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Social–ecological hotspots mapping: A spatial approach for identifying coupled social–ecological space

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Abstract

This paper advances the concept of a coupled social–ecological system (SES), where human and biophysical systems are closely linked, to examine and explain variations in landscape values perceived by people in their region. In this paper, we describe an approach that allows the mapping of SES by linking survey research with geographic information systems (GIS) to provide spatial representations of social and ecological system convergence. Using survey data that measured landscape values from multiple communities on the Kenai Peninsula, Alaska, we identify geographical areas where both human-perceived and physically measured ecological values overlap and are referred to as social–ecological "hotspots". Community landscape values, collected as point data, were used to generate point density maps to produce hotspot surfaces for each value. These value surfaces were spatially cross-correlated with other communities' value surfaces and with an ecological map layer (net primary productivity) to demonstrate social–ecological mapping. Moderate spatial cross-correlation coefficients were found between most landscape values by community with 18 hotspot surfaces pairings exhibiting strong positive spatial cross correlations. Moderately significant, positive linear relationships were found between perceived biological values and net primary productivity for three of six communities. The exploratory spatial analysis presented in this paper is a first step in identifying and describing the presence of SES in a regional context. We conclude the paper by discussing the potential managerial and ecological implications of coupled social–ecological systems including system resilience and vulnerability, and the limitations of the approach that need to be considered.

Keywords: Geographic information systems; Hotspots mapping; Landscape values; Perceptions; Resilience; Social–ecological systems

1. Introduction

Coupled social–ecological systems (SES) represent a broad concept of people in nature (Berkes et al., 2003) where human systems and ecological systems are viewed as being tightly and inextricably linked. In the sustainable use and management of natural resources, the notion of SES has been practiced for millennia in numerous indigenous and other resource-dependent cultures, yet it is relatively new to Western science and environmental management. At a time when communities, scientists, and managers are seeking approaches to respond to a changing environment (Walker et al., 2002), there is a need to consider the implicit connection between humans and ecosystems to implement sustainable resource use.

Communities that can successfully respond to changing environmental conditions, maintain functionality, and persist over time demonstrate resilience (Walker et al., 2004) and there is an increasing awareness that integrated SES is one component for successful resilience management (Walker et al., 2002). Various aspects of spatial resilience have been addressed in ecology (e.g., Van Nes and Scheffer, 1995; Peterson, 2002) but the sociocultural aspects of human values as they relate to ecological processes have received relatively little research attention.

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Dynamics in a SES arise as a consequence of spatiotemporal landscape heterogeneity, interdependencies of socio-cultural, economic and biophysical variables, and cross- and multi-scale feedbacks between these variables. Patterns of use, technology, and resource demand can elicit feedbacks between communities and their resources contributing to the complexity of SES wherein unpredicted outcomes may emerge. While land planners and managers often seek to anticipate future patterns and plan proactively, the complexity of the systems often precludes accurate predictions. Land managers are often faced with "moving targets" where management approaches may become inappropriate or ineffective because they are incompatible with changing social values at the community, regional, or even national levels.

A consequence of SES complexity is emergence, an outcome that cannot be easily understood or predicted by examining a narrow set of variables in isolation (Langton, 1990). Emergence results from dynamic interactions and feedbacks in a specific coupled social–ecological space or "hotspot" where multiple and diverse human values are co-located with a biophysical resource (e.g., a highly productive forest with a dense moose population where hunting is concentrated).

One of the first steps in articulating and anticipating emergence in a complex system, is to visualize sociocultural and economic values assigned by users to landscapes of interest. This involves mapping individual and community-articulated values in space and correlating these with metrics of resource types and productivity. There is a broad literature on the extension of resilience and complexity theory to management including both statistical and theoretical discussions (Walters, 1986; Hilborn and Mangel, 1997; Holling, 2001) but few provide tools that are useful to managers who must cope with these complexities on a daily, seasonal and yearly basis in a way that is transparent to the public.

The understanding and measurement of social–ecological space can be implemented by identifying social–ecological hotspots. Social–ecological hotspots are locales that exhibit spatial coincidence of both high perceived landscape values and high rating for biophysical conditions. For example, a SES hotspot might occur in an area perceived by community members to have high biological value along with high biological productivity as determined using quantitative measurement through a scientific process. Other spatial coincides may also be of interest in landscape management. For example, areas of low perceived landscape values and high biophysical rating, or what could be termed SES warmspots, may be useful areas to focus conservation efforts.

Approaches to hotspots mapping have emerged from the physical sciences for identifying critical locales in a wide range of fields including seismology (Chulick et al., 2001) and volcanology (Devey, 1988). In the social sciences there has been a steady effort to develop hotspot mapping including fields including in epidemiology (e.g., Lai et al., 2004) and criminology (e.g., Ratcliffe and McCullagh, 1998). An established and robust method in these applications of hotspots mapping is kernel density estimation of observed phenomena (Thurstain-Goodwin and Unwin, 2000; Borruso, 2003).

The capture of quantitative social data has increasingly used mapping tools to provide spatial representations of peoples' perceptions and evaluation of the environment (e.g., Carver, 1991; Kliskey, 1994; Kliskey, 2000; Brown, 2005; Brown and Raymond, 2007; Tyravainen et al., 2007). These approaches have been based on either generic feature mapping or specific place mapping. In generic feature mapping respondents are asked to rate, evaluate or quantify their preferences toward geographic features (e.g., hiking trails or deciduous forest) that can be mapped from an appropriate geographic database (e.g., Kliskey, 1994). Specific place mapping, in contrast, asks respondents to identify locations on a map where certain values (e.g., recreation) can be found, are held, or are experienced (Brown and Raymond, 2007).

In specific place mapping, humans associate values with places for different reasons ranging from instrumental value (e.g., places that provide sustenance) to symbolic value (places that represent ideas). Brown (2005) introduced the concept of a "landscape value" to provide an operational bridge between the "geography of place" and the "psychology of place" for

Table 1
Typology of perceived landscape values used in Kenai Peninsula case-study of perceived landscape values

Value	Description
Aesthetic	Areas valued for the scenery—mountains, glaciers, forests, beaches, tidelands, bays and islands
Biological	Areas valued because they provide places for a variety of plants, animals and wildlife
Cultural	Areas valued because people can continue to pass down wisdom, traditions, and a way of life
Economic	Areas valued because they provide economic opportunities such as fisheries, tourism, or processing
Future	Areas valued because they allow future generations to know and experience the areas as they are now
Historic	Areas valued because they are places and things of natural and human history
Intrinsic	Areas valued just because they exist, no matter what humans think about them or how we use them
Learning	Areas valued because we can learn about the environment
Life sustaining	Areas valued because they are places that produce, preserve, clean, and renew air, soil, and water
Recreation	Areas valued because they provide places for outdoor, recreation activities and experiences
Spiritual	Areas valued because they are sacred, religious, spiritually important
Subsistence	Areas valued because they provide necessary food and materials to sustain people's lives
Therapeutic	Areas valued because they make people feel better, physically and/or mentally
Wilderness	Areas valued because they are wild

use in land use planning. In this paper, we refer to landscape values as those values people associate with the places where they live, work, visit, or otherwise attach meaning. These values include, but are not limited to aesthetic, cultural, economic, historic, recreation and wilderness values (see Table 1). Residents' perceived landscape values may be viewed as extending outward from a given community in a patchwork of spatial intensity and saturation (Brown et al., 2004).

In this paper, we outline a method for mapping coupled social–ecological space (SES) to identify areas where multiple and diverse human values converge with biophysical values. We demonstrate this method for the Kenai Peninsula, Alaska and discuss the applicability of the technique for resilience and landscape management.

2. Methods

The methodology we propose for identifying social–ecological space applies point density mapping of human landscape values to overlay with mapped ecological space. This approach builds on the work by Brown et al. (2004) that compared biodiversity in Prince William Sound as assessed by biologists with biological importance in the same area as assessed by local residents. The approach utilizes survey

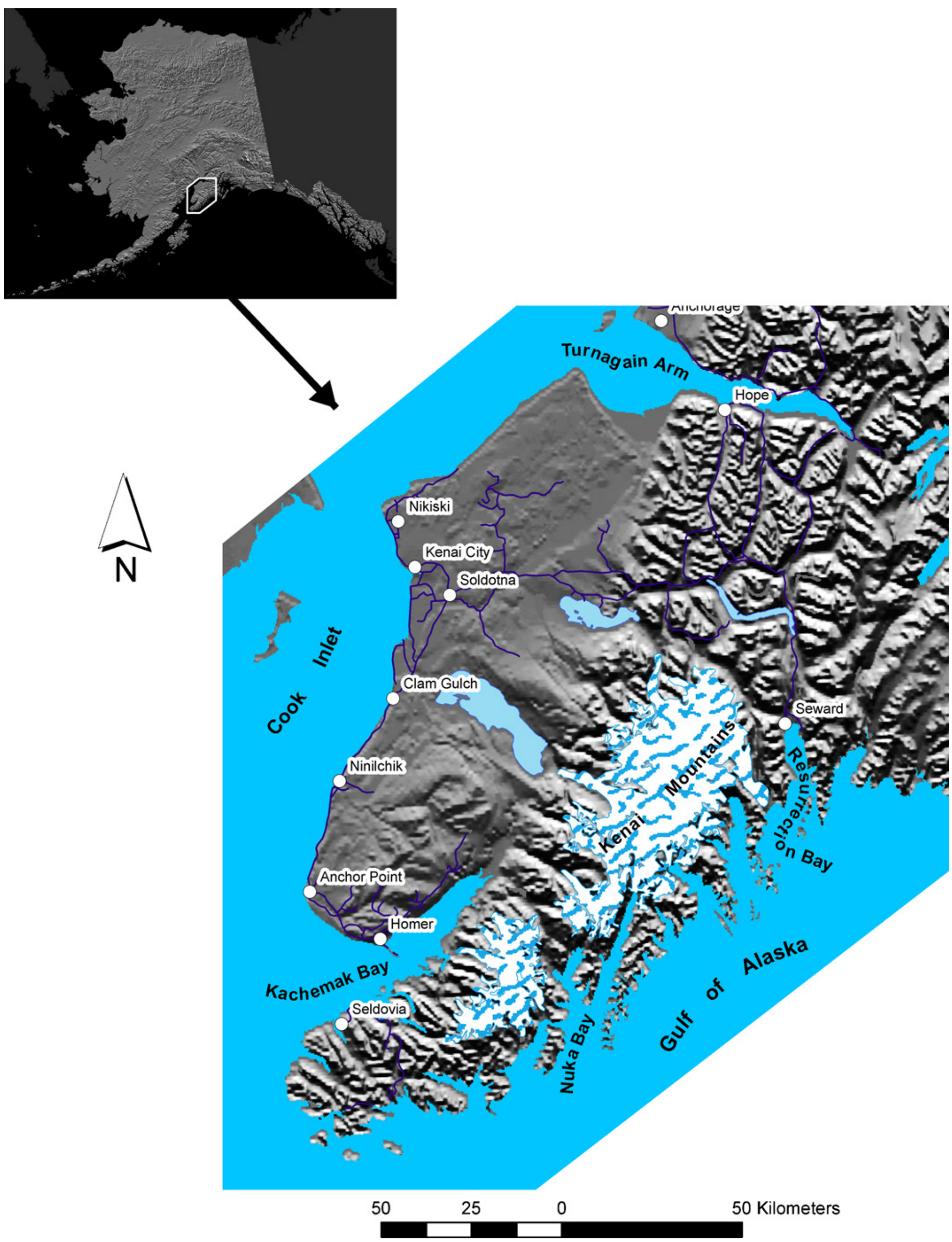

Fig. 1. Location map of Kenai Peninsula, Alaska.

instruments linked to geographic information systems (GIS) to provide a spatial representation of perceived values (e.g., Kliskey, 1994; Brown, 2005) using specific place mapping.

The methodology consists of seven steps:

1. Elicit and spatially locate landscape values (i.e., social space) using a survey questionnaire coupled with a mapping exercise (see Brown, 2005; Raymond and Brown, 2006).
2. Link the questionnaire responses with the digitized locations of landscape values using GIS.
3. Generate a density surface of perceived value from value locations using a point density function.
4. Determine the threshold for value hotspots based on kernel density estimation.
5. Identify ecological hotspots using observed data, e.g., net primary productivity determined from remote sensing.
6. Calculate the spatial correlation between social space and ecological space using a sample of randomly generated locations.
7. Overlay social and ecological space to represent social–ecological space, e.g., areas of high perceived biological value and high biological productivity (i.e., hotspots); areas of low perceived biological value and high biological productivity (i.e., warmspots), and; areas of low perceived biological value and low biological productivity (i.e., coldspots).

The approach makes no assumptions about political, administrative or ecological boundaries—respondents indicate point locations where values exist for them. This has the benefit of being a universal approach for a wide range of landscape values and enables the generation of density measures from the collective responses for a sample or sub-sample (e.g., for specific communities). While approaches that utilize polygon mapping, rather than point mapping, could be argued as being better for mapping recreation values in specific administrative units (e.g., within a National Park unit), for example, that type of approach has less applicability when examining multiple and varied landscape values or when considering regional analyses that cross potentially arbitrary administrative or political boundaries.

2.1. The case-study location: Kenai Peninsula, Alaska

We applied the SES hotspots methodology to the Kenai Peninsula, Alaska (Fig. 1). The Kenai Peninsula lies directly south of Anchorage and the waters of the Gulf of Alaska and Prince William Sound border the peninsula on the south and east with Cook Inlet bordering the peninsula to the west and north. The Kenai Mountains run north and south through the peninsula, with low-lying lands to their west. The peninsula encompasses a total of 21,100 km^2. The resident population of the peninsula was estimated to be 51,146 people in 2003 (source: U.S. Census Bureau) with the dominant economic sectors consisting of oil and gas production, commercial fishing, timber harvesting and tourism, with tourism the fastest growing industry (Kenai Peninsula Borough Council, 2002).

In 2002, a mail survey was developed to identify and measure the landscape values of residents of the Kenai Peninsula and Anchorage with respect to the Kenai Peninsula. The survey was sent to 2582 randomly sampled households drawn from the Permanent Fund Dividend database using a modified total design method (Dillman, 1978). Each survey had a unique identifying number to track responses. A reminder postcard was sent a few weeks after the initial mailing, and a second survey package was sent to non-respondents.

For the purposes of this study, responses were grouped into six sub-samples representing communities on or near the Kenai Peninsula—Anchorage, Clam Gulch, Homer, Seldovia, Seward, and Soldotna (Table 2). Specific place mapping was undertaken for each of the six sub-sample communities for all 14 landscape values in the typology. Density surface maps, described below, were produced for each community's values.

2.2. Mapping social space

To map social space, respondents were asked to identify the locations of landscape values using a typology of the following values: aesthetic, biological, cultural, economic, future, historic, intrinsic, learning, life sustaining, recreational, spiritual, subsistence, therapeutic, and wilderness values (see Table 1). The selection of landscape values was based on conceptual work by Rolston and Coufal (1991) who identified 10 basic landscape values: life support, economic, scientific, recreation, aesthetic, wildlife, biotic diversity, natural history, spiritual, and intrinsic. That typology was modified and expanded in subsequent studies to include 13 values by including subsistence, cultural, and therapeutic values (Reed and Brown, 2003; Brown, 2006; Raymond and Brown, 2006). For the Kenai Peninsula study, a 14th landscape value, "wilderness", was added to the typology.

Each respondent was also asked to rate the relative importance of each landscape value on an ordinal scale (effectively a standardized scale) when mapping the location (Table 1). The instructions stated, "Find the 'Values and Special Places' dot

Table 2
Sub-sample size and population estimates for Kenai Peninsula communities

Sub-sample	Communities included	No. of respondents	Population estimate 2002[a]
Anchorage	Anchorage, Eagle River, Girdwood	90	260,859
Clam Gulch	Clam Gulch, Kasilof, Ninilchik	77	674
Homer	Anchor Point, Homer	150	7,328
Seldovia	Port Graham, Seldovia	40	616
Seward	Moose Pass, Seward	73	2,973
Soldotna	Kenai City, Nikiski, Soldotna	101	15,758

[a] *Source*: State of Alaska Department of Labor & Workforce Development. URL: www.labor.state.ak.us/research/pop/estimates/05t4-3.xls.

sheet. There are 6 dots for each value with an 'importance' rating from 5 to 50 points. Some value dots are more important (50 points) than other dots (20, 10, or 5 points each). Stick the dots on the map where the values are important to you. The most important dots go with the most important places. Use as many or as few dots as you like." Thus, participants could map from 0 to 84 landscape value locations (14 landscape values times 6 dots per value). The 1:250,000 scale maps used for the mapping exercise allow resolution of a dot location to 250 m. Post-survey focus group discussions in communities following the mapping exercise revealed that respondents typically resolved the locale of a value on the ground to approximately 500 m but usually not finer. A resolution of 500 m was therefore used as the output grid size.

Each respondent's map of values was digitized and coded using GIS. The questionnaire data was entered into an SPSS® database and then joined with the spatial data in the GIS. The point data for each value type, e.g., recreation value, was subjected to spatial exploratory analysis using semi-variograms to measure spatial auto-correlation of the data (e.g., Burrough and McDonnell, 1998). This measures the degree of similarity between points that are close in distance compared to points that are farther away from one another.

Before conducting spatial cross-correlation of social data with ecological data, preliminary analysis was undertaken to determine the most appropriate spatial treatment of the landscape values point data. Continuous density surfaces for the landscape values data can be computed using either point density mapping methods (Brown, 2005) or spatial interpolation methods (Siniscalchi et al., 2006). Point density methods calculate the density of point features within a defined area (e.g., around a raster output cell) and produce a continuous surface representing the density of a selected feature. It is possible to use an attribute (e.g., the importance rating for a social value at a location) as a weighting factor for density mapping. Simple point density mapping calculates density based on the number of point features within a defined area, while kernel density mapping is based on a quadratic kernel function (Silverman, 1986) and fits a smoothly curved surface over each point producing a circular area (kernel) of a certain bandwidth (or search radius) around an indicator. The critical assumption in using kernel density estimation is in defining the search radius (Thurstain-Goodwin and Unwin, 2000; Van De Veen and Logtmeijer, 2005).

Several point interpolation methods are available for estimating the point value at an unsampled location based on measurements at sampled locations ranging from simple local interpolation (e.g., inverse distance weighting (IDW)) to potentially robust geostatistical interpolation (e.g., ordinary kriging). Kriging is typically undertaken with biophysical phenomena adhering to rigorous statistical criteria (Burrough and McDonnell, 1998) not present in subjective landscape values data. IDW has less stringent requirements than kriging (Watson and Philip, 1985) and is more attractive for using with social data (e.g., Siniscalchi et al., 2006), but the ability of any interpolative method to estimate landscape values at unsampled locations is unproven.

Previous trials using both point interpolation and point density methods with landscape value data from other studies yielded interpolated maps that were spurious and non-intuitive. Nonetheless, we felt it important to empirically investigate point interpolation of the landscape values data before proceeding with the corpus of the spatial analysis using density methods for the social data.

Maps were generated using point interpolation and density methods for aesthetic values for all respondents. The map in Fig. 2 shows the outcome of inverse distance weighting interpolation (Fig. 2A) and kernel density weighting (Fig. 2B) in the southwest portion of the Kenai Peninsula. Raw data points are shown with a cross (X) so the effect of each method can be seen. Interpolation estimates the aesthetic value *at all locations* using importance ratings from the closest set of data points. This can result in interpolated values at unsampled locations being inconsistent with what respondents actually think. Point density mapping, however, makes no assumption about values at unsampled locations—the method simply calculates density of sample points which can be optionally weighted by point importance ratings.

From our preliminary analysis, it is apparent that point density and interpolation methods can yield very different mapping results based on the importance ratings associated with each point. Of the two variables associated with respondent mapped points – location and importance – the importance ratings appear much less reliable and consistent across survey respondents. Thus, the use of spatial interpolation methods appears more appropriate in situations where it is known that there is a continuous spatial coverage of a variable across an area (e.g., noon air temperature). Because some mapped landscape values exhibit patchy distributions (e.g., similar to rainfall), they cannot be assumed to constitute continuous spatial variables across the entire study region. We conclude that the ability of interpolative methods to estimate landscape values at unsampled locations continues to be, at best, unproven, and at worst, misleading; the use of density functions appears more appropriate to analyze the landscape values data.

In adopting point density weighting we used a circular neighborhood with a 5000 m search radius. A circular neighborhood provides a bandwidth that is equidistant from the point location—the 5000 m search radius, at 10 times the spatial resolution, was the largest extent for which there was minimal change (no more than 5% of the area) in the density weighted output when search radii of increasing size was applied. Beyond 5000 m the density weighted output displayed changes of 5% or more while no significant differences were detected using search radii of 5000 m or less. The 5000 m radius appeared to provide a natural break between clusters of like locations and locations in a substantially different part of the landscape. This is consistent with other applications of kernel density estimation for visualizing locales of centrality for social phenomena (Thurstain-Goodwin and Unwin, 2000; Van De Veen and Logtmeijer, 2005).

2.3. Mapping ecological space

The mapping of ecological space can use the wide range of data sets that are collected for biophysical characteristics

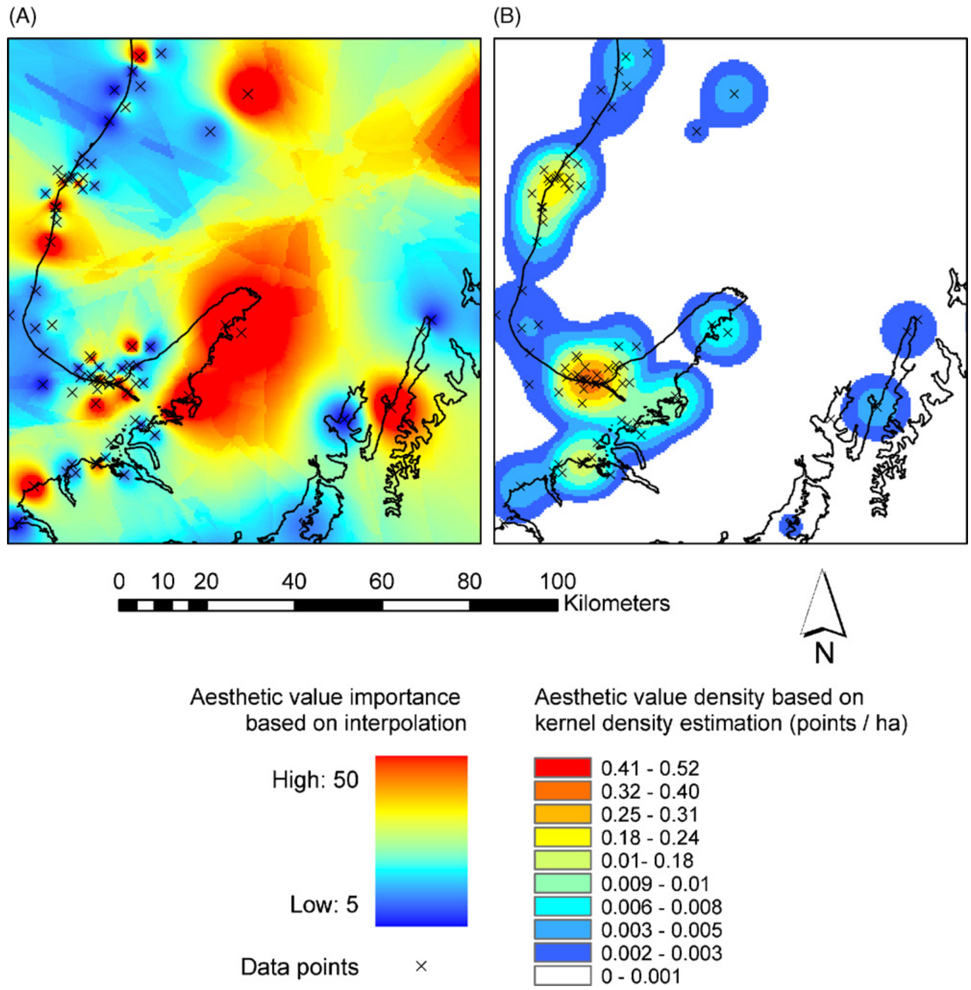

Fig. 2. Comparison of interpolative and density weighting mapping techniques using the example of perceived aesthetic value in Kachemak Bay, Kenai Peninsula, Alaska showing (A) interpolative mapping using inverse distance weighting, and (B) point density mapping using kernel density estimation.

of the environment such as vegetation, animal and biological productivity mapping from remote sensing, and ground survey techniques. Specific spatial ecological measurements might include vegetation classifications, animal distribution maps, species diversity indices, species richness indices, normalized vegetation indices (NDVI), chlorophyll concentration mapping, and net primary productivity (NPP) mapping. In this study, a standardized NPP index (source: NASA 2004) was used in the analysis because data was readily available for the study area at map scales consistent with the social hotspots mapping. NPP satellite imagery products provide accurate, regular measures of the growth of terrestrial vegetation (Running et al., 1999). We used MODIS product number 17 that measures annual NPP at 500 m resolution, and is based on the linear relationship between NPP and absorbed photosynthetically active radiation (Monteith, 1972). NPP has been shown to be positively correlated with species diversity for some taxonomic groups at some spatial scales (Zhao et al., 2006; Luck, 2007) and so can potentially be used as a surrogate for species diversity as well as a direct measure of biological productivity making NPP a useful representation of ecological space—it is not however the only possible representation of ecological space and is used primarily to illustrate the SES method.

2.4. Hotspot patterns and structure analysis

Analysis of the pattern and structure of value hotspots in the landscape, as with biophysical landscape patterns, is essential for understanding the dynamics between landscape pattern and process. Although hotspots can be identified graphically with subjective judgment, a more robust approach is to identify a threshold that defines a landscape value hotspot statistically using kernel density estimation similar to the approaches developed in crime hotspots mapping (Ratcliffe, 2004). This method for identifying consistent concentrations of high value (i.e., hotspots) uses incremental values of the mean and takes into account the statistical spatial distribution of the point data set. We used kernel density estimation to derive landscape value hotspots using the upper third of the index range, i.e., standardized density weightings above 0.66.

Landscape metrics have been developed to measure the density, size and shape of patterns in physical landscapes (Turner et al., 2001) and we used them to measure the structure and spatial arrangement of perceived hotspots (i.e., as landscape patches). Landscape values hotspots were quantified using landscape patch indices (McGarigal and Marks, 1985) to provide measures of the number of hotspots for each value by community, including the size, shape and number of the hotspots. Hotspot surfaces for a single value were compared between sub-samples representing different communities by computing the residuals between hotspot surfaces for each community. Comparisons between surfaces were also made using the spatial cross-correlation coefficient between hotspot surfaces computed from a set of randomly located points. By using a set of random points rather than the entire grid surface, it was possible to avoid the confounding effects of spatial autocorrelation.

3. Results

A total of 561 surveys were received for the Kenai Peninsula questionnaire survey providing an overall response rate of 23% after allowing for non-deliverable surveys. The response rate was comparable to other natural resource questionnaire surveys undertaken in Alaska that included a mapping exercise, with response rates ranging from 14% to 27% (Brown, 2005). The response rate on the map exercise was 20.4% (i.e., 89% of the survey response rate). The demographic profile of the respondent sample was close to (within 2.5% of) the Census 2000 statistics for Kenai Peninsula Borough for gender (54.2% male/46.7% female), age (34.3% 18–39 years/46.7% 40–59 years/17% 60 years+), ethnicity (white 87.0%/Native American or Alaskan 7.1%/other 5.9%) and educational achievement (none 0.2%/elementary 1.7%/high school 32.9%/college 33.4%/graduate 9.0%). Sub-sample demographics for each of the six communities were similar to the total respondent sample and within 2.5% of the Census 2000 statistics for each community. We consider our sample and sub-samples to be representative of the local populations.

3.1. Social value hotpots for sub-sample communities

The perceived biological value and recreational value for each of the six Kenai Peninsula communities are shown in the maps of Figs. 3 and 4. These maps highlight two trends. First, that there are locales of particularly high value (e.g., biological value and recreation value) in close proximity to the community in which they reside. For example, Seward residents perceive locales of high biological value (Fig. 3B) and recreation value (Fig. 4B) in the Resurrection Bay area near Seward. Homer

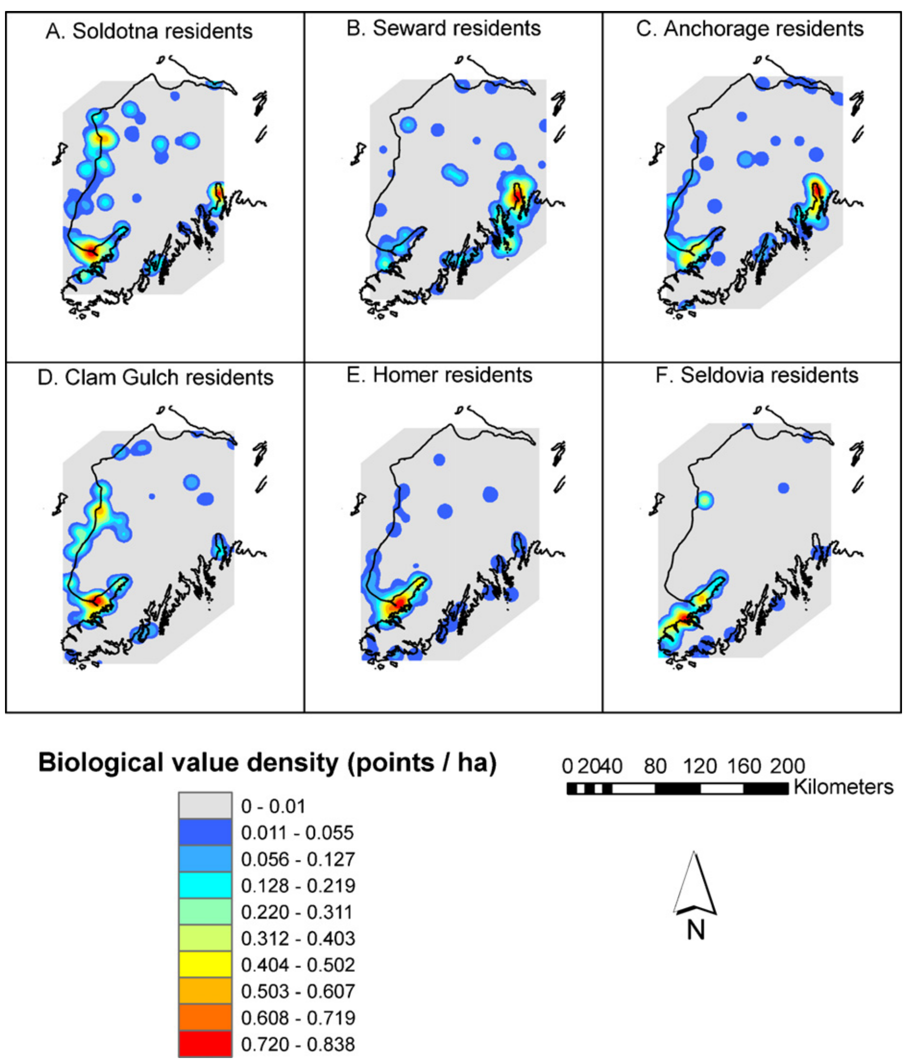

Fig. 3. Perceived biological value maps for six communities on the Kenai Peninsula, Alaska.

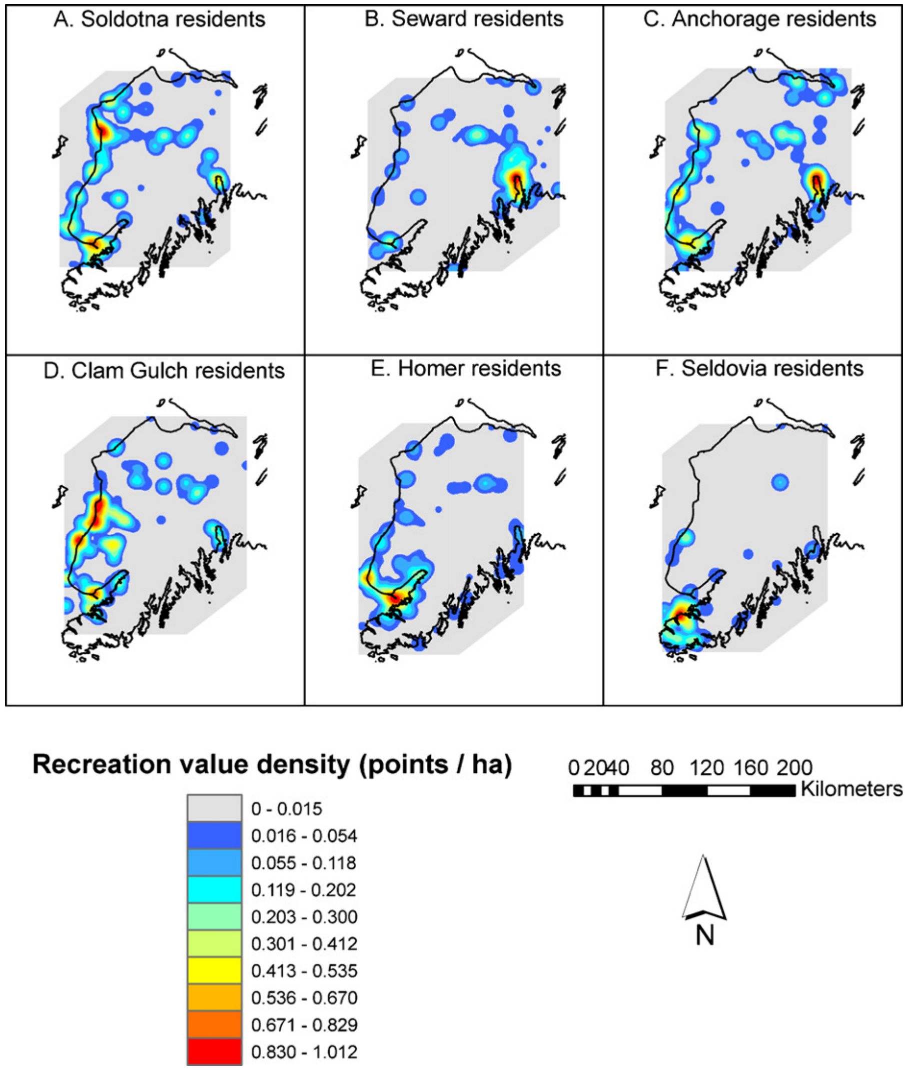

Fig. 4. Perceived recreation value maps for six communities on the Kenai Peninsula, Alaska.

residents perceive high biological value (Fig. 3E) and recreation value (Fig. 4E) in the Kachemak Bay area near Homer, while Seldovia residents who also perceive high biological value (Fig. 3F) and recreation value (Fig. 4F) in the Kachemak Bay area have hotspot locales that occur on the south side of Kachemak Bay in closer proximity to Seldovia. The second trend is that there is some consistency between communities with respect to the location of major hotspots but plurality with respect to the location of minor hotspots. For example, all communities perceive high biological value in parts of Kachemak Bay near Homer, to a greater or lesser extent, while all communities perceive high recreational value in the Resurrection Bay area near Seward to varying degrees.

Spatial cross-correlation coefficients between hotspot surfaces for each value were computed using 1000 randomly generated locations across the spatial extent of the study area. For most pairings of communities, the spatial cross-correlation coefficients for each value ranged between −0.3 and +0.4 indicating patterns of independence between hotpot surfaces and a moderate degree of plurality between communities' perceived hotspots. There were 18 hotspot surface pairings between communities that exhibited strong positive spatial cross-correlations indicating a higher degree of consistency in perceived hotspots for those communities (see Table 3).

There were positive spatial correlations between Anchorage and Seward residents for perceived aesthetic, biological, economic, historic, learning and recreation value hotspots (Table 3). There were positive spatial correlations between Anchorage and Soldotna residents for perceived biological, cultural, economic, historic, recreation and subsistence value hotspots (Table 3). Perceived biological, economic and subsistence values were all positively correlated for Clam Gulch and Soldotna respondents. These three community pairings (Anchorage/Seward, Anchorage/Soldotna, and Clam Gulch/Soldotna) thus have a moderate degree of consistency in perceived hotspot locales while all other community pairings displayed a higher degree of pluralism.

3.2. Hotspot pattern and structure

Landscape and class level metrics were computed for all perceived social hotspots for each community. A wide range of landscape metrics exist (McGarigal and Marks, 1985) but differ-

Table 3
Significant spatial cross-correlations between perceived landscape values

Value	Community 1	Community 2	Spatial cross-correlation coefficient
Aesthetic	Anchorage	Seward	0.696
	Homer	Soldotna	0.641
Biological	Anchorage	Soldotna	0.615
	Anchorage	Seward	0.722
	Clam Gulch	Homer	0.718
	Clam Gulch	Soldotna	0.661
Cultural	Anchorage	Soldotna	0.630
	Homer	Seldovia	0.686
Economic	Anchorage	Soldotna	0.763
	Anchorage	Seward	0.617
	Clam Gulch	Soldotna	0.639
Historic	Anchorage	Soldotna	0.608
	Anchorage	Seward	0.631
Learning	Anchorage	Seward	0.697
Recreation	Anchorage	Soldotna	0.614
	Anchorage	Seward	0.710
Subsistence	Anchorage	Soldotna	0.810
	Clam Gulch	Soldotna	0.642

ent metrics will not necessarily be independent of others (Riitters et al., 1995)—for this reason four representative metrics (total number of hotspots, mean area of hotspots, percent of the total landscape covered by hotspots, and a shape index) were used.

For perceived biological hotspots (as one example), there was an average of three hotspots with a mean area of 2244 km^2, covering on average 1.8% of the landscape of Kenai Peninsula, and with a mean shape index of 1.21 (a slightly irregular shape − 1.00 is perfectly regular or circular). The metrics for different communities' respondents varied (Table 4) with a range of 2–4 hotspots among the different communities, mean hotspot size ranged from 1574 to 2823 km^{2,} covering a small proportion of the landscape (range 1.4–2.7%), and the shape index ranged from highly regular (1.11 for Clam Gulch residents) to moderately irregular (1.42 for Anchorage residents).

When comparing the pattern of perceived hotspots for the different landscape values, there were differences between landscape values. The mean landscape metrics for biological value hotspots showed, for example, fewer (3 on average), larger (2244 km^2), more irregular (shape index = 1.21), and more landscape coverage (1.8%) than spiritual hotspots which were more numerous (9 on average), smaller (117 km^2), less irregular (shape index = 1.12), and that covered a relatively lower proportion of the landscape (1.2%). A linear regression for mean hotspot size and number of hotspots (Fig. 5) showed a strong, negative relationship ($p < 0.01$, $R^2 = -0.90$) highlighting the trend from many smaller hotspots to fewer larger hotspots. There were three identifiable clusters of landscape values at the upper, middle, and lower end of this relationship (Fig. 5). Four values at the upper end (spiritual, learning, future, and therapeutic values) represent more intangible locale-specific values that were found in more localities but covering a smaller area. Four values at the lower end (historic, cultural, recreational, and biological values) represent more tangible values that were found in fewer localities but covered a larger area. Tangible values refer to those landscape values that are directly anchored by a physical feature, setting or activity, for example, recreation value may be linked to fishing in a particular lake or river, and biological value may be linked to specific vegetation or wildlife. Intangible values, by contrast, may have no direct or explicit physical anchor, for example, spiritual value may result from a feeling gained at a location from phenomena other than the particular location. Six values occupied the middle cluster (intrinsic, aesthetic, life, subsistence and economic values) representing intermediate values of this relationship between hotspot number and area.

Table 4
Landscape metrics used to quantify perceived biological value hotpots for each community on Kenai Peninsula, Alaska

Community	No. of hotspots	Mean hotspot size (km^2)	Percent of landscape	Mean shape index
Anchorage	2	2823	1.7	1.42
Clam Gulch	4	1574	1.9	1.11
Homer	2	2689	1.6	1.19
Seldovia	3	1703	1.6	1.21
Seward	2	2168	1.4	1.18
Soldotna	3	2508	2.7	1.17
Mean	2.7	2244	1.8	1.21

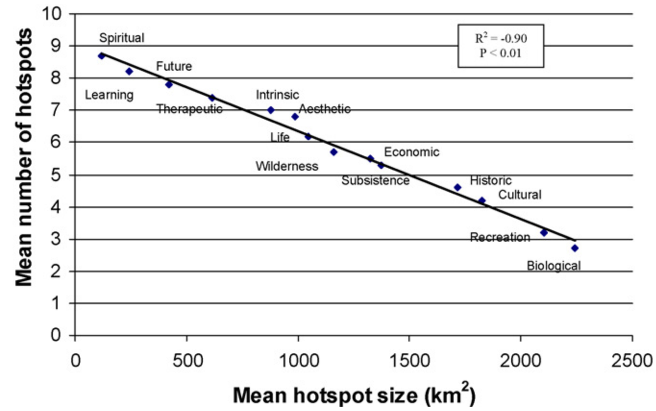

Fig. 5. Linear regression for number of hotspots and mean hotspot size for all perceived values and all communities on Seward Peninsula, Alaska.

3.3. Relationships between perceived biological hotspots and biological productivity

Social–ecological space was measured by the overlap between perceived landscape value maps and ecological maps. Using the example of net primary productivity as one measure of ecological space we examined the relationship between a standardized NPP index and perceived biological value (using a standardized index of the density weighting for a value) using linear regression. Moderately significant, positive linear relationships were found between respondents' perceived biological value and primary productivity in the landscape for the Kachemak Bay communities of Homer and Seldovia and also for the aggregated perceived biological values of all six communities (Table 5).

Table 5
Linear regressions for cross-correlations between standardized perceived biological value index and net primary productivity index for Kenai Peninsula, Alaska

Community	R^2	Significance level
Anchorage	0.29	ns
Clam Gulch	0.33	ns
Homer	0.78	0.05
Seldovia	0.75	0.04
Seward	0.12	ns
Soldotna	0.41	ns
Aggregate of all communities	0.60	0.02

Social–ecological space was mapped by overlaying perceived biological value with the NPP map. The example of one of the communities with a significant, though moderate, spatial correlation (Homer) is displayed to show the relationship between respondents' perceived biological value and the spatial distribution of net primary productivity (Fig. 6). This produced a social–ecological hotspot map highlighting locales of coincidence between high perceived biological value and high biological productivity—potentially critical areas in the landscape for management consideration if the perception of high value becomes manifested through actual use that is inconsistent with the maintenance of high biological productivity.

4. Discussion

4.1. Implications for landscape management

The SES hotspot mapping method identifies areas of significant convergence between social and ecological space. The identification of such areas is a first step toward developing sustainable land management plans that protect landscapes while providing for human needs. Each landscape value has an implicit or potential set of prospective human activities and specific land uses that may (or may not) be compatible with sustaining biologically productive and resilient systems. Reed and Brown (2003) described a process for determining the consistency of landscape values with potential forest management activities they termed "values suitability analysis". This type of land use planning and decision process is based on sound inventories of landscape values that are used in combination with expert judgment. For example, some would consider riding all-terrain vehicles (ATVs) an expression of recreation value, but the compatibility of this form of recreation with the protection of highly productive biological systems is doubtful. So while the identification of SES hotspots helps identify areas that merit special management attention, it does not eliminate the challenging task of determining which human activities and land uses are consistent with protecting the identified landscape values. Because the methodology is based on a specific place mapping approach that uses point identification and mapping it does not involve *a priori* judgments about boundary locations and is an approach useful to planners because it has applicability across arbitrary boundaries and polygons.

The relationship between the mean number of hotspots and the mean hotspot size for the 14 landscape values (Fig. 5) highlighted numerous, smaller, uniformly shaped hotspots for more intangible landscape values and fewer, larger, irregularly shaped hotspots for more tangible landscape values. The actual size, shape, and number of these hotspots are in part a result of the search radii and kernel density threshold that is used,

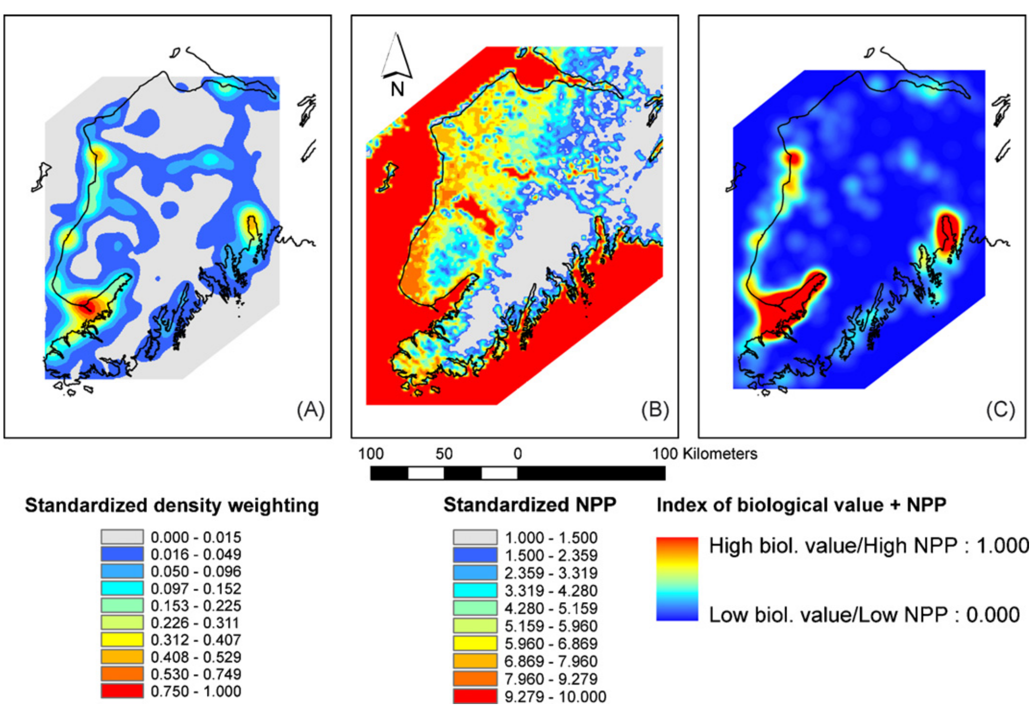

Fig. 6. Social–ecological hotspot map of Kenai Peninsula, Alaska for Homer respondents derived from the overlay of a standardized perceived biological value index map for Homer respondents and a net primary productivity index distribution showing (A) perceived biological value; (B) standardized index for net primary productivity, and the resulting; (C) social–ecological hotspot map.

however, the relative difference between landscape values is a consequence of the respondents' perceptions. This pattern in landscape metrics suggest that landscape managers need to focus attention for more intangible landscape values (e.g., spiritual value) at discrete, specific locales whereas the management for more tangible landscape values (biological) can be considered more broadly from a spatial perspective.

The spatial cross-correlation analysis of perceived landscape values is of interest for understanding the role of transient populations in a region and the effect of adjacent large population centers. First, Anchorage was involved in most (12 of the 18) of the significant community pairings (Table 3). This result does not seem surprising given that Anchorage is the only community not on the Kenai Peninsula. In this sense, Anchorage is a transient community and this analysis reveals where and why its residents travel to the Kenai Peninsula. Second, given that the Anchorage population is many times greater than the Kenai Peninsula communities, the areas of spatial cross-correlation could be considered to be "very hot" hot spots. This kind of analysis could be useful in identifying and conserving rural areas impacted by large population centers.

To illustrate the potential value of SES hotspot mapping for land use planning and management, consider the Coastal Zone Management Act (16 U.S.C.A. Section 1451 et seq. 1972). The CZMA provides federal grants to coastal states such as Alaska to develop and implement coastal management plans (CMPs) to "preserve, protect, develop, and where possible, to restore or enhance the resources of the Nation's coastal zone for this and succeeding generations". A CMP must define permissible land and water uses in the coastal zone and identify "areas of particular concern" with the opportunity of full participation by government agencies and private persons. The identification of "areas of particular concern" has been completed for many coastal management plans without the benefit of SES hotspot mapping, including the Kenai Peninsula Borough Coastal Management Plan (1990) that governs this study area. The identification of "areas of particular concern" is especially amenable to the SES hotspot mapping method because SES hotspots are linked with areas that are vulnerable to human overuse based on high values. Further, the KPBCMP contains policy language that is directly relevant to SES hotspot mapping. The coastal policy on retention of open space within the coastal zone states, "Publicly owned shorelines, beaches and upland areas which possess high value recreation, scenic, wildlife or environmental quality or are subject to natural hazards, shall be retained as public open space or recreation areas" (KPBCMP Section 4.3). The landscape values mapping methodology described herein explicitly identifies these landscape values and using a GIS, public lands that meet this policy criteria should be retained as open space or recreation areas. Additionally, density maps can be generated that display the location of one or more of these combined landscape values.

A second example of the potential application of the SES hotspot mapping method for natural resource management concerns the "subsistence" value in coastal zone management. The KPCMP requires that coastal districts and state agencies recognize and assure opportunities for subsistence usage of coastal areas and resources by identifying areas where subsistence is the dominant use (KPCMP Section 11(a) and (b)). While the identification of subsistence areas is, or should be done in consultation with Alaska Native corporations, non-natives on the Kenai Peninsula also engage in legally recognized subsistence activities. The mapping of subsistence values among the regional, non-native population can augment the more formal consultation with Native corporations under coastal zone planning.

While the normal tendency in SES mapping is to focus on geographic areas of both high social and ecological value because these areas appear most vulnerable to human exploitation, it may be prudent to direct conservation efforts toward areas with high ecological value, but low expressed social value—SES warmspots. These areas potentially represent the remaining "low hanging fruit" for conservation because the conflict over values that often accompanies conservation efforts could be lower in these areas as indicated by the landscape values. SES warmspots could be identified using exactly the same approach as that used for SES hotspots with the exception that index values for perceived value and high index values for measured ecological space would be recoded with a unique attribute code and displayed.

In addition to the direct benefit of SES mapping for identifying geographic areas of management interest, there are process advantages to using the SES hotspot mapping method for land and resource planning. By using scientific sampling techniques in the communities of interest, the method is genuinely more inclusive than traditional land planning consultation methods that usually involve interest groups rather than the "silent majority". Further, the method has the capacity to tap "indigenous" or "lay" knowledge to supplement the "expert" knowledge used to develop most resource management plans. By offering a contrast to expert derived knowledge, the method provides for iterative expert adjustment in mapping the "areas of particular concern." The experts responsible for deriving the areas of concern would benefit from a potentially different view of the landscape. The combination of lay and expert assessments provides an explicit type of 'ground-truthing' that is often missing from current land planning processes. Further, many of the landscape qualities or attributes that are the subject of protection or development provisions under various land planning and management statutes, including coastal zone management, are inherently subjective. Goals, objectives, and policies of a land or resource plan developed in relative isolation by experts may not survive close scrutiny on the subjective elements of the plan. If these same plan elements are logically derived from publicly held landscape values, in combination with the views of resource planners and managers, the plan will be more defensible, if not acceptable, to the local communities.

4.2. Limitations and further research

The output from SES hotspot mapping, and the results we report here, are dependent on two assumptions underlying the methodology. First, the definition of bandwidth (the search radius) used in the point density function affects the output, particularly the size of a hotspot. As indicated in the Methods section varying the search radii led to a natural break (5000 m in this instance) above which hotspot size varied by more than 5%. The relative differences between landscape values and different communities are valid since this was applied consistently, however, further sensitivity analysis is necessary to determine the optimal search radius. Second, the kernel density threshold for identifying hotspots is based on a specified range of standardized density values, in this case the upper range as defined by the upper third of the index range (and similarly a midrange for identifying warmspots). The actual range used will change the size and shape of hotspots, for example changing the threshold from 0.66 to 0.6 (i.e., upper third to upper two-fifths) increases the hotspot size for biological values for each community by a mean of 1.5%, while shape increases slightly in regularity (shape index changes from 1.21 to 1.20). Further work is needed to explore the optimal threshold range for identifying an absolute hotspot size. Our results are specific to a 5000 m search radius and a kernel density threshold of 0.67, and are limited to these values.

This case-study of the Kenai Peninsula focused necessarily more attention on landscape values mapping since measurement and visualization of ecological space is well established. We presented one ecological metric (NPP) to demonstrate how social–ecological space can be mapped rather than providing an exhaustive analysis of spatial variation in ecological metrics. We acknowledge that there are limitations in our use of NPP as a metric, specifically that the relationship between NPP and species diversity as reported by Luck (2007) was based on faunal groups and did not include flora, that the relationship was positively correlated with threatened birds but negatively correlated with threatened mammals, for example, and that this was based on Australian ecosystems (and East Asian in the case of Zhao et al., 2006) so applicability to Alaskan ecosystems requires additional work. Other metrics such as endemic species richness could and should be incorporated into social–ecological space mapping. Further work could make a more comprehensive examination of the overlay and correlation between various ecological metrics and perceived values to portray social–ecological space for a region. Additional landscape value studies across multiple regions and ecosystem types may reveal patterns of SES coupling that are unique or shared.

The methodology described herein can be applied at different spatial scales according to the scope and context of the questionnaire used, the map scale used in the mapping exercise, and the minimum resolution at which respondents' are able to identify value locations. For the Kenai Peninsula example, scale was constrained to the resident and adjacent population of the region, a 1:250,000 scale map, and a minimum resolution of 500 m for location of values. Finer scale mapping would ideally require a more specific sample population, finer scale map, and identification of the minimum resolution that respondents can identify the location of values. While scaling up of SES hotspots mapping could technically be achieved by remapping at a coarser scale, the result is still dependent on the scale of the raw data collection process.

The generation of hotspots from point densities could create a false sense of precision regarding the hotspot boundaries. This is an inherent limitation of virtually any method that creates boundaries from sampled data. The landscape values data, because of its subjective nature, is vulnerable to a critique regarding the absolute position of boundaries. We note, however, that there is often considerable uncertainty and imprecision associated with boundaries for ecological data as well, for example, home ranges, some flora and fauna population distributions, etc., that seldom receives full disclosure and acknowledgement. A useful area for further study would be the application of fuzzy logic in the hotspot mapping methodology.

5. Conclusion

SES hotspot maps provide a visual tool for land planners and managers and the constituencies they serve that enables the visualization of human/landscape relationships. We acknowledge that the methodology, and the results from applying it, are subject to several limitations already discussed (resolution, search radius, and kernel density threshold) and that practitioners need to be aware of these. Notwithstanding additional work on these limitations, the identification of SES hotspots can help identify areas of high concern (e.g., conflicting landscape values) or areas of intense sociocultural/biophysical processes (e.g., a highly valued area for recreation which is physically fragile). Similarly, SES warmspots identify prospective conservation areas with high ecological value but low social value.

Mapping social–ecological space is an important first step in identifying the components of a system that lend resilience or vulnerability. Community resilience may be summarized as the capacity of an interacting group of agents to respond to disturbance without collapsing into a functionally different state that is controlled by different (socially and/or culturally unfamiliar) sets of processes. A resilient ecosystem can withstand abrupt shifts and shocks, and reorganize itself as necessary. Resilience in social systems has the added capacity of enabling humans to anticipate, learn, and plan for the future (e.g., Holling, 2001), and is fostered if a diversity of options exist. This may also mean that a diversity of co-located values exist that may be synergistic or antagonistic.

Human interactions with the biophysical environment modify the biophysical space and are subject to such feedbacks. A SES becomes vulnerable when system diversity or sociocultural/economic adaptation is reduced, especially where multiple, antagonistic values overlap in space, leading to conflict, resource degradation and lower valuation. This process may lead to a loss of functionality in the system if it is not appropriately managed. The conventional approach of responsive management where action is taken once conflicts or impacts are identified in the field, often results in inadequate remediation, mitigation and/or resolution, not to mention frustration and mistrust on behalf of both the managers and the users of the resource.

Vulnerability can be countered through enhancing resilience by increasing diversity (e.g., the number of economic options) and flexibility of controlling forces (e.g., management that is adaptable to specific local conditions), while preserving sociocultural values that are dependent on a particular space (Robards and Alessa, 2004). However, if the SES is not mapped and the relationships between values and the environment are not understood, then articulating a resilient response to change is uninformed.

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