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Analysis

Global Estimates of Ecosystem Service Value and Change: Taking Into Account Uncertainties in Satellite-based Land Cover Data

Xiao-Peng Song

Department of Geographical Sciences, University of Maryland, College Park, MD, USA

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ABSTRACT

Global estimates of ecosystem service value (ESV) and change are often produced using satellite-based land cover maps. However, uncertainties in global land cover data and their impacts on ESV estimation have not been fully recognized. Considerably inflated estimates of land cover change and ESV change could be derived using a direct map comparison approach when classification uncertainties are not explicitly taken into account. This study collected all available global land cover datasets and applied an ensemble approach to derive the range and central tendency of terrestrial ESV estimates. Different input data caused ESV estimate varying between 35.0 and 56.5 trillion Int$/year. Wetland classes, albeit having the highest per unit value, were the most uncertain classes mapped using satellite data. To reduce uncertainty, a spatial data harmonization procedure was developed, which resulted in an improved ESV estimate at 49.4 trillion Int$/year. The study further illustrated the quantification of changes in forest ESV using a high-resolution global forest cover change dataset. An ESV loss of 716.0 billion Int$/year was estimated between 2000 and 2012—a result representing one fifth of previous estimates. These findings highlighted the importance of improving the characterization and monitoring of land cover for global ESV and change estimation.

1. Introduction

The world's ecosystems provide a range of essential goods and services to human beings, yet they are facing increasing pressure from human population growth, economic development, and growing demand for natural resources. With advanced tools and technology, unsustainable development practices can deplete natural ecosystems in an unprecedented pace, many of which through land use change activities (Foley et al., 2005). The fundamental rational of human-induced land use change is to seek the economic profit of converting natural land to human uses, while natural ecosystems are often perceived as ‘unproductive’ land. However, many goods and services provided by ecosystems are positive externalities that are not priced in the market (Daily et al., 2000; Kinzig et al., 2011). For example, the Amazonian rainforests are being transformed to agricultural frontiers for food production (Gibbs et al., 2010). However, forests not only directly provide food, fiber and fuel to local people, they are also regulating climate through carbon sequestration and supporting terrestrial biodiversity—benefits shared by everyone on the planet but are not fully recognized in either commercial market or public or private institutions.

Valuation of ecosystem services could be used to address the tradeoffs in land-use decisions by putting cost and benefit on the same scale (Goldstein et al., 2012). Translating ecosystem services to monetary value is not equal to privatization or commodification of public goods but rather represents a means of raising public awareness of natural resource scarcity and to inform policy making (Costanza et al., 2014). Indeed, valuation of ecosystem services has been widely accepted and natural capital accounting has started to shape national policies (Guerry et al., 2015; Ouyang et al., 2016; Pagiola, 2008). The research field has also enjoyed productive development in the past decades with many valuation approaches developed, including direct market valuation, revealed preference, stated preference and benefit transfer (TEEB, 2010). Although conceptually simple, benefit transfer is widely used for ESV estimation, especially over large geographic regions (Plummer, 2009).

Remotely sensed data is a main data source in ecosystem service research and land cover is the most widely used remote sensing variable for ecosystem service valuation (de Araujo Barbosa et al., 2015; Schägner et al., 2013). The areal extent of a land cover type is often combined with per unit ecosystem service value (ESV) to estimate ESV over a geographic region via benefit transfer. The spatially explicit nature of land cover data is useful for visualization and for prioritizing conservation efforts (Naidoo et al., 2008; Troy and Wilson, 2006). Moreover, high-spatial resolution land cover maps can be aggregated to derive ESV estimates at various scales, from local, regional to global. At the global scale, Costanza et al. (1997) estimated for the first time the value of the earth's ecosystems using a 1° × 1° spatial resolution

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E-mail address: xpsong@umd.edu.

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(~111-km × 111-km at the Equator) land cover map (Matthews, 1983). Li and Fang (2014) refined the global estimate using GlobCover, a satellite-based land cover map at 300-m × 300-m resolution (Bicheron et al., 2008). As an result of the new land cover data and an updated database of per unit ESV (de Groot et al., 2012), global flow of terrestrial ESV was revised up from US$ 17.0 trillion/year (Costanza et al., 1997) to US$37.2 trillion/year (Li and Fang, 2014), both in 2007 Int$/year.

Changes in ESV can also be estimated when land cover and land use change (LCLUC) is characterized using multi-temporal satellite observations or simulated using land use change models (Tallis and Polasky, 2011). Many studies have been conducted to estimate ESV change at local or regional scales (e.g. Kreuter et al., 2001; Metzger et al., 2006; Polasky et al., 2010; Wang et al., 2014; Yi et al., 2017; Zhao et al., 2004). Global-scale ESV change estimates are relatively rare due in part to the lack of reliable LCLUC dataset. Nevertheless, Costanza et al. (2014) recently estimated global ESV change between 1997 and 2011 as a result of land use change, which was derived by calculating the areal difference between the (Matthews, 1983) map and GlobCover. Acknowledging uncertainty, an ESV loss of $4.3–20.2 tillion/year was reported (Costanza et al., 2014).

Uncertainty refers to the lack of knowledge of the true value of a variable that can be described as a probability density function characterizing the range and likelihood of possible values (IPCC, 2006). Error refers to the difference between the true value of a variable and measured observations or estimates, which consists of two components: systematic error (lack of accuracy) and random error (lack of precision) (IPCC, 2006). Estimating uncertainties is highlighted as one of the principles of getting the science right for monitoring ecosystem services (Naeem et al., 2015). Transfer errors from the study site to the policy site is a well-recognized limitation of using benefit transfer in ESV estimation (Johnston and Rosenberger, 2010; Plummer, 2009; Richardson et al., 2015; TEEB, 2010). Another important source of error, when scaling up ESV estimation from local case study site to a larger geographic region, stems from the input land cover dataset. Benítez et al. (2007) showed that up to 45% difference in carbon supply from afforestation and reforestation activities could be attributed to discrepancy in different land cover maps. Schulp and Alkemade (2011) evaluated pollination efficiency in the Netherland using five different land cover maps and concluded that spatial resolution was a key factor affecting result uncertainty. Dong et al. (2015) simulated ecosystem service supply in Australia's agricultural land and found that errors in initial land use mapping could propagate through model and result in uncertainty at different scales. Using global and U.S. wetland as an example, Foody (2015) showed that area adjustment using confusion matrix could result in 30% difference in global wetland ESV estimate and 86% in the U.S., arguing for the value of conducting rigorous land cover validation.

Uncertainties of ESV estimates may be particularly pronounced at the global level. Since classification errors of different land cover classes are often not equally distributed (Strahler et al., 2006), the relative classification errors across different biomes and their impacts on global ESV estimation remain unknown. Moreover, research in the remote sensing literature have shown that the accuracy of land cover maps can exhibit large spatial variation at the local scale even on overall accurate maps (Foody, 2005; Song et al., 2017; Steele et al., 1998). Such spatial variation inevitably introduces uncertainty when land cover maps are translated to ESV maps. Significant knowledge gap also exists in estimating global ESV change as a result of LCLUC. Land cover change can be considerably overestimated due to error propagation when it is quantified using independent land cover data through a post-classification comparison approach (Lu et al., 2004; Sexton et al., 2015; Singh, 1989). Instead, changes in land cover should be characterized using specialized approaches, requiring high consistency in land cover definition, satellite data source and classification procedure (Song et al., 2014b; Song et al., 2016). For example, the annualized difference of global forest area between the year 2000 land cover map GLC2000 (Bartholomé and Belward, 2005) and the year 2006 map GlobCover is 126 million ha/year, 10 times larger than the 12 million ha/year net global forest cover change quantified by Hansen et al. (2013) using time-series Landsat images. This high-quality, 30-m resolution global forest cover change dataset provides an opportunity to reliably quantify changes in the value of global forest ecosystems. In addition, with the proliferation of global land cover products, recent research in the remote sensing field has demonstrated that land cover characterization could be improved by integrating different datasets (Fritz et al., 2011; Jung et al., 2006; Schepaschenko et al., 2015; Song et al., 2014a). Thus, an improved ESV estimate may also be derived.

The objectives of this paper are, progressively: 1) to analyze the uncertainties in global land cover area estimates and quantify their impacts on terrestrial ESV estimation; 2) to develop a procedure to harmonize multiple global land cover datasets to improve terrestrial ESV estimation; and 3) to estimate global forest ESV change using the 30-m resolution forest cover change product (Hansen et al., 2013). Lessons learnt from this forest example may be applied to other biomes as reliable land cover change datasets become available in the future.

2. Materials and Methods

2.1. Global Satellite-based Land Cover Datasets

Research on characterizing global land cover using remotely sensed data has been conducted since the mid-1990s. The first map was produced at 1° × 1° spatial resolution using data collected by National Oceanic and Atmospheric Administration (NOAA)'s Advanced Very High Resolution Radiometer (AVHRR) (Defries and Townshend, 1994). This map was subsequently updated to 8-km × 8-km resolution (DeFries et al., 1998) and 1-km × 1-km resolution (Hansen et al., 2000). In the 2000s, many global maps were developed using different satellite data and methodologies at various spatial resolutions (250-m to 1-km), including Global Land Cover Characterization (GLCC) (Loveland et al., 2000), the University of Maryland land cover (UMD LC) (Hansen et al., 2000), Global Land Cover 2000 (GLC2000) (Bartholomé and Belward, 2005), the Moderate Resolution Imaging Spectroradiometer land cover (MODIS LC) (Friedl et al., 2002), the MODIS Vegetation Continuous Fields (MODIS VCF) (Hansen et al., 2003) and GlobCover (Bicheron et al., 2008) (Table 1). Global-scale land cover mapping at moderate-to-high resolution (e.g. 30-m) has only become feasible in recent years, owing much to the United States Geological Survey (USGS)'s open Landsat data policy and the reduced cost of data storage and computation (Townshend et al., 2012; Wulder et al., 2012). So far, two 30-m × 30-m global tree-cover maps have been produced (Hansen et al., 2013; Sexton et al., 2013) and two 30-m × 30-m global land cover maps have been produced (Chen et al., 2014; Gong et al., 2013) (Table 1).

The proliferation of global land cover datasets provides users rich alternatives yet simultaneously creates confusions as to which dataset to choose in their specific application. The overall classification accuracy of a map is often users' primary concern (Congalton and Green, 2008; Foody, 2002). For instance, GLC2000 has an overall accuracy of 68.6% (Mayaux et al., 2006) and GlobCover has an overall accuracy of 67.1% (Bicheron et al., 2008). However, many datasets have simply not been validated. More importantly, the overall accuracy does not reflect the complex error structure of classification maps as errors in land cover classification are not evenly distributed across thematic classes as well as across regions (Foody, 2005; Song et al., 2017; Steele et al., 1998; Strahler et al., 2006). Deriving per-class accuracy with a probability-based validation sample (Olofsson et al., 2012; Stehman et al., 2012) has considerable value for ESV estimation (Foody, 2015). This much needed information is, however, rarely available for global datasets. Following earlier studies (Fritz et al., 2011; Jung et al., 2006; Schepaschenko et al., 2015; Song et