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Sociocultural mapping of ecosystem service values can inform where to mitigate wildfire risk: a case study from Colorado

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Sociocultural mapping of ecosystem service values can inform where to mitigate wildfire risk: a case study from Colorado

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Accounting for ecosystem service values in wildfire risk mitigation remains a challenge. In this study we utilize public participatory GIS methods to measure ecosystem service values and overlay those values with maps of wildfire hazard. Our first objective is to understand sociocultural demand for ecosystem services, and our second objective is to show how non-monetary ecosystem service valuation methods can be used to inform wildfire risk mitigation decisions. Regulating ecosystem services, such as water quality, biodiversity/habitat, and air quality, along with recreation and aesthetics, were the most highly valued ecosystem services in our study. These ecosystem service values were clustered around roads, towns, and water features and correlated with accessibility, education, and income. These values also had significant overlap with wildfire hazard, suggesting that this non-monetary mapping approach could provide a more participatory method of incorporating people's preferences into decisions about where to target wildfire mitigation efforts.

Keywords: ecosystem service demand; non-monetary valuation; public participatory GIS; wildfire management

1. Introduction

In the western United States (US), wildfire presents a particularly critical threat to the delivery of many ecosystem services that people value. While wildfire is a natural ecological process that plays a key role in many ecosystems, over the past several decades increasingly large areas have burned at high severity (Calkin *et al*. 2014; Abatzoglou and Williams 2016; Stephens *et al*. 2016; Kinoshita *et al*. 2016; Parks and Abatzoglou 2020). These worsening fire conditions can be attributed to a combination of factors, including past fire management practices, climate change, and increased development in forested areas (Veblen, Kitzberger, and Donnegan 2000; Westerling *et al*. 2003, Westerling *et al*. 2006). High intensity fires negatively impact many ecosystem services, including sediment control, water regulation, and clean water provision (Smith *et al*. 2011; Murphy *et al*. 2015; Hohner *et al*. 2016; Abraham, Dowling, and Florentine 2017; Cawley *et al*. 2018); regulation of air quality (Richardson, Champ, and Loomis 2012; Eisenman *et al*. 2015); and access to recreation and tourism activities (Sanchez, Baerenklau, and Gonzalez-Caban 2016; Molina and Silva 2019).

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Hazardous fuel reduction treatments are increasingly used to restore ecological integrity and reduce wildfire risks (Stephens *et al.* 2021). When fuel treatments are used, such as thinning or prescribed fire, areas important for ecosystem service provision, such as source water protection, can be targeted to reduce risk and increase societal benefits (e.g. Buckley *et al.* 2014; Kruse, Hartwell, and Buckley 2016; Jones *et al.* 2017). These targeting exercises often use process-based models that account for the complexity of ecosystem functions, and sometimes couple them with economic valuation methods to put a dollar value on the societal benefits (e.g. Buckley *et al.* 2014; Jones *et al.* 2017). These process-based models focus on protecting areas that supply ecosystem services, but there can be a mismatch between the areas that supply ecosystem services and where there is demand for ecosystem services by people (Bryan *et al.* 2011; Schröter, Remme, and Hein 2012; Burkhard *et al.* 2012). Additionally, the reliance on monetary valuation in these studies tends to overemphasize instrumental values that are more easily quantified, over sociocultural or relational values. The latter are defined as the values that are found within relationships between people and nature (Díaz *et al.* 2015; Pascual *et al.* 2017). An alternative approach for measuring human preferences or demand for ecosystem services at risk to wildfire is to use sociocultural valuation methods (Brown, Montag, and Lyon 2012a; Chan *et al.* 2012; Chan, Satterfield, and Goldstein 2012; Scholte, van Teeffelen, and Verburg 2015; Pascual *et al.* 2017).

Sociocultural valuation utilizes non-monetary methods to capture both instrumental and relational values (Chan *et al.* 2012; Chan, Satterfield, and Goldstein 2012; Plieninger *et al.* 2013; Díaz *et al.* 2015; Scholte, van Teeffelen, and Verburg 2015). Sociocultural valuation tends to be more participatory than economic valuation, asking people about their preferences versus pre-determining what is important. Mapping of sociocultural ecosystem service values is one approach to capturing people's non-monetary preferences and has become popular because of the spatial aspects of many ecosystem services (Wolff, Schulp, and Verburg 2015; De Vreese *et al.* 2016; Wolff *et al.* 2017; Fagerholm *et al.* 2019). Public participatory GIS (PPGIS) mapping is one approach to collecting knowledge from the public or experts on the spatial location and distribution of values (Sieber 2006; Brown, Montag, and Lyon 2012). PPGIS can be used to identify hotspots, or areas of high social value (Alessa, 2008), and can be used to understand drivers of ecosystem service demand such as socioeconomic factors or landscape conditions (Alessa *et al,* 2008; Wolff, Schulp, and Verburg 2015; De Vreese *et al.* 2016; Wolff *et al.* 2017; Fagerholm *et al.* 2019). Maps of ecosystem service demand have been used to inform management decisions, most notably around recreation, public lands, and user conflict (e.g. Brown and Reed 2009; van Ripper *et al.* 2012; Brown and Raymond 2014; García-Nieto *et al.* 2015; Ancona *et al.* 2022).

The relative recency of the PPGIS methodology for mapping ecosystem service demand has created a lack of consensus as to best practices (e.g. Sieber 2006; Anderson, Beazley, and Boxall 2009; Brown, Montag, and Lyon 2012; Brown and Fagerholm 2015; Brown, Weber, and de Bie 2015; Fagerholm *et al.* 2019). Previous PPGIS studies have varied in the ecosystem services mapped, the respondents, and the approach through which the sampling and mapping were conducted. The types of services mapped have been developed primarily either through a predetermined typology or left open-ended and allowed to emerge during the mapping process (Brown and Fagerholm 2015). The Millennium Ecosystem Assessment (MEA) typology has been a common choice for previous ecosystem service mapping (MEA (Millennium Ecosystem Assessment) 2003;

Brown and Fagerholm 2015), prior to the development of alternative frameworks such as Nature's Contributions to People (NCP) (Pascual *et al*. 2017; Díaz *et al*. 2018) that has been used in more recent PPGIS studies (Fagerholm *et al*. 2019). Another common platform has been the Social Values for Ecosystem Services (SolVES) program that was developed by the US Geological Society and uses a value typology that captures many cultural and non-material values (Sherrouse, Clement, and Semmens 2011).

The use of PPGIS can range from paper and pencil mapping to more technologically intensive computer-based mapping applications. Computer mapping – where viable – has the benefit of ease of access through online mapping services and requires fewer physical materials to carry out. For marking the locations of ecosystem services, points, versus polygons, have been found to be both the most common method (Brown and Fagerholm 2015), and the least cognitively challenging for participants (Brown and Pullar 2012). PPGIS can focus on the public or "experts" (Brown 2004; Brown, Montag, and Lyon 2012). Less visible supporting and regulating services can require greater expertise to properly identify, whereas public surveys have been shown to be more effective at identifying cultural and provisioning services (Brown, Montag, and Lyon 2012; Brown and Fagerholm 2015). Randomized household or landowner surveys are commonly used when sampling the general public, with sample sizes ranging from as low as 22 to the several thousands (Brown and Fagerholm 2015). Other sampling methods have included targeted sampling and sampling through "stakeholder workshops".

In this study, we use PPGIS to map sociocultural ecosystem service demand in a watershed in the western US and relate ecosystem service demand to wildfire risk. We have two objectives: (1) to understand sociocultural demand for ecosystem services in a new geographic area, and (2) to show how non-monetary sociocultural valuation methods can be used to inform wildfire risk mitigation decisions. For our first objective, we combine spatial and non-spatial approaches to measure people's preferences for ecosystem services. We draw on previous PPGIS studies to inform our methodology and measure ecosystem service preferences and drivers of demand. These results add to the growing body of literature on how ecosystem service demand varies by location and household characteristics. Our second objective is unique to our assessment in that we use spatially mapped ecosystem service preferences and overlay them with wildfire risk in our study area. While sociocultural ecosystem service assessments have been used to inform public land management, especially for recreation, they are not currently used to inform the targeting of wildfire risk reduction activities. The fact that both wildfire risk and ecosystem service demand can be represented spatially suggests that there are potential beneficial uses of this information for informing proactive fuel treatment decisions given scarce resources and tradeoffs. Overall, this paper contributes to a greater understanding of how non-monetary sociocultural ecosystem service valuation methods can be used to inform real-world management decisions.

2. Methods

2.1. Study area

We study the Big Thompson Watershed in Colorado (CO). The Big Thompson, located 50 miles northwest of Denver, encompasses approximately 1,448 square kilometers (km) from the Continental Divide east to the Front Range and Colorado Plains (Figure 1). The headwaters are located within the boundary of Rocky Mountain National Park. The watershed supplies fresh drinking water to over half a million

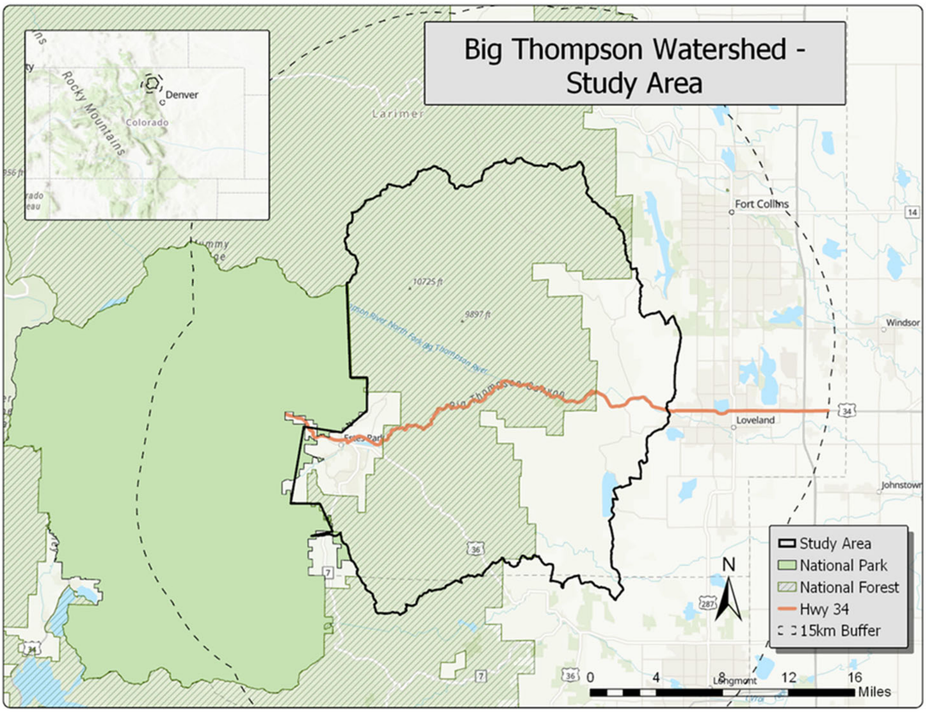

Figure 1. Big Thompson watershed and study area.

people, as well as water for corn, wheat, vegetable, and livestock operations in some of the most important agricultural counties in the state (US Census Bureau, n.d.). The watershed has several terminal reservoirs including Carter Lake, Lake Estes, Boulder Reservoir, and Horsetooth Reservoir that are used for both drinking water storage and for recreation and tourism. Large areas of public land in the watershed, including the Arapaho and Roosevelt National Forest, are home to hundreds of miles of hiking and biking trails.

The ecosystem services that the Big Thompson provides to residents and visitors are threatened by wildfires. Significant wildfire events in the area include the Big Elk Fire in Estes Park in 2002, the Picnic Rock Fire northwest of Fort Collins in 2004, the Fourmile Canyon Fire west of Boulder in 2010, and the High Park Fire in Roosevelt National Forest in 2012. The 2012 wildfire was followed by a historic 2013 flooding event that destroyed thousands of homes and caused widespread damage to roads and other infrastructure. In 2020, after this study was completed, the two largest fires in CO history – the Cameron Peak and East Troublesome Fires – occurred partially within the boundary of our study area.

We limited the extent of our study area for mapping ecosystem services to one HUC-8 watershed (Figure 1). This smaller study area extent falls mostly within Larimer County, with some area in Boulder and Weld counties. The 2019 population estimates for these counties is just over 350,000. This population is mostly white (93%) and educated (96% high school, 46% bachelor's degree or higher). The median household income (USD 2018) is $67,664, and the broadband internet access rate is high (88%) (Census QuickFacts n.d.).

Table 1. Ecosystem service typology and definitions.

Ecosystem Service	Category (from MEA (Millennium Ecosystem Assessment) 2003 and Díaz *et al.* 2018)	Survey Definition ("I value these places because … ")
Food	Provisioning, Material	They provide me with plants or animals to eat including meat, fish, fruits, vegetables, or mushrooms.
Natural Materials	Provisioning, Material	They provide me with coal, wood products, animal feed, firewood, fuel, or other natural materials I use.
Recreation	Cultural, Non-material	They provide me with recreation activities.
Social Interaction	Cultural, Non-material	They provide me with opportunities for social interaction.
Aesthetics	Cultural, Non-material	The scenery or the views.
Cultural Significance	Cultural, Non-material	The local culture, heritage, or history.
Spiritual Value	Cultural, Non-material	They are sacred, religious, or spiritually special to me.
Intellectual/Educational Value	Cultural, Non-material	They give me the opportunity to think creatively and to be inspired by nature.
Existence Value	Cultural, Non-material	They exist, no matter how I or others use them.
Habitat/Biodiversity	Supporting, Regulating	They provide a variety of plants, wildlife, other living organisms, and ecosystems.
Water quality	Regulating, Regulating	Their capacity to provide and preserve clean water.
Air quality	Regulating, Regulating	Their capacity to provide and preserve clean air.
Soil/Erosion Control	Regulating, Regulating	Their capacity to provide and preserve quality soil, and to prevent excess erosion.

2.2. PPGIS tool and survey instrument

We developed a PPGIS survey tool using the web mapping platform Maptionnaire (Appendix A [online supplementary material]). Participants were asked to map their home location and the location of places within the watershed study area boundary that they value. Participants were given a list of 13 ecosystem services and definitions from which they could choose to map (Table 1) and were not limited in the number of points that they could map. The 13 ecosystem services capture a range of material, non-material, and regulating ecosystem services (Díaz *et al.* 2018). We drew upon ecosystem service typologies used in previous sociocultural valuation studies (Brown, Montag, and Lyon 2012; Pascual *et al.* 2017; Fagerholm *et al.* 2019), and adapted them based on local context. As is the case with other participatory assessments, the typology here was chosen to understand subjective perceptions of benefits as well as direct use (Brown, Montag, and Lyon 2012; Fagerholm *et al.* 2019). The list was operationalized and framed for the individual perspective through a series of "I value" statements, placing the focus on the individual's perceptions of ecosystem services value.

Using the same list of 13 ecosystem services, respondents were also asked to rank their preference for each of the 13 ecosystem services through a value allocation exercise similar to that done in SolVES (Sherrouse, Clement, and Semmens 2011) to weight social values. Each respondent was given a hypothetical 100 USD and asked to assign a dollar amount from the total 100 based on what they believe are the most important services in the watershed to protect. The value allocation portion of the survey was given before the mapping portion. This choice was made to help respondents consider the ecosystem services definitions, and their perceptions and values for each of the 13 services, prior to mapping, to make the mapping portion less cognitively challenging.

Finally, respondents were asked a short list of social and demographic questions. These questions were aimed at understanding the respondent's relationship with the landscape. Specifically, we asked about their residential status, length of residency in CO, watershed familiarity, land ownership, how they use their land, household characteristics (e.g. number of adults and children in the household, occupation, income), and personal characteristics (e.g. gender, age, education). The survey instrument was pretested with 12 individuals and the survey revised based on the feedback. The final survey instrument was subject to human subject review and received Institutional Review Board approval (protocol number 19-9094H).

2.3. Data collection and response rate

An invitation to complete the survey was distributed to a random sample of 2,000 households in census blocks that intersected within a 15-km buffer zone around the watershed study area (Figure 1). A postcard with information about the survey and a link to complete the survey online was included. Among the 2,000 households, about 10% ($n = 190$) had an email address associated with their home address. These households were sent follow-up emails once a week for six weeks. After six weeks following the initial round of postcards and emails, a random subset of 1,000 households were sent a second round of postcards. Additionally, the survey was given to the Big Thompson Watershed Coalition, a local non-profit organization, to distribute in their quarterly newsletter, and was posted in various outdoor recreation and community social media groups in the area. There was no way to guarantee that someone did not receive solicitation for the survey from multiple sources. In total, the survey was available to be completed online for three months from August to November 2019.

In total, 98 individuals responded to at least a portion of the survey – a response rate of 5 percent. This rate is lower than other internet based PPGIS studies from CO (Brown, Montag, and Lyon 2012) and other regions (Fagerholm *et al.* 2019), but within the range of what has been collected in other PPGIS studies (Brown and Fagerholm 2015). One reason we may have a lower response rate is that due to resources, we were not able to mail a hard copy of our survey following the initial postcard to people who did not respond (Dillman, Smyth, and Christian 2014). Thus, our responses might be biased toward those who are more comfortable using online platforms. Of the 98 respondents, 84 individuals completed the non-spatial value allocation exercise. The responses from these 84 individuals were used for all non-spatial analyses because their participation in value allocation indicates a level of demand for ecosystem services. Only respondents who mapped at least one ecosystem service point were included in spatial analyses of ecosystem service demand; 72 people mapped at least one ecosystem service value.

2.4. Data analysis

First, we estimated sociocultural ecosystem service demand. Specifically, we considered both mapped ecosystem service points and the allocation of the hypothetical $100 USD as contributing to an individual's expression of demand. The two metrics were multiplied together to calculate a demand metric – a weighted preference scale – for each of the 13 ecosystem services listed in Table 1. The metric considers both spatial and non-spatial aspects of demand while ensuring that a respondent's demand is considered even if a particular service was not mapped (Equation 1).

$$ES\ Demand = Allocated\ \$ * (1 + \#mappedpoints) \tag{1}$$

Second, a kernel density estimation (KDE) of the mapped points within the study area was calculated. KDE creates a raster surface based on a point distribution. This is used as a visualization tool and can also be correlated with other density surfaces. Each ecosystem service mapped point location was assigned its demand value from Eqn. 1 and then the value of the raster surface smoothly decreases away from the point within a search radius (Silverman 1986). A KDE surface was created for the entire distribution of mapped points and for each of the 13 individual services separately. The KDE surfaces for the 13 individual ecosystem services were correlated against each other using the band collection statistics tool in ArcGIS Pro. The result of these correlations tells us which ecosystem services co-occur on the landscape most frequently (Plieninger *et al*. 2013; Hernández-Morcillo, Plieninger, and Bieling 2013).

Third, we created hotspot maps (Alessa *et al,* 2008). First, a 5 km^2 hexagon grid was laid over the study area, and the demand values from Eqn. 1 were summed within each grid cell. The demand value of each grid cell was then used as the weighting variable for calculating spatial autocorrelation and for detecting demand hotspots. In reviewing the literature there was no consensus on what to set as the resolution for the grid; however, 5 km^2 was within the acceptable range based on the number of points and the size of our study area (Hengl 2006). Next, Moran's Index (Moran's *I*) was calculated for each cell in the hexagon grid to indicate whether service demand is randomly distributed, clustered, or dispersed across the landscape (Moran 1950). Our hypothesis was that ecosystem service preferences would not be randomly distributed but clustered due to accessibility and popularity. Finally, the location of clustered features with similarly high or similarly low values when compared to neighboring values was calculated using the Getis-Ord Gi* statistic (Getis and Ord 2010).

Fourth, we compared ecosystem service demand to four landscape characteristics: accessibility (average slope, total road length, total publicly accessible area, average distance of mapped points from home, total building footprint), land cover (total area of water, developed, barren, forest, shrub/scrubland, herbaceous, pasture/cultivated, wetlands, and land cover variety), land ownership (private, local, state, federal), and aesthetic quality (total water area, total stream/river length, maximum elevation). The ecosystem service demand value of each 5 km^2 hexagon grid cell was used as the dependent variable and then Spearman's correlations were calculated. Significant correlations were considered at 90%, 95%, and 99% significance levels. All data sources for biophysical variables are detailed in Appendix B (Online supplementary material). We hypothesized that ecosystem service demand would increase with increased accessibility, increased aesthetic quality, and that water sources (captured both under land cover and an independent data layer) would have a strong association with demand.

To test socioeconomic demand drivers, we considered the five ecosystem services with the highest demand from Equation (1) and measured their correlation with socioeconomic data from the survey. Ecosystem service demand correlations with land ownership and state residency (binary variables) were tested using independent samples *t*-tests. Correlations with watershed familiarity, education, occupation, and income (categorical variables) were tested using ANOVAs. Finally, correlations between ecosystem service demand and age (continuous variable) were tested using a Pearson correlation. Based on previous studies (Brown, Montag, and Lyon 2012; García-Nieto *et al.* 2015; Fagerholm *et al.* 2019), we hypothesized that higher education would lead to increased demand for less visible and regulating ecosystem services. We also hypothesized that land ownership and higher income would lead to increased demand for services. Due to the importance and emphasis of water as a resource in this area, we also hypothesized that older respondents, CO residents, and respondents with a higher self-reported familiarity with the watershed would have a higher demand for water.

Finally, the hotspot analysis that was conducted for ecosystem service demand using 5 km^2 hexagon grids was repeated using previously modeled maximum wildfire hazard values for the watershed from Gannon *et al.* (2019). Total wildfire hazard takes into account two components: (1) the 25-year burn probability or burn likelihood modeled with the Large Fire Simulator (FSim; Finney *et al.* 2011; Gannon *et al.* 2019), and (2) burn severity based on crown fire activity (CFA) modelled using FlamMap 5.0 (Finney, McHugh, and Grenfell 2015; Gannon *et al.* 2019). Wildfire hazard, therefore, considers both the probability that a wildfire event will occur in a specific location, and how the wildfire will behave once burning (Gannon *et al.* 2019). By overlapping ecosystem service demand hotspots with wildfire hotspots, we are able to identify sociocultural values that are at risk to wildfire hazard and that could be prioritized when making decisions about mitigating wildfire risk.

3. Results

Survey respondents were overwhelmingly Colorado residents (70%). Respondents were approximately evenly divided between homeowners and non-homeowners, and between males and females. Overall, the respondents were more highly educated than the census average, with 31% having a postgraduate degree (MS or PhD) and 27% a bachelor's degree. The average respondent was middle-aged (48 years). Middle to upper income households were overrepresented, with 56% of respondents reporting annual household incomes greater than $65,000 USD.

3.1. Non-spatial distribution of ecosystem service demand

In total, 72 participants mapped 321 ecosystem service point locations within the watershed study area boundary (Figure 1). The most mapped services were recreation ($n = 105$) and aesthetics ($n = 78$), followed by biodiversity/habitat ($n = 42$), and water quality ($n = 35$). However, water quality was allocated the largest number of hypothetical dollars (average of $24.37 USD out of $100 USD), followed by biodiversity/habitat ($16.00 USD), air quality ($11.02 USD), and recreation ($10.08 USD) (Table 2). The demand (Eqn. 1) for each of the 13 ecosystem services followed a similar pattern, with the highest demand calculated for water quality, biodiversity/habitat, and recreation.

Table 2. Summary of mapped ecosystem service points, allocated value, and demand within the watershed boundary.

Ecosystem Service	# Mapped Points	Mean $ (USD) Allocated	StdDev $ Allocated	Mean Demand (from Equation 1)	StdDev Demand
Water quality	35	24.37	19.55	35.05	33.72
Biodiversity/Habitat	42	16.00	16.25	26.67	35.18
Recreation	105	10.08	9.93	26.58	32.89
Air quality	17	11.02	12.28	15.31	23.34
Aesthetics	78	6.81	7.87	15.08	21.17
Soil/Erosion Control	20	6.79	6.74	9.08	10.81
Food	12	6.65	8.75	8.44	12.94
Existence Value	24	5.13	10.87	7.67	20.84
Cultural Significance	16	3.77	5.10	5.20	8.24
Natural Material	8	2.62	4.76	3.15	5.85
Intellectual/Education	14	2.35	3.94	2.99	5.06
Spiritual	13	2.18	5.55	2.92	7.01
Social Interaction	31	1.31	2.60	2.18	4.96

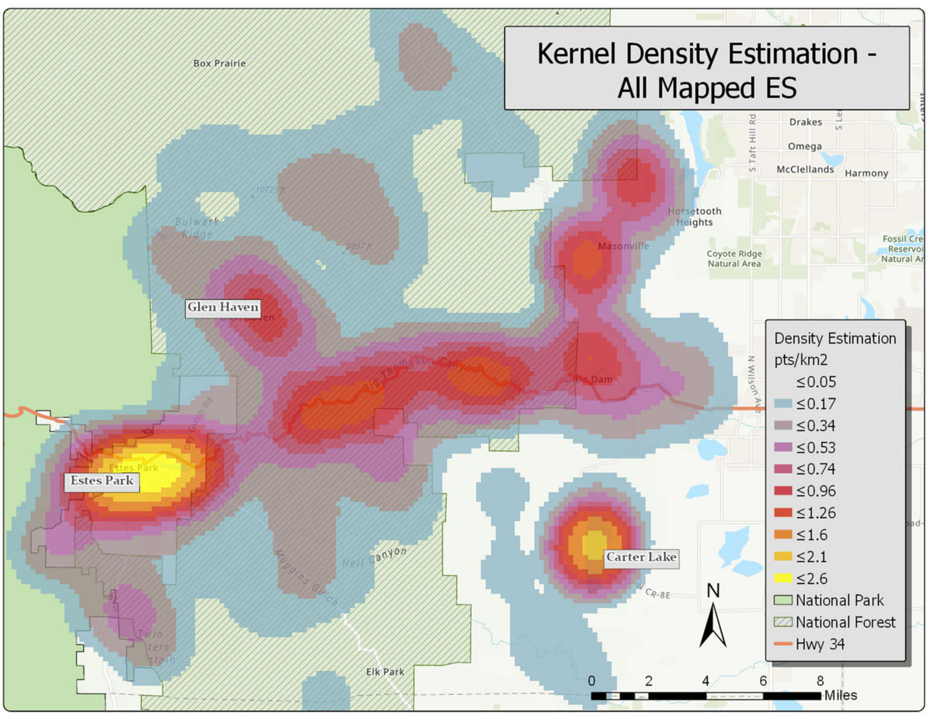

Figure 2. Kernel density estimation visualization of all 13 mapped ecosystem services.

3.2. Spatial distribution of ecosystem service demand

KDE visualization shows ecosystem service clustering near towns (e.g. Estes Park), along highways (e.g. Highway 34), rivers (e.g. the Big Thompson River flows parallel to Highway 34), and near several recreational reservoirs (e.g. Carter Lake) (Figure 2).

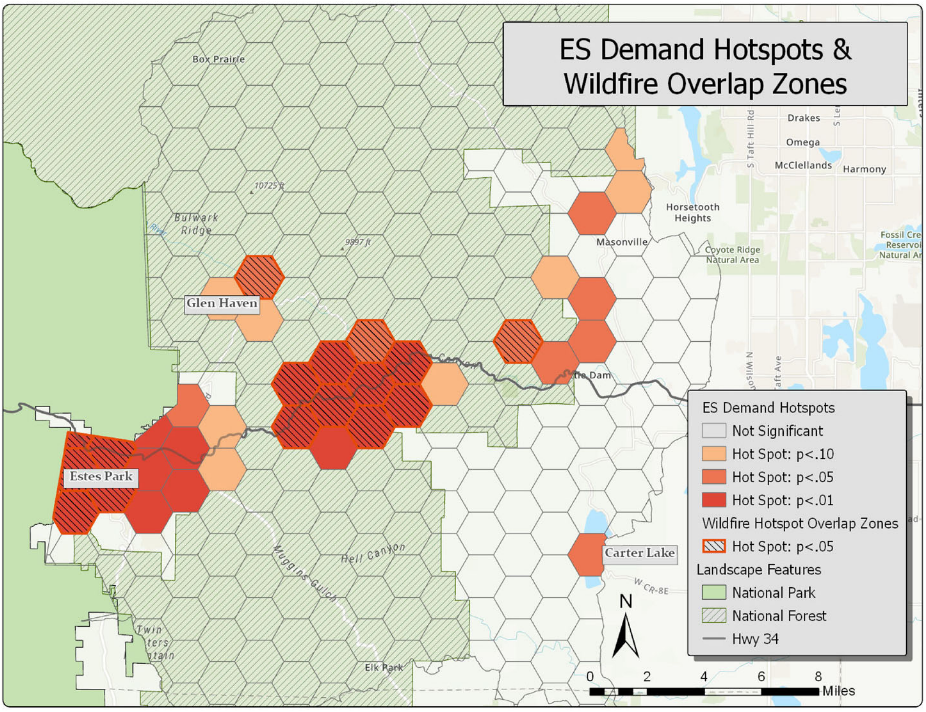

Figure 3. Ecosystem service demand hotspots and wildfire hazard hotspots.

KDE visualizations of the four most mapped ecosystem services (recreation, aesthetics, biodiversity/habitat, water quality) display slight variations in the density of mapped points at different locations, but all have high density around the town of Estes Park, Highway 34 and the Big Thompson River, and reservoirs (Appendix C [online supplementary material]).

Global Moran's I calculated for ecosystem service demand on the 5 km^2 hexagon grids resulted in a significant positive autocorrelation ($I = 0.045$, $z = 2.87$, $p = 0.004$). This result indicates that the demand values for the 13 ecosystem services within the 5 km2 hexagon grid cells are significantly clustered. In other words, grid cells are more likely to be near other cells with similar demand values than they are to be near cells with different demand values. The statistically significant Moran's I suggests that there are spatial processes underlying the distribution of demand for ecosystem services in the watershed. Hotspot analysis using the Getis-Ord Gi* statistic resulted in 37 ecosystem service hotspots at the $p < 0.10$ significance level, 29 hotspots at $p < 0.05$, and 19 hotspots at $p < 0.01$ (Figure 3).

3.3. *Landscape and socioeconomic correlations with ecosystem service demand*

Table 3 shows the correlations between ecosystem service demand in the 5 km^2 hexagon grid cells and landscape characteristics. Two of the five landscape accessibility variables showed significant positive correlation with the ecosystem service hotspots: total road length ($p = 0.008$) and total footprint of buildings ($p = 0.0006$). Of the land cover variables, ecosystem service demand showed a positive correlation with water

Table 3. Correlations between ecosystem service demand and biophysical landscape variables.

Variable	Coefficient	*p*-value*
Accessibility		
Distance from home (Mean)	−0.075	0.153
Public Access (Total Area)	−0.096	0.096
Slope (Mean)	−0.057	0.218
Roads (Total Length)	0.178	0.008***
Buildings (Total Footprint)	0.228	0.006***
Land Cover		
Water	0.176	0.007***
Developed	0.159	0.014**
Barren	−0.035	0.313
Forest	−0.203	0.002***
Shrub/Scrub	0.165	0.011**
Herbaceous	−0.126	0.040
Pasture/Cultivated	0.055	0.225
Wetlands	−0.086	0.116
Variety (total # land types)	0.163	0.012**
Land Ownership		
Private	0.072	0.160
County	0.100	0.083*
State	−0.099	0.086*
Federal	−0.099	0.085*
Aesthetic Quality		
Water	0.175	0.007***
Streams/Rivers (Total Length)	0.050	0.243
Elevation (Maximum)	−0.128	0.038**

*Significance levels: *90% **95% ***99%.

($p = 0.007$), developed places ($p = 0.014$), and shrub/scrubland ($p = 0.011$). Ecosystem service demand was also positively correlated with land cover variety ($p = 0.012$). Interestingly, demand was negatively correlated with forest cover ($p = 0.002$). Ecosystem service demand was correlated with public lands at the 90% level (county, state, and federal lands). Two of the three aesthetic quality landscape variables were significantly correlated with ecosystem service demand: total water footprint was positively correlated at the 99% confidence level ($p = 0.007$) and maximum elevation was negatively correlated at the 95% confidence level ($p = 0.038$).

Fewer socioeconomic variables had a statistically significant correlation at the 90% level or higher with demand for the top five ecosystem services—water quality, biodiversity/habitat, recreation, air quality, and aesthetics. Table 4 shows the four socioeconomic variables that had any statistically significant relationship with these five ecosystem services. Watershed familiarity had a positive correlation with demand for recreation, but not water quality, as we hypothesized. Education was positively correlated with demand for both recreation and water quality. Income was positively related to demand for aesthetics. Finally, age was positively correlated with demand for water quality.

3.4. Wildfire hazard and ecosystem service demand

Hotspot detection analysis of the maximum wildfire hazard within the 5 km^2 grid cells resulted in 58 hotspots at the $p < 0.10$ significance level, 51 hotspots at $p < 0.05$, and 33 hotspots at $p < 0.01$ (Appendix D [online supplementary material]). We overlapped

Table 4. Correlations between ecosystem service demand and socioeconomic variables.

Variable	Ecosystem Service	Coefficient	*p*-value*
Watershed Familiarity	Aesthetics	0.317	0.730
	Air quality	1.095	0.342
	Habitat/Biodiversity	1.079	0.347
	Recreation	2.561	0.087*
	Water quality	0.648	0.527
Education	Aesthetics	0.581	0.630
	Air quality	0.136	0.938
	Habitat/Biodiversity	0.491	0.690
	Recreation	4.395	0.015**
	Water quality	2.631	0.082*
Income	Aesthetics	2.328	0.066*
	Air quality	0.892	0.474
	Habitat/Biodiversity	0.288	0.885
	Recreation	1.98	0.134
	Water quality	0.488	0.745
Age	Aesthetics	0.186	0.135
	Air quality	−0.035	0.780
	Habitat/Biodiversity	0.067	0.591
	Recreation	0.143	0.251
	Water quality	0.228	0.066*

*Significance levels: *90% **95% ***99%.

the 51 wildfire hazard hotspots ($p < 0.05$) with the ecosystem service demand hotspots to show which demand areas were most at risk from wildfire (Figure 3). Wildfire hotspots overlapped with ecosystem service demand in the central and western parts of the watershed, near the town of Estes Park, along Highway 34, and along the North Fork of the Big Thompson River near Glen Haven (Figure 3).

4. Discussion

Our study provides a unique contribution to the literature on mapping sociocultural ecosystem service values both geographically, and by adapting ecosystem service hotspot detection overlap methods to identify wildfire-threatened zones of ecosystem service demand that can be used to inform wildfire risk mitigation decision making. Importantly, our study represents the preferences of our unique group of respondents, and our results should not be generalized broadly. Within our study area, ecosystem service demand preferences may be biased toward users who are more comfortable with internet-based surveys, have a higher income, and are more highly educated. Despite these caveats, the information obtained in this analysis has utility for managers in the study area as a baseline for understanding ecosystem service demand and contributes to the growing body of research on how to utilize geospatial technologies to capture ecosystem service preferences to inform applied management problems, such as wildfire management.

4.1. PPGIS for sociocultural valuation of ecosystem services

Water quality, habitat/biodiversity, and recreation are the most important ecosystem services to respondents in our study area, with air quality and aesthetics also having high value. Other PPGIS studies have also found that water, recreation, and aesthetics are highly demanded by the public (Brown, Montag, and Lyon 2012; Fagerholm *et al*. 2019). However, the high demand for habitat/biodiversity found in our study area is not common in the PPGIS literature (Brown and Fagerholm 2015). This divergence could be due to our sample being skewed toward more highly educated respondents (Brown, Montag, and Lyon 2012; Brown and Fagerholm 2015). Another explanation for the greater emphasis on biodiversity/habitat in this study area is that wildlife is a draw for many who move to or visit the area, as viewing large mammals such as elk and moose brings many residents and tourists to the town of Estes Park and Rocky Mountain National Park every year. Thus, there is connection to wildlife for its economic value from tourism, and relational value with the connection to the wildlife itself.

In general, respondents in this study mapped and highly valued many "less visible" regulating ecosystem services, such as water quality, biodiversity/habitat, air quality, and soil/erosion control. While some of the literature suggests that these types of services are better identified by "experts" (Brown, Montag, and Lyon 2012; Brown and Fagerholm 2015), our study shows that this is not necessarily the case, and that the public can recognize the importance of these services. However, many cultural ecosystem services, or non-material services, such as existence value, intellectual/education, spiritual, and social interaction, were less likely to be mapped or have a high demand value in this study. While the low number of mapped points for these cultural ecosystem services might reflect challenges in spatially attributing a specific place to these types of non-material values (Díaz *et al*. 2018); the simultaneous allocation of lower amounts of USD in the ranking exercise suggests that these types of services are not as important to the respondents of this survey.

Our KDE analysis indicates that underlying spatial processes drive the overall distribution of ecosystem service demand. This clustering around landscape features is found in other PPGIS studies (Brown, Montag, and Lyon 2012; Brown and Fagerholm 2015; Fagerholm *et al*. 2019). Most of the mapped points, and in particular aesthetic points, are clustered around Estes Park in our study area. Other studies have found that high elevation areas – particularly ones with high visitation rates – are clusters of aesthetic value (Brown 2004; Brown and Reed 2009). Estes Park is a central attraction in our study area for tourism, social events, wildlife viewing, and recreation, and this is reflected in where ecosystem services are mapped.

The most striking trend that we found among landscape correlations and ecosystem service demand is that altered landscapes produce the greatest social value in this study area. Two of the strongest correlations among demand and landscape variables in our study are with the total building footprint and the length of roads. Accessibility to benefits has been a consistently important demand driver across PPGIS studies (Brown, Montag, and Lyon 2012; Schröter, Remme, and Hein 2012; Fagerholm *et al*. 2019), and our results are consistent with that finding. Features that facilitate interactions between people and their environment are more likely to produce perceived benefits (Brown 2004), and buildings and roads provide ease-of-access. We also found demand to be strongly associated with water bodies. In our study area, open water sources are part of the built environment (e.g. man-made reservoirs). Brown, Montag, and Lyon (2012) found a similar result in CO, with open water being the most represented landcover type associated with ecosystem service preferences in their results.

Between socioeconomic factors and ecosystem service demand, we find that higher income is associated with greater aesthetic value; familiarity and education are correlated with greater recreation value; and age and education are associated with higher water quality value. The role of income and education in ecosystem service demand has been found in previous studies, with income correlated with higher valuation of "non-essential" benefits (Hernández-Morcillo, Plieninger, and Bieling 2013) and education associated with greater perception of "less visible" supporting or regulating ecosystem services (Brown, Montag, and Lyon 2012). The relationship found in this study between watershed familiarity and recreation demand may be because individuals who engage in recreation activities become more familiar with the landscape, rather than familiarity being the cause of demand for recreation. Previous studies have found familiarity to be one of the most important socioeconomic drivers of ecosystem service demand (Brown 2004; Brown, Montag, and Lyon 2012). Age was positively correlated with demand for water quality in our study, which may be due to an increased awareness of water's importance among older individuals who have lived in the area and lived through previous wildfire and flooding events. Our results vary somewhat from other PPGIS studies that found stronger connections between demand and land ownership and occupation (Fagerholm *et al*. 2019; Bryan *et al*. 2011; Brown 2004). The lack of statistical significance in our study may be due to our small geographic scale or response rate.

4.2. PPGIS as a tool to include sociocultural value in wildfire mitigation decisions

There has been a call among wildfire managers for "a better characterization of non-market resources at risk" in targeting wildfire mitigation activities in order to improve societal benefits (Thompson and Calkin 2011). However, to date, most of the literature assessing ecosystem service values in the wildfire literature has focused on source water protection and relied on monetary valuation methods (e.g. Buckley *et al*. 2014; Kruse, Hartwell, and Buckley 2016; Jones *et al*. 2017). Using PPGIS to understand areas of value to people allows for a more bottom-up and participatory approach to including values at risk in wildfire mitigation targeting and allows for ecosystem services that are harder to monetize, such as relational and cultural values, to be included. Thus, sociocultural methods could be a complement to other approaches being used to prioritize wildfire mitigation fuel treatments, but we are not suggesting that it replace other process-based models that can spatially identify the locations of ecosystem service provision (e.g. Gannon *et al*. 2019).

In our study, we found that the overlap zones of ecosystem service demand and wildfire hazard were around towns, roads, and water sources. Among the sixteen zones of overlapping hotspots, five were in or around Estes Park, ten were along Highway 34, and one was in the town of Glen Haven. These hotspot results reinforce the importance of access and open water to ecosystem service demand. It also suggests that accessibility (i.e. the presence of roads) is related to both sociocultural demand and wildfire hazard. The number one predictor of wildfire ignition is the presence of roads (Narayanaraj and Wimberley, 2012). Additionally, our results confirm the importance of water-based ecosystem services in prioritizing wildfire mitigation activities. While many organizations (e.g. water utilities) already make wildfire mitigation decisions based on risk to source drinking water (e.g. Jones *et al*. 2017), our PPGIS assessment suggests that local beneficiaries also prioritize water, but often at different locations.

Accounting for and managing non-market ecosystem service values at risk remains a significant roadblock for effective wildfire management planning (Thompson and Calkin 2011). Our study enhances the understanding of social preferences for ecosystem services in this study area, an important step towards reducing uncertainty in wildfire risk management equations (Calkin, Jones, and Hyde 2008; Thompson and Calkin 2011). Future studies could build on our analysis by considering sociocultural preferences across different user groups, similar to that done in PPGIS studies focused on recreation management (e.g. Brown and Reed 2009; van Ripper *et al.* 2012; Brown and Raymond 2014; García-Nieto *et al*. 2015; Ancona *et al*. 2022). As we found in this study, many ecosystem service preferences are driven by income and education, suggesting that there could be different ecosystem service preferences for more disadvantaged groups. While questions of environmental justice are beyond the scope of this study, federal management agencies are important arbiters for the equitable distribution of wildfire risks, as well as ecosystem service benefits (Adams and Charnley 2020). PPGIS and sociocultural ecosystem services valuation is an avenue by which environmental justice could be better incorporated into wildfire mitigation decision making.

5. Conclusion

Sociocultural valuation of ecosystem services can allow a broader representation of people's values in natural resource management decisions. Our analysis of ecosystem service demand and the associations with demand in the Big Thompson Watershed provides a snapshot into what is important to people in that area, and our spatial analyses paint a picture of where benefit perceptions are concentrated. By overlapping sociocultural and wildfire hotspots, managers can determine where benefits are threatened in their wildfire risk mitigation planning. Future studies can build on the PPGIS framework presented here by reaching a broader suite of stakeholders and decision makers. Our study was limited by its overrepresentation of voices that skew toward higher income and higher education. A greater effort to include the voices of those typically underrepresented in natural resources decision making would be a powerful addition in future PPGIS studies. Additionally, future analyses could examine community and group demand for ecosystem service benefits, an important aspect that can vary from individual demand (Pascual *et al*. 2017). Overall, this paper contributes to a greater understanding of sociocultural ecosystem service values and provides a framework for incorporating sociocultural values into future wildfire management strategies.

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Supplemental data

Supplemental data for this article can be accessed here.

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