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A Global Vision for Monitoring Ecosystem Services with Satellite Sensors

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1.1 General Overview of Remote Sensing of Ecosystem Services

Ecosystem services can be defined as "an activity or function of an ecosystem that provides benefit (or occasionally detriment) to humans" (Mace et al. 2012; see also Burkhard et al. 2012; Crossman et al. 2012). Repeated efforts have been made to quantify, value, map, monitor, and analyze the various ecosystem service components that sustain human well-being: from the early attempts of Costanza et al. (1997) and the Millennium Ecosystem Assessment (MA 2005) to the more recent integrative initiatives of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES 2013) and the Global System for Monitoring

Ecosystem Service Change (Tallis et al. 2012; GEO BON ES 2013). The latter initiatives join more than 50 international organizations and 80 governmental representations under the auspices of the Group on Earth Observations in order to develop the Global Earth Observation System of Systems (GEOSS). Their aim is to compile extensive and standard monitoring of multiple services to allow policymakers and scientists to explore, better understand, and prioritize trade-offs across socioecological settings and scales (from the national to the global level). The Group on Earth Observations Biodiversity Observation Network (GEO BON) identified four main sources of data: national statistics, field-based observations, remote sensing, and numerical simulation models (Tallis et al. 2012). Of these, remote sensing offers the potential to use the same standard protocols from local to global scales and through time, which is essential for long-term monitoring and for trade-off assessment across regions. Satellite-based earth observation is probably the most economically feasible means to systematically retrieve global information with high temporal, spatial, and spectral resolution over large areas (Ayanu et al. 2012). Decline in the cost involved in obtaining such data and increase in the computational power of higher resolution sensors to cope with larger data sets will maximize this advantage (Kreuter et al. 2001).

Remote sensing of ecosystem services has been a fast-growing research field in recent years. On searching the Scopus database (http://www.scopus.com) for documents that contain the terms "remote sensing," "earth observation," and/or "ecosystem services" in the title, abstract, or keywords, we found a total of 270 documents (Table 1.1). This search revealed that this is a relatively young research field (the first article dates back to 2001) that has been growing fast recently (50% of the articles have been published in the past two-and-half years, 2011–present). It is interesting to note the relatively active role that Chinese research is playing in the explicit assessment of ecosystem services through remote sensing tools, with 50% of articles being contributed by them. Of the remaining publications, 25% correspond to U.S. affiliations and the rest are affiliated with various countries. From the first 15 institutions (those who published five or more documents in this field), only five of them were not from China (i.e., the University of Buenos Aires, the German Aerospace Center, the Virginia Polytechnic Institute and State University, and Columbia University in New York). The journals that attracted more articles (five or more) were *Remote Sensing of Environment* (impact factor [IF] 4.574), *Acta Ecologica Sinica*, *Chinese Journal of Ecology*, *Ecological Indicators* (IF 2.695), *Chinese Journal of Applied Ecology*, *Acta Geographica Sinica*, and *Agriculture Ecosystems and Environment* (IF 3.004).

Some recent works have already compiled and highlighted the many possibilities that remote sensing offers for ecosystem services mapping (e.g., Naidoo et al. 2008; Feld et al. 2010; Feng et al. 2010; Ayanu et al. 2012; Crossman et al. 2012; Martínez-Harms and Balvanera 2012; Tallis et al. 2012).

TABLE 1.1

Number of Publications Per Year, and Ranking of the Top Countries, Authors, and Journals Publishing Articles on Earth Observation of Ecosystem Services

Year	#	Country	#	Authors	#	Journal Title	#
2013	18	China	134	Wang, K.	5	*Acta Ecologica Sinica*	17
2012	53	U.S.	66	Paruelo, J.	4	*Remote Sensing of Environment*	11
2011	61	Germany	19	Kuenzer, C.	4	*Chinese Journal of Ecology*	9
2010	43	U.K.	15	Pan, Y.	4	*Chinese Journal of Applied Ecology*	6
2009	35	Australia	11	Gu, X.	4	*Ecological Indicators*	6
2008	17	Netherlands	8	Zhu, W.	4	*Acta Geographica Sinica*	6
2007	21	Argentina	7	DeFries, R.	3	*Agriculture Ecosystems and Environment*	5
2006	6	Spain	7	Chong, J.	3	*Applied Geography*	4
2005	5	Italy	7	He, H.	3	*International Journal of Applied Earth Observation and Geoinformation*	4
2004	2	India	6	Li, J.	3	*Environmental Earth Sciences*	4
2003	3	Canada	6	Shi, P.	3	*Ecological Economics*	4
2002	3	Finland	6	Zhang, C.	3	*Environmental Monitoring and Assessment*	4
2001	3	Switzerland	5	Gond, V.	2	*International Journal of Remote Sensing*	4
Total	270	France	5	Dech, S.	2	*Remote Sensing*	4

Note: Publications in Scopus, from January 1, 2001 to April 1, 2013, containing the terms "remote sensing," "earth observation," and/or "ecosystem services" in the title, abstract, or keywords. # = number of articles.

Nevertheless, there is still an urgent need to develop a standardized and consistent methodological approach, or even a blueprint, for mapping the stocks and flows and the supply and demand of a fuller suite of ecosystem services (Crossman et al. 2012; Martínez-Harms and Balvanera 2012; Palomo et al. 2012). During the past 12 years, remotely sensed information has been mainly used to estimate provisioning and regulating ecosystem services due to the biophysical dimension of their supply but has scarcely been used to retrieve cultural services due to the inherent socioeconomic characteristics of their demand. Satellite images have provided relevant information for the assessment of ecosystem services from a multidimensional perspective (see Chapter 20), from the "supply side" (what does nature supply?) to the "demand side" (what do humans demand?). Only a few works have used remote sensing tools as accompanying information for the assessment of the demand side of ecosystem services (e.g., Sutton and Costanza 2002; Scullion et al. 2011).

Up until now, the most frequent use of satellite images in the supply side has been in the production of land use/cover maps that are later utilized in models to simulate the delivery of ecosystem services and their changes through time and space (Kreuter et al. 2001; Konarska et al. 2002; Zhao et al. 2004; De-Yong et al. 2005; Wang et al. 2006, 2009; Li et al. 2007, 2011, 2012; Hu et al. 2008; Du et al. 2009; Huang et al. 2009, 2011; Liu et al. 2009, 2012; Feng et al. 2010; McNally et al. 2011; Burkhard et al. 2012; Estoque and Murayama 2012; Hao et al. 2012; Bian and Lu 2013; Duan et al. 2013; Verburg et al. 2013; Zhao and Tong 2013). The former attempts aim to map ecosystem services by linking ecosystem service values to the different land use/cover types present in image classification. Then, changes in the ecosystem services delivery are estimated from changes in land use/cover types. However, there are spatial variabilities within land cover types; the same land cover may offer different landscape functions and, therefore, the delivery of multiple ecosystem services (Verburg et al. 2009). For example, the grazing capacity of semiarid grasslands varies greatly between the northern and southern exposures and between dry and humid years. Likewise, the same cropland category (e.g., soybean plantations) may have very different ecosystem functioning and may provide different ecosystem services depending on the land management (e.g., tillage versus no tillage) (Jayawickreme et al. 2011; Viglizzo et al. 2011). This is one of the reasons that Verburg et al. (2009) give for using land function dynamics assessments (which are continuous) rather than land cover change characterizations in ecosystem service assessments (which are categorical). Similarly, Euliss et al. (2010) point out that a more holistic and integrative approach to monitoring ecosystem processes and related services is necessary. For example, Schneider et al. (2012) combined the retrieval of direct estimates of ecosystem services related to land surface albedo and energy balance dynamics, derived from time series of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite images, with other simulated ecosystem services, derived from running a model (the Agro-IBIS dynamic global vegetation model) on a land cover map (Kucharik 2003), covering the effects on the carbon and water cycles and on the energy balance. In general, all models used in ecosystem services modeling and mapping utilize spatially explicit information regarding land cover, climate variables, and topography. In addition, they may incorporate other biophysical variables, such as evapotranspiration (ET), that can be derived from remote sensing data. Currently, the most widespread ecosystem service models are InVEST, ARIES, and POLYSCAPE (for a review and further details, see Chapter 20).

Satellite images can also be used to directly quantify one or a set of particular ecosystem services, that is, without modeling them through their link to particular land cover types. The remote sensing literature has plenty of conceptual and empirical models that link the spectral information to critical biophysical variables and ecosystem processes such as primary production, biomass, surface temperature, albedo, ET, soil moisture, surface roughness, species richness, and others (Verstraete et al. 2000; Jensen 2007; Chuvieco 2008). These biophysical variables are tightly linked to ecosystem functions and their associated ecosystem services; hence, they have been widely used in ecosystem service mapping and assessments (Jin et al. 2009; Krishnaswamy et al. 2009; Malmstrom et al. 2009; Newton et al. 2009; Tenhunen et al. 2009; Feng et al. 2010; Lane and D'Amico 2010; Porfirio et al. 2010; Rocchini et al. 2010; Woodcock et al. 2010; McPherson et al. 2011; Turner et al. 2011; Caride et al. 2012; Frazier et al. 2012; Ivits et al. 2012; Martínez-Harms and Balvanera 2012; Politi et al. 2012; Shi et al. 2012; Tallis et al. 2012; Volante et al. 2012; Forsius et al. 2013; Oki et al. 2013).

1.2 Overview of Book Sections and Chapters

The remaining 19 chapters in this book are presented in five sections: carbon cycle, biodiversity, water cycle, energy balance, and other components in ecosystem services. Each section provides a review of conceptual and empirical methods, techniques, and case studies linking remotely sensed data to the biophysical variables and ecosystem functions associated with key ecosystem services. The book does not aim to exhaustively cover all ecosystem service categories; instead, it provides a global look into the most relevant approaches for estimating key ecosystem services from satellite data.

1.2.1 Ecosystem Services Related to the Carbon Cycle

Regional and global primary production has probably been one of the ecosystem processes most frequently studied through remote sensing techniques (for a review of estimates, see Ito 2011). Many studies have used direct estimates or surrogates of primary production in order to evaluate ecosystem services from the supply side (e.g., Malmstrom et al. 2009; Paruelo et al. 2011; Turner et al. 2011; Caride et al. 2012; Volante et al. 2012). In Chapter 2, Paruelo and Vallejos offer a review of the remote sensing theoretical bases and techniques used to estimate fluxes and stocks of the carbon cycle utilizing optical and active sensors. They present the conceptual connection between provision of ecosystem services and key processes of the carbon cycle with application to sustainable land use planning. Chapter 3 by Garbulsky, Filella, and Peñuelas and Chapter 6 by Castro et al. assess the current knowledge and the advances and challenges in remote sensing for the estimation of light use efficiency, the most difficult aspect of quantifying and modeling the service that regulates the carbon gains. In Chapter 4, Epstein covers all components of the carbon cycle that have been studied through remote sensing in the northern high latitudes—from carbon uptake and fire emissions to methane fluxes and soil microbe respiration. In Chapter 5, Irisarri et al. present a remote sensing approach to a monitoring system of forage production.

Finally, Shimabukuro et al., in Chapter 7, address the use of remote sensing data to estimate biomass burning emissions in tropical forests.

1.2.2 Ecosystem Services Related to Biodiversity

Biodiversity may play three different roles in ecosystem service assessments (Mace et al. 2012): Biodiversity can act as a regulator of underpinning ecosystem processes (e.g., primary producers or soil microbes that govern nutrient cycling), as a final ecosystem service (e.g., wild crops, livestock, or fisheries), or as a good in itself with intrinsic value (e.g., charismatic, flagship, or umbrella species). Several studies have taken advantage of remote sensing tools for ecosystem services assessment and biodiversity conservation (Naidoo et al. 2008; Krishnaswamy et al. 2009; Rocchini 2009; DeFries et al. 2010; Feld et al. 2010; Jones et al. 2010; Rocchini et al. 2010; Cabello et al. 2012; Alcaraz-Segura et al. 2013). In Chapter 8, Fernández offers a thorough review of studies that use remote sensing data to estimate the aspects that biodiversity covers in ecosystem service assessments: from surveying and modeling species distributions to their relationships with key ecosystem processes. Cabello et al. provide an original exercise on how remote sensing may help to assess the effectiveness of protected area networks in representing biodiversity and in providing services related to the carbon cycle in Chapter 9. Finally, in Chapter 10, Tormos et al. use high spatial resolution imagery and object-based image analysis to evaluate whether riparian vegetation enhances river ecosystem integrity and ecosystem services.

1.2.3 Ecosystem Services Related to the Water Cycle

Ecosystems provide many provisioning and regulating services related to the water cycle, namely freshwater provision and flood control. Many remote sensing products can be useful for estimating and modeling multiple components of the water cycle, from rainfall to snow cover, ET, runoff, or groundwater consumption. Chapter 11, by Carvalho-Santos et al., first offers a conceptualization of hydrological services and how they are linked to key elements of the water cycle. Then, these authors present a thorough review of the most relevant satellite sensors and hydrological models in order to evaluate and monitor those elements of the water cycle. Chapter 12, by Herrero et al., is centered on the important role that the assimilation of remote sensing information has for hydrological modeling and the subsequent estimation of hydrological ecosystem services. In Chapter 13, Contreras et al. propose a remote sensing approach in order to identify and quantify the reliance of ecosystems on water inputs beyond precipitation that includes both groundwater and surface water inputs. Finally, the chapters by Polo et al. (Chapter 14) and Bonet, Millares, and Herrero (Chapter 15) focus on reviewing and applying two key elements of the hydrological cycle—ET and snow cover, respectively.

1.2.4 Ecosystem Services Related to Energy Balance

Ecosystems influence climate through biogeochemical processes, by emitting/absorbing greenhouse gases and aerosols to/from the atmosphere, and through biophysical processes that rule the land surface energy balance as a function of albedo, latent heat, and sensible heat. In Chapter 16, Alcaraz-Segura et al. explain the ways in which the biophysical or energy balance component of climate regulation is estimated using ecosystem service assessments. In addition, these authors introduce an original remote sensing method in order to indirectly monitor key biophysical properties of ecosystems that are relevant for climate modeling based on ecosystem functional types. In Chapter 17, Di Bella and Beget address the estimation of land surface albedo, one of the main components of biogeophysical feedback. They also evaluate the effect that land use changes have on surface reflectance and on spectral albedo. In Chapter 18, Marchesini, Guerschman, and Sobrino discuss the latent heat component of ET, the different models used to estimate ET via remote sensing, and the energy balance equation employed to predict the partition between latent and sensible heat fluxes. In Chapter 19, Sobrino et al. address land surface temperature, a biophysical property related to the sensible heat fluxes in the energy balance. They use the temperature and emissivity separation algorithm to evaluate the urban heat-island effect and to determine the best spatial resolution and overpass time to properly monitor this phenomenon from remote sensing platforms.

1.2.5 Other Dimensions of Ecosystem Services

As noted earlier, there is a need to develop a standardized and interdisciplinary framework, or even a blueprint, for mapping the stocks and flows, and the supply and demand of ecosystem services (Crossman et al. 2012; Martínez-Harms and Balvanera 2012). In Chapter 20, Castro et al. present a review of existing methodologies for assessing ecosystem services from the supply to the demand side, considering their multidimensional nature (i.e., biophysical, sociocultural, and economic), and highlighting where remote sensing tools may help to advance in an interdisciplinary comprehension of services assessment.

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Section II

Ecosystem Services Related to the Carbon Cycle