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RESEARCH ARTICLE

Evaluating alternative methods for biophysical and cultural ecosystem services hotspot mapping in natural resource planning

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Abstract
Context Data for biophysically modeled and Public Participatory GIS (PPGIS)-derived cultural ecosystem services have potential to identify natural resource management synergies and conflicts, but have rarely been combined. Ecosystem service hot/coldspots generated using different methods vary in their spatial extent and connectivity, with important implications.
Objectives We map biophysically modeled and PPGIS-derived cultural services for six U.S. national forests using six hot/coldspot delineation methods. We evaluate the implications of hotspot methods for management within and outside of designated wilderness areas.
Methods We used the ARIES and SolVES modeling tools to quantify four biophysically modeled and 11 largely cultural ecosystem services for six national forests in Colorado and Wyoming, USA. We mapped hot/coldspots using two quantile methods (top and bottom 10 and 33 % of values), two area-based methods (top and bottom 10 and 33 % of area), and two statistical methods (Getis-Ord Gi* at $\alpha = 0.05$ and 0.10 significance level) and compare results within and outside wilderness areas.
Results Delineation methods vary in their degree of conservatism for hot/coldspot extents and spatial clustering. Hotspots were more common in wilderness areas in national forests near the more densely populated Colorado Front Range, while coldspots were more common in wilderness areas in more urban-distant forests in northwest Wyoming.
Conclusions Statistical hotspot methods of intermediate conservatism (i.e., Getis-Ord Gi*, $\alpha = 0.10$ significance) may be most useful for ecosystem service hot/coldspot mapping to inform landscape scale planning. We also found spatially explicit evidence in support of past findings about public attitudes toward wilderness areas.

Keywords ARIES · Cultural ecosystem services · Hotspot analysis · Public Participatory GIS (PPGIS) · SolVES · Wilderness

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Introduction

Resource managers are increasingly seeking guidance on how to systematize ecosystem service assessments for use in decision making (36 CFR 219; McIntyre et al. 2008; U.K. National Ecosystem Assessment 2011; National Ecosystem Services Partnership 2014;

Council on Environmental Quality 2015; Schaefer et al. 2015). While biophysical models of increasing sophistication are helping to meet this need (Bagstad et al. 2013), cultural ecosystem services have not been well integrated into many assessments (Daniel et al. 2012), though Public Participatory GIS (PPGIS) approaches hold promise in this regard (Brown and Fagerholm 2015). For managers tasked with protecting and managing ecosystem services, an understanding of where the public values cultural services also holds promise in more proactively identifying management synergies and conflicts across space (Bagstad et al. 2015).

Bringing cultural ecosystem services into ecosystem service assessments

In recent years, consensus has emerged about the importance of biophysical modeling (Burkhard et al. 2012) and mapping (Hauck et al. 2013) as key components of ecosystem services assessments to support better environmental decision making. A variety of mapping and modeling tools have emerged to address this need (Kareiva et al. 2011; Martinez-Harms and Balvanera 2012; Bagstad et al. 2013; Villa et al. 2014). Most of these approaches are well suited for quantifying supporting, regulating, and provisioning services as defined by the Millennium Ecosystem Assessment (2005). However, with a limited number of exceptions, such as the viewshed component of aesthetic services (Kareiva et al. 2011; ARIES Consortium 2016), biophysical models are poorly equipped for quantifying cultural services-the non-tangible benefits that nature provides to people. Their intangible nature, lack of suitability or appropriateness for monetization, and the limited collaboration between ecologists and social scientists other than economists have limited the opportunities for cultural services to inform decision making (Chan et al. 2011, 2012; Daniel et al. 2012).

However, a parallel literature has developed, largely in the social sciences, to map public and expert perceptions of ecosystem services through PPGIS approaches that have been applied at sites worldwide (Sieber 2006; Dunn 2007; Raymond et al. 2009; Brown and Fagerholm 2015). These approaches ask the public, which can include residents, visitors, focus groups, and (or) online panels, to map locations that correspond to the places they perceive that the landscape provides ecosystem services. PPGIS may also include a value-allocation exercise that lets respondents prioritize different value types. These social-values mapping approaches are well suited to understanding values for cultural ecosystem services, including non-use values, and can thus quantify them to inform environmental planning and management decisions (Brown and Reed 2009; Brown 2012). Some PPGIS studies have asked respondents to also map supporting, regulating, and provisioning services (Raymond et al. 2009; Bryan et al. 2011; Brown et al. 2012). However, these studies acknowledge that asking the public to map complex ecological processes underpinning these service types places a high cognitive burden on respondents, which may reduce the accuracy of mapping these services using PPGIS.

In a recent paper (Bagstad et al. 2015), we proposed a method for jointly mapping cultural ecosystem services using PPGIS-derived maps alongside those services that are better assessed using biophysical models. Our method overlays hotspot maps for cultural and biophysical ecosystem services and identifies potential management issues that may arise in areas where there is concordance or discordance between these services. The approach allows cultural ecosystem services to be given equal weight in decision making with more easily monetized regulating and provisioning services, but it has not yet been demonstrated beyond one U.S. national forest. Concurrent mapping of biophysically modeled and cultural ecosystem services can provide a spatial approach to synthesizing such information for management in addition to more established approaches, such as multicriteria analysis (Hermans and Erickson 2007). Past work (Bagstad et al. 2015) and that presented here used the Artificial Intelligence for Ecosystem Services (ARIES, Villa et al. 2014) modeling platform to assess biophysical services and the social values for ecosystem services (SolVES, Sherrouse et al. 2011) tool to map cultural ecosystem services. However, other biophysical modeling and PPGIS approaches could be similarly combined.

Hotspots in conservation planning and ecosystem services assessment

Hotspots-areas of greater ecological value than the surrounding landscape-have a long history in conservation planning (Myers et al. 2000). Because biophysical and socioeconomic landscape characteristics are spatially heterogeneous and conservation budgets are limited, spatial targeting of conservation hotspots for biodiversity and ecosystem services can increase conservation's "bang for the buck" (Naidoo and Ricketts 2006; Polasky et al. 2008; Wünscher et al. 2008). Diverse hotspot delineation methods have been used increasingly in conjunction with ecosystem service mapping. Schröter and Remme (2016) provide a hotspot methods taxonomy for analysis of single and multiple services; commonly used methods include: (1) expert definition (Egoh et al. 2008), (2) quantile cutoffs, e.g., the top 10, 20, or 30 % of values (Gimona and van der Horst 2007; Alessa et al. 2008; Eigenbrod et al. 2010; Bai et al. 2011; Bryan et al. 2011; Law et al. 2015), and (3) statistical methods, such as the Getis-Ord Gi* statistic (Zhu et al. 2010; Bagstad et al. 2015) or Local Moran's I. Coldspots, the inverse of hotspots, and intermediate warmspots can be similarly spatially delineated.

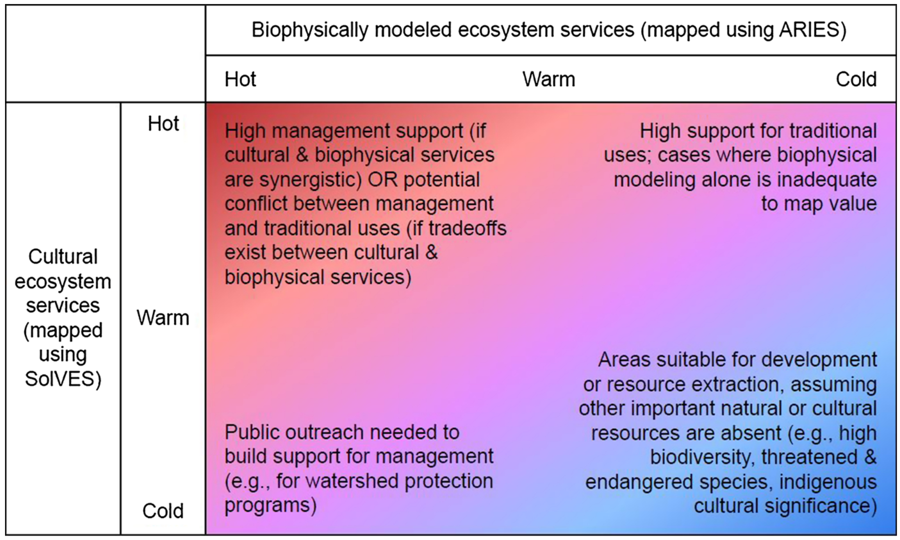
Sensitivity analysis on the implications of different choices of hotspot delineation methods has only recently been treated. Schröter and Remme (2016) compare results of multiple hotspot delineation methods for single and multiple services. Karimi et al. (2015) compare multiple hotspot delineation methods for PPGIS-derived cultural ecosystem services and their overlap with important biodiversity metrics, including an area-based approach (i.e., identifying the top values covering 10, 30, and 50 % of the study area). Both studies call for further research in this area. More work is particularly needed in combining biophysically modeled and PPGIS-mapped services as resource managers seek guidance on how to standardize ecosystem service assessments for use in decision making (36 CFR 219; McIntyre et al. 2008; U.K. National Ecosystem Assessment 2011; National Ecosystem Services Partnership 2014; Schaefer et al. 2015). While expert definition may be acceptable for one-time research projects or regional or national assessments, its subjectivity and the potential for it to give different answers depending on the expert group's composition renders it less desirable for systematic assessments. By testing how the use of different threshold values in quantile and area-based cutoffs and statistical hotspot delineation methods influence the presentation of biophysical and cultural ecosystem service assessment across a relatively expansive geographic region—six large national forests in the western U.S.—we can better understand how the choice of hotspot delineation method affects the conclusions presented to resource managers.

Bagstad et al. (2015) presented a 2 × 2 matrix describing potential management implications of ecosystem services hotspots/coldspots. In reality, however, hotspots and coldspots are a continuum rather than a dichotomy, as are their management implications (Fig. 1). In other words, a continuum of hotspots, warmspots, and coldspots–a 3 × 3 matrix—offers more information to resource managers about the relative value of the landscape. For instance, in our analysis of Colorado's Pike-San Isabel National Forest that used the Getis-Ord Gi* statistic with an $\alpha = 0.05$ significance level, 79.4 % of the landscape was classified as coldspots (i.e., everything but hotspots) for both cultural and biophysical ecosystem services (Bagstad et al. 2015). Splitting those coldspots into warm and cold regions would allow managers to better distinguish areas where greater human use can be distributed at less risk to ecosystem service provision, and where management resources are best spent in the protection and management of cultural and biophysical services.

Ecosystem services and wilderness areas

In the United States, wilderness areas are legally designated portions of public lands where, per the Wilderness Act of 1964, "…earth and its community of life are untrammeled by man, where man himself is a visitor who does not remain" (16 USC 1131–1136). For practical purposes, these areas have limited human influences on ecosystems, though they provide important ecosystem services (Watson and Venn 2012) and are open to non-motorized recreation. Efforts to catalog and quantify wilderness ecosystem services have, however, generally tended toward isolated case studies rather than systematic, quantitative, spatial analyses. In our previous study, we found that hotspots for biophysical and cultural services were relatively more common in wilderness than non-wilderness areas of the Pike-San Isabel National Forest, which is located near the cities of Denver and Colorado Springs (Bagstad et al. 2015). Conversely, in a preliminary analysis of cultural ecosystem services hotspots in the Bridger-Teton and Shoshone national forests in rural northwest Wyoming, drawn from Sherrouse et al. (2014), service values were greater

Fig. 1 Potential management implications of cultural and biophysical ecosystem services hotspot/coldspot analysis



outside of than within wilderness areas. One past PPGIS study, for the Chugach National Forest in Alaska, explored whether respondents are more likely to place certain value types within or outside wilderness areas (Brown and Alessa 2005). They found wilderness areas to be associated with intrinsic, future, and life-sustaining values and non-wilderness areas to be associated with recreation, economic, and subsistence values. However, the maps provided to survey respondents for the Alaska study did not have wilderness boundaries marked. Unlike the forests we analyze here, survey respondents in the Alaska study lacked a priori information about the location of wilderness and non-wilderness areas.

Past results from studies from three of the six national forests in this study (Clement and Cheng 2011; Sherrouse et al. 2014; Bagstad et al. 2015) generally support earlier research about attitudes toward wilderness in the western United States. In a nationwide survey, Cordell et al. (1998) found that metropolitan residents were slightly more likely than rural residents to feel that there has not been an adequate amount of wilderness designated nationwide. However, these differences were not statistically significant. Rudzitis (1999) found that while urban and rural residents both supported management of public lands for wilderness, urban residents' support for wilderness management was slightly stronger. He also found that individuals working in resource-based occupations including ranching, forestry, and mining ranked wilderness protection as less important than those who worked in other occupations. By contrast, Durant and Shumway (2004) found widespread local opposition to wilderness study areas (WSAs) in southeastern Utah. Residents of towns with more diversified economies and residents who had more recently moved to their city were more supportive of WSAs than longer-term residents and those living in towns with less diversified economies. Durant and Shumway attributed this opposition to WSAs to pushback against what some residents perceived as heavy-handed efforts by "outsiders" to designate wilderness in ways that bypassed local involvement in decision making. While public attitudes about wilderness are complex and multidimensional, our past findings (Bagstad et al. 2015) align with those from other studies of public attitudes toward wilderness, with urban residents placing greater value on wilderness than their rural counterparts. However, our work adds a spatial component to understanding wilderness values that has received limited past treatment, which may assist in understanding contexts of greater or lesser public support for wilderness. An analysis of biophysically modeled and cultural ecosystem service hotspots for six national forests offers the opportunity to expand our understanding of the spatial patterns of ecosystem services within and outside wilderness areas in Western national forests.

In this paper, we extend a past analysis for the Pike-San Isabel National Forest (PSI) in Colorado (Bagstad

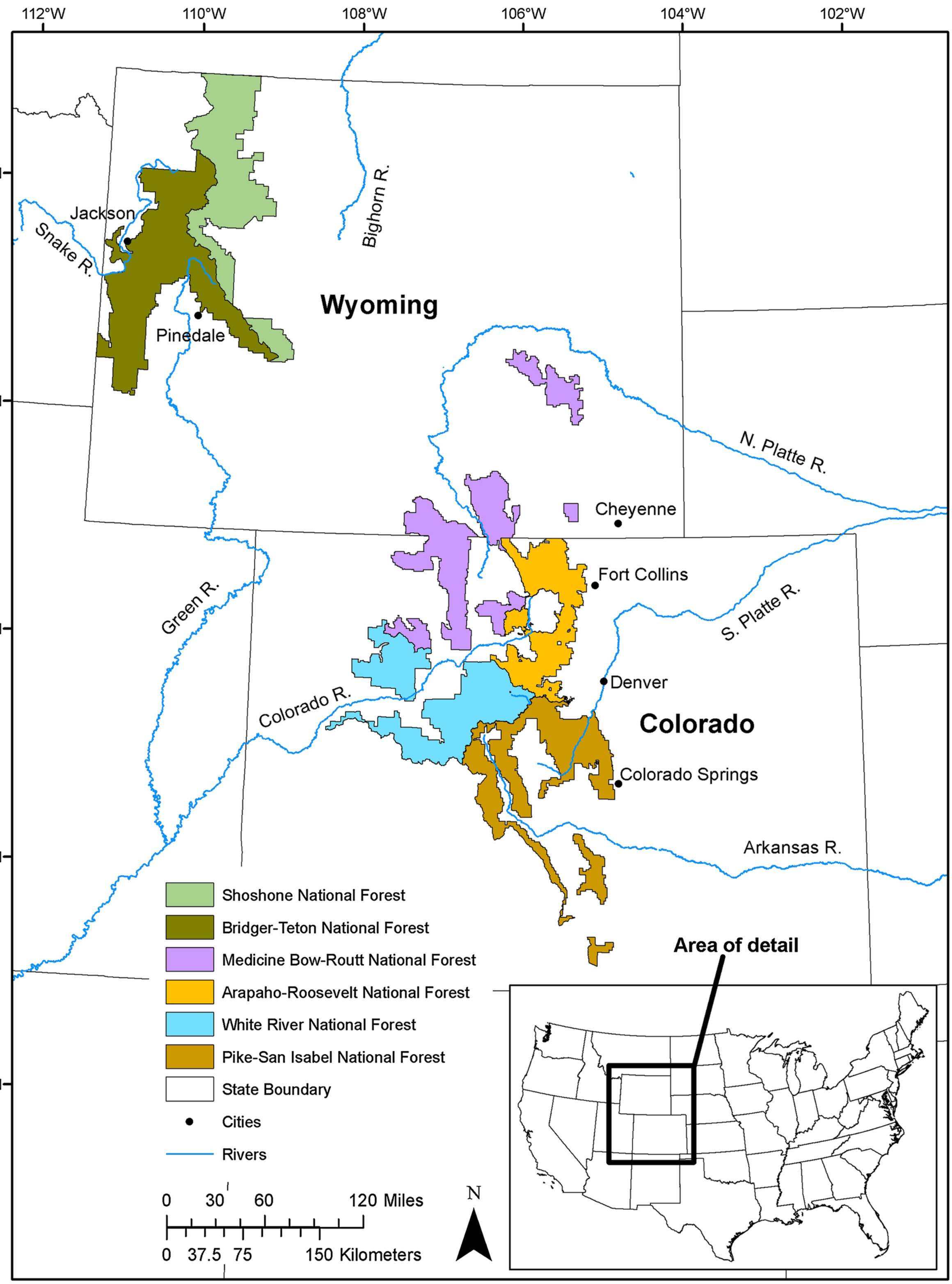


Fig. 2 Study area map

et al. 2015) to six national forests in Colorado and Wyoming (Fig. 2). From southeast to northwest, these include the PSI, Arapaho–Roosevelt National Forest (AR), White River National Forest (WR), Medicine Bow-Routt National Forest (MBR), Bridger-Teton National Forest (BT), and Shoshone National Forest (SNF). Our objectives are to: (1) provide an expanded example of the joint use of PPGIS-derived cultural and biophysically modeled ecosystem service information for use in natural resource planning, (2) evaluate the relative effects of the choice of hotspot/coldspot delineation method on the number and compactness of the delineated hotspot/coldspot areas, and (3) quantify differences in the provision of ecosystem services from Federally designated wilderness and non-wilderness areas across an urban–rural gradient.

Methods

Study area

Our study area includes six national forests in the Southern and Central Rocky Mountains, stretching from southern Colorado to northwest Wyoming (Fig. 2). They total 56,895 km^2, about 11 % of Colorado and Wyoming's combined land area. Ecologically they belong to the Southern and Central Rockies ecoregions. In Rocky Mountain forests with low- and mixed-severity fire regimes (i.e., excluding subalpine forests), a century of fire suppression has resulted in increased tree density, leading to more intense fires in recent years (Schoennagel et al. 2004). Additionally, recent bark beetle outbreaks have received growing public and scientific attention (Raffa et al. 2008). These forests are critical source areas for water in most of the western U.S., feeding the Arkansas, Platte, Colorado, Green, Missouri, and Snake Rivers. Socioeconomically they are far more heterogeneous. The PSI and AR are located directly adjacent to Colorado's populous Front Range, and are important recreational amenities for millions of residents and visitors. The WR includes some of the most visited ski areas in the U.S. Moving to the north, the MBR, BT, and SNF are located in less densely populated, more rural regions. The demographics of communities located near these forests thus differ substantially between the six forests (Clement and Cheng 2011).

PPGIS mapping of cultural ecosystem services

We generated maps of social values for ecosystem services, which largely correspond to cultural ecosystem services, using the SolVES 2.1 tool, a GIS application designed to quantify and map perceived social values for ecosystem services (Sherrouse et al. 2011, 2014). We acquired data from mail surveys, which were sent to a random sample of 2000 residents living within counties surrounding each of the BT, PSI, and SNF and 1500 residents within counties surrounding each of the AR, MBR, and WR national forests (Czaja and Cottrell 2014; Sherrouse et al. 2014; Supplementary material). The surveys first asked questions to gage respondents' attitudes and preferences toward forest management, then asked respondents to allocate 100 hypothetical dollars–not actually paid or spent by the respondent or the Forest Service-among 13 value types (based on Rolston and Coufal's (1991) forest values typology, Supplementary material). Finally, respondents were asked to mark locations on paper maps that correspond to those value types. Maps for each forest included the locations of forest boundaries, recreation sites, roads and other access points, place names, and designated wilderness boundaries. Two of these value types (biodiversity and life sustaining) were previously shown to be poor proxies for maps generated using biophysical models (Bagstad et al. 2015); we thus exclude these from our analysis. Of the remaining 11 value types, nine (aesthetic, cultural, future, historic, intrinsic, learning, recreation, spiritual, and therapeutic) correspond directly to cultural ecosystem services, while two (economic and subsistence value) correspond to provisioning services for which suitable biophysical data or models do not exist and PPGIS can serve as a suitable mapping method (Brown et al. 2012). Since cultural services make up nine of the 11 social-value types that encompass public perceptions of ecosystem services, we refer to them collectively as "cultural ecosystem services" through the rest of this paper.

The points marked by survey respondents on the forest maps were digitized into a GIS where they were related to their corresponding allocation amounts (Sherrouse et al. 2014). SolVES and the MaxEnt algorithm (Elith et al. 2011) were then applied to the data, developing statistical models relating the location of mapped points for each service to six environmental data layers (land cover, landforms, elevation, slope, distance to roads, and distance to water; Sherrouse and Semmens 2014). MaxEnt generates area under the curve (AUC) statistics that evaluate each model's goodness of fit to the study area (training AUC) and its potential for transferability to other regions where primary survey data are unavailable (test AUC). These models were generated individually for each forest to reflect the responses of each forest's survey respondents. Using these models, along with additional information describing the relative point density and total allocation amounts of each value type, SolVES derived a series of value maps for each forest rendered as a 10-point "value index." Value index maps for each service are calculated by multiplying the Maxent-derived logistic surface with values ranging from 0 to 1 (corresponding to the likelihood that respondents would assign value to a location) by a "Max VI" layer with values ranging from 1 to 10 (corresponding to a weighted kernel density surface normalized by the maximum density for each service, Sherrouse et al. 2014). The value index, ranging from 0 to 10, represents a relative, non-monetary, spatially explicit value for each cultural ecosystem service. All SolVES output was generated at a spatial resolution of 450 m, as determined from the scale of the hard-copy maps (1:450,000) included with the mail surveys.

Biophysical modeling of ecosystem services

We mapped four ecosystem services by pairing spatial data with biophysical models for the Rocky Mountains included in the ARIES modeling platform (Villa et al. 2014). We ran models for carbon sequestration and storage, water yield, sediment regulation, and aesthetic viewsheds from recreation sites and residences with views of the six forests. Based on our discussions with forest managers, these services are recognized for their importance in management—related to, for example, forests' ability to supply sediment-free water for diverse uses, to provide aesthetically valued views, and for tracking carbon sequestration and storage given the interrelated challenges of fire, bark beetle outbreaks, and climate change. Although viewsheds are typically classified as a cultural ecosystem service, it is possible to build biophysical models to represent them (Kareiva et al. 2011; ARIES Consortium 2016), as we do here.

We modeled carbon sequestration and storage using Bayesian models that account for vegetation, soil, and climatic influences. We calibrated carbon sequestration, vegetation carbon storage, and soil carbon storage models using Moderate-resolution Imaging Spectroradiometer Net Primary Productivity (Numerical Terradynamic Simulation Group 2016), National Biomass and Carbon Dataset (Kellndorfer et al. 2012), and Soil Survey Geographic Database (Natural Resources Conservation Service 2016) soils data, respectively.

We modeled scenic views to homeowners and recreationists using Bayesian models that rank ecosystems providing high-quality views and features that impede or degrade view quality (based on a review by Bourassa et al. 2004), along with locations of housing in view of and recreation sites within the national forests. These viewshed source, sink, and use locations were linked by a flow model that computed visibility along lines of sight from use locations to scenic viewshed features, which accounts for the influence of distance decay on view quality (Villa et al. 2014).

Although the revised universal soil loss equation (RUSLE) is commonly used to quantify erosion, it is known to perform poorly on younger, steeply sloped soils like those found in the Rocky Mountains (Renard et al. 1996). We instead modeled soil erosion using a Bayesian model incorporating vegetation, soils, topographic, and rainfall influences, calibrated on a relative scale using regional data from coarser scale and/or RUSLE-derived erosion models, with greater values for soil retention placed on areas of less soil erosion.

We quantified water yield using Bayesian models of evapotranspiration that accounted for vegetation, soil, and topographic influences on hydrology. We calibrated the models using coarser resolution hydrologic model output (Brown et al. 2008), then subtracted evapotranspiration from mean annual precipitation to estimate water yield.

Further descriptions of data sources, model structure, and assumptions are included in the Supplementary material and ARIES Consortium (2016). All models used national and regional spatial data. Based on a literature search about ecological processes and ecosystem service supply and use in the southern and central Rocky Mountains, we adapted models to account for regionally important ecological and socioeconomic influences on ecosystem service supply and demand. For instance, elements valued in viewsheds in the Rocky Mountains were incorporated based on regional visual preference studies, and the influence of bark beetle and fire damage to forests on ecosystem service provision was accounted for in the models (ARIES Consortium 2016).

Hotspot/coldspot analysis

We used six methods to map ecosystem service hotspots/coldspots, comparing results using quantile, area-based, and statistical methods and with varying levels of conservatism (i.e., more conservative methods identify fewer areas as hotspots/coldspots): (1) top and bottom 33 % of values, (2) top and bottom 10 % of values, (3) top and bottom values covering 33 % each of each forest's total area, (4) top and bottom values covering 10 % each of each forest's total area, (5) Getis-Ord Gi* statistic (Getis and Ord 1992) at $\alpha = 0.10$ significance level, and (6) Getis-Ord Gi* statistic at $\alpha = 0.05$ significance level. Although other spatial statistical methods like Local Moran's I can assess clustering (i.e., hotspots), the Getis-Ord Gi* statistic has the advantage of being able to distinguish hotspots/coldspots of clustered high and low value.

We summed the model outputs for the 11 PPGIS-derived cultural and the four biophysically modeled ecosystem services. The value index for cultural services can range from 0 to 10 for each service, yielding a theoretical maximum value of 110, but the maximum summed value index for all cultural ecosystem services in a given cell ranged from 37 in MBR to 52 in PSI. SolVES generates this value index based on respondents' relative weightings of the value types and the density of points placed on maps, which is why more frequently valued services like aesthetic and recreation have greater values than those like therapeutic and learning (Sherrouse and Semmens 2015). We equally weighted the four biophysically modeled services, normalizing each service's value from 0 to 1 (rescaling the individual maps for the two carbon and viewshed metrics—carbon sequestration and storage, views provided to recreation sites and residences—from 0 to 0.5) before summing them. A maximum value of four could theoretically occur for the summed biophysical ecosystem service layer, but the actual maximum actual value ranged from 2.69 in AR to 2.97 in PSI, indicating only moderate overlap between areas of maximum provision of the four services. An alternative approach, not taken in this paper, could be to weight biophysical services using monetary valuation or public or expert-generated weighting schemes (Whitehead et al. 2014).

We then identified the top/bottom 33 and 10 % of summed cultural and biophysical values plus the top/bottom values needed to cover the top/bottom 33 % and 10 % of each forest by area. We ran the Getis-Ord Gi* tool on both summed layers to identify hotspots/-coldspots at the two significance levels based on appropriate critical values. For each of the six methods, and for each forest (1) area of each forest within the nine categories of cultural and biophysical hotspots/warmspots/coldspots; (2) edge: area ratio of biophysical and cultural ecosystem service hotspots, calculated following Wilson et al. (2010) and Schröter and Remme (2016) as:

$$\text{Ratio} = \text{perimeter}/(2 \times \sqrt{(\pi \times area)}); \tag{1}$$

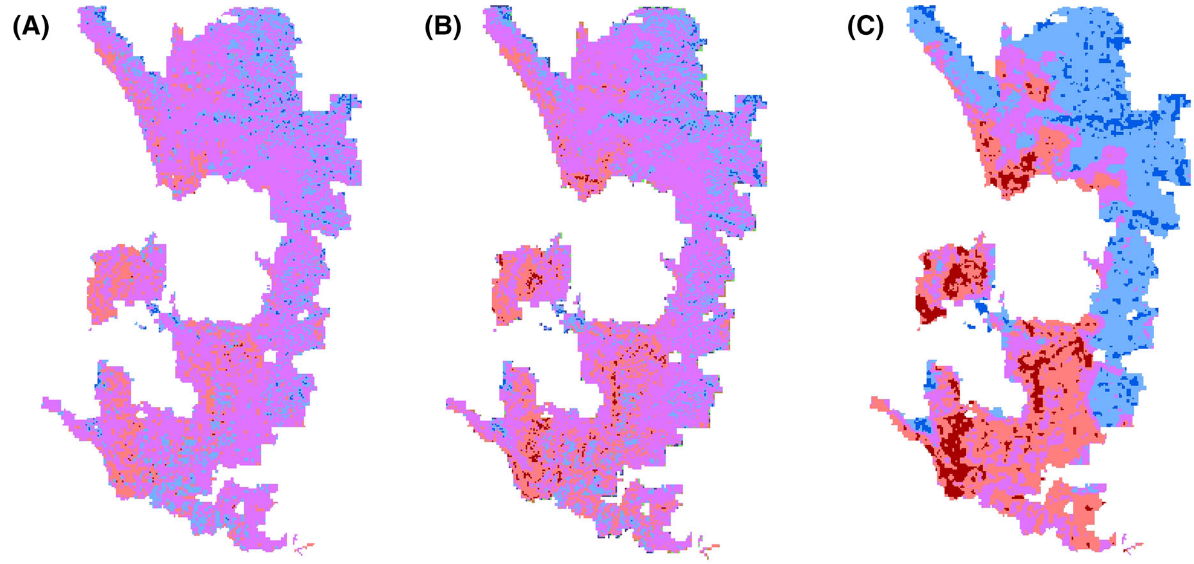
and (3) number of individual hotspot patches. The latter two metrics provide an estimate of the number and compactness of the hotspot areas, which has implications for conservation and management (Schröter and Remme 2016).

Fig. 3 Hotspot/coldspot maps and areas for Arapaho–Roosevelt National Forest under six alternative delineation methods–quantile cutoffs (*top* and *bottom* 33 and 10 % of values), area cutoffs (values covering the *top* and *bottom* 33 and 10 % of area), and statistical methods (Getis-Ord Gi* method at $\alpha = 0.05$ and 0.10 significance level). Wilderness areas are outlined in *black* and area summaries are provided for the Getis-Ord Gi* statistical method at $\alpha = 0.10$ significance level ▶

Results

Impacts of methodological choices on hotspot/coldspot areas

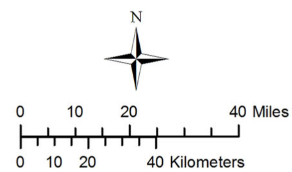
We present results for Arapaho–Roosevelt and Shoshone national forests below (Figs. 3, 4), and include spatial and tabular hotspot/coldspot results for the other four forests in the Supplementary material. Quantile and area-based cutoffs identified the greatest and least amount of area as hotspots/coldspots, i.e., were least and most conservative (top and bottom 33 and 10 % of values, respectively); statistical methods identified intermediate amounts of hotspot/coldspot area, with the $\alpha = 0.05$ significance level identifying less hotspot/coldspot area than at $\alpha = 0.10$

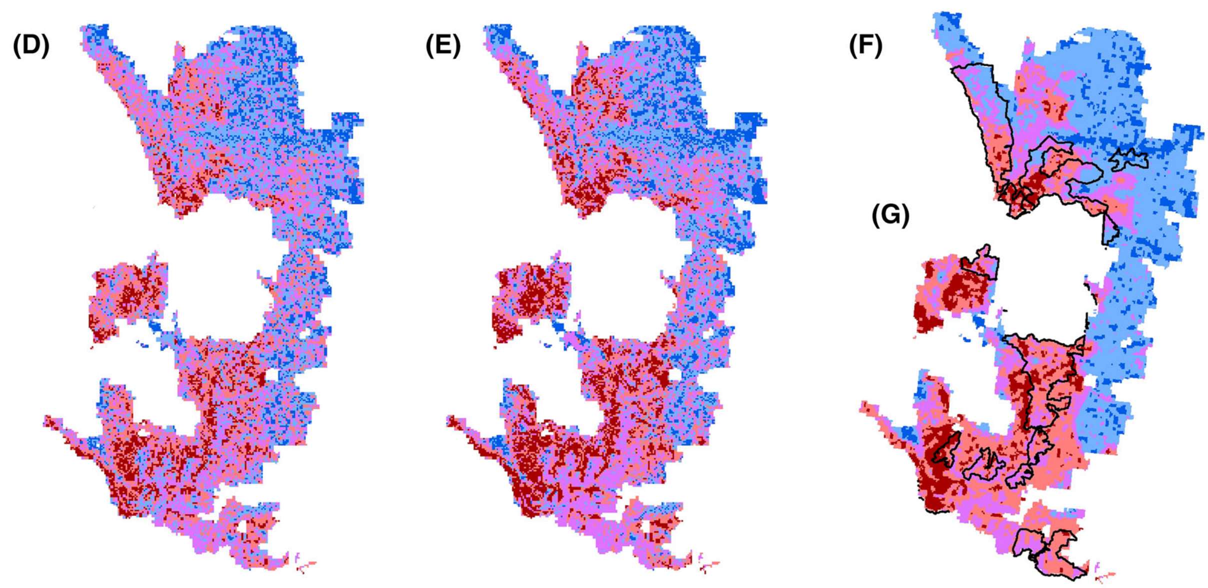


A) 10% - Quantile		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	0.1%	1.1%	0.5%
	Warm	9.7%	69.9%	8.2%
	Cold	0.1%	9.2%	1.2%

B) 10% - Area		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	1.2%	8.6%	0.1%
	Warm	6.7%	64.8%	8.7%
	Cold	2.0%	6.6%	1.3%

C) α = 0.05		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	7.2%	23.4%	6.3%
	Warm	2.9%	16.6%	1.7%
	Cold	1.2%	34.4%	6.3%





D) 33% - Quantile		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	9.1%	6.2%	7.3%
	Warm	16.4%	16.2%	14.9%
	Cold	7.8%	11.0%	11.1%

E) 33% - Area		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	12.0%	12.8%	8.5%
	Warm	10.5%	12.7%	10.5%
	Cold	10.4%	8.6%	14.0%

F) α = 0.10		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	9.7%	21.2%	7.4%
	Warm	3.8%	12.6%	1.8%
	Cold	2.5%	32.9%	8.1%

G) α = 0.10 wilderness only		Biophysical		
		Hot	Warm	Cold
Cultural	Hot	13.6%	37.1%	14.9%
	Warm	3.3%	10.2%	0.7%
	Cold	4.8%	14.1%	1.3%

significance. For example, the very conservative 10 % quantile method identified 69.9 % of AR and 63.8 % of SNF as warm/warm and just 1.3 and 1.5 % of AR and SNF as hot/hot or cold/cold. The very non-conservative 33 % quantile method identified 16.2 % of AR and 12.1 % of SNF as warm/warm and 20.2 and 20.9 % of AR and SNF as hot/hot or cold/cold. Quantile and area-based cutoffs typically yielded relatively similar results at comparable levels of conservatism (i.e., top and bottom 10 % or top and bottom 33 %). However, in a few cases, area-based cutoffs were somewhat less conservative than quantile cutoffs—for example, identifying greater areas as hot/hot and cold/cold (AR, MBR, WR) and less area as warm/warm (WR; Figs. 3, 4, Supplementary material).

Quantile- and area-based methods produced more pixelated, less clustered hotspot/coldspot maps than statistical methods, which by their nature delineate high and low value clusters (Figs. 3, 4; Table 1). The edge: area ratio for hotspots was about twice as great when using the 33 % quantile and area-based method as 10 % quantile and area-based methods and the statistical methods. Less conservative methods produced more individual hotspot patches. On average the 33 % quantile method identified eleven times the number of hotspot patches as the 10 % quantile method and 4.5–6.5 times the number of hotspot patches as the more clustered statistical methods. Similarly, the 33 % area method identified six times the number of hotspot patches as the 10 % area method and 5.3–7.6 times the number of hotspot patches as the statistical methods.

Fig. 4 Hotspot/coldspot maps and areas for Shoshone National ▶ Forest under six alternative delineation methods—quantile cutoffs (*top* and *bottom* 33 and 10 % of values), area cutoffs (values covering the *top* and *bottom* 33 and 10 % of area), and statistical methods (Getis-Ord Gi* method at $\alpha = 0.05$ and 0.10 significance level). Wilderness areas are outlined in *black* and area summaries are provided for the Getis-Ord Gi* statistical method at $\alpha = 0.10$ significance level

We present and compare hotspot/coldspot maps and areas for all six forests using the Getis-Ord Gi* statistic at $\alpha = 0.10$ significance level–a clustered delineation method of intermediate conservatism (Table 2, Fig. 5). Bridger-Teton National Forest had the greatest coverage of warmspots and relatively less area as hotspots/coldspots. This was followed by White River, Pike-San Isabel, and Shoshone National Forest. Medicine Bow-Routt and Arapaho–Roosevelt had the greatest hotspot/coldspot extents and the least warmspot coverage.

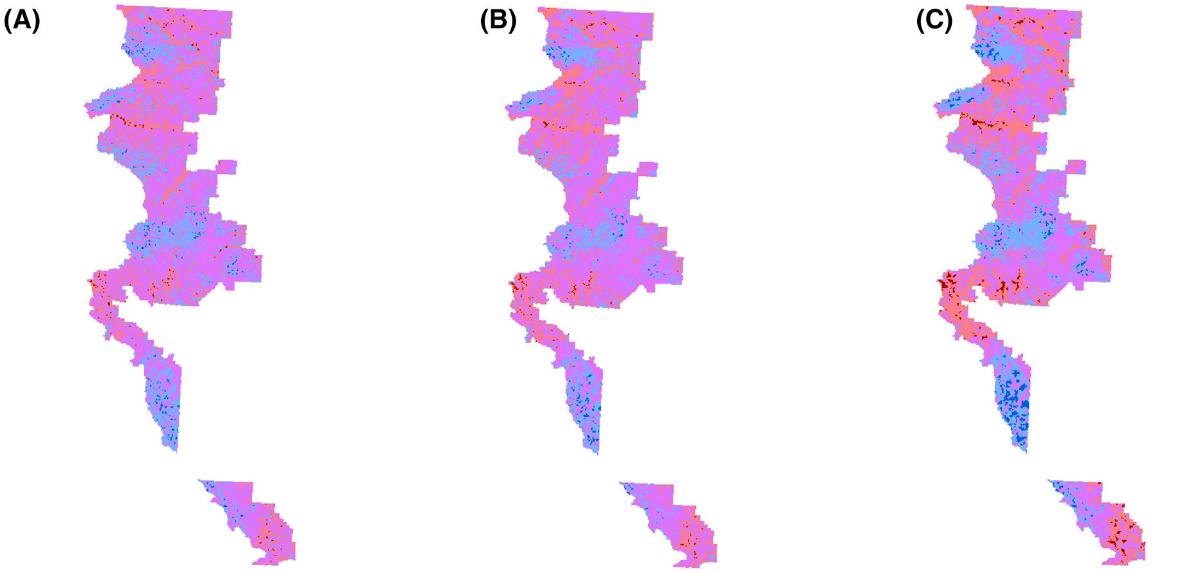
Ecosystem services hotspots/coldspots in wilderness areas

Wilderness areas provided consistently greater water yield and scenic viewshed values across all forests based on biophysical model results (Table 3). Public Participatory GIS-derived cultural ecosystem services were consistently greater in wilderness than non-

Table 1 Edge: area ratios and total number of hotspot patches for biophysically modeled and cultural ecosystem services, by forest and method

Method	AR	BT	MBR	PSI	SNF	WR	Average
Edge: area ratio							
10 % quantile	7.5	11.9	12.6	9.2	13.4	10.9	10.9
33 % quantile	32.1	54.7	40.9	38.3	35.6	15.7	36.2
10 % area	15.9	15.7	21.0	13.1	13.7	17.0	16.1
33 % area	32.2	53.8	36.9	41.5	32.8	47.9	40.9
Getis-Ord Gi*, $p < 0.05$	14.5	14.2	20.6	8.6	15.2	15.7	14.8
Getis-Ord Gi*, $p < 0.10$	15.8	18.4	21.9	11.6	18.5	20.5	17.8
# of hotspot patches							
10 % quantile	44	110	122	65	135	93	95
33 % quantile	693	2213	1120	1180	906	197	1052
10 % area	181	197	328	128	137	226	200
33 % area	623	2171	893	1346	783	1615	1212
Getis-Ord Gi*, $p < 0.05$	145	157	247	65	160	182	159
Getis-Ord Gi*, $p < 0.10$	165	249	280	125	239	314	229

AR Arapaho–Roosevelt National Forest, *BT* Bridger-Teton National Forest, *MBR* Medicine Bow-Routt National Forest, *PSI* Pike-San Isabel National Forest, *SNF* Shoshone National Forest, *WR* White River National Forest



A)

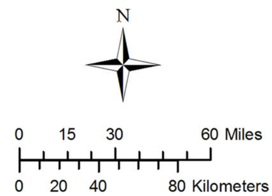
10% - Quantile		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	0.5%	5.8%	0.8%
Cultural	Warm	8.2%	63.8%	8.2%
Cultural	Cold	0.9%	10.8%	1.0%

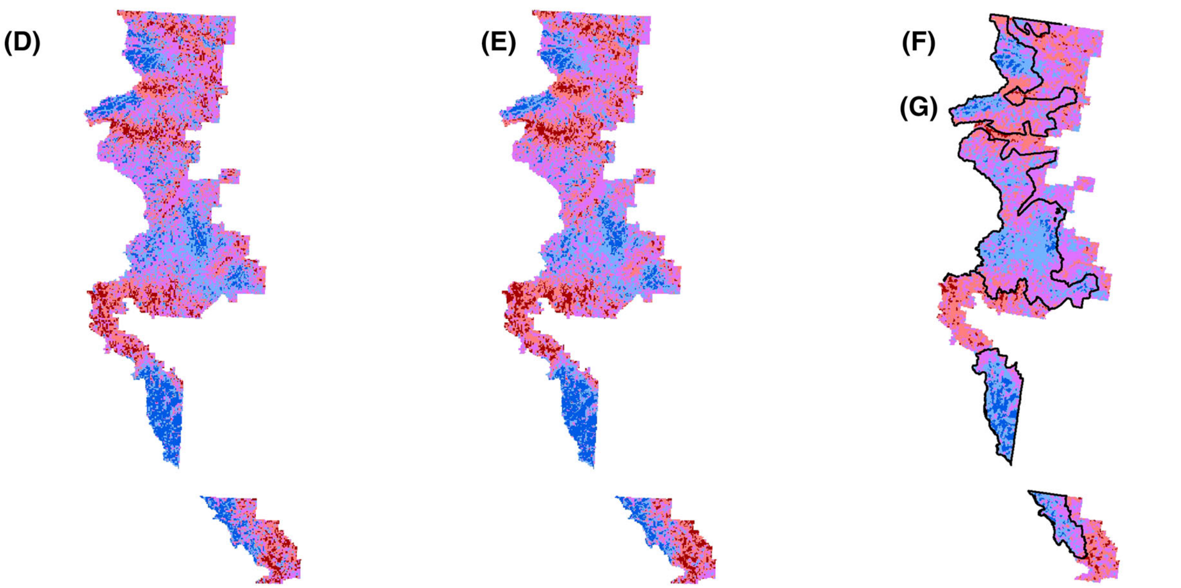
B)

10% - Area		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	0.8%	8.4%	0.7%
Cultural	Warm	7.8%	63.5%	8.8%
Cultural	Cold	1.4%	8.1%	0.5%

C)

α = 0.05		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	1.4%	13.0%	3.7%
Cultural	Warm	9.1%	47.8%	9.4%
Cultural	Cold	1.8%	11.2%	2.6%





D)

33% - Quantile		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	8.9%	9.4%	11.6%
Cultural	Warm	11.4%	12.1%	9.6%
Cultural	Cold	12.6%	12.4%	12.0%

E)

33% - Area		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	11.0%	10.5%	11.8%
Cultural	Warm	9.5%	12.1%	12.1%
Cultural	Cold	12.4%	11.5%	9.1%

F)

α = 0.10		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	2.5%	12.9%	5.2%
Cultural	Warm	10.7%	35.5%	9.2%
Cultural	Cold	4.3%	14.8%	4.9%

G)

α = 0.10 wilderness only		Biophysical Hot	Biophysical Warm	Biophysical Cold
Cultural	Hot	0.3%	1.4%	0.4%
Cultural	Warm	11.6%	35.2%	9.3%
Cultural	Cold	7.4%	25.7%	8.7%

wilderness areas in the PSI; the converse was true for SNF. For the remaining four forests, some wilderness values were greater than the forest-wide average (e.g., intrinsic value) while others were below average (e.g., subsistence value).

This led to hotspots that were more common in wilderness areas than for the entire forest in the Arapaho–Roosevelt, Medicine Bow-Routt, Pike-San Isabel, and White River national forests (Supplementary material). However, hotspots were relatively less common in Shoshone National Forest wilderness areas than for that entire forest. Conversely, coldspots were less common in wilderness areas than across the entire forest for the former four forests, and were more common within Shoshone National Forest wilderness than in that forest as a whole (Figs. 3, 4, 5). Wilderness areas in Bridger-Teton National Forest contained relatively more hotspots and coldspots than the forest as a whole.

Discussion

Implications of hotspot delineation methods for natural resource management

The choice of hotspot delineation method has important implications if hotspot analysis is to be useful for identifying management synergies and tradeoffs in landscape-scale conservation and natural resource management (Karimi et al. 2015; Schröter and Remme 2016). Quantile, area-based, and statistical methods differ by both the degree of hotspot/coldspot clustering and the number of individual hotspots/coldspots identified. By definition, statistical hotspot methods produce more clustered hotspots/coldspots than quantile cutoffs. For example, Schröter and Remme (2016) found edge-to-area ratios for ecosystem service hotspots of 15.8 using quantile cutoffs and 4.4 using the Getis-Ord Gi* method. Similarly, our edge: area ratios were over twice as large for the 33 % quantile and area-based cutoff method as the statistical methods (Table 1). More clustered hotspots/coldspots (i.e., using statistical methods) identify contiguous areas suitable for forest-scale identification of conservation, management, or extractive use areas. Clustering may, however, "miss" important small, scattered, or linear features–for instance, springs or riparian corridors that might still show up as high-value areas when using quantile cutoffs.

Fig. 5 Hotspot/coldspot maps for six national forests using Getis-Ord Gi* statistic at $\alpha = 0.10$ significance level. Wilderness areas are outlined in *black* ▶

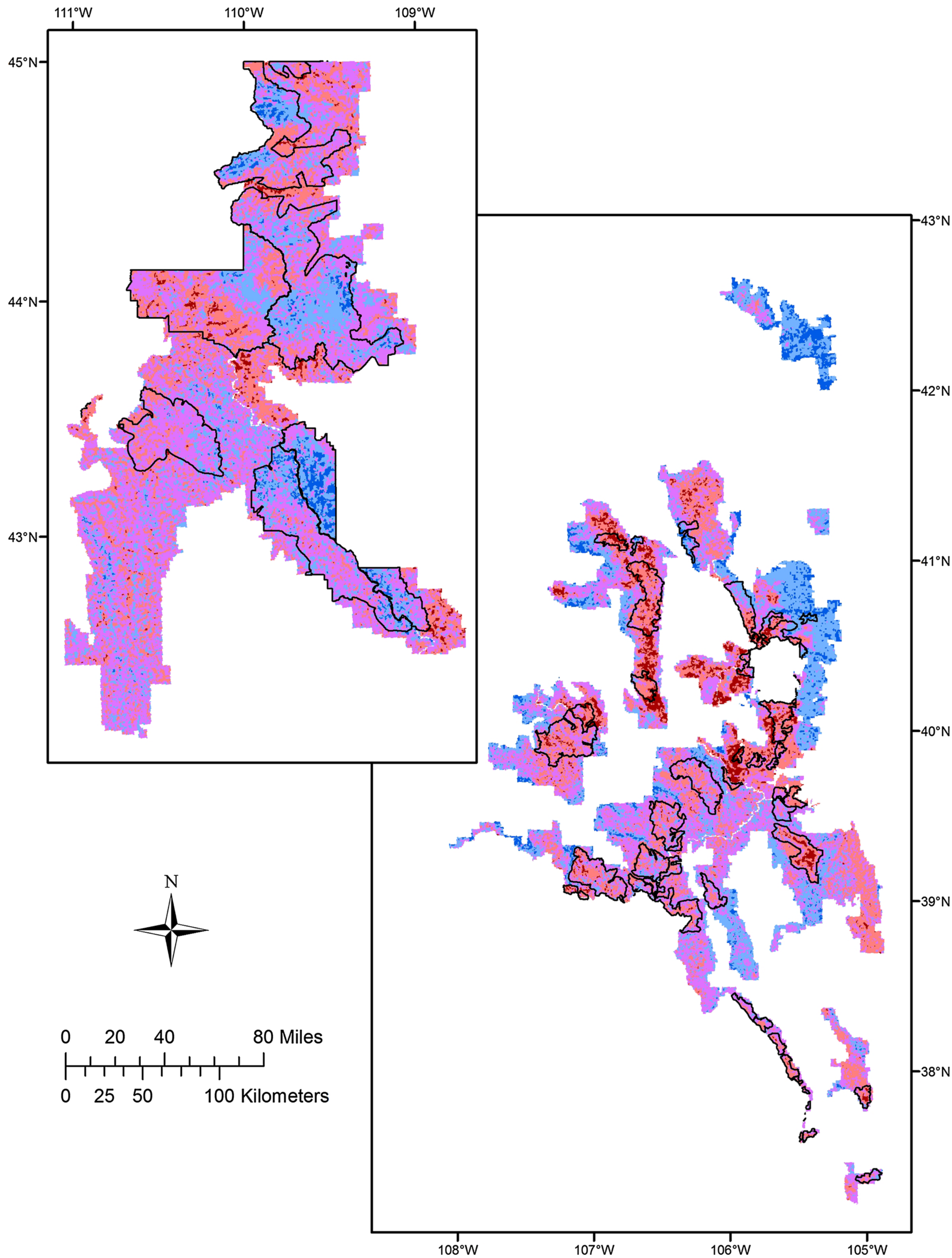
When undertaking planning for large national forests covering thousands of square kilometers, management designations are more likely to be applied over larger areas, with fine-scale management actions taking place later. Hence planning for the

Table 2 Hotspot, warmspot, and coldspot coverage for six national forests using Getis-Ord Gi* statistic at $\alpha = 0.10$ significance level

	AR (%)	MBR (%)	WR (%)	PSI (%)	BT (%)	SNF (%)
Cultural-hot/biophysical-hot	9.7	10.2	1.9	1.6	1.1	2.5
Cultural-hot/biophysical-warm	21.2	8.8	16.2	16.7	13.6	12.9
Cultural-hot/biophysical-cold	7.4	1.2	0.9	5.1	3.2	5.2
Cultural-warm/biophysical-hot	3.8	16.7	8.6	7.7	8.3	10.7
Cultural-warm/biophysical-warm	12.6	29.1	43.4	40.8	48.4	35.5
Cultural-warm/biophysical-cold	1.8	14.3	9.7	7.5	7.3	9.2
Cultural-cold/biophysical-hot	2.5	3.4	3.9	2.9	5.4	4.3
Cultural-cold/biophysical-warm	32.9	7.2	11.7	16.1	11.3	14.8
Cultural-cold/biophysical-cold	8.1	9.1	3.7	1.6	1.4	4.9

Columns sum to 100 % of the area of each forest

AR Arapaho–Roosevelt National Forest, *BT* Bridger-Teton National Forest, *MBR* Medicine Bow-Routt National Forest, *PSI* Pike-San Isabel National Forest, *SNF* Shoshone National Forest, *WR* White River National Forest


111°W
110°W
109°W
45°N
44°N
43°N
43°N
42°N
41°N
40°N
39°N
38°N
108°W
107°W
106°W
105°W
N
0 20 40 80 Miles
0 25 50 100 Kilometers

management of a larger number of more fragmented hotspots may be more difficult and less biologically meaningful than for fewer, larger, more clustered hotspots (i.e., the 33 % quantile method produced 4.6 times more hotspots with an edge: area ratio twice that of the Getis Ord-Gi* method with $\alpha = 0.10$ significance, and the 33 % area method produced 5.3 times more hotspots with an edge: area ratio 2.3 times greater than the Getis Ord-Gi* method with $\alpha = 0.10$ significance; Table 1).

Finally, a reasonable level of hotspot/coldspot resolution is desirable relative to warmspots (Karimi et al. 2015). Very conservative hotspot/coldspot delineation methods will identify most areas as warmspots. For the six forests, the very conservative 10 % quantile method identified 63.8–69.9 % of each forest as warm/warm and just 0.9–2.6 % of each forest as hot/hot or cold/cold. Identifying such small extents as hot/hot or cold/cold may be less helpful for decision making. Overly non-conservative methods identify larger hotspot/coldspot areas. For instance, the very non-conservative 33 % quantile method identified 10.3–28.4 % of each forest as warm/warm and 4.3–20.9 % of each forest as hot/hot or cold/cold. Comparable area and quantile-based cutoffs (i.e., 10 or 33 %) generally had similar conservatism, though for a few forests, area-based cutoffs identified somewhat greater hot/hot and cold/cold areas than their comparable quantile cutoff method. While a very non-conservative approach may be desirable in some cases, it lumps together extremely high- or low-value areas with moderately high- or low-value areas as hotspots/-coldspots, sacrificing resolution between high- and low-value areas. An approach that combines clustering and intermediate conservatism, such as the statistical hotspot method at $\alpha = 0.10$ significance, may

Table 3 Mean ecosystem service values within wilderness areas divided by mean value forest-wide for each of six national forests

Forest	AR (%)	BT (%)	MBR (%)	PSI (%)	SNF (%)	WR (%)
Biophysically modeled services						
Carbon	119.5	93.7	110.3	100.3	96.1	92.5
Water	112.8	115.2	146.6	125.3	111.5	121.8
Sediment	93.2	102.4	105.7	99.1	99.4	99.0
Viewshed	113.5	104.3	110.7	111.9	106.0	105.9
PPGIS-mapped services						
Aesthetic	89.6	92.8	126.6	132.7	64.0	115.5
Cultural	75.6	81.8	76.7	170.3	32.6	121.1
Economic	138.3	92.8	93.2	111.9	62.7	80.4
Future	91.5	95.8	139.5	143.6	73.1	116.4
Historic	79.1	94.4	94.1	131.9	55.8	117.5
Intrinsic	150.3	111.1	146.8	177.7	86.2	139.8
Learning	95.4	94.2	85.5	111.0	84.3	100.0
Recreation	103.9	75.1	93.1	110.7	45.0	92.8
Spiritual	88.0	91.1	115.2	171.2	96.6	143.2
Subsistence	100.0	61.8	93.9	Not measured	49.0	99.2
Therapeutic	101.5	91.3	98.2	131.6	64.4	121.9
Strongest environmental variable influences & sign of relationship to PPGIS-based hotspots	Elevation (+); Landform (mountains, +)	Distance to water (−); Slope (−)	Elevation (+); Landcover (forest, +)	Distance to roads (+); Elevation (+)	Distance to roads (−)	Landcover; Landform (inconsistent effects by value type)

Values greater and less than 100 % indicate greater or lesser values, respectively, in wilderness areas than forest-wide

AR Arapaho–Roosevelt National Forest, *BT* Bridger-Teton National Forest, *MBR* Medicine Bow-Routt National Forest, *PSI* Pike-San Isabel National Forest, *SNF* Shoshone National Forest, *WR* White River National Forest, *PPGIS* Public Participatory Geographic Information Systems

Table 4 Survey characteristics for cultural ecosystem services mapping in each of the six national forests

National forest	Survey dates	Effective response rate[a] (%)	Respondents completing maps	Total points mapped for 11 cultural services	Minimum/maximum/mean # of points mapped per cultural service	Respondents' mean age	Respondents' mean years living in community	Reference
Arapaho–Roosevelt	2011–2012	9	125	706	15/175/64	55	17	Czaja and Cottrell (2014)
Bridger-Teton	2007	21	299	2663	109/546/242	57	28	Clement and Cheng (2011)
Medicine Bow-Routt	2011–2012	6	87	416	12/115/38	56	24	Czaja and Cottrell (2014)
Pike-San Isabel	2004–2005	19	310	2127	81/573/213	54	18	Clement and Cheng (2011)
Shoshone	2007	18	232	1775	64/441/161	57	27	Clement and Cheng (2011)
White River	2011–2012	7	107	718	15/196/65	55	18	Czaja and Cottrell (2014)

[a] Some respondents returned surveys, but without completed value maps. For this spatial analysis of cultural ecosystem services, the effective response rate is the number of surveys returned with completed maps divided by the total number of surveys sent to valid addresses

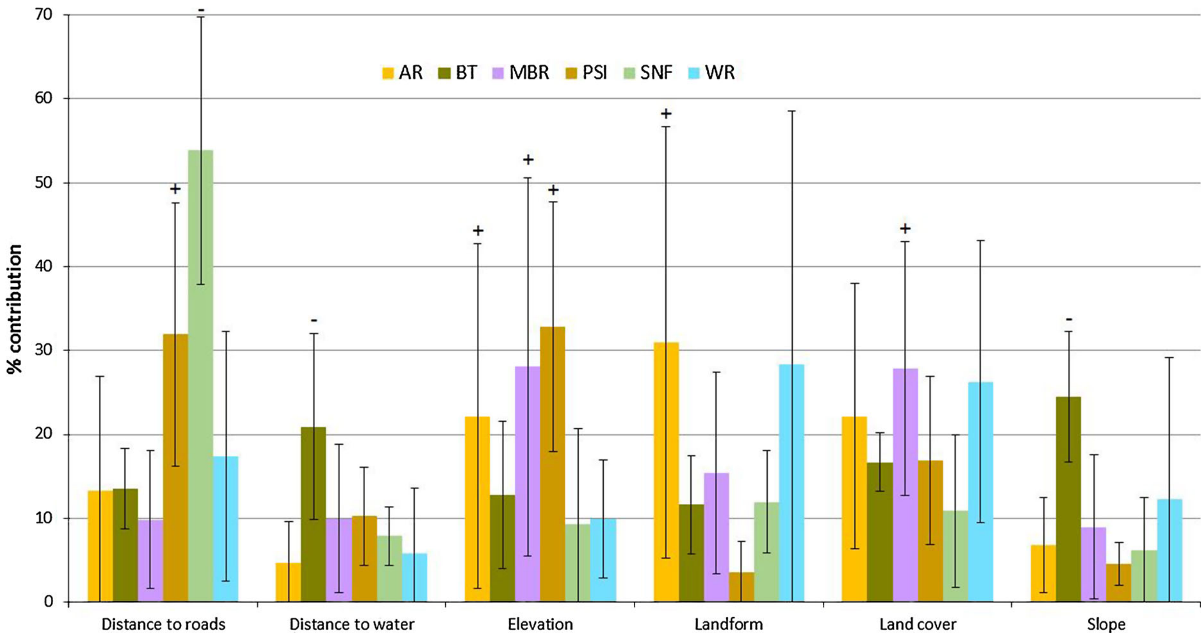


Fig. 6 Average contribution of six environmental variables to MaxEnt models of cultural ecosystem services in SolVES. *Error bars* show standard deviation and a + or − sign above a *bar* indicates a consistent positive or negative relationship between the environmental variable and cultural ecosystem services for that forest

thus provide the most useful information for planning. For this method, 12.6–48.4 % of each forest was identified as warm/warm and 2.5–19.3 % of each forest was hot/hot or cold/cold.

Comparison between forests and wilderness areas

One of the most notable differences between the six forests is their location along an urban–rural gradient from forests immediately adjacent to the densely populated Front Range (PSI, AR), those farther from but still within a few hours driving distance of these population centers (WR, MBR), and forests that are distant from any large population centers (BT, SNF). Respondents living near more urban-distant forests tended to have lived in their community for longer than those living near more urban proximate forests, but did not differ by age or other demographic characteristics (Table 4). Additionally, WR is unique in that it contains a large number of ski resorts, which are highly important cultural and economic features of this forest. While the presence of ski resorts did not have a large noticeable impact on biophysical ecosystem services, they may influence how people both allocated their values between cultural ecosystem services and distributed those values across space.

On average, wilderness areas produced greater water yield and scenic views than forests on the whole (Table 3). These findings align with expectations given that wilderness areas typically include high mountain areas that receive greater precipitation and include highly visible scenic peaks. Similar to a past PPGIS study in Alaska's Chugach National Forest (Brown and Alessa 2005), we typically found intrinsic values to be greater in wilderness areas than the entire forest (5 of 6 forests) and economic, recreation, and subsistence values to be less in wilderness areas (4 of 6 forests). Wilderness areas also typically have greater elevation, slope, and distance from roads. These factors, along with landform and land cover, influenced the SolVES MaxEnt models for cultural ecosystem services. For AR, MBR, and PSI, elevation, distance to roads, and mountainous landforms had a positive relationship with cultural ecosystem services. Conversely for BT and SNF, slope and distance to roads had a negative relationship with cultural ecosystem services (Table 3; Fig. 6).

These findings led to important differences between the six forests for hotspot/coldspot distributions within and outside of wilderness areas. Hotspots were more common and coldspots less common in wilderness areas of AR, MBR, PSI, and WR than in these forests overall. The opposite pattern occurred for SNF. In BT, the northernmost Teton Wilderness had a greater concentration of hotstpots than the surrounding forest, while the Bridger and Gros Ventre Wilderness areas included a greater concentration of coldspots. This may have occurred because the lower-elevation western half of the Teton Wilderness had greater cultural ecosystem service values than the other, mostly high-elevation wilderness areas in BT and SNF. Wilderness areas also covered a greater percentage of total forest area in SNF (56 % of total area) and BT (38 %) than in the other four forests, where wilderness covered 15–33 % of their area (Supplementary material). Residents living in counties near SNF and BT had lived in the area for longer than residents living near the other four forests, in addition to living a much greater distance from any urban centers (Table 4). These factors align with previous findings that support for wilderness areas is generally somewhat greater among populations that are more urban, have lived in the area a shorter time, and whose economies are less centered on ranching, forestry, and mining (Cordell et al. 1998; Rudzitis 1999; Clement and Cheng 2011), which played out in a different set of relationships between environmental variables and cultural ecosystem services in AR, MBR, PSI, and WR than BT and SNF. Our work thus adds a spatial dimension to previous scientific understanding about how the public values wilderness areas, and suggests contexts under which greater or lesser public support may exist for new wilderness designations.

Caveats

Four methodological caveats exist for our comparison of cultural ecosystem service data across the six forests. First, data were collected using very similar survey methods, but at different times (2004–2012). Although further study is needed on how PPGIS responses change over time, two studies have suggested that PPGIS results may be relatively stable over a comparable (6–14 year) period (Brown and Weber 2013; Brown and Donovan 2014).

Second, sample size varied by forest; for the newest three-forest surveys (AR, MBR, and WR), fewer surveys were mailed to residents living near each forest (see "PPGIS mapping of cultural ecosystem services"), and effective response rates were lower than for the BT, PSI, and SNF (Table 4). However, effective response rates across the PPGIS literature (i.e., respondents not just returning surveys but also completing mapping exercises) have been lower than response rates for other forms of survey-based research, owing in part to the cognitive challenge of mapping (Brown and Fagerholm 2015). Responses from the AR, MBR, and WR surveys were received across a demographic cross section; in their analysis of the survey results Czaja and Cottrell (2014) suggest that non-response bias should have been reduced, although non-response bias was not explicitly checked due to time and funding limitations and because the results were not intended to be generalized beyond the three forest study locations. Households receiving the survey may have lacked a geographic understanding of the study area; the mailing list may also have included second homeowners who did not return the survey (Czaja and Cottrell 2014). Despite the smaller sample size for the AR, MBR, and WR, enough points were obtained from respondents to generate acceptable training AUC statistics for the cultural ecosystem services models (Sherrouse and Semmens 2015). Still, due to these sample size limitations we suggest that PPGIS results for these three forests be interpreted with caution, particularly for those services where few points were available to generate cultural service maps, and that future PPGIS studies designed to map cultural ecosystem services strive for greater sample size that is more comparable to the response obtained for the BT, PSI, and SNF surveys.

Third, the digitization methods chosen for points differed slightly between the earlier BT, PSI, and SNF and the latter AR, MBR, and WR surveys. The latter used methods based on a set of rules to guide the digitization process (Sherrouse and Semmens 2015), which led to the exclusion of some points whose location was judged to be ambiguous. This somewhat reduces the comparability of results between the six forests. Importantly however, since our primary goal was to map hotspots/coldspots and their management implications for each forest using forest-specific data, these slight methodological differences do not interfere with our study objectives.

Fourth, SolVES uses MaxEnt to generate a continuous value surface for cultural ecosystem services from PPGIS-generated point data and continuous environmental data layers, analogous to MaxEnt's use in species habitat modeling, where environmental data are paired with presence-only point data.

Analogous to when it is applied for social-value modeling, where some but not all value locations are known, habitat modeling presence-only data include the location of some, but not all, individuals of a species (Elith et al. 2011; Sherrouse and Semmens 2015). PPGIS data are increasingly being used to generate continuous cultural ecosystem services data (Brown and Fagerholm 2015), using data for landscape features (Sherrouse et al. 2011), land cover (Brown et al. 2016), and combinations of landscape features and land cover (Brown and Brabyn 2012; Sherrouse and Semmens 2014). When considering the use of PPGIS-based models for value transfer in cultural ecosystem service mapping, past authors have noted the importance of correspondence between the landscape's physical characteristics and the socioeconomic characteristics of human populations who may value the region (Sherrouse and Semmens 2014), and of adequate sample size (Brown et al. 2016), as discussed above. Additional uncertainty may enter the analysis when these requirements for rigorous value transfer are incompletely met.

Conclusions

Hotspot approaches have widespread utility in spatially explicit conservation planning and management (Myers et al. 2000; Naidoo and Ricketts 2006; Polasky et al. 2008; Wünscher et al. 2008; Schröter and Remme 2016); in this study, we used hotspot/coldspot mapping in a novel ecosystem service assessment for six large U.S. national forests that cover a wide geographic extent (nearly 57,000 km^2). Building on recent comparative ecosystem service hotspot mapping studies (Karimi et al. 2015; Schröter and Remme 2016), we identified key differences in hotspot extent, number, and clustering when using quantile, area-based, and statistical hotspot delineation methods, which have important biological and social implications when applied to natural resource planning. In a landscape-scale planning exercise, then, statistical methods of intermediate conservatism may produce the most useful results for natural resource management. Other hotspot/coldspot delineation methods may be more appropriate when mapping at finer spatial scales or for management issues that demand more inclusive or exclusive definition of ecosystem service hotspots and coldspots. Finally, we compared ecosystem services derived from biophysical models and PPGIS in wilderness and non-wilderness areas. The biophysical setting and characteristics of surrounding human communities influenced perceptions and values of wilderness; this information can be helpful in understanding the extent of public support for wilderness designation.

Spatially explicit information about ecosystem services is increasingly requested in decision making (McIntyre et al. 2008; Zhu et al. 2010; U.K. National Ecosystem Assessment 2011), particularly by U.S. Federal agencies responsible for resource management (36 CFR 219; National Ecosystem Services Partnership 2014; Council on Environmental Quality 2015; Schaefer et al. 2015). Along with spatial planning, hotspot information has the potential to inform mitigation—particularly, for example, to identify avoidance areas (Fig. 1; Clement et al. 2014; Tallis et al. 2015). Others have used hotspot maps to generate conservation targets, an approach that could be appropriate in some cases (Egoh et al. 2011). As suggested here and elsewhere (Fig. 1; Bagstad et al. 2015), hotspot/coldspot maps can be used by natural resource managers to site resource extraction activities (i.e., in biophysical and cultural service coldspots), to proactively determine potential areas of management synergies or conflicts with the public (i.e., in biophysical and cultural hotspots), to identify areas where traditional uses by the public are unlikely to put ecosystem service delivery at risk (i.e., cultural hotspots/biophysical coldspots), or to single out places where outreach is needed to build public awareness of ecosystem services (i.e., biophysical hotspots/cultural coldspots). Of course, ecosystem service hotspot/coldspot information can still be combined with other management goals (e.g., threatened/endangered species, cultural heritage sites) as part of a more comprehensive analysis.

Several avenues for future research could extend our analysis to more deeply explore ecosystem service tradeoffs and the effects of including wilderness boundaries on maps provided to respondents when using PPGIS to map cultural ES. Spatial optimization, using approaches like Zonation and Marxan (Moilanen et al. 2011; Schroter and Remme 2016) and the analysis of ecosystem service bundles (Mouchet et al. 2014) are two approaches that others have used to more fully quantify ecosystem service tradeoffs. Finally, unlike another PPGIS study that considered the public's understanding of ecosystem services from wilderness areas for a national forest in Alaska (Brown and Alessa 2005), the maps provided to respondents in this study included wilderness boundaries. We recognize the tradeoff between providing respondents with the maximum amount of information needed to map cultural services and the fact that the choice to emphasize some locations over others simply by identifying them can also introduce confirmation bias. It would be interesting in a future study to assess the extent of such confirmation bias by comparing mapping results generated by individuals given maps with and without markings identifying wilderness boundaries and other geographic information, in conjunction with questions about attitudes toward wilderness.

Our approach used biophysical and cultural ecosystem service maps generated using the ARIES and SolVES tools, respectively. These approaches offer certain methodological advantages–the ability for new models to inform an intelligent modeling system in the case of ARIES (Villa et al. 2014) and the potential transferability of model results within SolVES (Sherrouse and Semmens 2014). The use of these models thus contributes toward the goal of reducing resource requirements for future ecosystem service assessments, an important need for resource management agencies (Bagstad et al. 2015). However, a wide variety of approaches exist for both biophysical modeling of ecosystem services (Kareiva et al. 2011; Martinez-Harms and Balvanera 2012; Bagstad et al. 2013) and PPGIS (Brown and Fagerholm 2015). Biophysical and cultural ecosystem service maps generated using these alternative methods could similarly be combined using the methods presented here. As the number of ecosystem service assessments grows and archives for data sharing expand (ESP Maps 2014), increasing opportunities may exist to combine biophysical and cultural ecosystem services information to broaden the scope of spatially explicit ecosystem service assessments.

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