Landscape and Urban Planning 175 (2018) 11–22

Contents lists available at ScienceDirect

Landscape and Urban Planning

journal homepage: www.elsevier.com/locate/landurbplan

Research Paper

Assessing the sensitivity of urban ecosystem service maps to input spatial data resolution and method choice

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ARTICLE INFO

Keywords:
Ecosystem services
Mapping
Accuracy
Validation
Carbon storage
Urban forest

ABSTRACT

Ecosystem service (ES) mapping frequently uses secondary data and value-transfer methods to map services over broad extents at coarse resolutions, possibly causing poor prediction accuracy. Although ES map quality has received some recent attention in the literature, little is known about the accuracy of these maps in urban contexts or about the factors that influence this accuracy. To address this issue, we quantitatively compared and validated ES maps in a heterogeneous urban landscape to generate insight into ES map accuracy in these environments. Using aboveground biomass carbon storage as an example, we examined how input data resolution and assessment method affect the accuracy of urban ES maps. Two mapping methods were employed: (1) maps based on ecosystem components involved in carbon storage (trees and lawns) and (2) maps based on land-cover proxies and data at coarse and fine spatial resolutions. We compared carbon storage predicted by these methods to that estimated by using field-collected data to examine the accuracy of predictions and spatial variation therein. Different methods and data produced similar study area-wide estimates; however, the spatial distribution of estimates varied among methods. Estimates using ecosystem components agreed with the actual observations better than the proxy-based estimates, although map accuracy was improved by using higher resolution land-cover data. Thus, when study area-wide estimates suffice for decision making, proxy-based methods and coarse-resolution data should provide adequate assessments. Detailed ecosystem structure and composition data are needed when fine-resolution, spatially-explicit estimates are required.

1. Introduction

The ecosystem services (ES) concept phrases environmental quality in terms that can be readily incorporated into decision making, thus offering a solution to the issue of environmental externalities (Burkhard, Crossman, Nedkov, Petz, & Alkemade, 2013; Maes, Paracchini, Zulian, Dunbar, & Alkemade, 2012). This concept is difficult to operationalize, however, partially due to challenges in spatially identifying and measuring ES and in predicting the impacts of decisions upon them (Daily et al., 2009). ES mapping, the process of assessing the spatial-temporal distribution of ES by making the contribution of specific landscape locations to human well-being clear, offers a means for better-operationalizing this concept (Hauck et al., 2013). ES maps are useful tools for supporting policy making in such fields as environmental accounting (Boyd & Banzhaf, 2007), biological conservation (Chan, Shaw, Cameron, Underwood, & Daily, 2006), urban and landscape planning (Andersson et al., 2015), and sustainable development (Derkzen, Teeffelen, & Verburg, 2015). Because ES supply and demand result from interactions in complex, poorly-understood social-ecological systems, however, these maps are inherently laden with high and often unassessed uncertainty (Grêt-Regamey, Brunner, Altwegg, & Bebi, 2013).

Quality issues may arise in ES maps for reasons including reliance on secondary proxy data, coverage of broad extents at coarse spatial resolutions, and lack of legitimate verification and independent validation (Hou, Burkhard, & Müller, 2013; Martínez-Harms & Balvanera, 2012; Ochoa & Urbina-Cardona, 2017; Pagella & Sinclair, 2014; Schägner, Brander, Maes, & Hartje, 2013; Seppelt, Dormann, Eppink, Lautenbach, & Schmidt, 2011). The choice of ES mapping method (see Maes et al., 2012; Schägner et al., 2013 for a full review of methods) typically represents a trade-off between the cost in time and effort associated with data acquisition and the desired level of detail and has implications for output map accuracy. Primary ES data are rarely available, causing over half of mapping studies employ secondary land-use and land-cover (LUC) proxies and global statistics at regional (over 1000 km^2, but less than continental scale) to continental scales (Eigenbrod et al., 2010b), often as the sole ES surrogate (Martínez-Harms & Balvanera, 2012). Some assessments use surrogates as single

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https://doi.org/10.1016/j.landurbplan.2018.03.007
Received 22 February 2017; Received in revised form 10 March 2018; Accepted 11 March 2018

or predominant causal factors in production functions to model ES supply (Nelson et al., 2009; Tallis & Polasky, 2009) or as base maps from which localized, context-specific primary ES data are extrapolated to broader extents (Burkhard, Kandziora, Hou, & Müller, 2014; Costanza et al., 2014). Given their coarse resolution and reliance on generalized relationships, ES maps based on such proxies may be less accurate than maps based on more data-intensive spatial models (Schröter, Remme, Sumarga, Barton, & Hein, 2014), although this result may vary with the heterogeneity of ES distribution in a landscape.

ES maps are rarely validated or assessed for accuracy due to a lack of primary data (Eigenbrod et al., 2010b), particularly in ES studies over small extents (10–1000 km^2) (Kremer et al., 2016; Zulian, Maes, & Paracchini, 2013). This issue has only recently received attention in the literature (Burkhard & Maes, 2017; Kandziora, Burkhard, & Müller, 2013; Schägner et al., 2013; Willemen, Burkhard, Crossman, Drakou, & Palomo, 2015) with studies indicating poor correspondence between LUC proxy-based estimates and primary data, likely due to variation in ES delivery within a single LUC type, sampling bias and extrapolation effects (Eigenbrod et al., 2010a, 2010b). Studies of ES map sensitivity indicate that the utility of coarse LUC data for ES mapping is limited to relatively homogeneous landscapes and that reliance on finer resolution LUC data may alter estimated ES values (Kandziora et al., 2013; Konarska, Sutton, & Castellon, 2002; Redhead et al., 2018; Rendenieks, Tērauds, Nikodemus, & Brūmelis, 2017; Schulp & Alkemade, 2011; Schulp, Burkhard, Maes, Van Vliet, & Verburg, 2014). Additional studies of the impact of LUC measurement error on ES maps suggest that misclassification bias in LUC maps propagates to ES maps and that error increases as assessment resolution moves from national to global scales (Dong, Bryan, Connor, Nolan, & Gao, 2015; Foody, 2015; Sun, Congalton, Grybas, & Pan, 2017). While these studies shed light on ES map quality at broad scales, we know less about finer-scale map accuracy.

Urban ES mapping presents a special case given the high, fine-resolution spatial heterogeneity of these settings that could lead to high mapping error. Most urban ES maps rely on readily-available LUC datasets that lack the spatial and thematic detail needed to capture the fine-scale landscape components supporting ES provision (Derkzen et al., 2015; Gaston, Ávila-Jiménez, & Edmondson, 2013; Kremer et al., 2016). LUC proxies are widely used to perform assessments of single (Gittleman, Farmer, Kremer, & McPhearson, 2017) and multiple (Stoll et al., 2015) urban ES and in ES bundle analysis (Baró, Gómez-Baggethun, & Haase, 2017). Few urban studies using LUC proxies address the dynamics of land-use intensity in urban areas (Haase et al., 2014). Recent studies introduced novel urban landscape classifications to capture more detailed aspects of the relationship between LUC and urban ES (Haase et al., 2014; Kain, Larondelle, Haase, & Kaczorowska, 2016; Larondelle, Hamstead, Kremer, Haase, & McPhearson, 2014; Van der Biest et al., 2015), but such studies remain rare and systematic model validation against primary data is uncommon (Roussel, Schulp, Verburg, & van Teeffelen, 2017; Van der Biest et al., 2015). This creates a gap in our understanding of the biases and precision of urban ES maps and of the impacts of different methods and input data resolution on map quality. Because ES maps are used in assessing and setting real-world policy in urban environments, it is critical that we better understand their accuracy and utility.

Carbon storage by vegetation, a regulating ES whereby ecosystems remove and store anthropogenic CO_2, exemplifies an ES that municipalities map to support planning and policy making, often with little to no attempt at validation or accuracy assessment. Trees and other vegetation can store substantial amounts of carbon (Strohbach & Haase, 2012) and are often incorporated into policies aimed at achieving municipal carbon reduction goals. Three major methods are used to estimate carbon storage services provided by trees. The first two methods focus on ecosystem composition and structure. *Allometric models* use empirically-established relationships among vegetation configuration, biomass and carbon storage (e.g., via the i-Tree model, http://www.itreetools.org) to provide high-accuracy estimates of local carbon storage across stands, but require extensive time and labor to obtain forest measurements in the field. Consequently, these models cannot be applied where such information is lacking or difficult to collect. *Process-based models* (e.g., 3-PG, CENTURY) consider the dynamics and temporal patterns of carbon storage by simulating flows among carbon pools via photosynthesis, respiration and decomposition beyond the temporal scale of allometric models (Miehle et al., 2009). These models function well in natural settings, but may not reliably estimate carbon storage in urban environments where human disturbance alters ecological processes and strong spatial heterogeneity in carbon storage occurs.

The third model type identifies carbon storage via proxies, typically LUC, based on expert knowledge, causal relationships and production functions using both primary and secondary data. For example, both Artificial Intelligence for Ecosystem Services (ARIES) (Villa & Ceroni, 2009) and the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) set of models (Sharp et al., 2016) rely on LUC to identify carbon storage. InVEST's Carbon Storage and Sequestration Model uses a value-transfer approach, estimating landscape-level carbon storage based on mean carbon storage potential per unit area by LUC type and carbon pool. These values are multiplied by the total area of each LUC type to identify net carbon storage, representing an easily-implemented means for estimating regional or local carbon storage, but with potentially low accuracy in heterogeneous urban environments. For example, tree cover and associated carbon storage vary substantially across small extents within a LUC class based on property-owner preferences related to removal or planting of trees of different species. Inaccurate estimates of carbon storage may result when mean storage values are applied across cities, treating these heterogeneous areas as homogeneous.

This study seeks to explicitly identify the degree to which ES map accuracy is reduced when LUC proxies, rather than ecosystem component-based approaches, are used in assessing ES in heterogeneous urban environment. To this end, we focus on answering the following research questions:

1. Do ecosystem component-based approaches more accurately estimate aboveground biomass carbon storage at the local scale than LUC proxy-based models?
2. How does LUC proxy-based carbon storage map accuracy vary with the spatial resolution of input land-cover data?

We hypothesize that ecosystem component-based approaches will better approximate actual carbon storage compared to LUC proxy-based models and that finer-resolution LUC data will improve the accuracy of LUC proxy-based estimates. Following a case study approach, we quantitatively examine error in aboveground biomass carbon storage maps produced using different approaches and data resolutions in a heterogeneous urban landscape (Iowa City, Iowa, USA). We map carbon storage using two methods that differ in their input data, modeling approach and spatial scale and compare and validate resulting maps. Through these assessments, we provide insight into the accuracy of urban ES maps and its relationship to modeling methodology and the resolution and type of input data used in their production. This insight will inform the identification of appropriate spatial scales, datasets, and techniques for constructing ES maps for assessing and managing urban ES.

2. Methods

2.1. Study area description

This study focuses on Iowa City, Iowa, in the Midwestern US (Fig. 1). Iowa City is representative of small American cities in its extent (65.47 km^2), population (73,415 in 2014) and spatially-heterogeneous urban forest (Fig. A.1). Iowa City seeks to implement policies and