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Trade-offs among ecosystem services in coastal wetlands under the effects of reclamation activities

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ABSTRACT

In recent years, unsustainable reclamation activities have damaged coastal ecosystems and degraded ecosystem services, as a result, management of coastal wetland ecosystem services has received increasing attention. Because different ecosystem services respond differently to management, there are inevitable trade-offs among some of these services, and understanding these trade-offs has gradually become a research hotspot. As the research on trade-offs has deepened, it has become possible to quantify them. Based on the interpretation of remote sensing and socioeconomic data for the Yellow River Delta's coastal wetlands since 1989, the InVEST model was used to evaluate the spatial patterns and dynamic evolution of coastal wetland ecosystem services and the trade-offs among them. Production possibility frontier curves were then selected to identify optimal combinations of ecosystem service values; a trade-off intensity index was constructed to quantify the magnitude of the trade-offs, and the effects of reclamation activities on the trade-offs and synergies among ecosystem services were analyzed. A trade-off existed between material production and habitat quality from 1989 to 2015, and its intensity increased yearly. In addition, the relationship between carbon storage and material production transformed from a synergy into a trade-off in 2008, although the strength of the trade-off has been increasing since then. The results of our study will provide a scientific basis for improving wetland management and ecological restoration by alerting managers to the need to mitigate the tradeoffs.

1. Introduction

Wetlands are one of the world's most threatened ecosystems (MEA, 2005) for complex reasons, such as invasion by exotic species, water pollution, and human activities. Many of their problems result from their proximity to large human populations, which increasingly exploit the services provided by these rich ecosystems. In recent years, with accelerating economic development and the expansion of urbanization in coastal zones, reclamation of wetlands has become a significant problem (Murray et al., 2014). Large-scale reclamation activities provide large socioeconomic benefits, but also jeopardize the coastal wetland ecosystems and the services they provide through changes such as habitat fragmentation and habitat loss (Bulleri and Chapman, 2010). To maximize the benefits from wetland use while maintaining the ecosystem's health, wetland managers must balance the competing needs of socioeconomic development and conservation. Because this balance inevitably involves trade-offs, trade-off analyses have become increasingly necessary. Quantifying these trade-offs (and the synergies that sometimes emerge) can improve the management and protection of coastal wetlands by revealing the optimal allocation of wetland services.

Trade-offs among multiple ecosystem services occur when an improvement in one ecosystem service is achieved at the expense of a decrease in another; conversely, when an improvement in one ecosystem service leads to an increase in another, the relationship is a synergy. Trade-offs generally exist between provisioning services, between provisioning services and regulating services, and between supporting services (Chisholm, 2010; Martín-López et al., 2012). Synergies exist between all four categories of ecosystem services, and are relatively common in regulating, supporting, and cultural services (Lamsal et al., 2015). Trade-offs or synergies are not static or homogeneous, as they exhibit temporal dynamics and spatial heterogeneity (Rodríguez et al., 2005). In addition, the reversibility of trade-offs varies: some ecosystem services could recover to their original state if the factor that disturbed the service is mitigated or eliminated (Rodríguez et al., 2005), whereas other services exhibit threshold behavior, and cannot recover without strong human assistance (Bai et al., 2010).

More and more scholars have begun to study the trade-offs and synergies between ecosystem services based on continuous improve-

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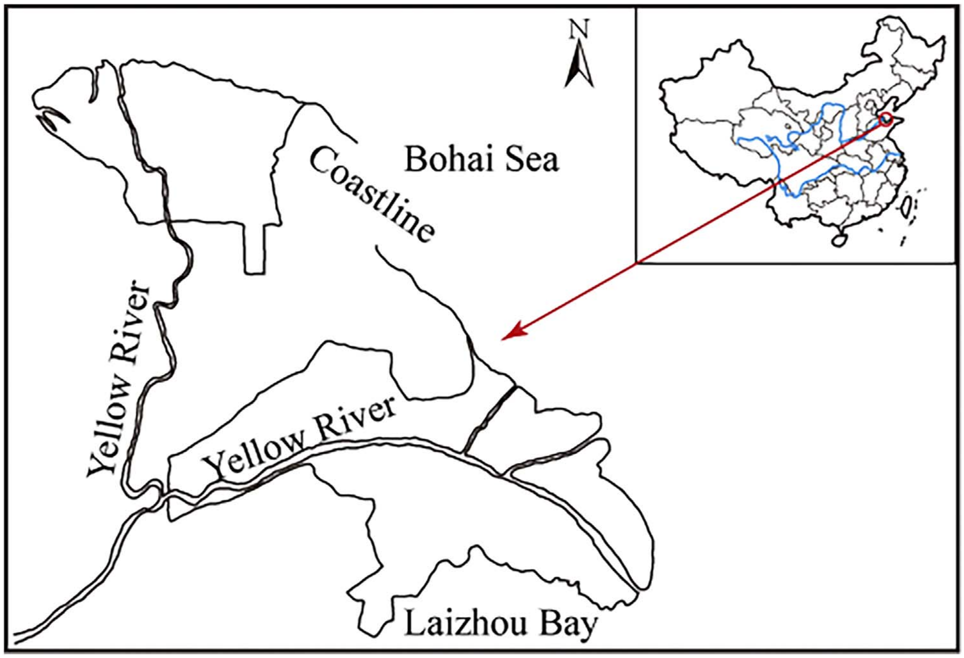

Fig. 1. Map of the coastal wetlands in the Yellow River Delta.

ment of valuation methods for these services (Schröter et al., 2014; Cavender-Bares et al., 2015a,b). Some trade-offs between ecosystem services are direct, inter-related, and self-generated (Nappi et al., 2010). In contrast, others result from indirect interactions caused by the actions of a co-driver (Jansson et al., 2015). Direct trade-offs are often revealed by the presence of statistically significant correlations (Bennett et al., 2009). There are two main methods used to reveal indirect trade-offs: service cluster analysis based on statistical clustering theory (Raudsepp-Hearne and Mooney, 2010) and impact analysis of iterations based on relational matrices (Altman et al., 2011). In addition, process-based ecosystem service models can be used to analyze trade-offs among services. These models can integrate changes in ecosystem processes with an assessment of ecosystem services and ecosystem management (Min et al., 2012). Because of excellent ability to evaluate process-based ecosystem services combined with service cluster analysis and impact analysis, the InVEST model was used in the present study. Studies of landscape-scale co-drivers of ecological processes (such as climate change and urbanization) have focused on the impact of land use or cover changes on the trade-offs or synergies between ecosystem services (Carreño et al., 2011).

Current methods for analyzing trade-offs and synergies include threshold analysis (Viglizzo and Frank, 2006), extreme-value analysis (Lv and Cheng, 2007), multi-objective analysis (Yan and Li, 2013), and model analysis (Haines-Young et al., 2012). Lautenbach et al. (2010) noted that the commonly used methods for examining trade-offs and synergies were based on graphical comparisons, whereas Butler et al. (2012) described scenario analysis and model simulation. There have also been studies that revealed trade-offs by assessing the economic and environmental benefits at a landscape scale in different years (Carreño et al., 2011). However, these studies only identified trade-offs between ecosystem services by comparing the magnitude of the shift in ecosystem services, and did not quantify the intensity of the individual trade-offs. Production possibility frontier curves (PPFs) offer a way to provide this quantification. This approach is based on an economic concept in which analysis can reveal the maximum outputs of combinations of two resources that simultaneously use the same set of inputs, thereby quantitatively describing the magnitude of the trade-off between the two outputs (King et al., 2015). Ager et al. (2016) used spatial optimization to analyze alternative restoration scenarios and examined the trade-offs based on PPFs for the relationships between selected restoration objectives.

However, studies of trade-off intensity have received little attention. Bradford and D'Amato (2012) used the root-mean-square error (RMSE) to quantify the trade-offs among multiple benefits. RMSE quantifies the average difference between each individual benefit and the mean benefit, and thus describes the magnitude of their difference from the mean, which in the Bradford and D'Amato study represented the distance from the "1:1 line" that represented equal benefits. Although RMSE is a simple but effective metric to quantify the trade-offs, it requires large amounts of measured value data, it is unsuitable for analyzing the data produced by evaluation models, and the "1:1 line" that represents equal benefits may not represent the optimal trade-off. Xue (2013) defined a trade-off strength coefficient (*TI*) that equals the ratio of the rate of change of a service to the rate of change of a target service. This approach can be used to evaluate the sensitivity of the change in a service value with respect to changes in the target service. Unfortunately, the same *TI* value may correspond to different combinations of ecosystem services, which may make it an ineffective indicator of trade-offs when the goal is to find the optimal combination.

Although early studies indicated that changes in ecosystem services could be attributed to the effects of land reclamation (Shi et al., 2013; Wang et al., 2014), there is still a need to quantify the relationship between reclamation and its effects on ecosystem services. In this paper, the InVEST model was used with remote sensing and socioeconomic data for the Yellow River Delta's coastal wetlands to evaluate the spatial patterns and dynamic evolution of coastal wetland ecosystem services since 1989 and to identify trade-offs and synergies among the services. By combining this analysis with PPF curves, a trade-off strength index was constructed and used to analyze the effects of reclamation activities on the trade-offs or synergies between ecosystem services. The results of our study will provide scientific support for the planning and implementation of reclamation activities and will contribute to the protection and management of wetland ecosystems in coastal areas.

2. Methods and models

2.1. Study area

The Yellow River Delta (37°35′N to 38°12′N, 118°33′E to 119°20′E) is located on the western coast of the Bohai Sea, in the northern part of