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Methodological and Ideological Options

Mapping Watershed-Level Ecosystem Service Bundles in the Pearl River Delta, China

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ABSTRACT

Managing multiple ecosystem services (ES) is a pressing field in sustainability research. ES bundles (ESBs), which closely link ES trade-offs and synergies, provide a comprehensive approach to exploring the relationship between natural ecosystems and human well-being. In this study, we quantified eight ES in terms of provisioning, regulating and cultural services using geographical data and other available information (both ecological and social) in the Pearl River Delta, China. We identified ESBs based on K-means clustering and redundancy analysis. The results showed that spatial patterns of each ES were quite heterogeneous at watershed level. Provisioning services were mainly distributed in watersheds with high proportion of cultivated land and waterbody. Remote forest areas provided high regulating services. Moreover, densely populated urban areas provide high cultural services. Five ESBs were detected ranging from 2941 to 16,249 km^2. According to the Pearson correlations and the Root Mean Squared Error (RMSE), we detected the trade-offs between provisioning and cultural services, and between regulating and cultural services, and synergies happened within regulating services. Intensive land-use and management in urban areas contributed to ES trade-offs. These results provide deeper understanding of the relationship between ES and land-use type at watershed level and detailed guidelines for ecosystem management.

1. Introduction

Ecosystem services (ES) are broadly defined as the benefits obtained directly or indirectly by humans from ecosystems, and are often distinguished as provisioning, regulating, cultural, and supporting services (MA, 2005). These services link the earth's ecosystem with human society (Perrings et al., 2011) and provide fundamental life-support for human civilization (Costanza et al., 1997; Daily, 1997). ES is an excellent way to understand human well-being and regional sustainable development, and can also be viewed as an important part of land use planning and ecosystem management (Daily et al., 2009). Considering the complexity and interactions of ES for the human society, understanding the relationship among multiple ES are essential for meeting urban residents' increasing demands from natural ecosystems (Qiu and Turner, 2013). ES research has been increasing exponentially over the past decades from single ES to multiple ones. In the first stage of ES research, ecologists and economists largely focused on the biophysical units, and valuated the provisioning (e.g. food, wood and fresh water) and regulating services (e.g. flood regulation, nutrient regulation) in monetary terms (de Groot et al., 2002; Luck et al., 2009; Ojea et al., 2012). As natural ecosystems have been transforming into semi-natural and semi-artificial ecosystems and artificial ecosystems during the process of urbanization, the multiple ES provided in urban regions has been highlighted (Barthel et al., 2010). A growing number of studies have conducted empirical assessments of multiple ES and their interactions (Klain et al., 2014), especially taking social and cultural services into account (Daniel et al., 2012). A win–win solution between ecosystems and society is a goal of sustainable development. Relevant authorities need to ensure a beneficial condition between ecosystems and services in the process of urban planning and management (Su et al., 2014). Evidence suggests that when multiple ES are considered in policy- and decision-making, optimal outcomes of land-use management are more efficient (Fisher et al., 2009).

Managing multiple ES, especially addressing trade-offs and synergies between services, is among the most pressing concerns within the field of sustainability research (Bennett et al., 2009; Carpenter et al., 2009). Trade-offs are defined as the situations in which one service increases while another service decreases, and synergies arise when multiple services are enhanced simultaneously (Qiu and Turner, 2013). Recognizing trade-offs and synergies among multiple ES (Power, 2010),

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identifying the influences of trade-offs on human welfare, and maximizing the benefits of multiple ES have been encouraged by researchers and different stakeholder groups (Li et al., 2015). Based on an analysis of multiple nonlinear relationships among ES, knowledge of the resulting trade-off characteristics, formation mechanism and spatiotemporal patterns in different scales could help authorities make scientific strategies under a regional sustainable development framework (Rodriguez et al., 2006; Zheng et al., 2013). Moreover, due to the large amount of ES demanded by humans, the global ecosystem is simultaneously degrading (Kuemmerle et al., 2013). By confronting the global challenges facing ecosystems and the environment, trade-off analysis of multiple ES can help identify the balance between costs and benefits to promote the diverse ES required to satisfy human needs. Thus, land-use management associated with trade-offs of ES should consider both meeting human requirements and maintaining ES provisions in the long-term.

Social-ecological complexity requires new empirically based research in trade-offs of multiple ES (Daily and Matson, 2008), and Ecosystem services bundles (ESBs) offer a new way to understand the relationships between multiple ES (Yao et al., 2016; Baro et al., 2017). ESBs are defined as a mix of positively correlated ES provided together (Renard et al., 2015), and they are sets of ES that repeatedly appear together across space or time (Raudsepp-Hearne et al., 2010). These groups of services link closely with ES trade-offs and synergies, and provide a comprehensive view of the links between natural ecosystems and human well-being (Renard et al., 2015). Quantification of spatial bundles could capture how specific ES are linked with human dominant land use and associated ES (Dick et al., 2011). The quantification of spatial ESBs is usually based on cluster analysis. However, bundles of services partitioned by cluster analysis varied due to the diversity of the ES provided, and are always dominated by one or a few ES, which makes it easier to ecosystem management for policy-makers (Renard et al., 2015). Dittrich et al. (2017) used the method of self-organizing maps (SOM) to define and map eight types of ESBs, and found that ESBs linked to underlying socio-environmental conditions. Queiroz et al. (2015) examined the existence of ESBs across the Norrström drainage basin in the Stockholm region using correlation and K-means clustering analyses. Raudsepp-Hearne et al. (2010) identified patterns of interactions among 12 ES through the analysis of ESBs in Quebec, Canada using principal component analysis and clustering analysis, and found the trade-offs between provisioning and regulating ES. Shoyama and Yamagata (2016) used a public participation geographic information system (GIS) tool to detect ESBs in the Kushiro watershed, suggesting that public participation could identify ESBs differences among stakeholders. Clements and Cumming (2017) identified 4 cultural ESBs and showed that the private protected areas' management strategy would reflect the cultural ES preferences.

Ecosystem services modelling tools allow the quantification, spatial mapping, and monetary valuation of ES. GIS-based spatial mapping analyses are increasingly applied in ES trade-off research because they offer detailed visual information (Kirchner et al., 2015). The Integrated Valuation of ES and Trade-offs (InVEST) model was designed and frequently applied to inform land-use management decisions and planning (Nelson et al., 2009). Redhead et al. (2016) validated the InVEST water yield model in 22 UK catchments. Goldstein et al. (2012) revealed the trade-offs between carbon storage and water quality under different land use scenarios. Moreover, among the clustering methods, K-means clustering analysis has been proved to perform well in identifying ESBs clusters (Hamann et al., 2015). Several studies have focused on the spatial approaches to detecting the ES bundles at municipality scale (Queiroz et al., 2015) or grid scale (Turner et al., 2014). Some researches have tried to map the ES bundles under the social–ecological framework (Hamann et al., 2015). However, for densely populated and economically developed urbanized areas, in-depth assessments of ES bundles at watershed scale (which could better reflect biophysical characteristics than other scales) are still scarce.

In this study, we chose the most rapidly urbanizing areas, the Pearl River Delta (PRD) in China as the case study area, which was a typical urban agglomeration. We divided the regions into small watersheds and took the watersheds as compound ecosystems. This was because as a coupling social-economic-natural ecosystem, watershed was an excellent spatial unit to explain some social, economic and natural phenomena, with both natural and social attributes (Simonit and Perrings, 2013). We chose eight ES for bundle analysis, which could be classified into provisioning, regulating and cultural services as MA categories. We did not distinguish the category of supporting services, because supporting services represented the ecological processes that underlie the functioning of an ecosystem, with influence on human society indirectly, and they were difficult to be quantified and could be represented by the other three kinds of ES (Hein et al., 2006). We combined geographic data and other available information at watershed scale, and then identified ESBs using K-means clustering and redundancy analysis (RDA). The study had four main goals as follows: (a) to assess spatial patterns of multiple ES at watershed level, (b) to characterize the interactions between each pair of individual services, (c) to detect ESBs and identify the main characteristics of each bundle, and (d) to discuss the influencing factors of trade-offs between each pair of services.

2. Materials and Methods

2.1. Study Area and Data Sources

The Pearl River Delta region is located in the southeast of

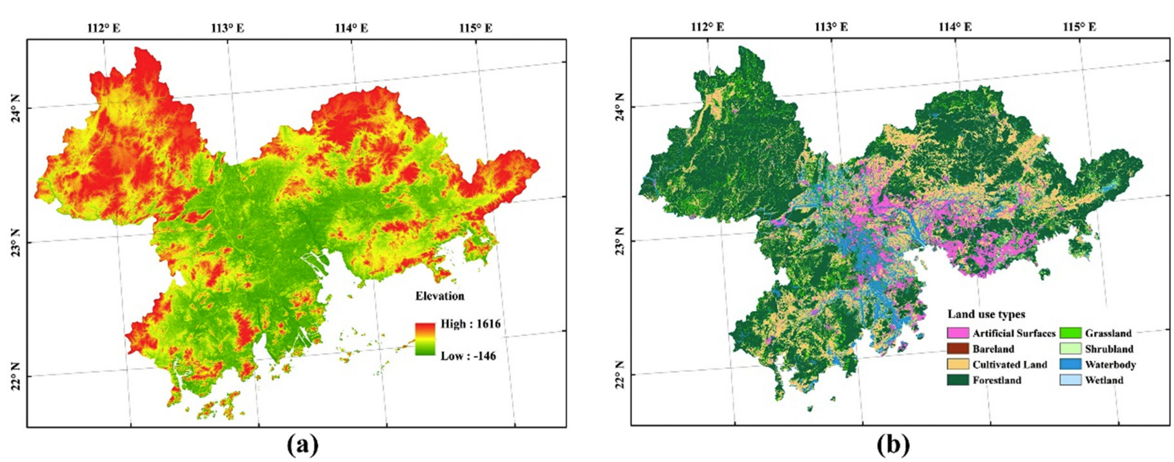

Fig. 1. Spatial patterns of topography (a) and land-use types (b) in the Pearl River Delta, China.