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Review

Remote sensing of ecosystem services: A systematic review

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ABSTRACT

Appropriate integration of remote sensing technologies into ecosystem services concepts and practices leads to potential practical benefits for the protection of biodiversity and the promotion of sustainable use of Earth's natural assets. The last decade has seen the rapid development of research efforts on the topic of ecosystem services, which has led to a significant increase in the number of scientific publications. This systematic review aims to identify, evaluate and synthesise the evidence provided in published peer reviewed studies framing their work in the context of spatially explicit remote sensing assessment and valuation of ecosystem services. Initially, a search through indexed scientific databases found 5920 papers making direct and/or indirect reference to the topic of "ecosystem services" between the years of 1960 and 2013. Among these papers, 211 make direct reference to the use of remote sensing. During the search we aimed at selecting papers that were peer-reviewed publications available through indexed bibliographic databases. For this reason, our literature search did not include books, grey literature, extended abstracts and presentations. We quantitatively present the growth of remote sensing applications in ecosystem services' research, reviewing the literature to produce a summary of the state of available and feasible remote sensing variables used in the assessment and valuation of ecosystem services. The results provide valuable information on how remotely sensed Earth observation data are used currently to produce spatially-explicit assessments and valuation of ecosystem services. Using examples from the literature we produce a concise summary of what has been done, what can be done and what can be improved upon in the future to integrate remote sensing into ecosystem services research. The reason for doing so is to motivate discussion about methodological challenges, solutions and to encourage an uptake of remote sensing technology and data where it has potential practical applications.

Contents

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1. Introduction

The last decade has seen the rapid development of research on the topic of ecosystem services and, increasing awareness of the economic value of ecosystem goods and services among decision-makers and the general public (Morgan et al., 2008; Fisher et al., 2009; de Groot et al., 2010; Fish, 2011; de Groot et al., 2012; Maes et al., 2012; Bagstad et al., 2013). Following the release of the Millennium Ecosystem Assessment in 2005, a significant increase in the number of scientific publications on the subject has been observed (Egoh et al., 2007; Skourtos et al., 2010; White et al., 2010; Costanza and Kubiszewski, 2012).

Preliminary work has made considerable advances in highlighting the links between social and environmental change influencing the capacity of ecosystems to maintain provisioning, regulating, supporting and cultural services (Costanza et al., 1997; Imhoff et al., 2004; de Groot, 2006; Reid et al., 2006; Deegan et al., 2012; Porras, 2012). Since then, spatially-explicit approaches have been used widely to map a multitude of ecosystems services, merging theory and practice to advance more effective sustainability and conservation actions (Sutton and Costanza, 2002; Costanza et al., 2008; Kienast et al., 2009; Liu et al., 2010; Murray et al., 2012; Alcaraz-Segura et al., 2013; Xie and Ng, 2013; Alamgir et al., 2014).

Remote sensing plays an important role in the study of complex environmental interactions between natural and social systems, and has been used widely to quantify and map ecosystem properties and functions and infer ecosystem processes through a combination of existing instruments and data (Chopra et al., 2001; Ustin et al., 2004; Chambers et al., 2007; Muraoka and Koizumi, 2009; Palacios-Orueta et al., 2012). A key advantage of remote sensing is the capability to perform synoptic, spatially continuous and frequent observations resulting in large data volumes and multiple datasets at varying spatial and temporal resolutions (Estreguil and Lambin, 1996; Stolle et al., 2004; Knaeps et al., 2010; Baraldi and Boschetti, 2012; Atzberger and Rembold, 2013; Lewis et al., 2013). With the emergence of new and more sophisticated products, Earth observation data will continue to contribute extensively to research on modelling, mapping and valuation of ecosystem goods and services (Nemani et al., 2009; Verburg et al., 2009; Marghany and Hashim, 2010; Zinnert et al., 2011; Cabello et al., 2012).

There have been numerous efforts to classify the services provided by ecosystems (Costanza et al., 1997; Daily, 1997; de Groot et al., 2002; MA, 2005), and more recent efforts on understanding the various contexts in which the ecosystem services concept has been used have the potential to move a step closer to the establishment of a meaningful and clear classification system. Nevertheless, there has not yet been agreement on a single classification scheme that provides a meaningful and consistent definition for ecosystem services, with different countries adopting different classification schemes, making assessment and valuation studies dependent on realities that are in many occasions site specific. (Faber, 2006; Boyd and Banzhaf, 2007; Wallace, 2007; Schmitt et al., 2013).

Remote sensing measures reflected radiation, and by making use of such measurements and a forward model of the interaction of light with the Earth's surface, it is possible to inversely estimate properties of the Earth's surface such as land cover type, biomass, and leaf area index for each image pixel. Such properties represent spatially varying states at particular points in time. However, other properties of interest (e.g., land use; the function of the land) can only be inversely and indirectly inferred and mapped through contextual relations across space.

Some ecosystem services, like primary production have a more direct relation with the reflected signal (e.g. satellite-derived chlorophyll measurements), while others, like climate regulation are only indirectly related to the reflected signal (e.g. satellite-derived land surface temperature). Many economically important services, such as production of raw materials and food provision cannot be valued and assessed sufficiently by remote sensing alone and it may, therefore, be necessary to couple spectral information with other available datasets (Fig. 1).

This paper provides a systematic review of the scientific literature related to the use of remotely sensed data within the explicit context of ecosystem services valuation assessment. We present examples from the literature that summarise (i) what has been done so far using remote sensing, (ii) what can be done in the future, and (iii) what can be further improved. For this purpose the selected literature was reviewed systematically, searching for specific information regarding the remote sensing platform used, remote sensing product used (e.g. land cover, biophysical indices, etc.) temporal coverage, and other relevant more technical aspects of remote sensing.

2. Methodology

2.1. Search and selection strategy

This review focused on papers that used ecosystem services concepts, and made use of Earth observation data to estimate value flows of past and current availability of provisioning, regulating, habitat/supporting and cultural services.

The approach taken to querying the literature consisted of a selective keyword search in specific scientific libraries (such as Scopus and Web of Knowledge). At each query, terms and keywords such as 'Ecosystem Services', 'Ecological Services', 'Environmental Service' 'Remote Sensing' and 'Earth Observation were used individually to produce an extensive list of articles. Using Scopus and Web of Knowledge the body of literature was searched based on a fixed set of inclusion criteria:

(i) The literature should address ecosystem services as either main or secondary subject.
(ii) The predefined keywords should exist as a whole in at least one of the fields: title, keywords or abstract.
(iii) The paper should be published in a scientific peer-reviewed journal.
(iv) The paper should be written in the English language.

Fig. 2 represents the literature search and selection process.

The initial steps of the search process in Fig. 2 returned 5920 published articles on the topic of ecosystem services alone. The search was subsequently refined by querying through the first set of results. Searching for predefined keywords and terms related to the