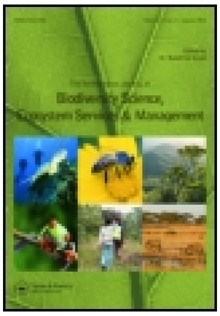

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Methods for mapping ecosystem service supply: a review

María José Martínez-Harms [a] & Patricia Balvanera [a]

[a] Centro de Investigaciones en Ecosistemas, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de La Huerta C.P. 58190, Morelia, Michoacán, México

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Methods for mapping ecosystem service supply: a review

María José Martínez-Harms* and Patricia Balvanera

Centro de Investigaciones en Ecosistemas, Universidad Nacional Autónoma de México, Antigua Carretera a Pátzcuaro No. 8701, Col. Ex-Hacienda de San José de La Huerta C.P. 58190, Morelia, Michoacán, México

Mapping key areas for ecosystem service (ES) supply is essential for the development of strategies that will ensure their future supply. Given the rapid development in this area of research, we performed a review of different approaches used to map ES, with a special focus on those that use social–ecological data. We used an analytical framework based on five criteria for analyzing and comparing the methodological approaches: the types of ES, availability of data sources, types of data sources, spatial scale, and methods used to model ES. We found that regulating services were the most commonly mapped, followed by provisioning, cultural, and supporting services. Secondary (readily available) data were used more frequently than primary data to map ES. Biophysical data (land-cover variables) and mixed sources (databases like global statistics) were the most commonly employed ones. Most studies were performed at the regional or at the national scale. The most commonly used method to model services was the development of models based on the well-known causal relationships between environmental variables, followed by the extrapolation of ES values from primary data to the total analyzed area frequently using land-cover maps. Our synthesis reveals that the majority of studies are based on secondary data, applied at broad scales, without validation techniques. There is an urgent need to develop methods for deepening our understanding of the social–ecological processes behind the supply of ES in order to improve our ability to map ES for decision making.

Keywords: ecosystem service supply; human well-being; Millennium Ecosystem Assessment; social–ecological data; spatial scales; models

Introduction

Ecosystem services (ESs), the benefits people obtain from ecosystems, are increasingly being considered critical for decision making in the search for sustainability (Costanza et al. 1997; Foley et al. 2005; Millennium Ecosystem Assessment (MA) 2005; Carpenter et al. 2009). The development of international initiatives such as the MA (2003) or the UNEP Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) highlights the increasing need to synthesize information around ESs for balancing human well-being with the maintenance of critical ecological processes (Perrings et al. 2011).

ES maps are important tools for decision makers and institutions, enabling them to spatially identify which areas should be maintained due to their high supply of ES (Balvanera et al. 2001). These maps are also important to assess spatial trade-offs among ES, synergies among multiple ES, as well as to prioritize areas that will allow alignment of multiple conservation goals (Daily and Matson 2008; Egoh et al. 2008; Naidoo et al. 2008; Tallis et al. 2008; Anderson et al. 2009; Nelson et al. 2009; Raudsepp-Hearne et al. 2010).

Given the paramount importance of ES maps for decision making, there has been a rapid increase in the number of studies that map their spatial distribution. Many different types of approaches to mapping ES for decision making have been developed, but at present a systematic synthesis of all these approaches is needed to understand which are the most commonly used and the most useful methods used to date.

Approaches for mapping ES can be broadly classified into three main approaches. Valuation of ES through benefit transfer applies a monetary value to a land-cover map based on previous studies from sites having similar land-cover types (Costanza et al. 1997; Kreuter et al. 2001; Sutton and Costanza 2002; Troy and Wilson 2006; Turner et al. 2007). Community value methods have included spatial measures of social values and other perceptions of place obtained through preference surveys to ES maps that systematically integrate these perceptions with biophysical data (Brown 2005; Raymond and Brown 2006; Raymond et al. 2009; Sherrouse et al. 2011). Social–ecological assessments of the ES supply have modeled the relationship between measurable ecological (e.g., field samples of services, climate, land-cover, hydrological, remote-sensed data) and social variables (e.g., population, census data, road layers) to quantify and map the amount of ES supplied through space (Chan et al. 2006; Naidoo et al. 2008; Nelson et al. 2009; Eigenbrod et al. 2010a). This last approach is the most heterogenous in methods and the one reviewed here.

In this work, we review studies that have mapped ES supply based on social–ecological data. In particular, we (i) identify what type of ES were mapped, (ii) identify the types of sources of information and the specific sources of

*Corresponding author. Email: mariajosesmart@gmail.com

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information that were used to map ES, (iii) identify the spatial scales at which ES were mapped, and (iv) classify the types of methods used to model and map ESs under the social–ecological approach. We conclude by discussing the advantages and disadvantages of the types of methodological approaches to mapping ES.

Methods

Definitions and scope

ESs are components of ecosystems that are directly consumed and enjoyed, or that contribute to human well-being conditions through interactions with other components, for example, climate regulation or erosion control (Boyd and Banzhaf 2007; Quijas et al. 2010). We focus here on ES supply, that is, the full potential of ecological functions or biophysical elements in an ecosystem to provide a potential ES, irrespective of whether humans actually use or value that function or element currently (Tallis et al. 2011), on which most studies to date focus; yet, ES provision is also determined by human 'consumption' of the supply, but has been studied much less often and was thus not considered for this review.

Sources of information

We identified all peer review publications about ES mapping using the electronic databases of the Web of Science ISI Web of knowledge, Science Direct, and Google Scholar. We used the following keywords, either alone or in combination: 'ecosystem services,' 'mapping ecosystem services,' 'ecosystem function,' 'ecosystem process,' 'ecosystem goods,' 'ecosystem value,' 'human well-being,' 'natural capital.' We identified a total of 70 publications published from 1995 to 2011 that have mapped ES (Figure 1).

To focus solely on these publications that use a social–ecological approach to map the supply of ES, we excluded

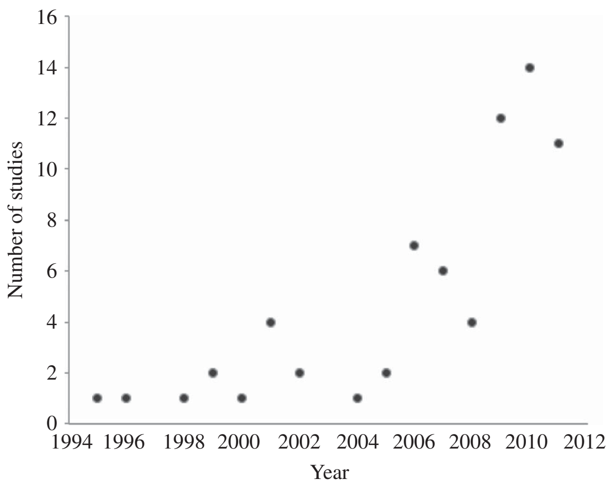

Figure 1. Number of studies that mapped ESs from 1995 to 2011.

29 studies that used the value transfer or participatory mapping approaches. We further analyzed the remaining 41 studies that quantified ES supply using five criteria for comparison among approaches (Table 1); we considered individual entries for each of the ES mapped in each of these studies. We used the MA classification (2003) of ES into supporting, regulating, provisioning, and cultural services and the definitions of these categories by Maass et al. (2005). We distinguished the type of information available between the primary data, obtained by the authors of the manuscript (field data, interviews, census data), and the secondary data, which were readily available from external sources (land-cover data, geographical databases, remote-sensed data). Then, we identified the specific sources of biophysical (hydrological, soil, climate, topographical, remote-sensed, and land-cover layers) and socioeconomic data (population, road maps, census data) as well as mixed sources (databases, surveys, and bibliography). We identified the spatial scale as the total extent of the area mapped. We then described the methods for mapping ES, that is, the way in which data sources were used to quantify and map the ES supply, and classified them into five categories. The first category is the use of a constant ES value to each land cover, also called 'look-up tables'; values are obtained from previous studies at other places and other spatial scales. The second approach corresponds to 'expert knowledge,' in which experts are asked to rank an environmental variable category based on the knowledge that they have about the potential of these categories to supply ES. The third one is the development of 'causal relationships' that incorporate existing documented knowledge about the relationship between an environmental variable category and the supply of ES. The fourth approach is called 'extrapolation of ES values from primary data to the total analyzed area'; in this case, the value of ES supply for a given environmental variable category (e.g., a land-cover class) is extrapolated from field data, for mapping the distribution of ES. The fifth category is called 'regression models,' which corresponds to modeling the relationship between field samples of ES (response variables) and readily measurable environmental variables (explanatory variables). Finally, we also explored which studies have validated their methods to map ES.

Results

ESs that have been mapped to date

We found that 41 studies mapped ES based on social–ecological data; considering each ES mapped within each reference, our database had 95 entries.

Nineteen different ESs have been mapped to date (Figure 2). The most commonly mapped services are carbon storage, carbon sequestration, food production, and recreation. Regulating services were the most commonly mapped services, followed by provisioning, cultural, and supporting services.

Table 1. Criteria used to classify the types of approaches used to map ES supply based on social–ecological data.

Criteria	Categories considered	Rationale
Types of ESs	Cultural	Tangible and intangible benefits derived from the relationship between man and the ecosystem, such as recreation, scenic beauty, and so on
	Provisioning	Products obtained from ecosystems, such as water, food, fiber, etc.
	Regulating	Emergent properties of ecosystems that regulate the environmental conditions in which human beings live (e.g., climate regulation, hydrological cycles, water quality)
	Supporting	Basic ecosystem processes that maintain the generation of all other services (e.g., soil formation, pollination, nutrient cycling)
Availability of data sources	Primary data	Maps derived from sampling in the field (e.g., field data, surveys, or interviews or census data)
	Secondary data	Maps derived from readily available information not verified in the field (e.g., cartographical data, remote-sensed data, socioeconomic data, and mixed sources like databases like global statistics)
Types of data source	Biophysical data	Land-cover, remote-sensed, topographical, hydrological, and climate data
	Socioeconomic data	Road map, population map, photos, and census data
	Mixed Sources	Database (global statistics, e.g., Olson's global map of carbon storage and FAO reports), bibliography, surveys, and field data.
Scale	Patch	$10–10^2$ km^2
	Local	$10^2–10^3$ km^2
	Regional	$10^3–10^5$ km^2
	National	$10^5–10^6$ km^2
	Global	$>10^6$ km^2
Method	Look-up tables	Use of existing ES values from the literature to land-cover classes
	Expert knowledge	Experts rank land-cover types based on their potential to provide specific ES
	Causal relationships	Incorporate existing knowledge about how different layers of information related to ecosystem processes and the services to create a new proxy layer of the ES
	Extrapolation of primary data	Field data databases weighted by cartographical data (generally land cover)
	Regression models	Employing field data of ESs as response variables and proxies (e.g., biophysical data and other sources of information obtained from GIS) as explanatory variables

Note: ES, ecosystem service.

Types of information sources and specific sources of information

Secondary data were more commonly used (59% of the entries), compared to primary data (41%; Figure 3). This was the case for the four types of ESs. The main proxies used to map ES were land-cover variables for all four ES categories. Regulating ES had been assessed using databases (FAO statistics or carbon estimates derived from a global map of carbon stored in vegetation (Olson et al. 1985)), topographical variables (Digital Elevation Models), field data, and remote-sensed information (mainly the Normalized Vegetation Index (NDVI)) (Figure 4).

Scale

Most ES mapping was done at the regional scale (57% of the entries) followed by the national one (15%), with much fewer studies at the patch, local, and global scales. The regional scale was the most common for the four types of ES (Figure 5).

Methodological approaches to map ES

The most commonly used method to map ES was to apply well-known causal relationships between social–ecological variables and ES (37% of the entries). Another common approach to map ES was the extrapolation of primary data to the total analyzed area (20% of the entries).

Cultural services

The most common method to map cultural ES was the causal relationship, frequently relying on the amount of land in natural areas, distance to roads, and land-use data (urban and forest uses) (Figure 6(a)). For example, Chan et al. (2006) mapped recreation weighting proximity to major roads, population density, level of public access, and the amount of land in natural or agricultural cover. Another common method was the extrapolation of primary data (e.g., surveys, census data) to land-cover maps. For example, Arriaza et al. (2004) mapped scenic beauty via survey of observer preferences through photos; the visual quality assigned to each scene on a derived interval scale was combined with the landscape attributes and a land-cover map.

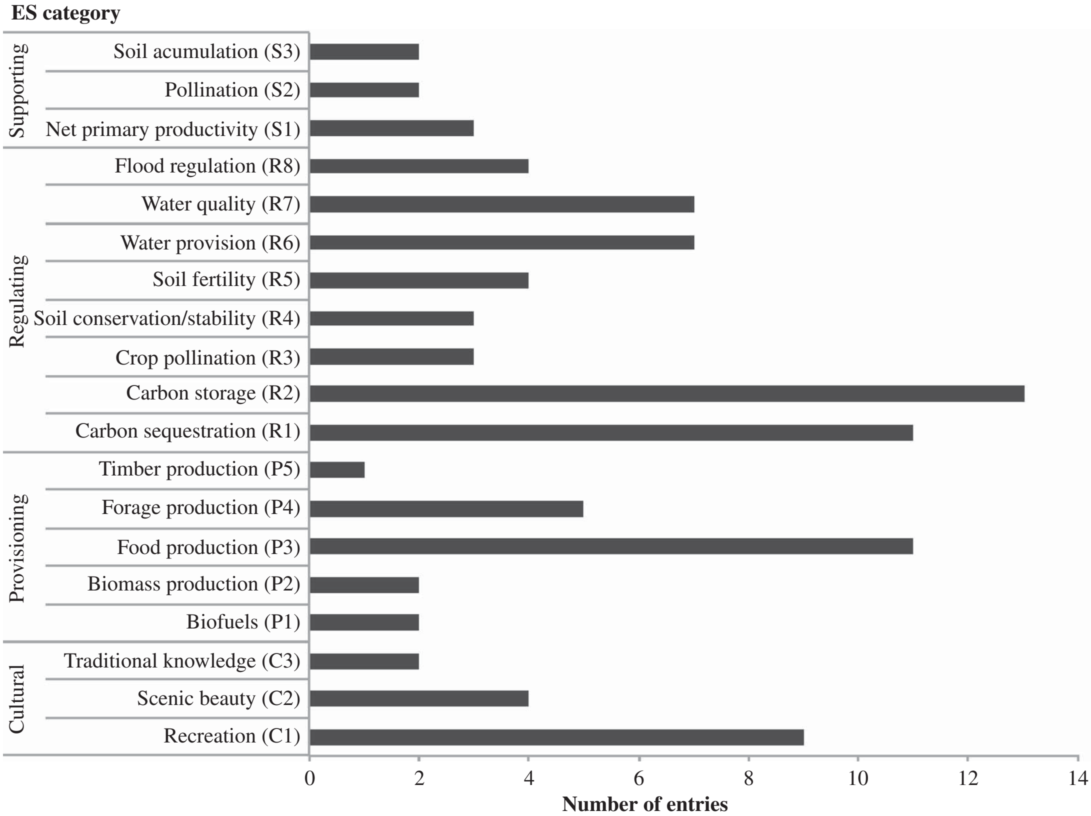

Figure 2. Frequency distribution of studies mapping ESs (entries correspond to each service within each reference).
Note: ES, ecosystem service.

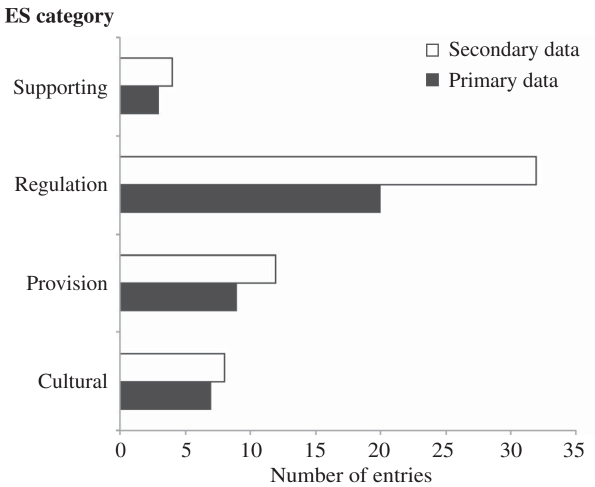

Figure 3. Type of data source of the entries used in the database for different types of ESs.
Note: ES, ecosystem service.

Regulating services

The most common approach was to apply causal relationship based on secondary data (e.g., climate, soil data, elevation) to model ES (Figure 6(c)). Lautenbach et al. (2011) quantified and mapped crop pollination by defining an area of the potential nesting sites, using the distance between potential nesting habitats and the nearest arable land cell. Also, the use of primary data extrapolated has been frequently used. For example, Raudsepp-Hearne et al. (2010) have mapped soil fertility using average values for organic matter in soil for each municipality and extrapolating these values to a cartographic layer of municipal districts. The expert knowledge approach, a bit less frequently used, was applied by Egoh et al. (2008) to map carbon storage where experts classified vegetation types according to their carbon storage potential, into three categories: low to none (e.g., desert), medium (e.g., grassland), high (e.g., thicket, forest).

Provisioning services

The most common approach was the causal relationship based on secondary data (e.g., agricultural census) extrapolated to the study area through land-cover maps (Figure 6(b)). Regression models have also been frequently used. Malmstrom et al. (2009) have mapped forage production assessing field relationships between remotely sensed data (spectral vegetation indices) and biomass values observed in the field.

Supporting services

These were the most commonly mapped with regression models, as well as with models developed with causal relationships between biophysical data (Figure 6(d)). For

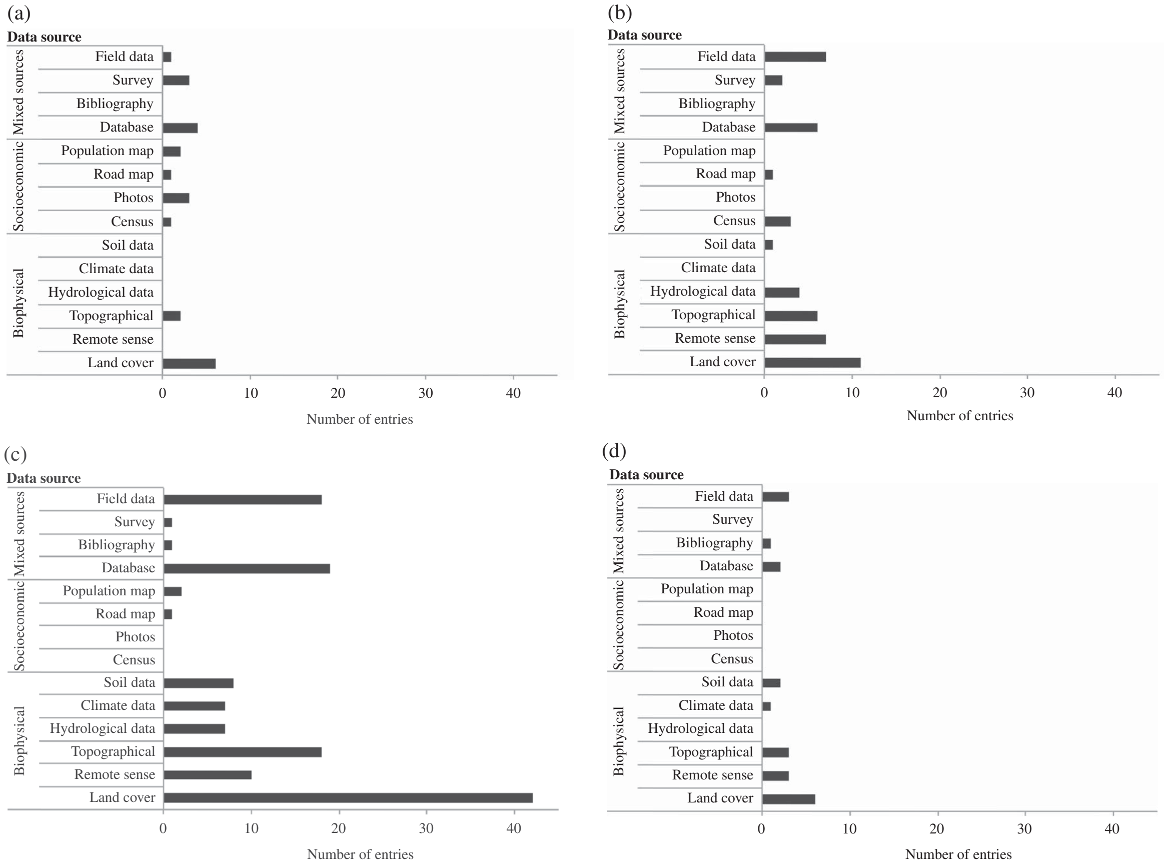

Figure 4. Specific sources of information used in the studies mapping ES for (a) cultural, (b) provisioning, (c) regulating, and (d) supporting ES.
Note: ES, ecosystem service.

example, Lavorel et al. (2011) modeled several ESs based on a field data about plant functional traits combined with land-cover (one categorical variable) and abiotic variables (four continuous variables: elevation, radiation, water holding capacity, and fertility) applying general linear models.

Most of these different mapping approaches have gone untested, with only 15 of 95 records that have actually used any validation technique to test the accuracy of the developed model. All the records that used validation used primary data, yet they correspond to many different types of ESs and spatial scales.

Discussion and conclusions

Our synthesis reveals that there is an increasing body of literature destined to quantify and map ES. Despite these advances, the sources of information and modeling methods are diverse; also, in the majority of the studies, detailed methodological information was missing.

Our review exposes some clear trends. Key ESs that are today being called upon for decision making have been frequently mapped, as is the case of carbon storage, carbon sequestration, and food production. Yet, it is notable that ESs that may be critical for the maintenance of ecosystems and human welfare, such as primary productivity or scenic beauty, are rarely addressed; others such as disease regulation or cultural services such as identity have not been included in this list to date. There is a clear lack of formal research on many of these services.

The most commonly used sources of information include land-cover variables (Chan et al. 2006; Naidoo et al. 2008; Lautenbach et al. 2011), topographical information (Egoh et al. 2008; Nelson et al. 2009; Swetnam et al. 2011), and spectral vegetation indices (Deng et al. 2007; Zheng et al. 2007; Lavorel et al. 2011), that are readily available and have been widely used to guide management decisions. Yet, the relationships between land-cover variables and ES supply have been untested in most regions of the world (Naidoo et al. 2008; Bennett et al. 2009; Nelson et al. 2009). Eigenbrod et al. (2010a), compared to the use of land-cover variables to map ESs based on a field data approach, and showed that methods based only on land cover can have strong errors, particularly when applied at the local scale.

The most frequently used method to map ESs is the use of causal relationships, based on the understanding of ESs and readily available information. This approach was particularly common for mapping cultural and regulating ESs. Eigenbrod et al.

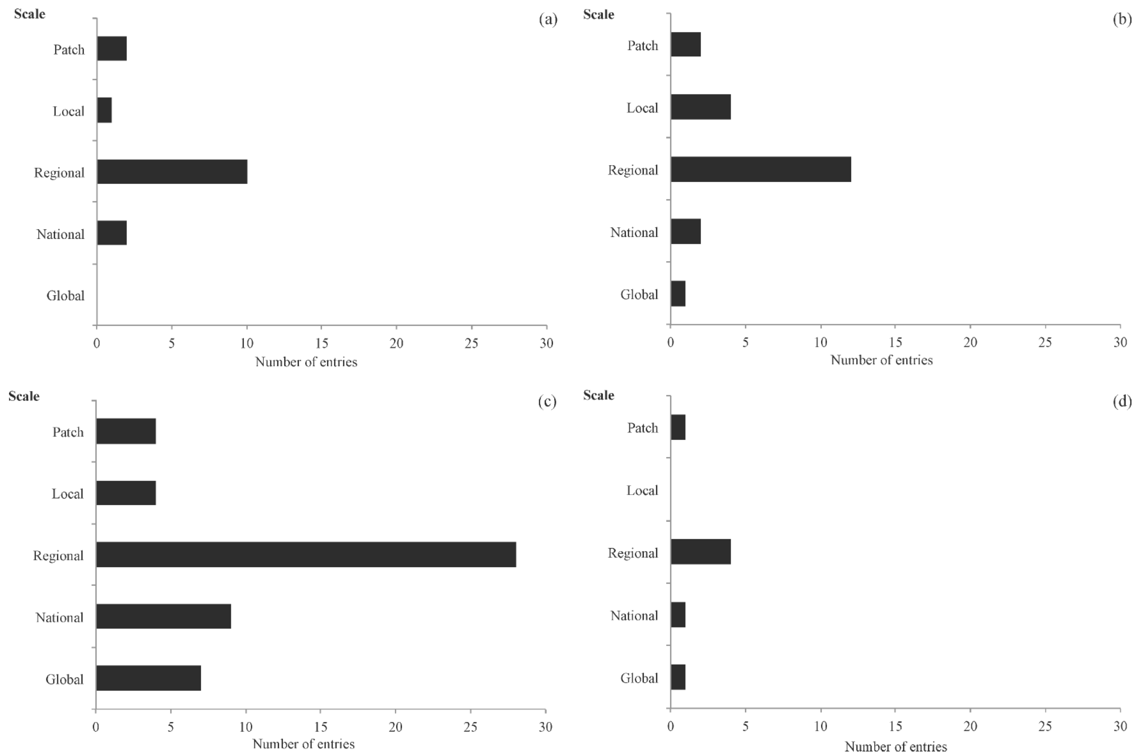

Figure 5. Spatial scales at which ESs have been mapped, for (a) cultural, (b) provisioning, (c) regulating, and (d) supporting ES. Scales: patch ($10–10^2$ km^2); local ($10^2–10^3$ km^2); regional ($10^3–10^5$ km^2); national ($10^5–10^6$ km^2); global ($>10^6$ km^2) scale.
Note: ES, ecosystem service.

(2010a) have shown that causal relationships can improve the fit of ES maps when primary data are absent, weighting land-cover variables by key biophysical variables related to ES supply (Chan et al. 2006). Nevertheless, the effectiveness of this approach will depend on how well the biophysical and social variables determining the distribution of ES are understood and such knowledge is likely to be poor for ES.

The use of primary data, which are spatially extrapolated using land-cover data, is also a quite frequently used method especially for cultural, provisioning, and regulating ES. This approach relies on few sources of information that are then adjusted to the particularities of the studied ES and site so it is relatively simple and relatively quick. The disadvantage of this approach is that there is probably a lack of concordance between the actual distribution of ES explained by a uniformity error (Eigenbrod et al. 2010b) caused when a single average value of ES is assigned to an entire cartographical category (Plummer 2009), resulting in a poor fit of ES estimates.

Regression models based on field data and environmental variables have been mainly applied for provisioning, regulating, and supporting ES. They correspond to quantitative approaches through the collection of field data, modeling and extrapolating this data at different spatial scales using biophysical and management layers as explanatory variables. It would be desirable for this approach to be used more frequently in the future to inform about the key biophysical variables explaining the spatial distribution of ES to further refine the ES maps. Having an in-depth understanding of these key variables could significantly improve the causal relationship approach. The disadvantage of this approach is that it requires much time and resources to do field work and data analysis.

The approach of the look-up tables has been mainly applied to regulating ES. For example, the carbon storage layer (Gibbs 2006) has been used by Naidoo et al. (2008) and Wendland et al. (2010), giving a single estimate of carbon for each biome. This approach has been applied mainly at global scales and has the disadvantage of the uniformity error giving very broad estimates of ES supply.

The expert knowledge approach has been mainly applied to cultural and regulating ESs, to incorporate the perspectives of the different stakeholders into the mapping process. This approach has the advantage of being a relatively fast assessment that pools the knowledge of experts. Nevertheless, it has the disadvantage of having high levels of subjectivity in the assessment and it does not provide quantitative estimates of ES.

The selection of a methodological approach to mapping ES is data dependent. When there are secondary data available and there is not much time and resources, a good approach will be the look-up tables; otherwise, if there is a need to improve the quality of the maps and there

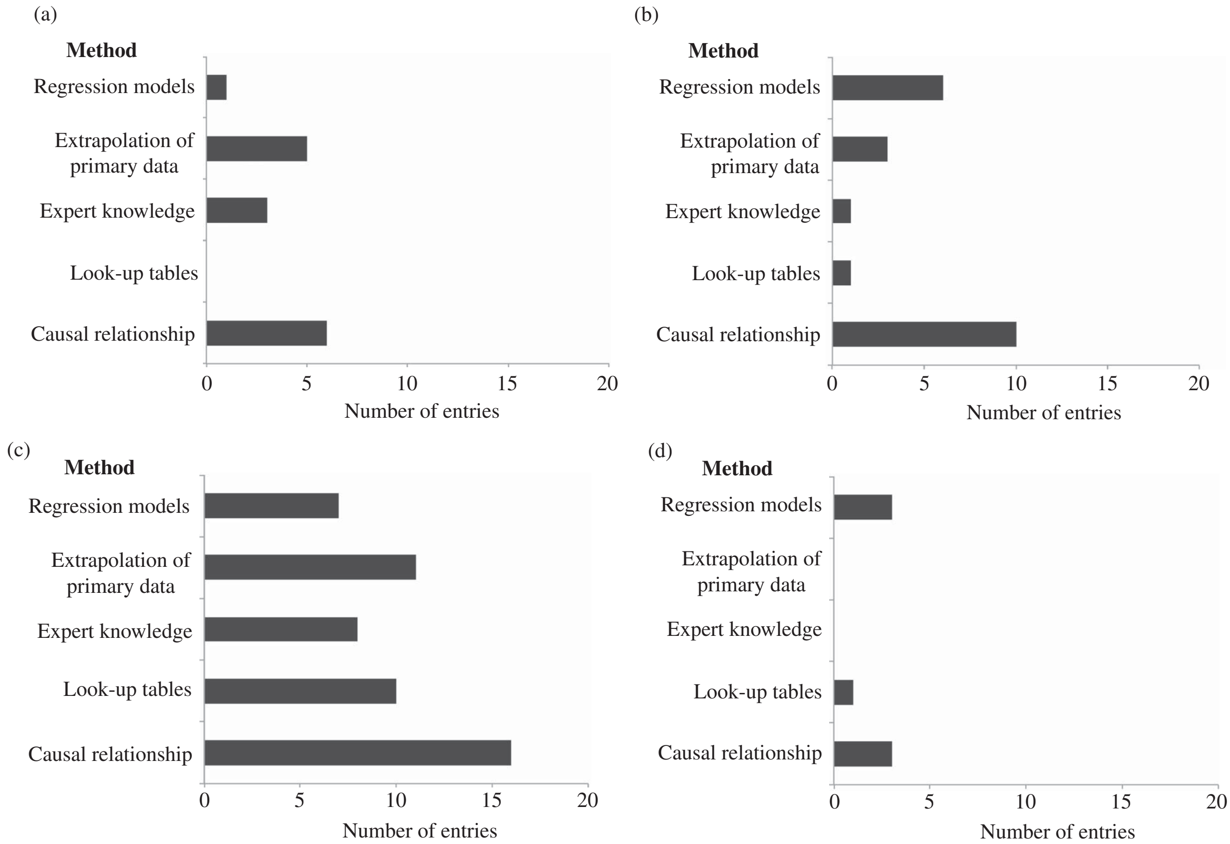

Figure 6. Type of methods used in the studies mapping ES for (a) cultural, (b) provisioning, (c) regulating, and (d) supporting ESs.

is more time and resources, the expert knowledge is a good approach to select. The causal relationship approach can also be applied based on the secondary data and occasionally can rely on some primary data to guide the model. This approach requires good knowledge of the ES and once developed it can be easily applied to other sites with similar environmental conditions (Figure 7).

When there are primary data available, the selection of the method will depend on whether there are primary data that are not representative of the study site or whether it is a representative sampling of the study site. In the first case the method selected should be able to extrapolate the primary data to the study area obtaining modeled surfaces of ES. In the second case the method selected should be the regression models, that is the best supported approach providing the more accurate spatial distribution of ES but at the same time implies more time, resources, and knowledge for its application (Figure 7).

As seen in this review, the frequent use of secondary data and the use of simple modeling techniques is explained by the availability of data and because these methods are easier to apply when there are restrictions in time, data, or budget availability. Nevertheless, over-simplification sometimes can mislead the decision-making process (Seppelt et al. 2011). The increasing use of regression models can allow for a comprehensive understanding of the social–ecological processes behind the supply of ES and lead to reliable data and results (Anderson et al. 2009; Eigenbrod et al. 2010a). This method allows the identification of explanatory variables and assesses the uncertainty of the models (e.g., to apply validation and test the relationships between the predictions and what is observed in the field). The regression model approach also gives valuable information on the causal relationship approach making these models more robust, contributing to systematic comparisons through time and space for several ES (Eigenbrod et al. 2010a). The use of validation techniques to assess the errors associated with any of the above approaches is urgently needed; information obtained from these assessments can further be incorporated to fine-tune causal relationships or regression models.

Given that mapping ES is becoming a key tool to guide decision making, the quality of such ES maps is important in order to be able to provide the most accurate information. In addition, the increasing changes in ES supply require assessment and monitoring of these changes, triggering the urgent development of a standardized methodological approach to model and map ESs under a biophysical and social basis (Seppelt et al. 2011). Here, we strongly suggest a complementary approach between regression models and the causal relationship approach toward developing tools to carry out relatively quick assessments, while deepening our understanding of the biophysical components and processes associated to ES supply.

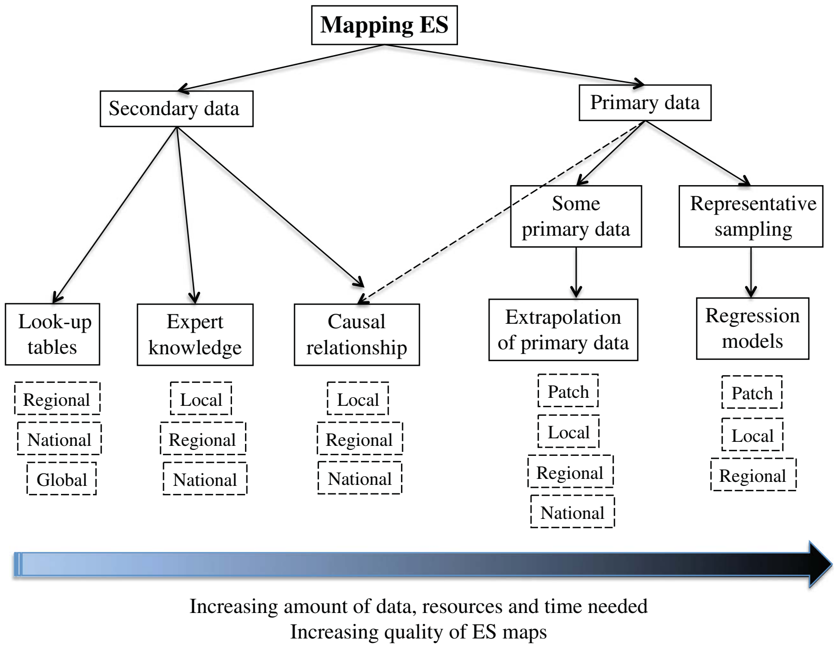

Figure 7. Decision tree highlighting the methods used according to the data availability.

Supplementary material

The complete database used in the quantitative analysis according to the criteria described in the manuscript is available online as Appendix S1.

Acknowledgments

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