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# METHODS FOR MODELING ECOSYSTEM SERVICES: A REVIEW

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**ABSTRACT**: Modeling ecosystem services (ES) is an essential tool for the development of strategies that will ensure their future supply, provision and quantification. Given the rapid development in this area of research, a review of the different approaches used to model ES was performed, using an analytical framework based on five criteria for comparing the existing methodological approaches: the types of ES, availability of data sources, spatial scale, types of models used and the possible outcomes of the models. Regulating services were the most commonly modeled, followed by provisioning, cultural, and supporting services. The most frequently used data for modeling were secondary data (already available from scientific literature or data banks). Most studies were performed at the regional or at a global scale. Mechinicist models, based on state and flow equations, were the most commonly used method, but the survey showed a relatively homogeneous distribution of all the identified types of modeling. The synthesis reveals that the majority of studies are based on secondary data, applied at broad scales, without validation techniques, similar to the existing information regarding the mapping of ESs.
**KEY WORDS:** ecosystem services; Millennium Ecosystem Assessment; social–ecological data; spatial scales; models

## 1. INTRODUCTION

The Millennium Ecosystem Assessment defined ecosystem services (ES) or the services generated by the functions of ecosystems as theoretical concept, although they were implicitly discussed and analyzed by ecologists and environmental experts a long time before (Harrison and Hester, 2010). In that order, ecosystems are considered to provide the human society a series of services, classified as provisioning, regulating, supporting and cultural services.

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).

Scientific efforts regarding the quantification, classification and mapping of ecosystem services are increasing in number in the last years, and consistent reviews are already made in the scientific literature (Fleskens and Hubacek, 2013; Martínez - Harms and Balvanera, 2012; Vigerstol and Aukema, 2011; Volk, 2013). On the other hand, the construction of mathematical models of ecosystem services and of their relations with various parameters is a relatively new approach, with various paper published in the last few years, and a systematization of the existing information in the field is highly needed.

In this work, I reviewed studies that have modeled ES supply based on social–ecological data. In particular, I (i) identified what type of ES were modeled, (ii) identified the types of sources of information that were used in modeling ES, (iii) identified the spatial scales at which ES were modeled, and (iv) classified the types of methods used to model ESs under the social–ecological approach. I concluded by discussing the advantages and disadvantages of the types of methodological approaches to model ES.

## 2. METHODS

### 2.1. 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.

Two approaches are mainly used in scientific studies: ES supply, or the full potential of ecological functions or biophysical elements in an ecosystem to provide a potential ES, which is the focus of most studies to date, and ES provision, determined by the rate human society consumes the supply, much less often studies, but of equal importance from this review's point of view.

### 2.2. Sources of information

I identified all peer review publications about ES modeling using the electronic databases of the Web of Science ISI Web of knowledge, Science Direct, and Google Scholar. The following keywords were used, either alone or in combination: „ecosystem services", „modeling ecosystem services", „ecosystem function", „ecosystem process", „ecosystem value". A total of 63 publications published from 1998 to 2015 were identified that have modeled ES. To focus solely on these publications that constructed mathematical models of ES, 14 studies that presented frameworks for further models were excluded from the analysis.

The remaining 47 studies (Figure 1) that modeled ES supply and provision were further analyzed using five criteria for comparison among approaches, based on the methodology presented by Martínez-Harms and Balvanera (2012) (Table 1),

individual entries for each of the ES modeled in each of these studies being used.

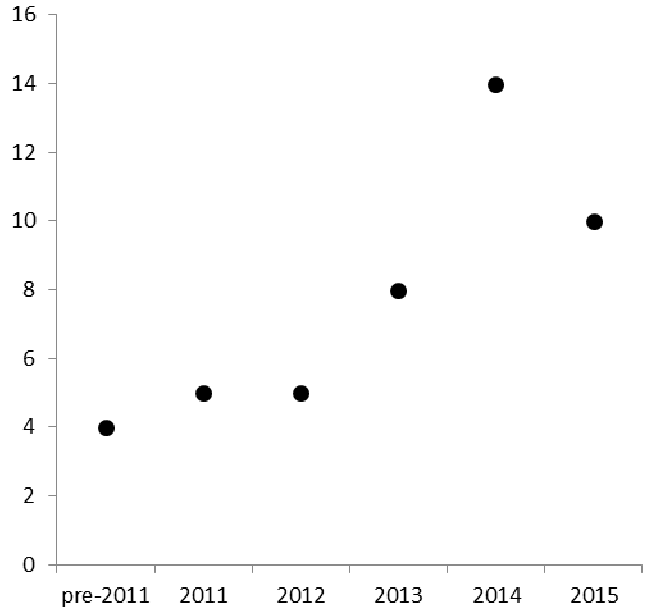


**Figure 1.** Number of studies that modeled ESs.

The MA classification (2003) of ES into supporting, regulating, provisioning, and cultural services was used for the differentiation among the investigated studies. I identified the spatial scale as the total extent of the area from which the information was gathered for modeling.

We then described the methods for modeling ES, mainly the way in which the information was compiled and processed, and classified them into five categories. The first category is the use of state and flow equation between the parts of the system viewed as individual entities, using „mechanicist models". The second approach corresponds to „probabilistic models", in which cybernetic information, such as Bayesian Belief Networks, decision trees or Expert Knowledge are used for prognosis and estimation of ES. The third one is a „statistical" approach, in which statistical tests, correlations and regression are used.

The fourth approach is called „GIS-based models", where prognosis and estimation is based on the use of different GIS modules that process the information. The fifth category is called „conceptual models", using information from different types of models presented above and the way to relate the heterogeneous modeling information.

**Table 1.** Criteria used to classify the types of approaches used in modeling ES (adapted after Martínez-Harms and Balvanera, 2012).

| 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 | Information derived from sampling in the field (e.g., field data, surveys, or interviews or census data) |
| | Secondary data | Information 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) |
| | Simulated data | Information generated by the researcher in order to prove the viability and usability of the model |
| 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$^2$ |
| Model | Mechanicist | Use of state and flow equation between the parts of the system viewed as individual entities |
| | Probabilistic | Use of Bayesian Belief Networks, Expert Knowledge or other forms of Artificial Intelligence to transform existing information into future prognosis |
| | Statistical | Use of field data of ESs as response variables |
| | GIS-based | Use of GIS modules for integration of field data into prognosis and estimation maps |
| | Conceptual | Use of information from different types of models presented above and the way to relate the heterogeneous modeling information |
| Model outcomes | Prognosis | Estimation of a future value starting from present day data |
| | Quantification/estimation | Estimation of the total value starting from discrete data |

## 3. RESULTS AND DISCUSSION

### 3.1. Ecosystem services modeled

I found 47 studies modeling ES based on social–ecological data; considering each ES modeled within each reference, the database had 105 entries. A detailed list of the literature studied is presented in Appendix 1.

Fourteen different ESs have been modeled to date (Figure 2). The most commonly mapped services are water provision, food production, carbon storage and cultural services, from a general point of view. Regulating services were the most commonly modeled services, followed by provisioning, supporting, and cultural services.

### 3.2. Types of models

Mechanicist approaches were the most frequently used in ES modeling (28.57%), followed by GIS-based models (24.49%; Figure 3). However, excepting conceptual models, all the other four types of modeling were relatively homogeneously represented in the studies found in the field.

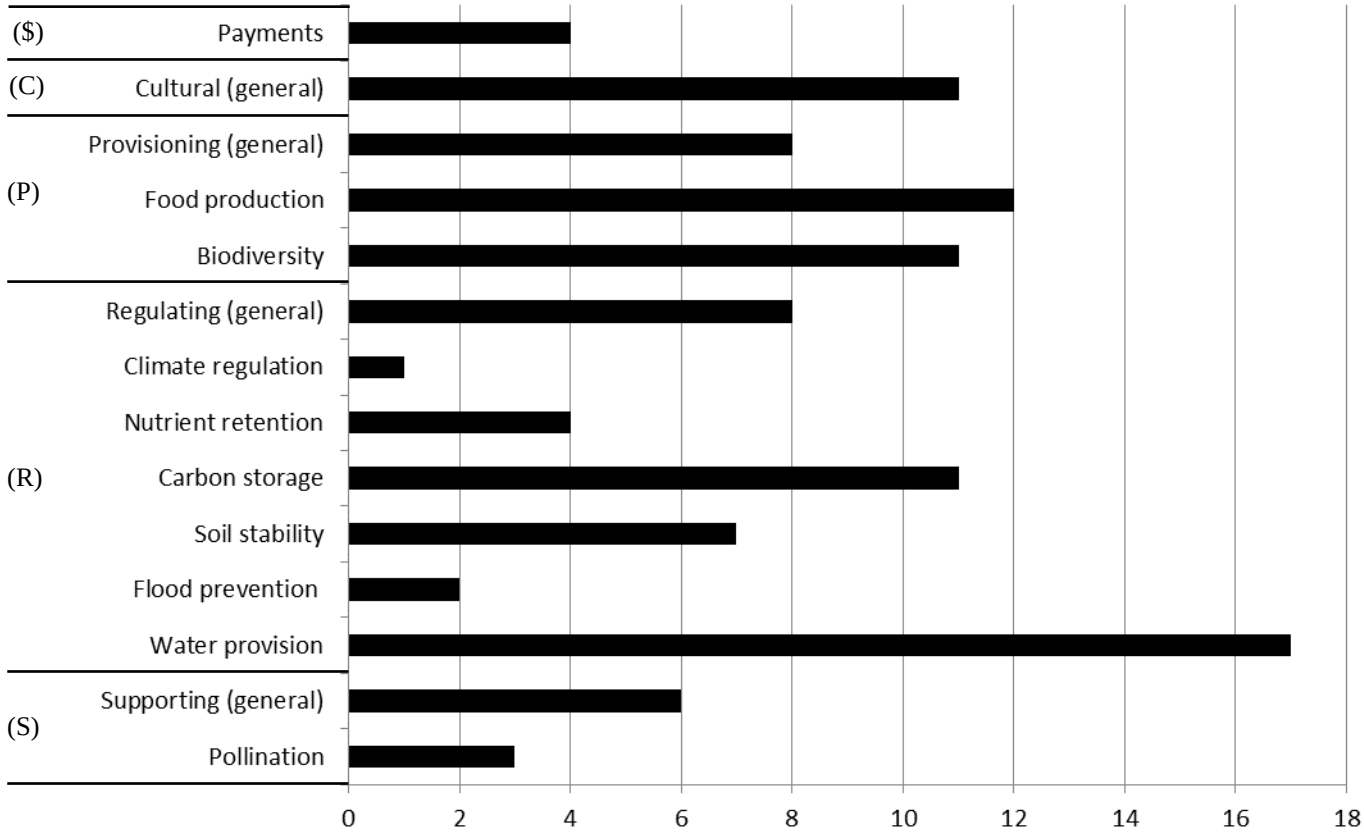


**Figure 2.** Frequency distribution of studies that modeled ESs (entries correspond to each service within each reference; S – supporting services; R – regulating services; P – provisioning services; C – cultural services; $ - payments for ecosystem services).

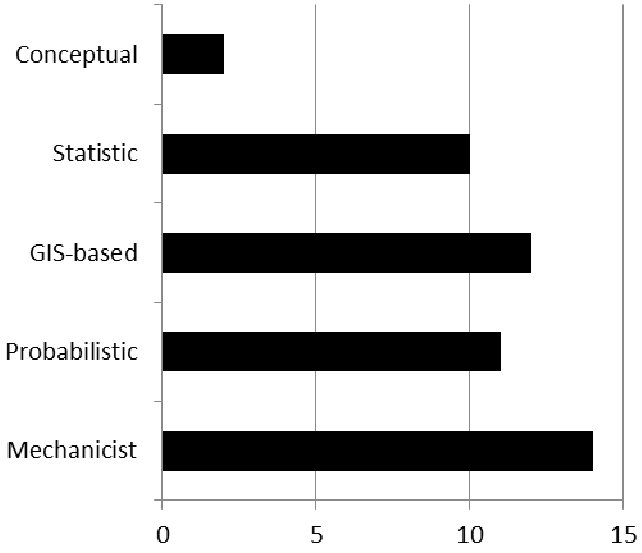


**Figure 3.** Number of studies that modeled ES.

### 3.3. Scale

Most ES modeling was done at the regional scale (36.36% of the entries) closely followed by the global one (29.54%), with much fewer studies at the patch, local, and national scales. The global scale was the most common for the four types of ES (Figure 4).

### 3.4. Types of data used in modeling

At a general point of view, secondary data were the most commonly used (48.78%), as compared to simulated data (36.26%) and primary data (16.26%) (Figure 5). For the four types of ESs investigated, secondary data was the most used information for regulating and provisioning services, while simulated data was the basis for most of the models regarding cultural and supporting services.

### 3.5. Model outcomes

Prognosis is the main outcome of the generated models regarding ESs, with over 68% of the models used for anticipating the evolution of ESs starting from known values (Figure 6). The remaining 31.65% are models that estimate or quantify the complete value of ESs from discrete data available

to the researchers. The situation applies for each of the four ES categories, cultural services having the most equilibrated ratio between the two categories of model outcomes (60% prognosis to 40% estimation/quantification).

## 3.6. Information gaps and future perspectives

The synthesis reveals an increasing amount of literature regarding the modeling of ES, the number of papers being gradually higher in the last period, with studies in the field already published in 2015 at almost the same number as in the entire 2014, as seen in Figure 1. Despite these advances, the sources of information and modeling methods are highly diverse, and most studies lack detailed methodological information, situation consistent with the findings of Martínez-Harms and Balvanera (2012) for mapping ESs.

Some clear trends are also visible, key ESs that are today considered for decision making being frequently modeled, such as carbon storage, food production or water provision. In the same way as for mapping (Martinez-Harms and Balvanera, 2012) ESs that may be critical for the maintenance of ecosystems and human welfare (e.g. primary productivity, disease regulation or cultural services such as identity or scenic beauty), have not been included in this list to date, creating the idea of a lack of interest on many of these services. Other important ESs, such as pollination, climate regulation or flood prevention are rarely addressed.

Another important aspect to be observed is the general perspective presented in a consistent part of the analyzed literature, with cultural, provisioning, supporting and regulating services modeled as uniform entities, and not a specific ESs, part of a larger category. Almost a third (31.43%) of the entries included in the analysis consists of ESs modeled as an entire category, creating a rather confusing approach, difficult to use in practice for prognosis or quantification.

Even more, the relatively recent experience in the field of modeling ESs generated a large amount of methodologies and not a consistent, coherent approach, with only 2 papers (Sun and Müller, 2012; Smajgl et al., 2015) using more than one modeling technique, given the fact that the data required are heterogeneous and a singular approach is unable to encompass all the information gathered for an integrated approach. From that point of view, a future direction should probably consist of integrating several modeling techniques into larger, more comprehensive models, capable of prognosis and quantification of ESs at a larger scale.

Last but not least, very few of the investigated models refer to payments for ESs and their reflection into the future evolution of the services' quality and quantity, an aspect that should raise a more consistent approach, due to the close relation between public awareness and the conservation of natural capital. Future discussions should also take into consideration this aspect and relate its particularities to the prognosis of ESs.

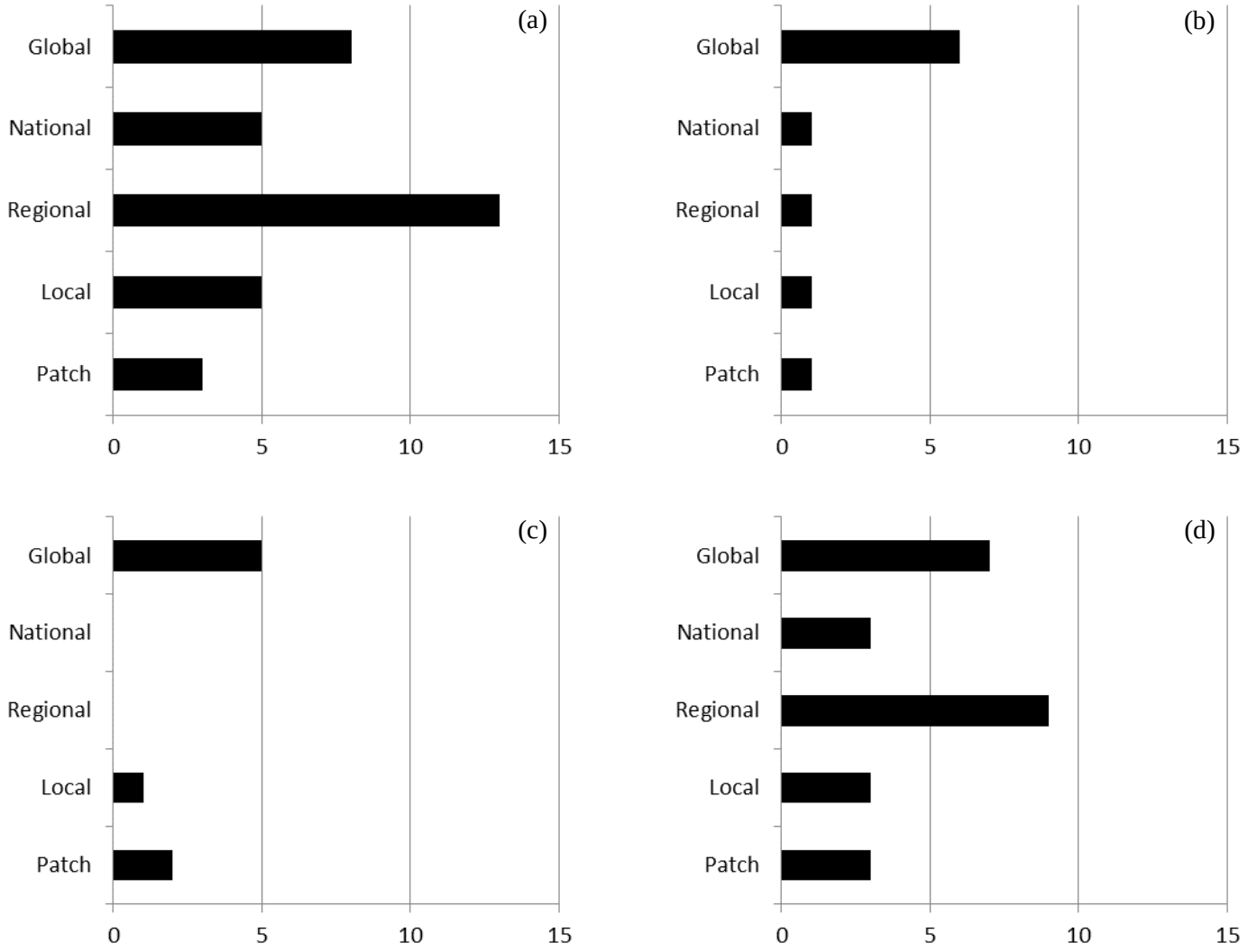


**Figure 4.** Spatial scales at which ESs have been mapped, for (a) regulating, (b) supporting, (c) cultural, and (d) provisioning ES (scales are the one provided in Table 1).

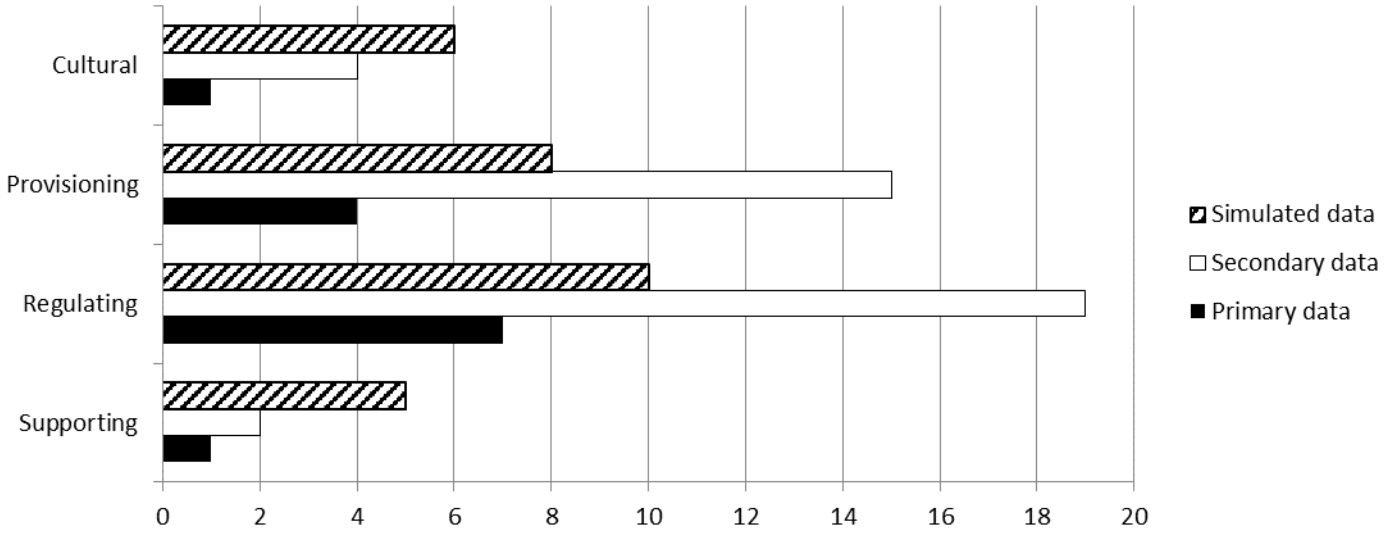


**Figure 5.** Type of data source of the entries used in the database for different types of ESs.

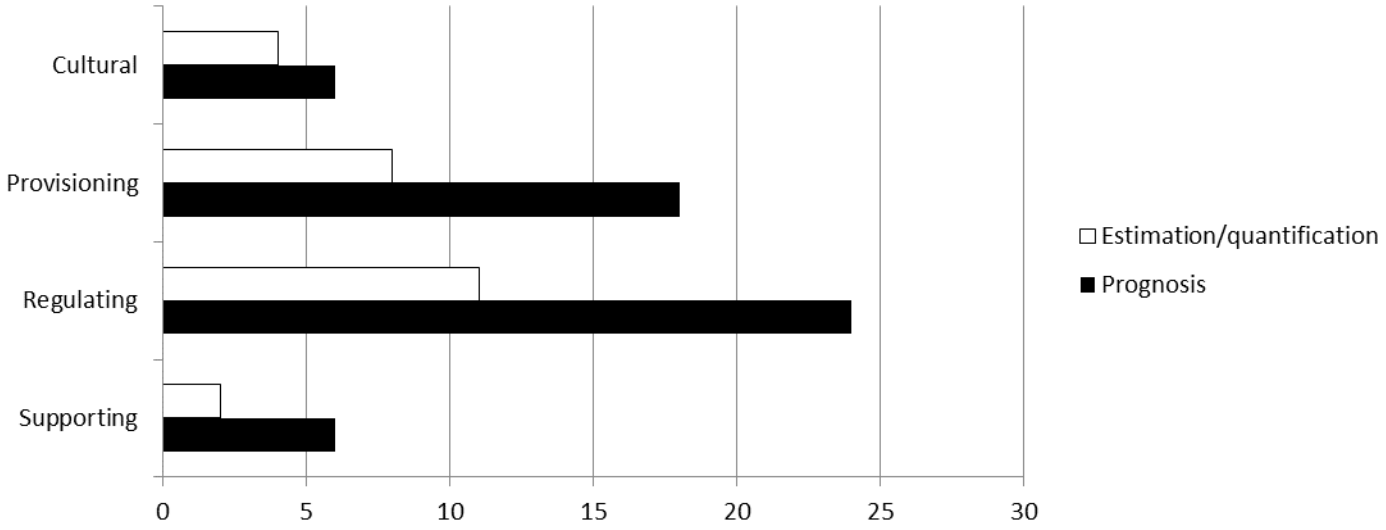


**Figure 6.** Number of studies that modeled ES.

## 4. ACKNOWLEDGEMENTS

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Appendix 1: List of scientific paper presenting modeling approaches of ESs.

| No. | Authors | Year | Ess modeled |
|---|---|---|---|
| 1. | Arbault et al. | 2014 | provisioning, cultural, supporting, regulating |
| 2. | Bagstad et al. | 2013 | provisioning, cultural, regulating |
| 3. | Bai et al. | 2013 | regulating |
| 4. | Balbi et al. | 2015 | provisioning, regulating |
| 5. | Bennet and Gosnell | 2015 | regulating |
| 6. | Boumans et al. | 2015 | regulating |
| 7. | Brady et al. | 2012 | provisioning |
| 8. | Brander et al. | 2007 | cultural |
| 9. | Chen et al. | 2012 | cultural |
| 10. | Connor et al. | 2015 | provisioning, regulating |
| 11. | Commelo et al. | 2014 | provisioning, regulating |
| 12. | Cordier et al. | 2014 | provisioning, cultural, supporting, regulating |
| 13. | Delphin et al. | 2013 | regulating |
| 14. | Ding and Nunes | 2014 | provisioning, cultural, regulating |
| 15. | Feng et al. | 2011 | regulating |
| 16. | Gebremariam et al. | 2014 | regulating |
| 17. | Grêt-Regamey et al. | 2008 | provisioning |
| 18. | Grêt-Regamey et al. | 2013 | regulating |
| 19. | Guerra et al. | 2014 | regulating |
| 20. | Guerry et al. | 2012 | provisioning, cultural, supporting, regulating |
| 21. | Guillem et al. | 2015 | provisioning |
| 22. | Harmáčková and Vačkár | 2015 | regulating |
| 23. | Hou et al. | 2014 | provisioning |
| 24. | Johnson et al. | 2012 | provisioning, cultural, supporting, regulating |
| 25. | Johnston et al. | 2011 | provisioning |
| 26. | Keller et al. | 2015 | provisioning, supporting, regulating |
| 27. | Koniak et al. | 2011 | provisioning, regulating |
| 28. | Larocque et al. | 2014 | provisioning, cultural, supporting, regulating |
| 29. | Lauf et al. | 2014 | provisioning, regulating |
| 30. | Locatelli et al. | 2011 | regulating |
| 31. | Martin-Ortega et al. | 2013 | payments |
| 32. | Meylan et al. | 2013 | regulating |
| 33. | McVittie et al. | 2015 | regulating |
| 34. | Moor et al. | 2015 | provisioning |
| 35. | Notter et al. | 2012 | provisioning |
| 36. | Nuppenau | 2014 | provisioning, cultural, supporting, regulating, payments |
| 37. | Petz et al. | 2014 | provisioning, regulating |
| 38. | Poppenborg and Koellner | 2014 | regulating |
| 39. | Sabatier et al. | 2013 | supporting |
| 40. | Schlüter et al. | 2009 | provisioning, regulating |
| 41. | Smajgl et al. | 2015 | provisioning, payments |
| 42. | Sun and Müller | 2013 | payments |
| 43. | Swetnam et al. | 2011 | regulating |
| 44. | Villa | 2009 | provisioning, regulating |
| 45. | Watanabe and Ortega | 2014 | provisioning, regulating |
| 46. | Zanchi et al. | 2014 | provisioning, regulating |