Artificial Intelligence for Ecosystem Services tool. Hotspots for both perceived and modeled services were disproportionately located within the PSI's wilderness areas. Additionally, we used regression analysis to evaluate spatial relationships between perceived biodiversity and cultural ecosystem services and corresponding biophysical model outputs. Our goal was to determine whether publicly valued locations for aesthetic, biodiversity, and life-sustaining values relate meaningfully to results from corresponding biophysical ecosystem service models. We found weak relationships between perceived and biophysically modeled services, indicating that public perception of ecosystem service provisioning regions is limited. We believe that biophysical and social approaches to ecosystem service mapping can serve as methodological complements that can advance ecosystem services-based resource management, benefiting resource managers by showing potential locations of synergy or conflict between areas supplying ecosystem services and those valued by the public.

K. J. Bagstad (✉) · J. M. Reed · D. J. Semmens ·
B. C. Sherrouse
Geosciences and Environmental Change Science Center, U.S.
Geological Survey, Denver, CO, USA
e-mail: kjbagstad@usgs.gov

J. M. Reed
e-mail: jmrdspt@gmail.com

D. J. Semmens
e-mail: dsemmens@usgs.gov

B. C. Sherrouse
e-mail: bcsherrouse@usgs.gov

J. M. Reed
Department of Geography, University of Denver, Denver, CO,
USA

A. Troy
Department of Planning and Design, University of Colorado
Denver, Denver, CO, USA
e-mail: austin.troy@ucdenver.edu

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Introduction

A large and rapidly growing body of research seeks to quantify and value ecosystem goods and services—the benefits that ecosystems provide to people (Millennium Ecosystem Assessment 2005)—in support of better resource management and decision making (Ruhl et al. 2007; Daily et al. 2009). This has included spatially explicit biophysical modeling of ecosystem services, both through modeling tools intended to be applicable across

diverse geographic contexts (Kareiva et al. 2011; Villa et al. 2014) and locally developed and applied ecosystem service models (Martinez-Harms and Balvanera 2012). The Millennium Ecosystem Assessment (MA 2005) advanced the now well-known typology of supporting services (ecological processes that underpin the provision of other types of ecosystem services), regulating services (control of environmental conditions within optimal ranges for the survival of people and other species on which we depend), provisioning services (goods supplied by ecosystems), and cultural services (nonmaterial benefits that enhance individual and social well-being). Many biophysical ecosystem service models have developed out of past ecological, hydrologic, and other physical process models, and have proven useful in quantifying supporting, regulating, and provisioning services. By contrast, cultural services have often remained more difficult to quantify. With the exception of a limited number of cultural ecosystem services, such as the viewshed component of aesthetic values (Kareiva et al. 2011; ARIES Consortium 2014), biophysical models are poorly suited to quantifying cultural services. Their intangible nature and the limited collaboration between ecologists and social scientists outside of the field of economics have historically limited the opportunities for cultural services to inform decision making (Chan et al. 2011, 2012; Daniel et al. 2012).

Scientists have, however, mapped public and expert perceptions of ecosystem services, through Public Participatory Geographic Information Systems (PPGIS) approaches (Brown 2005; Sieber 2006; Dunn 2007; Raymond et al. 2009). They have also developed tools to systematize the mapping of social values for ecosystem services, i.e., using surveys of the public's values and attitudes to map their perceived values for ecosystem services (Sherrouse et al. 2011). We define social values as those assigned by people to places in the world (Ives and Kendal 2014), expressed as nonmonetary preferences. These approaches ask the public, which could include residents, visitors, focus groups, and/or online panels, to allocate value across a series of social-value types and/or to place points on maps that correspond to the locations where they feel the landscape provides these values. Social-values mapping largely focuses on understanding values for cultural ecosystem services, including non-use values, although most social-value typologies have included biological diversity (a supporting service) and life-sustaining values (defined by past surveys as “help[ing] produce, preserve, clean, and renew air, soil, and water,” roughly corresponding to multiple regulating services). Social-values mapping thus offers a means of quantifying cultural and other services to inform environmental planning and management decisions (Brown and Reed 2009; Brown 2012).

Multiple methods exist for eliciting social values. An extensive peer-reviewed literature has been developed using point-based, social-value elicitation methods and representative sampling of visitors to or residents of an area (Alessa et al. 2008; Bryan et al. 2011; Brown et al. 2012; van Riper et al. 2012; Sherrouse and Semmens 2014). Others have used polygons or fuzzy boundaries (Evans and Waters 2008; Carver et al. 2009) and/or semi-structured interviews, which often seek to answer different, though related, questions than representative sampling (Carver et al. 2009; Fagerholm et al. 2012; Klain and Chan 2012). Additional work has been undertaken to use internet-based mapping surveys and understand trade-offs in responses based on paper and internet surveys (Pocewicz et al. 2012). Brown and Pullar (2012) compared the results of polygon versus point-based studies. Theoretically, PPGIS results obtained using points should converge to polygons given an adequate sample size. Brown and Pullar found this to be the case, though they caution that this convergence may not occur for value types that are infrequently mapped. Brown and Pullar recommend the use of polygons for focus group-based research and points when surveying individuals and note that polygons covering all or nearly all of an area must usually be discarded, as they give little distinguishing information and can introduce error.

While some survey-based studies have asked the public or experts to specifically map supporting, regulating, and provisioning services in addition to cultural services (Raymond et al. 2009; Bryan et al. 2011; Brown et al. 2012), those same studies acknowledge the difficulty in asking the public to map complex ecosystem processes and services of which they may have only limited understanding. Regulating and supporting services are likely to be the most cognitively challenging landscape attributes for the public to map (Brown 2012, 2013). In a study conducted in coastal Wales, only more technical respondents (i.e., academics and representatives of environmental groups, but not representatives of business, fisheries, or recreational groups) chose to map supporting and regulating services at all (Ruiz-Frau et al. 2011). In another case study in South Australia, cultural services were most frequently mapped by respondents, followed by provisioning, then regulating, then supporting services (Bryan et al. 2011).

Indeed, in a study that asked the public to map 22 ecosystem service types, Brown et al. (2012) noted that “Although the purpose of [our] exploratory research was not to scientifically validate the ecosystem service data generated through PPGIS, future research should undertake this challenge. While few would question the validity of using PPGIS to generate maps for identifying cultural ecosystem services, many would question the utility of consulting the ‘public’ to identify more complex and

‘invisible’ ecosystem services (p. 647).” Brown et al.’s (2012) suggestion is to have the general public and experts independently map ecosystem services. Carefully combined use of social-values mapping and biophysical modeling may, however, be a better strategy to integrate cultural services into ecosystem services assessments (Chan et al. 2012; Plieninger et al. 2013). In this study, we thus compare survey-derived maps from the general public against outputs of biophysical models designed to quantify and map corresponding ecosystem services, rather than against maps generated solely by expert opinion.

Although biophysically modeled ecosystem services have not, to our knowledge, been mapped against corresponding social values, others have used spatial statistics to explore the strength of relationships between social values and diverse types of ecological data. Brown et al. (2004) found moderate overlap between public perceptions and expert opinion in locating biodiversity hotspots in Prince William Sound, Alaska. They also found that commercial fishermen, who make their living from the ocean’s biodiversity, were better able to identify biodiversity hotspots than the general public. Donovan et al. (2009) mapped social values against biodiversity in the Palouse region of Idaho and Washington, and found that the public was able to identify meaningful places for “natural diversity” that overlapped with forest and prairie remnants. Finally, Alessa et al. (2008) compared public perceptions of biological value to net primary productivity on the Kenai Peninsula, Alaska, and found a moderately significant positive relationship. Others have demonstrated the potential value of combining mapped social values and ecological data in support of land use and conservation planning in Australia (Bryan et al. 2011; Whitehead et al. 2014).

Aside from these past studies combining social values mapping and ecological data, biophysical modeling and social-values mapping of ecosystem services have largely taken place independently. Yet they could function as complementary approaches to support resource management—pairing social-values data to quantify and map cultural services with biophysically derived approaches to assess regulating and supporting services. As public agencies seek to incorporate ecosystem services information into planning (36 CFR 219; McIntyre et al. 2008; Zhu et al. 2010; U.K. National Ecosystem Assessment 2011; Bagstad et al. 2013a), information about cultural ecosystem services will be as important to consider as other services. The difficulty in monetizing cultural services has led to the development and use of multicriteria analysis for decision support (Hermans and Erickson 2007). Yet concurrent mapping of biophysically modeled services and social values could provide another approach to synthesizing such information for management.

Alessa et al. (2008) identified “social-ecological hotspots”—areas of high ecological and/or social value and their converses—“coldspots” with low ecological and/or social value. A 2×2 matrix of social values and biophysically modeled ecosystem services (hereafter social value and/or ecosystem service hotspots and coldspots) can describe potential public land management implications for these hotspots and coldspots (Table 1). Our approach is also analogous to 2×2 decision matrices used in the social values mapping literature to help guide mixed public–private land management (Bryan et al. 2011; Whitehead et al. 2014) and climate change adaptation (Raymond and Brown 2011). By identifying social-ecological hotspots and coldspots, we might conduct more complete ecosystem service analysis than by using biophysical models or social-values mapping alone, better informing resource managers about potential synergies, trade-offs, and conflicts between existing or planned uses, management strategies, and the provision of ecosystem services. This approach also offers a way to conceptualize trade-offs and synergies between cultural and other ecosystem services and to consider some difficult-to-monetize cultural ecosystem services in quantitative, spatial ecosystem service assessments.

In this study, we extend on these themes from past analyses, using the Pike–San Isabel (PSI) National Forest in Colorado as a study area. We first map hotspots for summed social values and ecosystem services and their overlap, to provide a mapped example of the management implications hypothesized in Table 1. If social-values mapping and biophysical modeling of ecosystem services are indeed complements and not substitutes, joint mapping may thus more comprehensively map and value a broader array of ecosystem service types. Second, we statistically model the relationship between three individual social values and five corresponding biophysically modeled ecosystem services to determine whether survey respondents are capable of mapping those services that we can concurrently assess using biophysical models (Table 2). If corresponding social values and ecosystem service maps align well, then we may be collecting redundant information, suggesting that it may only be necessary to use one approach rather than both. If they align poorly, one or the other type of map may be inappropriate, suggesting that the less scientifically trusted approach could be dropped. Based on the findings of Bryan et al. (2011) and Brown (2012, 2013), we hypothesize that non-expert survey respondents will best be able to map cultural services, which public preferences are integral to understanding, next best able to map provisioning services, i.e., ecosystem goods used by the public (provided they are willing to identify the locations on which they depend for basic resources, Klain and Chan

Table 1 Potential management implications of social values and ecosystem service hotspot analysis

	Biophysically modeled ecosystem services (mapped using ARIES)	
	Ecosystem service hotspot	Ecosystem service coldspot
Social values (mapped using SolVES)		
Social-value hotspot	High management support (if social values and services are compatible) OR potential conflict between management and traditional uses (if social values and services are not complementary)	High support for traditional uses; cases where biophysical modeling alone is inadequate to map value
Social-value coldspot	Public outreach needed to build support for management (e.g., for watershed protection programs)	Areas suitable for development or resource extraction, assuming other important natural or cultural resources (e.g., high biodiversity, threatened and endangered species, indigenous cultural significance) are absent

Table 2 Hypothesized relationships between social values and biophysically modeled ecosystem services

Social value	Biophysically modeled services (Millennium Ecosystem Assessment ecosystem service type)				
	Scenic viewsheds (cultural)	Vertebrate species richness (supporting)	Carbon sequestration and storage (regulating)	Sediment regulation (regulating)	Water regulation and supply (provisioning)
Aesthetic	Strongest				
Biodiversity		Weakest			
Life-sustaining			Weakest	Weakest	Intermediate

2012), and least able to map more complex regulating and supporting services (Table 2).

Materials and methods

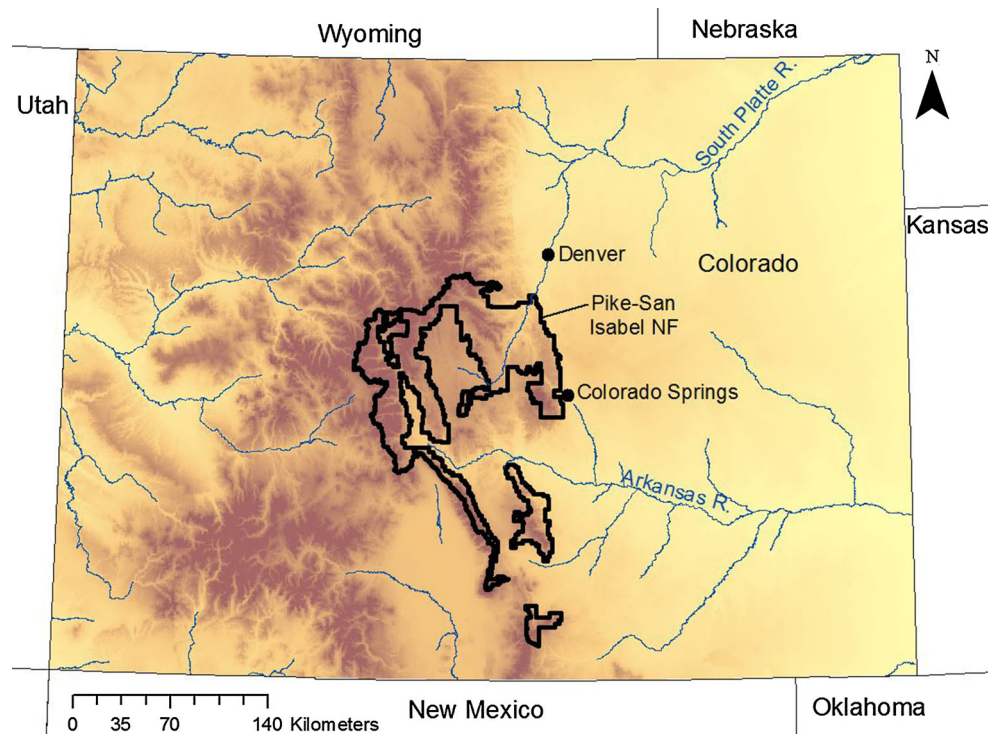
Study area

The PSI is located on the eastern side of the Continental Divide in the Southern Rocky Mountains and covers 9,011 km², about 3.3 % of Colorado's land area (Fig. 1). With approximately 6.8 million recreational visits per year, the PSI ranks third in the nation for annual national forest recreational visits, providing visitors with a wide range of outdoor recreational opportunities. The headwaters of the Arkansas and South Platte Rivers are located within the PSI, which provides over 60 % of the Denver metropolitan area's water (USDA 2012). The region thus provides important ecosystem services based on its recreational visitation and delivery of sediment-free water for metropolitan Denver alone. Like most forests in the arid and semiarid intermountain western USA, the PSI's forests frequently burn. Notably the Buffalo Creek (1996) and Hayman (2002) fires burned nearly 150,000 acres and cost Denver Water \$26 million in dredging and water treatment costs for reservoirs located within or downstream of the PSI. The Hayman fire also caused nearly \$39 million in insured property losses, \$42 million in fire suppression

costs, and \$37 million on post-fire restoration and stabilization. In 2010, the Forest Service and Denver Water created a "Forests to Faucets" partnership designed to invest \$33 million into forest thinning, clearing, and fuel break creation within priority water supply watersheds in the PSI, Arapahoe-Roosevelt, and White River National Forests (Denver Water 2014). Such management trade-offs illustrate the importance of understanding the biophysical and social interactions between resource management and ecosystem services provided by the PSI.

Social-values mapping and ecosystem service modeling

We generated social-values maps for this analysis using the Social Values for Ecosystem Services (SolVES) 2.0 tool, a GIS application intended to quantify and map perceived social values for ecosystem services (Sherrouse et al. 2011, 2014). We drew data from results of a mail survey conducted in 2004–2005, which was sent to a random sample of 2,000 residents living within 72 km of the PSI (Clement and Cheng 2011). Along with a series of questions to gauge respondents' attitudes and preferences toward forest management, the survey asked respondents to allocate 100 hypothetical dollars (not actually paid or spent by the respondent or the Forest Service) among 12 value types (based on Rolston and Coufal's (1991) forest values typology; Table 3), then to mark locations on a paper map corresponding to those value types. Of 2,000 surveys, 684,

Fig. 1 Study area map

or 34 %, were returned. Of those 684, 55 % of respondents completed maps, yielding an effective response rate of 19 %. Respondents mapped 2,289 total points within the PSI—approximately six points mapped per respondent. After the points were manually digitized into a GIS, Sherrouse et al. (2014) applied SolVES and the MaxEnt algorithm (Elith et al. 2011) to develop statistical models relating the location of mapped points to six environmental data layers (land cover, landforms, elevation, slope, distance to roads, and distance to water). Using these models, Sherrouse et al. (2014) created raster layers covering the entire PSI for each social-value type. SolVES creates a value index for each layer, ranging from 0 to 10 depending on the frequency and density that values were selected and mapped by respondents. The value index does not represent monetary values for ecosystem services but relative values for each social-value type.

We quantified ecosystem services using biophysical models included in the Artificial Intelligence for Ecosystem Services (ARIES) modeling system (Villa et al. 2014). We ran models for carbon sequestration and storage, surface water supply, sediment regulation, and aesthetic viewsheds from both recreation sites and residences with views of the PSI (Table 4). Detailed descriptions of data sources and model structure and assumptions used in ARIES are provided by ARIES Consortium (2014). The models incorporated regionally specific spatial data and account for ecological and socioeconomic influences on ecosystem service supply and demand that are specific to

the Southern Rocky Mountains. We also used biodiversity data from Boykin et al. (2013), who aggregated deductive habitat modeling results of vertebrate species distributions in the U.S. Southwest (generated for 817 amphibian, bird, mammal, and reptile species as part of the Southwest Regional Gap Analysis (SWReGAP) project) to yield species richness maps. We used this summed habitat for all terrestrial vertebrate species as our biophysically based species richness measure.

Hotspot analysis

To identify social value and ecosystem service hotspots, coldspots, and regions of overlap (Table 1), we used the Getis-Ord G_i^* statistic (Getis and Ord 1992) of local spatial autocorrelation on summed social and ecosystem service values. Past social-values mapping studies have used different methods for hotspot analysis: Alessa et al. (2008) mapped the upper third of values as hotspots, Bryan et al. (2011) mapped the upper 20 % of values, and Zhu et al. (2010) used the Getis-Ord G_i^* statistic. We follow Zhu et al. (2010), because this approach lets us identify statistically significant clusters of high landscape values at the $\alpha = 0.05$ significance level. We conducted this analysis using ArcGIS 10.1 with data at a spatial resolution of 450 meters to match the resolution of the SolVES output.

We equally weighted then summed the modeled surfaces for the 12 social values and 4 biophysically modeled ecosystem services (excluding biodiversity) and ran the

Table 3 Social-values types used in each analysis

Social value	Definition: “I value these forests...”	Data used for
Aesthetic	“Because I enjoy the scenery, sights, sounds, smells, etc.”	Regression and hotspot analysis
Biological diversity	“Because they provide a variety of fish, wildlife, plant life, etc.”	Regression and hotspot analysis
Cultural	“Because they are a place for me to continue and pass down the wisdom and knowledge, traditions, and way of life of my ancestors”	Hotspot analysis
Economic	“Because they provide timber, fisheries, minerals, and/or tourism opportunities such as outfitting and guiding”	Hotspot analysis
Future	“Because they allow future generations to know and experience the forests as they are now”	Hotspot analysis
Historic	“Because they have places and things of natural and human history that matter to me, others, or the Nation”	Hotspot analysis
Intrinsic	“In and of themselves, whether people are present or not”	Hotspot analysis
Learning	“Because we can learn about the environment through scientific observation or experimentation”	Hotspot analysis
Life-sustaining	“Because they help produce, preserve, clean, and renew air, soil, and water”	Regression and hotspot analysis
Recreation	“Because they provide a place for my favorite outdoor recreation opportunities”	Hotspot analysis
Spiritual	“Because they are a sacred, religious, or spiritually special place for me or because I feel reverence and respect for nature there”	Hotspot analysis
Therapeutic	“Because they make me feel better, physically and/or mentally”	Hotspot analysis

Table 4 Biophysically modeled data used in each analysis

Social value or ecosystem service	Method	Measure	Data used for
Views received by SolVES aesthetic value points	Bayesian model of viewshed quality, with line-of-sight model connecting respondent-marked aesthetic value points to visible viewshed features and their quality ^a	Relative ranking of view quality (0–100) received by each cell	Regression analysis
Views provided to recreation sites	Bayesian model of viewshed quality, with line-of-sight model connecting PSI recreation sites to visible viewshed features and their quality ^a	Relative ranking of view quality (0–100) provided by each cell	Regression and hotspot analyses
Views provided to residences	Bayesian model of viewshed quality, with line-of-sight model connecting residences with views of the PSI to visible viewshed features and their quality ^a	Relative ranking of view quality (0–100) provided by each cell	Regression and hotspot analyses
Vertebrate species richness	Deductive habitat models for 817 amphibian, bird, mammal, and reptile species, summed to generate species richness data	# of terrestrial vertebrate species per cell	Regression analysis
Carbon sequestration	Bayesian model of carbon sequestration ^b	Tons carbon/year	Regression and hotspot analyses
Carbon storage	Summed results of Bayesian models for vegetation and carbon soil storage ^b	Tons carbon	Regression and hotspot analyses
Surface water yield	Summed results of Bayesian models for evapotranspiration and infiltration subtracted from mean annual precipitation ^b	mm water yield/year	Regression and hotspot analyses
Soil erosion	Bayesian model of soil erosion ^b	Tons sediment eroded/year	Regression and hotspot analyses
Sediment deposition	Bayesian model of sediment deposition ^b	Tons sediment deposited/year	Regression and hotspot analyses

^a Bayesian models of viewshed quality incorporate positive (e.g., mountains and water features) and negative (e.g., commercial development or beetle-killed forests) influences on viewshed quality, as derived from regional visual preference studies. Model details are provided by ARIES Consortium (2014)

^b Bayesian models of biophysical processes incorporate the influences of vegetation, soils, climate, and topography on relevant processes, and are calibrated based on regional or national datasets. Model details are provided by ARIES Consortium (2014)

Getis-Ord Gi* tool on both summed layers, using a fixed distance band specified to ensure that all features had at least one neighbor. We excluded biodiversity from the ecosystem service hotspot analysis because, by definition as a supporting service, it benefits humans indirectly. The maximum summed value index for a given cell across all 12 social-value types was 61. We normalized ecosystem service values by setting each service (scenic views from housing and recreation sites, carbon sequestration and storage, sediment deposition, and water yield) from 0 to 1, rescaling the individual maps for the two viewshed and carbon metrics (views provided to recreation sites and residences, carbon sequestration and storage) between 0 and 0.5, and summing all layers. This gave equal weight to each of the four biophysically modeled ecosystem services. Although a maximum value of four could thus theoretically be achieved, the actual maximum actual value was 1.79, indicating relatively little overlap between areas of maximum provision of each of the four services.

Regression analysis

Our regression analyses build on recent comparisons between spatially explicit social values and ecological data, such as expert-derived biodiversity maps (Alessa et al. 2008) or ecological metrics including protected areas, species richness, and patch size (Bryan et al. 2011). To quantify the relationship between social values and ecosystem services, we developed nine univariate regression models comparing social values (dependent variable, Table 3) and biophysically modeled ecosystem services (independent variable, Table 4). We compared life-sustaining value against biophysical model results for (1) carbon sequestration, (2) summed vegetation and soil carbon storage, (3) surface water yield, (4) soil erosion, and (5) sediment deposition. We compared aesthetic values to modeled viewshed quality provided to (6) PSI recreation sites and (7) residences with views of the PSI, measured as developed land cells with views within a 48 km range of the PSI, and viewshed quality received by (8) aesthetic value points marked by survey respondents to the social values survey. Finally, we compared (9) biodiversity values against vertebrate species richness modeled by SWReGAP. We used Ordinary Least Squares (OLS) regression analyses within ArcGIS 10.1.

The only spatially explicit biodiversity data for the region were for vertebrate species richness, which does not perfectly align with the survey's description of biological diversity value. We compared the aesthetic value survey results to spatially explicit viewshed quality model results (themselves calibrated based on visual preference studies for the Rocky Mountain region); obviously viewshed models capture only the visual component of aesthetic

quality and exclude other sensory elements important to aesthetics. The survey's description of life-sustaining value comes close to definitions of regulating ecosystem services; we thus compared this value to modeled results for clean air (carbon sequestration and storage), soil (soil erosion and sediment deposition), and water (water yield). Despite the imperfect alignment of the description of social values and biophysically modeled services, we feel that the biophysically modeled services come close to matching the defined social values.

We used point locations for our regression models that were marked by survey respondents for each value type ($n = 238$ life-sustaining points, 242 biodiversity points, and 466 aesthetic points). These points were located at an average minimum distance of 1.24 km from each other, helping to avoid inflation of test statistics due to spatial autocorrelation of values. Rather than using the statistically modeled raster surface generated by SolVES using the MaxEnt algorithm (which could also yield unacceptably high spatial autocorrelation), we divided the number of dollars allocated by each respondent to a given value type during the value allocation exercise by the number of points they marked for that value type. For instance, if a respondent allocated 60 dollars to aesthetic value, then marked three points on their map, each point would be assigned a value of 20. We then extracted the corresponding biophysically modeled ecosystem service values for each point layer. Jarque–Bera tests revealed a highly non-normal distribution of residuals for the initial OLS results, so we applied Box–Cox power transformations to transform the dependent variable in each model using the lambda value recommended by the Box–Cox test (Box and Cox 1964). Box–Cox transformed model results reduced the Jarque–Bera test statistics by 92–99 %, and also yielded 35–60 % smaller values for Akaike's Information Criterion. The use of spatially adjusted regression (i.e., spatial error modeling) may be appropriate for spatial statistical analysis when test statistics are inflated due to spatial autocorrelation; however, given the very low test statistics we found (see “Results” below), we did not apply spatially adjusted regression.

Results

Hotspot analysis

Just over 20 % of the PSI was classified as statistically significant hotspots for social values and/or ecosystem service at the $\alpha = 0.05$ significance level, and less than 2 % of the PSI was classified as hotspots for both (Table 5). Nine federally designated wilderness areas are located within the PSI, totaling approximately 18 % of the

PSI's total land area. Ecosystem service and social value hotspots were overrepresented within these wilderness areas (Table 5; Fig. 2). Statistically significant ecosystem service hotspots were generally clustered at higher-elevation locations with greater values for water yield and scenic viewsheds, and also at locations below treeline where forests sequestered and stored more carbon in their vegetation and soils. Social-value hotspots were generally found around the “Fourteeners” (mountain peaks greater than 14,000-ft (4,267 m) in elevation) at the western edge of the PSI (along the Continental Divide), within some lower-elevation wilderness areas, and along the corridor of the South Platte River (which flows south–north through the northeastern portion of the PSI).

Regression analysis

Using a linear functional form with Box–Cox transformation of the dependent variable, all OLS results were non-significant at the $\alpha = 0.05$ level (Table 6). Contrary to our hypotheses, we found the smallest p values for biodiversity and some of the largest p values for aesthetics; however, all p values were large and adjusted R^2 values were extremely small.

Discussion

Hotspots and coldspots: Implications for planning and resource management

Wilderness areas were generally found at higher elevation and despite their relative inaccessibility were perceived by the public as valuable locations (Fig. 2). Colorado is home to 54 “Fourteeners,” which are highly visible landmarks and popular locations for hiking, mountaineering, and backcountry skiing. Thirty of these Fourteeners are located within or adjacent to the PSI, including the highest point in the state, Mt. Elbert (14,439 ft/4,401 m). Recreation sites were relatively well distributed throughout the PSI and were found within, near, and distant from social-value/ecosystem service hotspots. The location of wilderness areas and Fourteeners thus seems to better explain

concentrations of social values than the location of general purpose recreation sites.

Wilderness boundaries were marked on the maps that respondents used to locate social value points. Notable social values hotspots outside of wilderness areas included the South Platte River corridor and southern end of the Collegiate Peaks. Non-wilderness ecosystem service hotspots included the Pikes Peak area, Wet Mountains, and the southernmost part of the PSI located west of the Spanish Peaks Wilderness. Using summed social-values data, PSI wilderness areas, on average, were valued 32 % more than non-wilderness areas. Based on the results of parallel studies in more rural northwest Wyoming that also included wilderness boundaries on maps marked by respondents (Sherrouse et al. 2014), however, the summed value index for non-wilderness areas was 15 % greater than wilderness areas in the Bridger-Teton National Forest (BTNF) and 100 % greater than in the Shoshone National Forest (SNF). In their study of nearby residents' attitudes about forest management in Colorado and Wyoming, Clement and Cheng (2011) found that PSI respondents favored wilderness more than BTNF or SNF respondents, whereas BTNF and SNF respondents were more favorable to fishing and hunting, motorized recreation, and oil/gas drilling. Wilderness areas provide important ecosystem services (Watson and Venn 2012), though efforts to catalog and quantify them have generally tended toward isolated case studies rather than systematic, quantitative, spatial analyses. Additional studies to map social values and biophysically modeled ecosystem services for wilderness and non-wilderness areas would improve our understanding of ecosystem services generated by wilderness areas, particularly for a greater variety of services and geographic contexts.

Ecosystem services are increasingly entering into the decision processes of public agencies, particularly those charged with planning and resource management (McIntyre et al. 2008; Zhu et al. 2010; U.K. National Ecosystem Assessment 2011). In Colorado's national forests, joint mapping of cultural and biophysically modeled ecosystem services has implications for resource management by the USDA Forest Service and adjacent land management agencies such as the National Park Service and Bureau of

Table 5 Ecosystem service and social-value hotspots within the Pike–San Isabel National Forest

	% of total PSI	% of PSI wilderness areas	% of hotspot area contained within wilderness
Social-value and ecosystem service hotspot	1.8	6.8	69.2
Social-value hotspot/ecosystem service coldspot	10.1	24.7	44.1
Social-value coldspot/ecosystem service hotspot	8.8	20.0	40.1
Social-value and ecosystem service coldspot	79.4	48.6	11.0

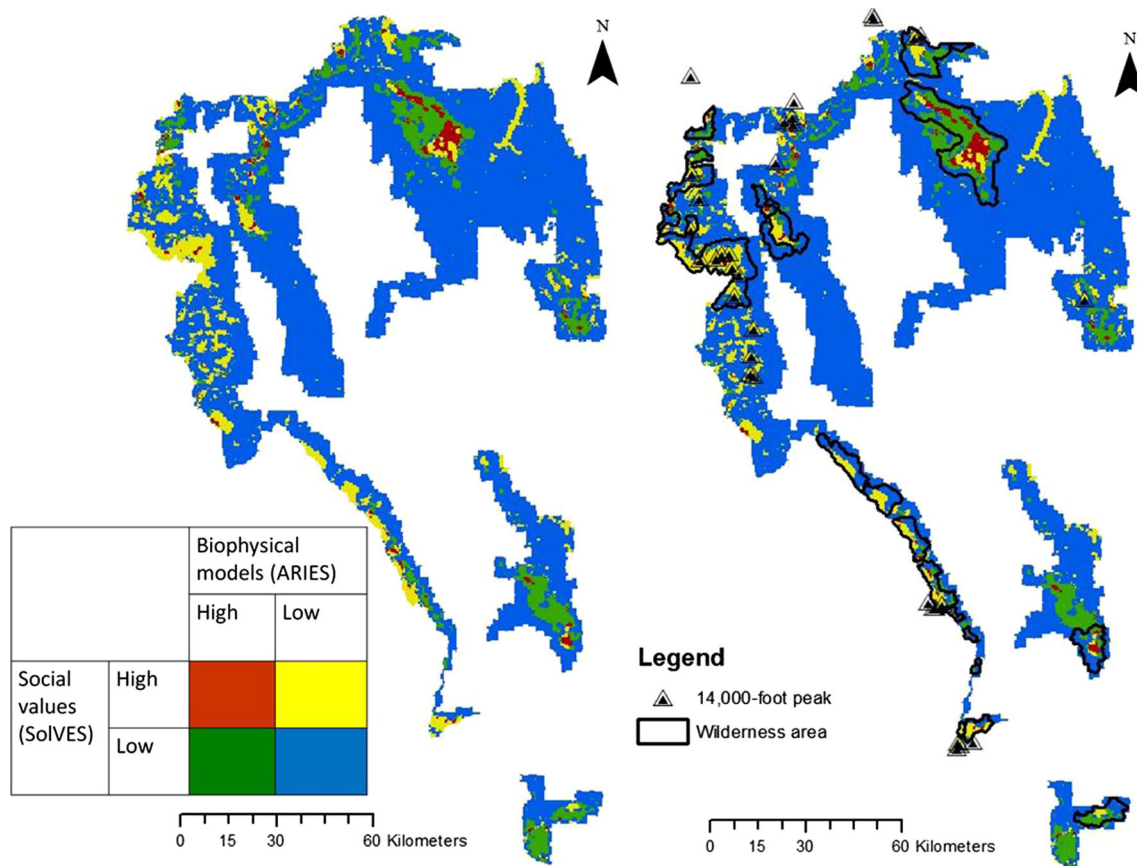


Fig. 2 Ecosystem services and social-values hotspots (*left*), Hotspots, with wilderness areas and 14,000-foot (4,267 m) peaks overlaid (*right*)

Table 6 Box–Cox transformed regression results

Dependent variable and independent variable	<i>n</i>	<i>p</i> value	Adj. <i>R</i> ²
Biodiversity and vertebrate species richness	242	0.0583	0.0108
Aesthetic and viewsheds provided to residences	466	0.7117	−0.0018
Aesthetic and viewsheds provided to recreation sites	466	0.9154	−0.0021
Aesthetic and viewsheds received by respondent-marked aesthetic points	466	0.2713	0.0005
Life-sustaining and carbon sequestration	238	0.1335	0.0053
Life-sustaining and carbon storage	238	0.4222	−0.0015
Life-sustaining and soil erosion	238	0.6394	−0.0029
Life-sustaining and sediment deposition	238	0.5770	−0.0033
Life-sustaining and water yield	238	0.1500	0.0046

Land Management (Bagstad et al. 2013a), particularly given the Forest Service’s 2012 Planning Rule requirement to account for ecosystem services in the development of new Forest Plans (36 CFR 219). Hotspot analysis results enable spatial and visual comparisons between cultural and other ecosystem services, putting difficult-to-monetize cultural services on a level playing field for decision making with biophysically modeled services that are more amenable to monetary valuation. In planning contexts, hotspot results can be used to identify potential resource management synergies, trade-offs, and conflicts between

existing or planned uses, management strategies, and the provision of ecosystem services (Table 1).

Given that resource extraction and motorized recreation are prohibited within wilderness areas, we expect that threats to ecosystem services there would originate more from either global change (e.g., climate change) or access-related environmental degradation. Risk and value can be incorporated into resource management, with resources directed to higher-value and/or higher-risk landscapes (Raymond and Brown 2011). Outside these wilderness areas, managers could overlay the spatial extent of

potential management actions atop social-values and ecosystem service maps to better visualize human/landscape relationships (Alessa et al. 2008) and areas of potential management synergies or conflicts. Coldspots were prevalent outside of wilderness areas (Fig. 2). While coldspots have lower total ecosystem service values than hotspots, managers should not assume that these areas are devoid of value. Coldspot management strategies may include raising awareness of their value or distributing human use and related impacts to underutilized areas, while being aware that greater use can degrade sensitive environments (van Riper et al. 2012).

Public perceptions of biodiversity and ecosystem services

Although no results were statistically significant (Table 6), visual inspection of selected ecosystem service combinations is still instructive (Fig. 3). Similar parts of the PSI—notably high-elevation regions, the South Platte River corridor, and wilderness areas (see “Hotspot analysis” above) had high aesthetic, biodiversity, and life-sustaining social values. Many areas marked by the public as being important for high biodiversity in fact have very low vertebrate species richness; this is particularly true for low-diversity, high-elevation parts of the PSI (Fig. 3a). Although visitors’ views of mountain peaks and water bodies at recreation sites are distributed heterogeneously through the PSI, no clear visual relationships with the aesthetic value type are obvious (Fig. 3b). Water yield seems to align well with life-sustaining value, with high-elevation parts of the PSI important to both value types. However, the South Platte River corridor is notably marked as important for the life-sustaining value type but not for modeled water yield (Fig. 3c); though its built capital (i.e., reservoirs) does play a critical role for the region’s water supply.

We hypothesized that the public might perform best at mapping cultural services (e.g., aesthetics), next best at mapping provisioning services (e.g., water yield), and find the mapping of biophysically complex supporting and regulating services (e.g., biodiversity, carbon sequestration and storage, and sediment yield) to be the most challenging (Bryan et al. 2011; Brown 2012, 2013) (Table 2). However, all results were non-significant at the $\alpha = 0.05$ level and lacked explanatory power (adjusted R^2 values of 0.01 or less, Table 6). The statistical fit between biodiversity value and vertebrate species richness indicated the strongest relationship ($p = 0.058$); however, the public fared better in mapping biologically significant areas in Alaska and the Palouse region of Idaho and Washington than in

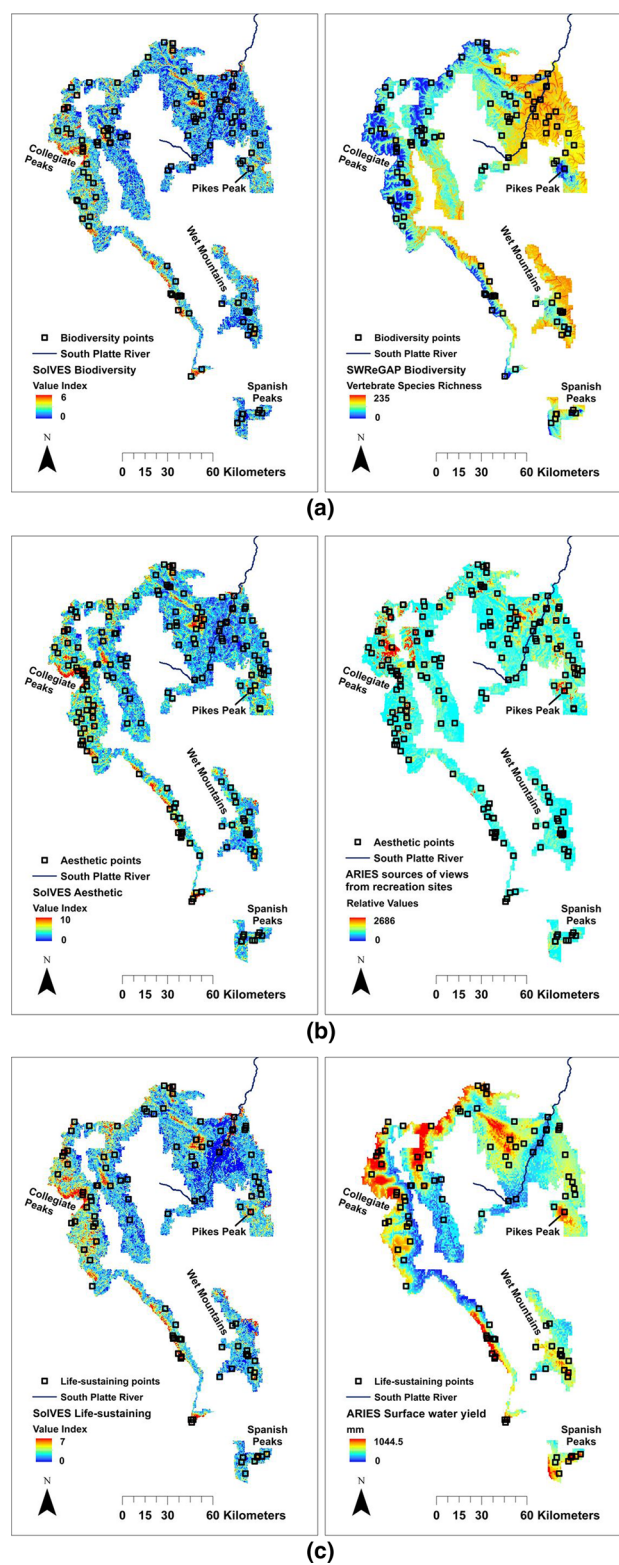


Fig. 3 SolVES and biophysical model outputs for selected ecosystem service comparisons: **a** biodiversity-SWReGAP vertebrate species richness, **b** aesthetic-ARIES viewsheds from recreation sites, **c** life-sustaining-ARIES water yield

this study (Brown et al. 2004; Donovan et al. 2009). Further research could test the relationship between public perceptions of ecosystem services and their biophysically modeled values in other geographic contexts to more widely support or refute these hypotheses from the social values mapping literature.

Our findings align with past studies that acknowledge the difficulty, in terms of a potentially high cognitive burden, in asking the public to map biophysically complex ecosystem services (Raymond et al. 2009; Bryan et al. 2011; Ruiz-Frau et al. 2011; Brown et al. 2012). Brown et al. (2012) recommend that the general public and experts be asked to separately map ecosystem services and that researchers compare results to better understand the strengths and limitations of public and expert ecosystem service mapping. In this study, we extend this approach by using maps generated using ecosystem service modeling tools rather than through elicitation of expert opinion. Indeed, the use of ecosystem service modeling tools is becoming more widespread and is an increasingly viable option for ecosystem service assessments that go beyond elicitation of expert opinion (Kareiva et al. 2011; Bagstad et al. 2013a; Villa et al. 2014).

We believe that biophysical ecosystem service models and survey-based assessments of cultural services provide complementary information. As biophysical models and social values mapping are applied more broadly, a key question for their use is whether the information that both methods collect about biodiversity and non-cultural ecosystem services is redundant (i.e., aligns well) or divergent (i.e., aligns poorly). If both align well, the more difficult-to-apply approach could potentially be dropped; if they align poorly, as was the case in this study, the less scientifically trusted approach might be dropped. The weak alignment of biophysical and social data has implications for the values typology used in future social-values studies. The values typology used with such studies has generally remained relatively stable across a broad array of studies, dating to Brown and Reed's (2000) validation of Rolston and Coufal's (1991) "forest value typology" (though more recent work has sought to better understand social value types in coastal contexts, Cole 2012). In the light of our findings, we question whether the continued inclusion of value types like "biological diversity" or "life-sustaining" values is sensible in future PPGIS or social-values mapping typologies, or whether spatially explicit information collected from the general public about cultural ecosystem services and non-use values is better paired with maps of biodiversity, regulating, and provisioning services that draw directly from biophysical data or models. If the general public tends to default to mapping charismatic or well-known places when asked to map non-cultural ecosystem services, such data will poorly represent high-value

areas for these services. Public understanding of the concept of biodiversity and recreationists' perceptions of ecological condition are often limited and unreliable (Brown et al. 2004; Manning 2011). This suggests that the value of using PPGIS or social-values mapping for biodiversity and non-cultural ecosystem services may be limited, except for in cases where researchers lack corresponding biophysical data and models or specifically aim to test the divergence between social and biophysical values. This point has been noted by past authors, who for example excluded life-sustaining value from their values typology (Beverly et al. 2008) or argued that PPGIS should solely consider cultural and provisioning services (Brown 2013).

However, an alternate view suggests that since building trust and empowerment is a primary goal of PPGIS, reducing the scope of PPGIS studies by reducing the number of value types included in social values mapping would have negative consequences. Since conservation planning must achieve social license as it seeks to protect biodiversity and ecosystem services, comprehensive assessments of social values are important to evaluate alongside biophysical assessments (Bryan et al. 2011; Whitehead et al. 2014). The question of whether community empowerment and conservation planning success would decline if fewer value types were elicited during PPGIS efforts may thus require further research before certain value types are excluded from social values mapping exercises. Additionally, when communicating ecosystem services concepts with the lay public, simpler metaphors may be more useful than the complex linked biophysical-socioeconomic models that have dominated research to date (Raymond et al. 2013).

Limitations and future work

Four caveats or assumptions were built into our work and could be revisited in future studies. First, potential error and scale effects in our biophysical ecosystem service models could lead to error in either our regression or hot-spot analysis. Data for our analysis were collected at different spatial scales. SolVES recommends analysis at a scale (output cell size) one thousandth the denominator of the survey map scale, with the assumption that a hand-marked point on a map is approximately one millimeter in width (Sherrouse and Semmens 2012). As rule-of-thumb guidance, this does not account for the uncertainty introduced by the ability of individual respondents to resolve a point to an intended location on the map; however, analyzed collectively, the points from all respondents provide a reasonable estimate of valued locations. The PSI map scale was 1:450,000, so we conducted our analysis at 450 m resolution. SWReGAP biodiversity data were

modeled at 30 m; ARIES input data ranged from 30 to 800 m, and ARIES modeling was conducted at 450 m to facilitate direct comparison to SolVES data. The effects of scale in the analysis of ecosystem services modeling have been an under-researched area, though research is appearing to address this gap in the literature (Kandziora et al. 2013; Grêt-Regamey et al. 2014). We used relevant datasets to parameterize each biophysical model (e.g., carbon sequestration and storage, evapotranspiration, infiltration, and soil erosion; ARIES Consortium 2014); however, the poor spatial resolution of many of these datasets precluded more rigorous model calibration via Bayesian network training (Villa et al. 2014). An initial comparative analysis of multiple biophysical ecosystem service assessment tools to a common context found general agreement between tools about the impacts of landscape-scale change on ecosystem service provision (Bagstad et al. 2013b). However, further work is needed to improve our confidence about the appropriateness of using different biophysical ecosystem service modeling tools across diverse geographic contexts.

Second, we weighted all biophysically modeled ecosystem services equally in our hotspot analysis. These services could alternatively be weighted through monetary valuation or public or expert-generated weighting schemes (Whitehead et al. 2014).

Third, the Getis-Ord G_i^* statistic provides a statistical method for hotspot delineation, but is not the only approach to hotspot identification and mapping. The Getis-Ord G_i^* statistic has both advantages and disadvantages. Unlike other approaches, such as Local Moran's I , Getis-Ord G_i^* can distinguish between hotspots of clustered high value and clustered low value. Its limitations include an inability to detect negative autocorrelation, a somewhat greater likelihood of Type 1 (false positive) errors than Local Moran's I , and greater sensitivity to the presence of overall global spatial structure or second-order trends in the data (i.e., the influence of other environmental gradients aside from clustering affecting hotspot analysis results). However, a preliminary comparison of hotspots for the PSI derived using Getis-Ord G_i^* and Local Moran's I methods yielded relatively similar hotspot extents and patterns. Sensitivity analysis that compares ecosystem service hotspot extents using different methods would be a useful area for further study.

Fourth, we recognize that not all of the social-values types align perfectly with the corresponding biophysically modeled services that we used in this study and that this is a potential source of error in our regression models (Tables 3, 4). In survey-based research, the wording and presentation of questions are well known to influence responses (Schwartz 1999). However, we believe that the very weak relationships we found indicate that even had

perfectly aligned biophysical measures been available for comparison to social values, weak relationships would have persisted.

Neither biophysical modeling nor social-values mapping tools have yet received widespread adoption by the Forest Service (Brown and Reed 2009). To be tractable at an agency-wide scale, particularly given limited agency resources and growing management demands, ecosystem service assessments need to be quantifiable, replicable, credible, flexible, and affordable (Bagstad et al. 2013a). Agency field offices, which are typically resource limited, could benefit greatly from generalizable models that can be applied across diverse geographic contexts (Kareiva et al. 2011; Villa et al. 2014) and demonstrably transferrable social-value models (Brown and Brabyn 2012; Sherrouse and Semmens 2014). Although local stakeholders and managers often feel their sites are too unique for generalized approaches to be applicable, generalized modeling tools have in some cases been shown to have adequate accuracy when compared to more data-intensive models (Tallis and Polasky 2011). The further development and testing of transfer models for social-values data (Sherrouse et al. 2011; Sherrouse and Semmens 2014) and of adaptable modeling systems (Villa et al. 2014) are two important paths forward. With expanding recent work to map and understand social values in national forests and elsewhere (Brown and Reed 2009; van Riper et al. 2012; Sherrouse et al. 2014; Sherrouse and Semmens 2014), the proliferation of tools for biophysical ecosystem service modeling (Bagstad et al. 2013a), and venues to archive and share such maps for wider use (ESP Maps 2014), it should be increasingly possible to pilot test our approach in other case study regions.

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