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Empirical PPGIS/PGIS mapping of ecosystem services: A review and evaluation

Greg Brown [a,*], Nora Fagerholm [b,c,1,2]

[a] School of Geography, Planning and Environmental Management, The University of Queensland, Brisbane, QLD 4072, Australia
[b] Geography Division, Department of Geography and Geology, University of Turku, FI-20014 Turku, Finland
[c] Department of Geosciences and Natural Resource Management, University of Copenhagen, Rolighedsvej 23, 1958 Fredriksberg C, Denmark

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ABSTRACT

We review public participation GIS (PPGIS) and participatory GIS (PGIS) approaches for ecosystem services to identify current and best practice. PPGIS/PGIS are spatially explicit methods that have evolved over the past decade to identify a range of ecosystem services. Although PPGIS/PGIS methods demonstrate high potential for the identification of ecosystem services, especially cultural services, there has been no review to evaluate the methods to identify best practice. Through examination of peer-reviewed, empirical PPGIS/PGIS studies, we describe the types of ecosystem services mapped, the spatial mapping methods, the sampling approaches and range of participants, the types of spatial analyses performed, and the methodological trade-offs associated with each PPGIS/PGIS mapping approach. We found that multiple methods were implemented in nearly 30 case studies worldwide with the mapping of cultural and provisioning services being most common. There was little evidence that mapped ecosystem data was used for actual decision support in land use planning. Best practice has yet to coalesce in this field that has been dominated by methodological pluralism and case study research. We suggest greater use of experimental design and long-term case studies where the influence of mapped ecosystem services on land use decisions can be assessed.

1. Introduction

The mapping of ecosystem services emphasizes the spatial relationships between landscape characteristics such as land use/cover, and their contribution to human wellbeing (de Groot et al., 2010). Spatially explicit assessment is necessary to better understand and quantify the supply and demand of ecosystem services to support communication and decision-making, and to achieve priority on the political agenda to ensure future supply (Crossman et al., 2013; Cowling et al., 2008; Maes et al., 2012; Martínez-Harms and Balvanera, 2012; Opdam, 2013).

The mapping of ecosystem services using public participation GIS (PPGIS) and participatory GIS (PGIS) is a relatively new field that offers a supplemental approach to expert-driven ecosystem service mapping and modelling. PPGIS/PGIS refers to spatially explicit methods and technologies for capturing and using spatial information in participatory planning processes (Rambaldi et al., 2006; Sieber, 2006). In practice, there is continuing ambiguity in use of the terms PPGIS and PGIS. Brown and Kyttä (2014) attempt to provide some clarity, observing that PPGIS has typically been implemented by government planning agencies or academics to enhance public involvement in developed countries for urban and regional planning, often using random sampling methods and digital mapping technology with a primary focus on spatial data quality. In contrast, PGIS has been typically sponsored by NGOs in rural areas of developing countries to build social capital using purposive sampling and non-digital mapping technology, where spatial data quality has been of secondary importance. These characterizations, based on practice to date, are highly fluid given the pace of global technological and social change. Further, the general concept of "participatory mapping" can describe any process where individuals share in the creation of a map and would include the concept of volunteered geographic information (VGI) systems described by Goodchild (2007). Participatory mapping would arguably include early human cave paintings or even sketches in the dirt that describe the location of what we would now be call "provisioning" ecosystem services. To bound our review, we describe published research that has been, or would reasonably be classified as participatory GIS (PGIS), public participation GIS (PPGIS), or volunteered geographic information (VGI) by the authors.

PPGIS/PGIS has been increasingly used to engage the general public and stakeholders to identify a range of ecosystem services that originate in place-based, local knowledge instead of proxy

* Corresponding author. Tel.: +61 7 3365 6654; fax: +61 7 3365 6899.
E-mail addresses: greg.brown@uq.edu.au (G. Brown), nora.fagerholm@utu.fi, ncf@ign.ku.dk (N. Fagerholm).
[1] Tel.: +358 2 333 5591.
[2] Tel.: +45 353 21533.

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data from literature or process modelling (e.g. Burkhard et al., 2012; Raudsepp-Hearne et al., 2010; Schulp et al., 2012; Willemen et al., 2008). In the mapping of ecosystem services, participants identify spatially explicit direct and indirect benefits from ecosystems that contribute to human well-being and may also include an assessment of the relative importance of the services provided. PPGIS/PGIS studies have shown that participatory mapping of ecosystems services are especially appropriate to identify provisioning and cultural benefits that are grounded in personal experience (Brown et al., 2012b; Fagerholm et al., 2012).

Empirical mapping is especially suitable to assess cultural services that have been traditionally inferred from recreation and tourism locations, scenic beauty, cultural heritage sites, or assumptions derived from literature (e.g. Grêt-Regamey et al., 2008; O'Farrell et al., 2010; Raudsepp-Hearne et al., 2010; Schulp et al., 2012; Willemen et al., 2010). The recent literature on ecosystem services indicates that the mapping of cultural services lags behind other service categories and is common only for recreation service (Crossman et al., 2013; Egoh et al., 2012; Martínez-Harms and Balvanera, 2012). This limited focus underestimates the multiple, cultural benefits that are widely recognized as critical for human welfare and, hence, the need to acknowledge and map a broader variety of cultural services has been recognized widely (Chan et al., 2012; Daniel et al., 2012; Plieninger et al., 2013; Setten et al., 2012).

The importance of PPGIS/PGIS is supported by the concept of crowd wisdom wherein collective intelligence can be harnessed to find superior solutions to challenging social problems (Surowiecki, 2005). But crowd wisdom may also be harnessed to identify ecosystem services. With cultural services in particular, it would appear necessary to consult the actual people that derive the ecosystem benefits. Place-based mapping provides the means to operationalize the ecosystem service concept for appreciating and articulating multiple values and resolving conflicts (Potschin and Haines-Young, 2013) and for understanding the context of everyday place-based experiences and knowledge (Kyttä, 2011). Pragmatically, the participatory mapping of ecosystem services can play a crucial role when addressing outstanding environmental policy questions such as those in the European Union (Maes et al., 2012).

The mapping of ecosystem services using PPGIS/PGIS is intended to provide a more comprehensive assessment of ecosystem services where trade-offs can be examined, contributing to current efforts to advance ecosystem service mapping (Crossman et al., 2013; Raudsepp-Hearne et al., 2010; TEEB, 2010). However, to date, there has been no systematic review to evaluate PPGIS/PGIS methods to determine their relative strengths and limitations in measuring and analyzing ecosystem services. In this paper, we examine peer-reviewed, empirical PPGIS/PGIS studies involving the mapping of ecosystem services to determine current and best practice of PPGIS/PGIS methods for identifying and analyzing ecosystem services.

2. Methods

For the review, we included PPGIS/PGIS studies that reported the empirical mapping of ecosystem services, or related articles that were published using the mapped data. Peer-reviewed articles were identified using the electronic databases of ISI Web of Science (topic, title search) and Scopus (document search: title, abstract, key words). In addition, the Google Scholar database (advanced search) and PPGIS/PGIS bibliographies were included in our search (McCall, 2012a, 2012b). All the searches were performed between 30th December 2013 and 6th October 2014. We searched for publications containing the following key words in combination with 'ecosystem service*': 'PPGIS', 'public participation GIS', 'public particip* GIS', 'PGIS', 'participatory GIS', 'particip* GIS', 'VGI', 'volunteered geographic information', 'volunt* geogr* information'. We also included several recently published articles that did not appear in the searched databases. We identified over 40 peer-reviewed papers that reported 32 empirical cases between 1998 and 2014. We reviewed each of the articles to describe the case study context, the types of ecosystem services mapped, the participatory mapping methods, and the types of spatial analyses performed. The studies that form the basis of this review appear in Table 1. Several of these studies were also identified by Milcu et al. (2013) as comprising a cluster of social and participatory research methods.

The purpose of our review was to characterize the published research and evaluate the studies against criteria and indicators of best practice in mapping ecosystem services using PPGIS/PGIS. One of the challenges for this evaluation is that the use of PPGIS/PGIS for identifying ecosystem services is an emerging field of research that has been dominated by case study research where external validity is intrinsically weak. The distinctiveness of each study in Table 1 necessarily limits the generalization of findings to other persons, places, and contexts. Nonetheless, following a review of the studies, we provide a subjective, qualitative evaluation of the various PPGIS/PGIS ecosystem service mapping methods and results to identify research needs for advancing the state of knowledge rather than defining normative PPGIS/PGIS practice. Three criteria were selected for our evaluation because they are indicators of the potential future use of PPGIS/PGIS for mapping ecosystem services: (1) PPGIS/PGIS data quality, (2) utility of the PPGIS/PGIS methods for integration in decision support, and (3) feasibility of implementation.

3. Results

3.1. Methodological characteristics of the reviewed studies

3.1.1. Geographic Scope of PPGIS/PGIS studies

The list of empirical studies (1998–2014) included in this review appears in Table 1. At least one study has been completed on all continents with the exception of Asia and Antarctica. The majority of mapping studies were located in North America, Europe, and Australia and all but two mapping studies were completed in *developed* countries. The largest study area mapped was the state of Victoria in Australia covering more than 237,000 km^2 and the smallest study area mapped was a region on the island of Zanzibar, Tanzania, covering less than 25 km^2.

3.1.2. Purpose for PPGIS/PGIS mapping

The stated research purpose for each of the mapping cases may be characterized as either primary for mapping ecosystem services or ancillary to answering a research question related to ecosystem services. Several studies with the primary purpose to map ES directly include the Plieninger et al. (2013) study whose purpose was the "spatially explicit participatory mapping of the complete range of cultural ecosystem services", the Brown et al. (2012b) study whose purpose was to "examine the distribution of ecosystem services" in Grand County, Colorado, and the Fagerholm et al. (2012) study whose purpose was the "spatial assessment of landscape service indicators". In contrast, ecosystem services mapping was a means to address a more specific research purpose as in the Cox et al. (2014) study whose purpose was "identify specific places on a map that [the public] would like to see maintained for the conservation of particular threatened species", the Pfueller et al. (2009) study that "aimed to identify sites on the Victorian bank of the Murray River where community values indicate that either further conservation is desired or where development is acceptable", and the Raymond and Brown (2011) study whose purpose was to examine "spatially referenced perceived landscape values and climate change risks … for potential use in climate change planning".

Table 1
Empirical PPGIS/PGIS studies for mapping ecosystem services (1998–2014) included in this review and appearing in publication databases up through 6 October, 2014. Descriptive information appears for each study including its contribution to advancing PPGIS/PGIS practice.

Study year	Location	Ecosystem services mapped	Participatory mapping technology	Spatial mapping method	Map scale	Sampling method, participants, data collection method	Spatial analyses	Published references	Contribution to advancing PPGIS/PGIS practice
2014	Victoria, AU	Landscape values typology	Digital internet map—Google Maps	Points	(zoom level =12) 1:72,000[a]	Onsite visitors to public lands and volunteer public (survey) (n=1905)	Calculated metrics (abundance, richness, diversity) for ES values mapped in public land units	Brown, Weber, and de Bie (2014)	Data quality: Mix and importance of ES will vary by landscape unit across a region
2012	Channel Islands, US	Landscape values typology	Cartographical map	Points	1:50,000 to 1:25,000	Onsite visitors to Channel Islands (survey) (n=323)	Nearest neighbour analysis (R index), kernel density, SolVES 2.0 application used to identify point densities and relationships with biophysical features	van Riper and Kyle (2014)	Data quality: Participant held values (environmental worldviews) influence the type and spatial location of mapped ecosystem values
2012	Saxony, DE	Cultural services and disservices, modified MEA typology	Topographical map	Assign attributes to pre-identified sites on a map	1:20,000	Purposive resident household (interviews) (n=93)	Calculated ES metrics (intensity, richness, diversity) for predefined land units; spatial correlation analysis between ES, hierarchical cluster analysis and principal component analysis to identify ES bundles	Plieninger et al. (2013)	Data quality: ES can be tagged to predefined land units. Cultural ES can be grouped into different bundles
2012	Lower Hunter Valley, New South Wales, AU	Modified MEA typology	Cartographical map	Point	1:125,000	Random landholder and planning practitioners (survey) (n=393)	Point densities; spatial overlay with proposed urban development polygons	Raymond and Curtis (2013), Brown and Raymond (2014)	Decision support: mapped ES values can be combined with land use preferences to identify areas of potential land use conflict
2012	Mobile Bay, Alabama, US	Biological (species habitat)	Aerial image map	Points	1:150,000	Random household (survey) (n=242)	Kernel density hotspots; spatial overlay of hotspots with species habitat maps	Cox et al. (2014)	Data quality: Lay public can identify wildlife habitat as an ES
2012	Chugach National Forest, Alaska, US	Landscape values typology	Digital internet map—Google Maps	Points	(zoom level =12) 1:150,000[a]	Random household (survey) (n=215)	Kernel density hotspots; spatial overlay of 2012 hotspots with mapped hotspots in 1998 to determine longitudinal changes using phi coefficients	Brown and Donovan. (2014), Brown et al. (2014)	Data quality: Mapped ecosystem values show general stability over time. Workshop vs. survey PPGIS methods yield different mapped spatial results
2012	3 National Forests, California, US	Landscape values typology	Digital internet map—Google Maps	Points	1:150,000[a]	Random household (survey) (n=228)	Mapping behaviour of different sampling groups	Brown et al. 2014b	Data quality: Volunteer and convenience sampling methods in PPGIS can introduce bias in mapped results.
2011	South Suriname	Landscape services	Cartographical map with DEM basemap	Polygons	1:100,000 to 1:250, 000	Convenience residents, indigenous peoples (workshop & interviews) (n=191)	ES hotspots generated from overlapping polygon areas	Ramirez-Gomez et al. (2013)	Feasibility: ES can mapped in remote locations with indigenous peoples
2011	Hinchinbrook National Park, Queensland, AU	Landscape values typology	Cartographical map	Points	Not reported	Onsite visitors (survey) (n=209)	Nearest neighbour analysis (R index), kernel density, SolVES application used to identify point densities and relationships with physical features	van Riper et al. (2012)	Data quality: Mapped ES related to physical landscape features Different survey subgroups utilize and/or appreciate different natural resource conditions for the ES and benefits provided
2011	Doñana and Sierra Nevada protected areas, Andalusia, ES	MEA services customized for each of two sites	Topographical map	Points	1:175,000 and1:100,000	Purposive expert (workshops) (n=41)	Density maps of ES provision hotspots, degraded service provision hotspots (risks), and service benefitting areas, analysed by protected area category, conceptual map of ES flows	Palomo et al. (2013), Palomo et al. (2014)	Feasibility: Workshop format can be cost effective method to gather experts for mapping

Table 1 (*continued*)

Study year	Location	Ecosystem services mapped	Participatory mapping technology	Spatial mapping method	Map scale	Sampling method, participants, data collection method	Spatial analyses	Published references	Contribution to advancing PPGIS/PGIS practice
2010	Vancouver Island, British Columbia, CA	Monetary and non-monetary values	Nautical charts	Polygons	1:400,000	Non-proportional quota stakeholders (interviews) ($n=30$)	Intensity of ES monetary and non-monetary values, and ES threats determined by aggregating number of participant responses in grid cells that were overlayed on study area	Klain and Chan (2012)	Data quality: In-depth interviews with stakeholders effective for inductive approach in ES identification and mapping Intangible cultural ES can be difficult to map underrepresented in the dataFeasibility: Participants may refuse to map locations for several reasons Cultural and provisioning services more frequently mapped than supporting services
2010	Wales, UK	Modified MEA typology	Cartographical map	Selection of 10km grid cells	1:500,000	Non-proportional quota stakeholders (interviews) ($n=22$)	Pearson's correlations identify geographicrelationships between pairs of ES benefits; Moran's I calculated to identify clusters of ES benefits	Ruiz-Frau et al. (2011).	Feasibility: Grid overlays on maps can be used to identify areas of ecosystem benefits
2010	Grand County, Colorado, US	Modified MEA typology	Digital—internet	Points	About 60 percent mapped at 1:575,000 and 40% mapped 1:290,000 or larger[a]	Random household (survey) ($n=58$)	ES point data tabulated within land use/cover areas to determine if there is spatial association between specific ecosystem services and land use/cover categories	Brown et al. (2012a)	Feasibility: Cultural and provision ES are easiest for lay public to map; regulating and supporting services most challenging
2010	Cheju-Unguja Ukuu Keabona, Zanzibar, Tanzania	Landscape services	Aerial image map	Points	1:12,000	Purposive resident (interviews) ($n=218$)	Distance of mapped locations to home, analysis of point clustering (nearest neighbour), Kernel density from points, spatial correlation analysis between LS, landscape metrics (intensity, richness, Shannon diversity) for LS, spatial generalisation of LS, spatial generalisations integrated in landscape characterisation, spatial overlay of LS with LC/LU map, spatial statistics between LS and LC change data	Fagerholm et al. (2012), Fagerholm et al. (2013), Käyhkö et al. (2013)	Data quality/feasibility: Interviews are time intensive but can increase data quality e.g. positional accuracy. Mapped ES related to physical landscape features and explain landscape change.Settlementand geographic distance should be includedwhen modelling landscape service potential
2011	Otago and Southland Regions, NZ	Landscape values typology	Digital—internet	Points	1:150,000[a]	Random household, onsite visitors, volunteer (survey) ($n=608$)	ES point data tabulated within landscape categories to determine spatial associations with landscape types based on landform, land cover, water, water views, and infrastructure. These relationships used to extrapolate ES values to areas where PPGIS data not collected	Brown and Brabyn (2012a and 2012b)	Data quality: Mapped ES are related to physical landscape features
2010	Kangaroo Island, South Australia, AU	Landscape values typology	Digital—internet	Points	About 60 percent mapped at 1:575,000 and 40% mapped at 1:290,000 or larger[a]	Random household (survey) ($n=102$)	Nearest neighbour analysis (R index), longitudinal change in ES values determined by measuring spatial overlap of kernel density hotspots with phi-coefficient statistic	Brown and Weber (2012)	Data quality: Mapped ecosystem values show stability over time but changes in land use can influence mapped values
2010	Alle di Ledro, IT	Landscape values	Aerial image map	Points	1:27,000	Onsite visitors (interviews) ($n=106$)	Kernel density analysis according to values and different tourist types	Scolozzi et al. (2014)	Data quality: Interviews with tourists using inductive approach can identify diverse tourism landscapes based on mapped cultural ES
2008	Murray-Darling Basin, South Australia, AU	Modified MEA typology	Cartographical maps	Points	1:325,000	Non-proportional quota decision-makers (interviews) ($n=56$)	Mapped the spatial distribution of natural capital assets and the provisioning, regulating, cultural, and supporting ES using summed intensity scores, calculated spatial indices of abundance, diversity, rarity and risk based on the intensity scores, spatial coincidence of the highest scoring areas for each index to derive high priority management areas through spatial overlay	Raymond et al. (2009), Bryan et al. (2010)	Data quality: In-depth interviews with natural resource decision-makers and community representatives effective for inductive approach in ES identification and mapping

2007	Matemwe, Zanzibar, Tanzania	Landscape values typology	Aerial image map	Polygons	1:5000	Purposive resident (interviews) ($n = 149$)	Distance of mapped locations to home, intensity maps from overlapping polygons, landscape metrics (total patch area, number of patches, patch area mean, range and standard deviation, Euclidian nearest neighbour distance) for intensity layers, Shannon diversity, intensity hotspots (Getis-Ord Gi⁎ statistics)	Fagerholm and Käyhkö (2009)	Data quality/feasibility: Participants can identify places on aerial image maps with little supportDecision-support: Cultural values tend toward spatial clustering and co-existence while provisioning values show scattered landscape pattern
2007	Mt Hood National Forest, Oregon, US	Landscape values typology	Digital—internet	Points	1:250,000	Random household (survey) ($n = 179$)	Nearest neighbour analysis (*R* index) and social landscape metrics derived from spatial distributions.	Brown and Reed (2009)	Data quality: Number and type of cultural ES mapped is influenced by participant socio-demographic characteristics
2007	Deschutes and Ochoco National Forests, Oregon, US	Landscape values typology	Digital—internet	Points	1:425,000	Random household (survey) ($n = 344$)	Nearest neighbour analysis (*R* index) and social landscape metrics derived from spatial distributions.	Brown and Reed (2009), Brown and Reed (2012b)	Decision support: Mapped ES values can identify compatibility of proposed land uses with public values for areas
2007	Fleurieu Peninsula, AU	Landscape values typology	Cartographical maps	Points	1:125,000	Random landowner (survey) ($n = 130$), workshop (survey) ($n = 245$)	Measure spatial associations between ES values and perceived climate change risks using two approaches. Jaccard coefficients used to measure the degree of spatial overlap between value and climate change risk polygons (vector approach) and spatial cross-correlation analysis used to determine relationship between values and climate change risk grid cells (raster approach)	Raymond and Brown (2011)	Feasibility: Facilitated workshops are effective means to identify ES values
2006	Murray River Reserves, AU	Landscape values typology	Cartographical maps	Points	1:294,000	Random household (survey) ($n = 346$), visitors and tour operators (survey) ($n = 207$)	Kernel density analysis, Getis–Ord Gi⁎ statistics used to identify spatial clusters of statistically significant ES values (i.e., hot spots), spatial correlation analysis between ES (phi correlation coefficient)	Pfueller et al. (2009), Zhu et al. (2010)	Data quality: Dot marker size and map scale create challenges for mapping locations smaller than the marker and subsequently ambiguity in spatial analysis. PPGIS/PGIS mapping of ES compatible with environmental values of the study area obtained through biophysical assessment and consultation.
2006	Coconino National Forest, Arizona, US	Landscape values typology	Digital—internet	Points	1:250,000	Random household (survey) ($n = 257$)	Nearest neighbour analysis (*R* index) and social landscape metrics derived from spatial distributions.	Brown and Reed, (2009), Brown and Reed (2012a)	Decision support: Mapped ES can be used to generate metrics to compare services in different areas
2005	Alberta, CA	Landscape values typology	Digital—internet	Points	1:350,000	Random household (survey) ($n = 305$)	Nearest neighbour analyses (*R* index and Ripley's *K* functions)	Beverly et al. (2008)	Data quality: Settlement and geographic distance important in modelling ES potential
2005	Otways Region, Victoria, AU	Landscape values typology	Cartographical maps	Points	1:125,000	Random household (survey) ($n = 560$), visitors (survey) ($n = 220$)	Kernel density analysis and spatial cross correlation	Brown and Raymond, (2007), Raymond and Brown (2007)	Decision support: Mapped ES can help identify "place attachment" and new lands to be added to national park system
2005	Idaho, Oregon, US	Landscape values typology	Cartographical maps	Points	1:100,000 to 1:215,000	Random property owners (survey) ($n = 863$)	Density-based cluster analysis of ES values to determine which ES values spatially cluster at different map scales, spatial correlation analysis between ES (point buffering contingency statistics)	Nielsen-Pincus (2011)	Data quality: Weighted markers do not offer analytical benefit compared to simple mapping frequencies and appear to be cognitively challengingDecision-support: Some mapped landscape values have a tendency for spatial co-existence while others tend to avoid each other
2005	Pike and San Isabel National Forests, Colorado, US	Landscape values typology	Cartographical maps	Points	1:380,000 to 1:500,000	Random household (survey) ($n = 684$)	Nearest neighbour analysis (*R* index) of ES values and average distance of mapped locations to communities. SolVES application calculates Value Index derived from mapped ES to identify relationships with physical features and provides for value transfer (extrapolation). Maxent modelling integrated in latest version.	Clement-Potter, (2006), Sherrouse et al. (2011), Sherrouse et al. (2014)	Decision support: ES trade-off analysis potential through modelling of PPGIS data with biophysical information sources
2004	Kangaroo Island, South Australia, AU	Landscape values typology	Cartographical maps	Points	1:125,000	Random household (survey) ($n = 431$)	Nearest neighbour analysis (*R* index) of ES values followed by using values as predictors of development preferences	Brown (2006)	Decision support: Mapped ES values can be compared to development plan zoning to determine consistency of zone with values

Table 1 (*continued*)

Study year	Location	Ecosystem services mapped	Participatory mapping technology	Spatial mapping method	Map scale	Sampling method, participants, data collection method	Spatial analyses	Published references	Contribution to advancing PPGIS/PGIS practice
2002	Kenai Peninsula, Alaska, US	Landscape values typology	Cartographical maps	Points	1:444,000	Random household (survey) ($n=561$)	Identify coupled social–ecological space by spatial overlay of social ES hotspots (kernel density) with net primary productivity	Alessa et al. (2008),	Data support: Can identify areas of coupled social-ecological space
1999	Prince William Sound, Alaska, US	Landscape values typology	Cartographical maps	Points	1:230,000	Random household (survey) ($n=542$), purposive expert (workshop) ($n=31$)	Calculated spatial coincidence of lay public mapped biological values with expert mapped values from a workshop	Brown et al. (2004)	Data quality: Moderate level of spatial coincidence between lay public and expert maps of biological values, with some differences in mapped hotspots.
1998	Chugach National Forest, Alaska, US	Landscape values typology	Cartographical maps	Points	1:500,000	Random household (survey) ($n=821$)	Mapped location of ES values used to determine suitability of forest management options.	Brown and Reed (2000), Reed and Brown (2003)	Feasibility: ES values can be operationalized in typology and mapped by general public sample

[a] Map scale is an estimate based on Google Maps zoom level. The estimated scale is the most common scale used by mapping particpants.

3.1.3. Range of ecosystem services mapped

The type of ecosystem services or indicators that have been mapped include those contained in a predefined typology or those that were emergent in the mapping process. The use of a typology requires an operational definition be specified for each ecosystem service to be mapped. Three common typologies for mapping ecosystem services include the *Millennium Ecosystem Assessment* (MEA (Millennium Ecosystem Assessment), 2003) typology, the *landscape services* typology, and the *landscape values* typology. These typologies with the most common ecosystem services appearing in them are shown in Table 2. We labeled each of the ecosystem services in the typologies using one of the four common categories of provisioning, supporting, regulating, or cultural services. While the MEA typology includes all four classes of ecosystem services, the *landscape values* typology is dominated by cultural ecosystem services, and the *landscape services* typology contains a mix of cultural and provisioning services. The number and type of services mapped in a given research project are often customized to meet the needs of the PPGIS/PGIS application. There are other ecosystem service classification systems such as the Common International Classification of Ecosystem Services (www.cices.eu), but this system has yet to be trialed in participatory mapping research. From Table 1, the *landscape values* typology has been the most frequently used typology for PPGIS/PGIS mapping of ecosystem services.

An alternative to providing a pre-determined typology of ecosystem services is to allow the type of ecosystem services located in the study region to emerge from the research process, often through interviews. For example, the Raymond et al. (2009) study asked interviewees to place plastics discs/dots representing natural assets on a map and then the interviewer asked what ecosystem services the particular assets provided. In the Klain and Chan (2012) study, interviewees were asked to identify regions in the study area that were important for monetary and non-monetary reasons. These areas were then classified by the researchers into categories of benefits, many representing ecosystem services. In the Scolozzi et al. (2014) study, tourists were interviewed in the field and asked to identify their subjectively valued places in the study region on an aerial image using 10 green sticky labels, and then to specify the particular values associated with the sites.

3.1.4. PPGIS/PGIS mapping approach

The technology used to map ecosystem services has involved two basic types: (1) hardcopy cartographical/topographical maps or aerial image maps combined with a marking system such as pencil, pen, stickers, beads, cubes, or discs, and (2) digital mapping on a computer, especially using internet map services such as those provided by Google®. The most common marking method has been the use of points to represent areas of ecosystem services rather than polygons, especially in self-administered mapping where there is no facilitator to assist in the mapping process (Table 1). Participatory mapping with points appears less cognitively challenging for most people (Brown and Pullar, 2012). No studies have used lines to identify the location of ecosystem services, one study applied the assignment of attributes to pre-identified land cover units (Plieninger et al., 2013), and one study asked participants to identify ecosystem benefits in predefined 10 km^2 grid cells overlayed on marine areas along the coast of Wales (Ruiz-Frau et al., 2011).

The map scale used for participants to identify ecosystem services has been highly variable, ranging from the smallest map scale of 1:5000 in Zanzibar (Fagerholm and Käyhkö, 2009) to map scales near 1:500,000. Whereas hardcopy maps have a fixed mapped scale, digital, internet mapping offers multiple map scales that can vary depending on how the participant zooms the map image when navigating and placing markers. With internet-based,

Table 2
Common typologies for operationalizing ecosystem values and services in PPGIS/PGIS.

Typology	Value or service	Ecosystem service category
Landscape values (Brown and Reed, 2000), also called social values for ecosystem services (Sherrouse et al., 2011)	Aesthetic/scenic	Cultural
	Recreation	Cultural
	Economic	Cultural/provisioning
	Life sustaining	Regulating/supporting
	Biological	Provisioning/supporting
	Subsistence	Provisioning
	Learning/education	Cultural
	Spiritual	Cultural
	Historic	Cultural
	Cultural	Cultural
	Intrinsic	Cultural
	Future	Cultural
	Wilderness	Cultural
Landscape services (e.g., Fagerholm et al. 2012)	Food	Provisioning
	Ornamental resources	Provisioning
	Geological resources	Provisioning
	Medicinal resources	Provisioning
	Fuel	Provisioning
	Raw materials	Provisioning
	Spiritual/religious	Cultural
	Aesthetic	Cultural
	Social relations	Cultural
	Intrinsic	Cultural
	Cultural heritage	Cultural
MEA Typology (MEA (Millennium Ecosystem Assessment), 2003)	Food	Provisioning
	Fresh water	Provisioning
	Fuelwood	Provisioning
	Fiber	Provisioning
	Biochemicals	Provisioning
	Genetic resources	Provisioning
	Air quality maintenance	Regulating
	Climate regulation	Regulating
	Disease regulation	Regulating
	Water regulation	Regulating
	Erosion control	Regulating
	Water purification	Regulating
	Regulation of human diseases	Regulating
	Biological control	Regulating
	Pollination	Regulating
	Storm protection	Regulating
	Soil formation	Supporting
	Nutrient cycling	Supporting
	Primary production	Supporting
	Spiritual and religious	Cultural
	Recreation and ecotourism	Cultural
	Aesthetic	Cultural
	Inspirational	Cultural
	Educational	Cultural
	Sense of place	Cultural
	Cultural diversity and heritage	Cultural
	Social relations	Cultural

digital maps such as Google® maps, the map scale can be set to a minimum or maximum map scale when identifying ecosystem services. This feature seeks to ensure a minimum level of mapping precision when participants place markers on the map while providing the user with flexibility to orient and navigate within the study region.

3.1.5. PPGIS/PGIS sampling approach

The most common sampling method has been to use random household or landowner sampling within the study region (Table 1). Sample sizes have ranged from $n=22$ at the low end, to $n=1905$ at the high end. Other sampling methods have included recruitment of visitors in the study area as well as purposive sampling of stakeholders or "experts". The most common method for data collection has been self-administered surveys with a mapping component. Personal interviews and group workshops have also been used, but much less frequently. The most frequent target of sampling has been the lay public rather than "experts" or "stakeholders". Of relevance here, the Brown et al. (2012b) pilot study examined the ability of a lay public (residents) to identify the full range of ecosystem services described in the Millennium Ecosystem Assessment. The study found that participants were able to readily identify provisioning and cultural services, but were quite challenged to identify regulating and supporting ecosystem services. Only one study examined the level of spatial agreement between a public sample ($n=521$) and expert workshop ($n=31$) in mapping biological values, finding a moderate level of spatial agreement, but with some clear differences in mapped biological hotspots (Brown et al., 2004a).

3.1.6. Spatial analyses of mapped PPGIS/PGIS data

The spatial analysis of ecosystem service data collected through PPGIS/PGIS has focused more on descriptive rather than inferential analyses. Several types of analyses have been used to describe the spatial distribution of ecosystem services within the study region (Table 1). The *R* index (Clark and Evans, 1954) indicates whether a point distribution deviates from a complete spatial random (CSR) distribution by quantifying the degree of clustering, uniformity, or dispersion within the study area. Second order *K* functions (Ripley, 1976) also determine whether a point distribution deviates from CSR, but accounts for the density of points within the study area. These descriptive statistics provide a useful starting point for understanding the general spatial distribution of services in the study region, but they do not provide location-specific information. The *R* index has been reported in multiple studies, while second order *K* functions have only been reported in one study (Beverly et al., 2008).

Intensity analysis methods provide locational information about the spatial arrangement of ecosystem services and show where services tend to concentrate in "hotspots" within the study region. The most common type of intensity analysis uses kernel density estimation (Silverman, 1986) to create polygonal "hotspot" areas or density surfaces by specifying the parameters of cell size and search radius. This analysis provides the spatial location of areas of relative higher concentration of ecosystem services. Kernel density estimation is a common method to analyze PGIS/PPGIS data and is often calculated from PPGIS/PGIS point data to generate a grid with a specified cell size (Alessa et al., 2008; Brown, 2004; Bryan et al., 2010; Sherrouse et al., 2011). Polygon intensity surfaces are produced by aggregating overlapping polygon delineations. An alternative to kernel density is the use of the Getis-Ord or Gi⁎ statistic which measures the degree of association that results from the concentration of all weighted points within a radius of a certain distance from the original weighted point (Getis and Ord, 1992). The Gi⁎ statistic is used to identify statistically significant localized areas within the study region that have relatively more (hotspots) or less (coldspots) mapped ecosystem services than would be expected by chance (Fagerholm Käyhkö, 2009; Zhu et al., 2010).

Various landscape metrics such as intensity, abundance, richness, and diversity have also been used to quantify the distribution of mapped ecosystem services within the study area (e.g., Alessa et al., 2008; Bryan et al., 2010; Fagerholm et al., 2012; Plieninger et al., 2013). The spatial indices provide a means to compare ecosystem services across different landscape units within the study area, but require that the study area be partitioned into meaningful spatial units of analysis. Brown and Reed (2012a) and Fagerholm and Käyhkö (2009) show that PPGIS data, including the mapping of ecosystem services, can also be analyzed with the suite of landscape metrics used by landscape ecologists such as those available in Fragstats (McGarigal et al., 2012).

The spatial overlap (concurrence) between different ecosystem services has been quantified using the phi correlation coefficient (Brown and Donovan, 2014; Zhu et al., 2010) or the Jaccard coefficient and Pearson's product-moment correlations (Raymond and Brown, 2011). Between pairs of ecosystem services, spatial relationships (co-existence) have also been analyzed with Pearson's and Spearman's correlation coefficients (Fagerholm et al., 2012; Plieninger et al., 2013; Ruiz-Frau et al., 2011) and point buffering contingency statistics (Nielsen-Pincus, 2011).

Because the distance between each mapped ecosystem service location and the participant's home may explain some of the variation in the spatial patterns of landscape values and benefits (Brown et al., 2002), Euclidian distance analysis has been useful, especially when it comes to mapping of ecosystem services with study area residents (Fagerholm and Käyhkö, 2009; Fagerholm et al., 2012).

While it is important to understand the general spatial distribution of ecosystem services within the study area, more complex spatial analysis of ecosystem service data examines the spatial relationships between ecosystems services and other physical landscape features. The spatial concurrence of ecosystem services with ecological data (Alessa et al., 2008) or land use/land cover characteristics and their retrospective change trends have been examined in multiple studies (Brown et al., 2012a; Brown and Brabyn, 2012a; Käyhkö et al. 2013). An example of a more interpretative method to integrate PGIS mapped landscape services with various physical landscape features can be found in local landscape characterization maps that aim to support intuitive interpretation (Fagerholm et al., 2013). Brown (2013) completed the first meta-study examining the relationship between mapped ecosystem values and global land use/land cover data across 11 PPGIS studies. He found that the highest frequencies of values for ecosystem services were associated with forested land cover. Water bodies were highly valuable relative to the land area occupied, and agricultural land and areas of permanent snow and ice were least valuable.

Our review of the empirical PPGIS/PGIS mapping studies on ecosystem services indicates that analysis of ecosystem service trade-offs and flows is not yet common. Palomo et al. (2013) developed the concepts of service provision hotspots (SPH) and service benefiting areas (SBA) to map the supply and demand of services and to identify their respective flows as a conceptual map of the situation in protected areas. To address the issue of mapping ecosystem service bundles, Plieninger et al. (2013) identified two specific bundles of cultural services for further work in comprehensive assessment and participatory mapping of ecosystem services.

All but two PPGIS/PGIS studies to date have been cross-sectional, involving the mapping of ecosystem services at a single point-in-time. However, the dynamic nature of both natural and human systems suggests the importance of longitudinal studies to determine if, and to what extent, ecosystem services change over time. Two longitudinal studies examined changes in cultural ecosystem services over a six year time period in Australia (Brown and Weber, 2012) and 14 years in Alaska (Brown and Donovan, 2014). Both studies found relative stability in the type and location of ecosystem values mapped.

3.1.7. Extrapolation and modelling of ecosystem services using PPGIS/PGIS data

A logical extension of quantifying the empirical relationships between mapped ecosystem services and physical landscape features is to extrapolate these relationships to landscapes where no participatory mapping data was collected. Two systems have been developed and trialed for this purpose. The SolVES model (van Riper et al., 2012; Sherrouse et al., 2011, 2014) quantifies the relationship of mapped ecosystem values to environmental variables and uses these relationships to "value transfer" the social values for ecosystems to other landscapes. The SolVES model was recently revised to include Maxent entropy modelling software to generate more complete social-value maps from available value and preference survey data and to produce more robust models describing the relationship between social values and ecosystems (Sherrouse et al., 2014). An alternative to SolVES was developed by Brown and Brabyn (2012b) that quantifies the frequencies of mapped ecosystem values found in the landscape classes of a comprehensive land classification system and uses these empirical, quantitative relationships to extrapolate ecosystem values to non-mapped landscapes such as the entire country of New Zealand. At a local scale, spatial generalization has also been implemented through manual delineation and interpretation of the spatial arrangement of mapped landscape services together with land cover and land use data (Fagerholm et al., 2013; Käyhkö et al,. 2013).

3.1.8. Assessing accuracy of PPGIS/PGIS data

An important type of analysis involves the validation of mapped ecosystem services. Several studies have examined the positional accuracy of PPGIS data by requesting that participants identify physical landscape features. By inference, if the lay public can reasonably identify physical landscape features such as native vegetation (Brown, 2012) or wildlife habitat (Cox et al., 2014), then the mapping of more subjective ecosystem services may be presumed valid.

3.2. Evaluation of PPGIS/PGIS for mapping ecosystem services

3.2.1. Data quality

3.2.1.1. Positional accuracy and completeness. For many of the ecosystem services identified in the literature, there are no objective standards or benchmarks to assess the positional accuracy and completeness of the mapped PPGIS/PGIS data. The validity of traditional GIS data can be assessed by the accuracy of attribute identification, positional accuracy, logical consistency, and data completeness. Assessment of PPGIS/PGIS mapped data using these criteria is challenged by the subjective nature and ambiguous spatial delineation of cultural ecosystem services, in particular. For example, how does one determine whether the mapped locations for the cultural ecosystem services of scenery, spirituality, or even recreation are accurate? Arguably, the mapped cultural ecosystem services by people that are familiar, proximate, and that use the natural areas are *prima fascia* valid measures (i.e., exhibit attribute accuracy) of these cultural ecosystem services, but there is uncertainty regarding the positional accuracy and completeness of the areas identified. However, the validity of mapped ecosystem service data remains largely unexamined and will continue to be an important research question. In the absence of objective spatial data quality measures such as positional accuracy and completeness, data quality in PPGIS/PGIS must be assessed through proxy indicators of spatial data quality such as existing biophysical or ecosystem service spatial data when available.

3.2.1.2. Sample quality. Normatively, larger, representative samples of regional populations provide better data quality than smaller, non-representative samples (Brown and Kyttä, 2014). And yet, achieving high participation rates using probability sampling is difficult in PPGIS/PGIS practice, leading some researchers to trial other methods such as internet panels for participatory mapping (Brown et al., 2012a; de Vries et al., 2013). Lower participation rates have been accompanied by a participant profile that deviates from the target population. For example, in the U.S., Brown and Reed (2009) reported that PPGIS participants were older, disproportionately male, more highly educated, and had higher household incomes levels than the target population. In Canada, Beverly et al. (2008) also found that PPGIS participants differed from the target population, being disproportionately male, more highly educated, and with higher average income. In Australia, participants also tend to be disproportionately male, older, and with higher levels of formal education (Raymond and Brown, 2007, 2011). An analysis of the mapped ecosystem services by demographic variables suggest that gender, age, formal education, and especially knowledge of the study area can influence the number and type of cultural services that participants map (Brown and Reed, 2009). Further, participant held values regarding the environment (termed “environmental worldview”) can influence the type and spatial location ecosystem services that are mapped (van Riper and Kyle, 2014). The use of quota sampling may achieve better population representativeness, but has yet to be used in PPGIS/PGIS studies. Thus, an important proxy indicator of mapping data quality is the quality of the sample representing the target participant population.

3.2.1.3. Mapping effort and data usability. Several other indicators for data quality have been proposed in the PPGIS literature. For PPGIS surveys, Brown et al. (2012b) suggest two metrics for data quality—*mapping effort* and *data usability.* Mapping effort is the exertion of physical and mental power to complete the PPGIS mapping activity and is hypothesized to be related to measurement error and thus data quality, i.e., less mapping effort is associated with lower spatial data quality. PPGIS data usability is the proportion of mapped PPGIS data that is appropriate and useable for the purpose of the study. Usability can be operationalized by a range of criteria such as marker location (e.g., markers placed outside study area may be considered unusable) or map scale at time of marker placement (e.g., markers must be placed at a minimum map scale to increase precision in placing a marker). Few PPGIS/PGIS studies have reported mapping effort and data usability.

3.2.1.4. Scope of ecosystem services mapped. Data quality may be influenced by the number and type of ecosystem service categories requested to be mapped, but no studies have directly assessed data quality as a function of the scope of the mapping request. There is no strong evidence for a significant relationship between the available number of ecosystem services to be mapped and the actual amount of spatial data generated. Participant mapping effort, at least in self-administered PPGIS surveys, appears to be more or less fixed such that providing more types of ecosystem services to be mapped will not actually increase the number of locations mapped, but will simply spread the mapping effort across more services. For example, in comparable internet-based PPGIS/PGIS studies, Beverly et al. (2008) reported an average participant mapping rate of about 26 markers per map from a total 60 available markers while Brown and Reed (2009) reported similar averages despite having an available 78 markers. In a more recent internet-based PPGIS/PGIS design that allowed an *unlimited* number of markers to be placed by participants, the average number of markers placed was about 15 in Australia (Brown and Weber, 2012) and 24 in New Zealand (Brown and Brabyn, 2012a).

Regarding the type of categories requested to be mapped, the evidence shows that when mapping MEA defined ecosystem services (e.g., Brown et al., 2012a; Palomo et al., 2013), instead of ecosystem service indicators consisting of related practices/uses and values for these services (e.g., Fagerholm et al., 2012, Plieninger et al., 2013), the categories of regulating and supporting services show the fewest number of mapped locations and highest cognitive challenge among the general public (Brown et al., 2012a). Thus, the choice of the spatial attributes to be mapped is an essential aspect of PPGIS/PGIS design that affects the resulting data. Of greater importance than the number of available services, practices, or values to be mapped may be the communication to participants regarding the desired mapping effort. Clear communication to participants about the expectations of PPGIS mapping effort would represent best practice, but there have been no studies that have investigated the efficacy of different communication strategies and the quantity and quality of spatial data generated.

3.2.1.5. Location and relative importance. When ecosystem services are mapped using PPGIS/PGIS, spatial location is the primary information captured in the mapping process. Early PPGIS studies trialed the used of weighted markers to be able to assess the relative value of the services mapped, but concluded that weighted markers did not yield sufficient added analytical benefit over the use of simple mapping frequencies (Nielsen-Pincus, 2011). Relative value ranking of services has also been performed by study participants independent of the actual mapping activity (Brown and Reed, 2000; Beverly et al., 2008; Clement-Potter, 2006; Fagerholm et al., 2012). Brown (2013) showed that the relative importance of different ecosystem values mapped using point data can be determined using different metrics such as frequency, density, proportionality, or diversity, but that the selected metric influences the rankings of the relative importance of ecosystem services within the study area. If the PPGIS/PGIS process for service selection is neutral, unbiased, and allows the participant to select from a list of services, the relative importance of the services mapped can be assessed using one of the valuation criteria such as frequency, density, or diversity. Thus, if the relative value of services mapped is needed in addition to spatial location, best practice would ensure that the PPGIS data collection process provides unbiased opportunities for the selection and mapping of ecosystem services. If ascertaining the relative value of ecosystem services is not a required outcome of the mapping process, there is greater flexibility in how participants are instructed to identify the ecosystem services.

One PPGIS/PGIS design variable – the choice of whether ecosystem services are mapped using points or polygons – has the potential to influence the resulting data quality. The one study that examined this PPGIS/PGIS design choice found that points and polygons will converge on a collective spatial 'truth' within the study area provided there are enough mapped observations (Brown and Pullar, 2012). However, the study also found that the degree of spatial convergence between the methods varied by PPGIS attribute type (ecosystem service) and the quantity of data collected. Ecosystem services that exhibit greater spatial dispersion and variability such as economic value will require more spatial data to be collected than more clustered values such as recreation. Moreover, participants tend to prefer the point mapping method which contributes positively to mapping effort (Brown and Pullar, 2012). Thus, the extent to which PPGIS/PGIS mapping produces more or less spatial data will influence the resulting data quality, but the effect on data quality is likely to be specific to the ecosystem service mapped.

Another PPGIS/PGIS design choice – the use of hardcopy maps versus internet mapping – was also studied to determine its potential effects on data quality (Pocewicz, et al. 2012). The implications of the study findings for data quality are mixed. For all but one of the spatial attributes mapped, there was no difference in the spatial distribution of places mapped between internet and hardcopy map methods, suggesting little effect on data quality. However, the hardcopy PPGIS survey also resulted in a higher response rate (2.5 times higher for the hardcopy method), reduced participant bias, and greater mapping participation, all variables that influence sample and data quality. Thus, there would appear to be merit in using a mixed methods approach for ecosystem services mapping if it can increase participation and thus the quality of the sample.

To summarize, in the absence of authoritative spatial information to benchmark PPGIS/PGIS for ecosystem services or values, the quality of mapped data must be determined by potential indicators of data quality such as *sample quality*, *mapping effort* and *data usability*. PPGIS/PGIS process *design choices* such as *unbiased selection of spatial attributes,* if the relative value of the ecosystem services is a required outcome of the mapping process, and the number and type of ecosystem services requested to be mapped may also influence the resulting data quality. However, the effect of varying the list of services, practices, or values to be mapped still requires further research. Other design choices such as the use of points or polygons, or the identification of pre-defined map areas, and the use of mixed data collection methods can influence the quality of mapped data to the extent that they influence the *quantity* of spatial data collected for each ecosystem service and the *participation rate*.

3.2.2. *Utility of participatory mapping for decision support*

Because the PPGIS/PGIS for mapping ecosystem services is relatively recent, it is not surprising that there aren't examples from the reviewed articles describing how mapped ecosystem service data were used for actual decision support. And yet, many of articles reference the hypothetical potential of the mapped data for decision support. For example, Plieninger et al. (2013) write that "cultural services mapping assessments should be pushed ahead as indispensable elements in the management and protection of cultural landscapes" and that "a collaborative, demand-side assessment of cultural services should become part of landscape planning". Cox et al. (2014) state that "PPGIS offers a practical toolset for efficiently capturing and analyzing stakeholder management preferences, allowing managers to make informed decisions and understand tradeoffs". van Riper et al. (2012) write that "the density of social value points and the types of values that congregate in places can help decision-makers anticipate conflict among user groups" while Fagerholm et al. (2013) argue that "management decisions on land should not only be based on the existing material benefits from nature's services, but also to consider the total well-being of the community". Thus, many of the reviewed articles contain highly aspirational statements about the potential of the mapped data for decision support, but provide few specific detailed recommendations (Brown and Reed, 2009; Raymond and Curtis, 2013) on how to actually integrate mapped ecosystem data into decision support systems that would be used by politicians, planners, or land managers, depending on the decision context. Opdam (2013) was even more direct in his assessment of the ecosystem services research required for decision support, stating that "from the current literature it is obvious that ecosystem service research does not provide the type of science that is required to support sustainable, community-based landscape planning…there is a strong demand for approaches that are able to involve local governance networks and move the ecosystem services research out of the static mapping and evaluation approaches …" (p. 77).

Thus, none of the articles reviewed herein report the use of mapped ecosystem services in actual decision support for planning or land management. But the failure to integrate participatory GIS data into land use planning decisions is not limited to mapped ecosystem services but extends to participatory mapping in general. In a recent review of empirical PPGIS studies that also included many urban planning applications, Brown and Kyttä (2014) noted that "despite an increasing number of PPGIS studies, there is still little evidence that PPGIS has influenced specific land use decisions" (p. 133). They argue that for PPGIS to have decision influence will "…require that existing power structures accept that lay segments of society have valuable knowledge and experiences, beyond mass opinion, that can substantively contribute to land planning and management decisions" (p. 132).

The barriers for integration of participatory mapped ecosystem services into land use decision support appear formidable. For example, de Groot et al. (2010) identify several important research questions related to participatory mapping and decision support, "How can analytical and participatory methods be combined to enable effective participatory policy and decision making dialogues?" and "How can landscape design-alternatives be visualized and made accessible for decision-making, e.g. through expert systems and other decision and policy support tools?" (p. 261). These issues are related to both the participatory mapping methods and to the institutional and societal context in which land use decisions are made. With regard to the participatory mapping methods, there remains ambiguity regarding what is actually being measured in the participatory mapping process—ecosystem service supply or demand? Benefits or values? Stocks or flows? Bundles or independent services? What type of value is captured by spatial location and how can this information be used in trade-off analyses? Can mapped ecosystem services be converted into values that are commensurate with land use alternatives expressed in monetized values? How can complex modelling approaches influence decision making?

With regard to the institutional context of land use decisions, rational synoptic tools that rely on optimization or efficiency criteria only apply to a limited set of technical, land use planning decisions. Arguably, the most significant land use decisions confronting society tend to be more subjective than objective, more incremental than comprehensive, and more political than economic in character. To generalize, the current institutional and societal framework, both in developed and developing contexts, is one in which (1) rational decision support tools have limited application, (2) broad public participation is accepted more in principle than in practice, and (3) the importance of ecosystem services remains on the fringe of mainstream economic thought.

One modest path forward in the area of decision support is offered by Reed and Brown (2003) who developed the idea of values suitability analysis wherein mapped ecosystem data is incorporated into traditional land suitability analysis, similar to the way that biophysical spatial data determine land suitability. Because all current and prospective land use decisions are intrinsically spatial, land use alternatives can be made commensurate with mapped ecosystem services through spatial location. Decision support is provided by examining whether a proposed land use is *compatible* with the mapped ecosystem values wherein compatibility can be operationalized with a variety of decision rules. The method was illustrated with a hypothetical example that examined the compatibility of proposed off-road vehicle use areas on public lands with the distribution of mapped cultural ecosystem service data (Brown and Reed, 2012b). This type of decision support system avoids the challenging task of assigning monetary values to services before examining land use tradeoffs.

The best practice in development and adoption of decision support based on participatory mapped ecosystem service data will require that (1) the ecosystem service data be spatially explicit with clear operational definitions for mapped attributes, (2) provide for some degree of standardization and commensurability across services, and (3) provide an opportunity to engage in systematic trade-off analysis. Beyond the technical requirements, the use of participatory mapping for decision support will require greater acceptance of the premise that land should be planned and managed for land uses that are consistent with the values that a broader public holds for the areas in question. This progressive idea challenges the prevailing top-down approach to land use decisions wherein narrow political and economic interests wield disproportionate influence in decision outcomes. Countries such as Finland may be a bellwether for the rest of the world as the first country to commission the development of national PPGIS software for use by local governments and public agencies throughout the country, an outcome made possible by a cultural propensity to embrace new technology and a general high level of trust in government and citizen participation.

3.2.3. *Feasibility of implementation*

The third criterion for evaluation of PPGIS/PGIS methods for mapping ecosystem services relates to the feasibility of the implementation, addressed here through cost effectiveness, stakeholder representativeness, and PPGIS/PGIS practice.

3.2.3.1. Cost effectiveness. When evaluating the cost effectiveness of a PPGIS/PGIS process, time and money allocated are the key indicators. The most resource intensive methods are interview campaigns where lay public stakeholders are targeted (Fagerholm and Käyhkö, 2009, 2012; Raymond et al., 2009; Ruiz-Frau et al., 2011; Klain and Chan, 2012; Plieninger et al., 2013). Scheduling interviews among the stakeholders requires time and patience, and performing the interviews often requires a group of facilitators trained prior to the process. Although interviews provide opportunities for in-depth discussion and communication with an informant that contributes positively to data quality (Fagerholm et al., 2012), they often take more time to complete compared to individual, self-directed mapping methods. Mapping in a workshop or group setting has not been very common among the reviewed cases but shows cost effectiveness especially among experts who can be gathered for a workshop with relatively low effort (Palomo et al., 2013). Self-administered surveys, the most common method for identifying ecosystem services with PPGIS/PGIS thus far, allow individual participants to decide when and where to complete the survey and, hence, are most cost effective among the different mapping approaches.

The technology used for mapping ecosystem services can influence cost effectiveness, although the reviewed cases provide limited information for evaluation. In their evaluation of the use of internet panels for participatory mapping, Brown et al. (2012b) reported the cost per mapping completion using an online panel was approximately $42, a higher cost than implementing a random household sampling design. However, this cost is comparable to the on-site recruitment of PPGIS participants involving geographically-dispersed sampling locations. The cost of creating and printing hardcopy maps combined with a marking system are highly variable depending on map characteristics such as color versus grayscale, size, paper quality, and the degree of customization of the marking system. Most of the reviewed studies that used hardcopy maps also provided custom-printed stickers with marker legends for participants, increasing the cost of implementation. There is also the additional cost of digitizing the hardcopy spatial data into a GIS, a time-consuming step that is not required in digital mapping applications. For digital mapping surveys, the costs consist of coding and setting up the mapping interface which requires knowledge of web programming and database management. Some companies such as Mapita®, a software development company in Finland, specialize in internet mapping systems and offer turn-key PPGIS surveys that can be reasonably cost effective for set-up and administration. An important technology development is the emergence of application generating software (e.g., see www.maptionnaire.com) that allows individuals to design and implement a digital PPGIS mapping survey using a set of ready to use software building blocks and tools. PPGIS/PGIS survey generators have yet to be trialed for the mapping of ecosystem services but such applications are likely in the future.

The cost of technology for implementing internet mapping systems, if it follows other technology trends, is likely to decrease as more alternatives and greater competition emerge, while the cost of sampling and recruitment of mapping participants is likely to increase. The quality of PPGIS/PGIS data is inextricably linked with sampling and participation rates. And yet, as Brown and Kyttä (2014) observe, "engaging stakeholders and lay audiences in PPGIS is challenging in a fast-paced society where people confront increasing demands on their time" (p. 133). All modes of survey data collection show declining response rates (Couper and Miller, 2008) and achieving quality social data collection will require more effort and money. Offering prospective mapping participants a choice in the mapping technology (a mixed methods design) offers a partial response to the larger social trend of difficulty in participant recruitment. Thus, a mixed methods approach with both hardcopy and internet mapping has been suggested for PPGIS surveys that combine the cost effectiveness of an internet survey with wider representation in the hardcopy mapping survey (Brown and Reed, 2009; Brown and Weber, 2012). But defining best practice to achieve cost effectiveness remains ambiguous because cost trends appear to moving in opposite directions. If current trends continue, the cost of effective sampling and recruitment will likely exert a stronger influence on the overall participatory mapping cost to achieve the data quality necessary for decision support.

3.2.3.2. Stakeholder representativeness. On the aspect of stakeholder representativeness in PPGIS/PGIS for mapping ecosystem services, in the majority of cases, participation has been implemented by sampling regional residents within the study area, engaging what others have termed the "silent majority" (Brown, 2004). Ideally, participatory and collaborative efforts in environmental management and participatory spatial planning should include as wide as possible stakeholder involvement to cover various interests and needs (Reed 2008; McCall and Dunn, 2012). Identifying the benefits that ecosystems provide to humans with PPGIS/PGIS is related to how stakeholders operate at various levels of society, often with mixed roles as both beneficiaries of these services, and as suppliers (e.g., through direct land ownership or management decisions on public lands). These complex and interlinked roles of interest groups are a challenge for PPGIS/PGIS facilitators, but should be considered in the participatory mapping of ecosystem services (Opdam, 2013). Best practice would identify and prioritize relevant stakeholders, for example, by applying stakeholder analysis to incorporate the multiple societal interests and values in the participatory mapping of ecosystem services. And yet, obtaining commitment from stakeholder groups for participation cannot be assumed as given, and represents a potentially significant feasibility barrier which affects the utility of the process for decision support. For example, Ruiz-Frau et al. (2011) were only able to obtain participation from 14 of 24 identified stakeholder organizations. Brown (2012) observed resistance from both environmental and industry stakeholders to engage in participatory mapping processes because these groups view participatory mapping as a wildcard, a process for which they are unfamiliar and cannot control.

3.2.3.3. Good practice in PPGIS/PGIS. The feasibility of implementation can also be evaluated from the perspective of following good practice in PPGIS/PGIS that is founded on collaborative and participatory spatial planning. Successful PGIS practice is identified, especially in the context of developing countries, as effective participation through a carefully planned and inclusive process that becomes embedded in long-lasting and locally driven spatial decision-making processes that are adapted to different socio-cultural and bio-physical environments (Corbett and Rambaldi, 2009; Rambaldi et al., 2006). In a developed country context, PPGIS emphasizes the production of high quality, place-based spatial data for integration with formalized land use planning processes (Brown and Kyttä, 2014). In both developing and developed countries, the reviewed cases described a single mapping effort that was not integrated with the larger land planning or management process. The approach can be described as consultative participatory spatial planning process with one directional information flow dominating and lacking dialogue and negotiation (Tippett et al., 2007; McCall, 2003; McCall and Dunn, 2012). Only a few of the reviewed studies included steps beyond consultation such as a review of the mapped data with the key stakeholders (Fagerholm et al., 2012; Fagerholm and Käyhkö, 2009; Ramirez-Gomez et al., 2013). Although the development of effective PPGIS/PGIS methods remains an important research need, there is a compelling need to provide tangible evidence of the benefits of mapping ecosystem services for improving environmental management outcomes.

Thus, best practice for identifying ecosystem services with PPGIS/PGIS would not only integrate the data mapped into actual participatory land use planning decision processes (Brown and Kyttä, 2014; McCall and Dunn, 2012), but also increase public awareness to mainstream ecosystem service information into policy and governance (Opdam, 2013), and ultimately, make the case for ecosystem protection, conservation and management (Setten et al., 2012). However, following best practice, at least as it relates to participation, would actually decrease the feasibility of implementation for many mapping projects. While the ecosystem service mapping activity can be accomplished in a relatively short timeframe (e.g., 3 to 4 months), integration of the results into a land use planning and decision process requires an extended period of time, often years. The essential element of building of trust between participants and decision makers requires time and patience, both pre- and post-mapping activity. The mismatch between the time required for mapping data collection and analysis and the time required for ecosystem data integration into tangible decision outcomes helps explain the proliferation of mapping projects by academics that have a relatively short time horizon for producing publishable results. But land use planning and management is a long-term process that requires participatory mapping sponsors and facilitators willing to persevere to see tangible outcomes. Public planning agencies and NGOs can provide the long-term continuity necessary to achieve best participatory practice, but as yet have been reluctant to embrace PPGIS/PGIS (Brown, 2012). Table 3.

4. Discussion

This review identified and described nearly 30 empirical studies involving the use of PPGIS/PGIS to identify ecosystem services. There is demand to evaluate and assess nature's services in place-based ways from different stakeholder's perspectives and engage them in the planning for multifunctional management (Cowling et al., 2008; Opdam, 2013; Potschin and Haines-Young, 2013), but this area of research and practice remains embryonic with progress toward best practice proceeding unsystematically through the accumulation of case studies that are challenging to compare. Presently, there exist no definitive guidelines regarding best mapping practices for a given context to produce valid and reliable results.

Best practice for PPGIS/PGIS mapping of ecosystem services is multi-dimensional, requiring consideration of the type of ecosystem services being mapped, the importance of spatial validity for decision support, and the importance of participation to build social capital. The relationships between these dimensions likely involve tradeoffs. For example, to identify cultural and provisioning ecosystem services, large-scale surveys may be necessary to reduce spatial completeness error, but surveys constitute low-level participation that do not contribute significantly to the building of social capital. Alternatively, cultural and provisioning ecosystem services could be mapped in small, interactive community workshops with greater potential to enhance social capital through community discourse, but the inferential power of the mapped data for decision support would be reduced. The mapping of regulating and supporting ecosystem services require greater knowledge of ecological processes to accurately identify wherein crowd-sourcing through regional PPGIS surveys may not produce better results than smaller, expert mapping processes. Thus, defining best practice will require establishing the relative importance of the utility of the spatial data for decision support versus the importance of community engagement to enhance social outcomes.

Movement toward best practice in PPGIS/PGIS for mapping ecosystem services will require additional research. Brown and Kyttä (2014) identified four priorities for PPGIS/PGIS research in general: increasing participation rates, identifying and controlling threats to spatial data quality, improving the participation component to enhance community discourse and collaboration, and evaluating the effectiveness of PPGIS/PGIS practice. These priorities are equally relevant to the mapping of ecosystem services. However, the participatory mapping of ecosystem services has additional complexity that merits further elaboration.

(1) PPGIS/PGIS mapping of ecosystem services would greatly benefit from experimental design and research controls that provide for the systematic comparison of outcomes using alternative operational definitions, mapping approaches (points, polygons, and predefined areas), at different map scales (local, regional, national), with different sampling designs. As this review has demonstrated, there is little comparability across case studies that are socially and geographically context dependent. Future PPGIS/PGIS mapping

projects involving ecosystem services should embed opportunities that advance mapping methods for best practice. For example, Brown et al. (2014) were able to compare survey-based PPGIS outcomes with workshop-based PPGIS in the same study region for the same cultural ecosystem services. The results suggested that both sample size and the PPGIS mapping methods influence the mapped results with strong implications for use of the spatial data in decision support. Best practice in mapping methods is unlikely to be a single approach, but rather a series of approaches that are culturally contextual and dependent on the proposed use of the mapped data for decision support. Experimentation is needed across multiple and different land use applications.

(2) Integration of ecosystem service concepts, in general, into land use decision support remains elusive. While there is growing acceptance that the ecosystem services, as a conceptual framework, should exert greater influence over future land use decisions at multiple scales, operational pathways are lacking. Given that PPGIS/PGIS mapping of ecosystem services produces spatially explicit results and that all prospective land uses are inherently spatial, there should be a means to integrate ecosystem service concepts into explicit land use decision criteria. But the complexities of the social and political systems that determine land use allocation and management have confounded attempts to integrate and embed ecosystem service information into decision outcomes. Best practice in PPGIS/PGIS mapping of ecosystem services would produce maps and supporting information that would actually be used in land use decision-making, but the type of mapped outcomes that would exert influence in the decision process remains unknown. There is a need to demonstrate a pathway from the inception of PPGIS/PGIS mapping of ecosystem services through integration and use of the information for land use decision support. This will require a significant commitment of resources over an extended period of time, conditions that don't align well with academic research cycles. And yet, best mapping practice for decision support will not advance without some examples that track the mapping of ecosystem services from inception to decision impact.

(3) The PPGIS/PGIS mapping of ecosystem services, a process driven largely by academics, has primarily focused on producing rational, scientifically defensible results at the expense of the "participatory" component. Academics will assert that best practice must produce scientifically credible results which necessarily put emphasis on the spatial information produced. But participatory processes have multiple objectives and the production of an end product that influences land use decisions is but one of them. Social learning and the creation of social capital are arguably equally important objectives in the achievement of sustainable future land use. In the PPGIS/PGIS mapping of ecosystem services, little attention has been devoted to the assessment of these other social objectives. In a perfect world, the participatory mapping of ecosystem services would not only produce valid and useful spatial information about ecosystem services for land use decisions, it would produce better social outcomes for both participants and non-participants. Participation exists along a spectrum of engagement and best mapping practice is likely to differ along this spectrum. Regional, probability surveys of households to identify ecosystem services provide for minimal social engagement compared to collaborative, workshop based processes. Best mapping practice will need to be identified along the participation continuum.

The purpose of this article was to identify current and best practices in using PPGIS/PGIS for mapping ecosystem services by evaluating the empirical case studies implemented over the last 15 years. Best practice has yet to solidify into a coherent body of knowledge as participatory mapping remains more a craft than a science. Methodological pluralism and case study research remain the norm in the field and the quest continues for tangible examples of decision influence in practice. On the optimistic side, if the concept of ecosystem services is to ever become the dominant paradigm for guiding

Table 3
Summary of evaluation criteria to identify best practice in mapping ecosystem services using PPGIS/PGIS.

Evaluation Criteria	Potential means to assess best practice….	Conclusions
Data quality	• Compare mapped results against existing ecosystem service spatial data (if available) • Sample quality (size and representativeness) • Mapping effort and data usability • Design of PPGIS/PGIS process – Clear communication of mapping expectations to participants – Unbiased selection of ecosystem services for mapping – Mapping ecosystem services appropriate to participant knowledge and ability	No data quality standards exist for the mapping of ecosystem services. Sample quality, mapping effort, data usability, and mapping process design serve as proxy measures for mapping data quality. Process design choices effect quantity of spatial data and participation rate but still requires further evidence on selection of ecosystem services
Utility for decision support	• Clear operational definitions for the services/attributes being mapped • Standardization and commensurability of results with other measures of value • Provides opportunity for trade-off analyses • Compatible with the social and institutional context of land use decision process	No mapped ecosystem services data have been used in actual land use decision support
Feasibility of implementation	• Cost effectiveness • Ability to engage diverse, relevant, and sometimes reluctant stakeholders • Follows good participatory practice	Advances in geospatial technology making internet-based participatory mapping more feasible, but trend is offset by greater challenges in participant recruitment to ensure data quality Mismatch between the goals of good PPGIS/PGIS practice in reality

human activity on earth, there must be a means to operationalize it for land use decisions. There are two approaches – to measure and quantify ecosystem services in traditional economic values that reveal the importance of natural systems and assets that provide long-term human benefit vis-à-vis other land use alternatives (Schägner et al., 2013) – or to focus on place-based valuation of services in non-monetary terms to provide spatially-explicit guidance for future land use decisions. Arguably, both approaches are needed, but both remain on the outside, looking in, struggling to gain acceptance within a society guided by short-term economic goals.

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