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Temporal variation and spatial scale dependency of the trade-offs and synergies among multiple ecosystem services in the Taihu Lake Basin of China

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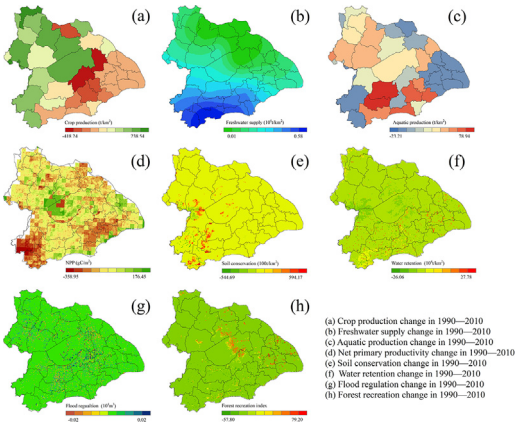
HIGHLIGHTS

- We proposed a framework to assess trade-offs and synergies among ecosystem services (ES).
- Temporal variation and spatial scale dependency of Disaggregated ES and Bundled ES were analyzed.
- Changes of provisioning services led to trade-offs among provisioning services, regulating services and cultural services.
- A new synergy between freshwater supply and aquatic production occurred at the pixel scale in 2010.
- It can help the delineation of ecological conservation redline and implement the project of “Grain for Green”.

GRAPHICAL ABSTRACT



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ABSTRACT

Grasping the temporal-spatial characteristics of interactions and spatial scales of multiple ecosystem services is the foundation for sustainable ecosystem management. Eight ecosystem services, including crop production, freshwater supply, aquatic production, net primary production, soil conservation, water retention, flood regulation, and forest recreation were measured at the 1-km^2 pixel scale in the Taihu Lake Basin (TLB) of China from 1990 to 2010. Furthermore, we quantified the trade-offs and synergies of services at different periods of urbanization and across the 1-km^2 pixel scale and the county scale. We aim to find which ecosystem services interactions temporally vary and depend on spatial scale. Our results found that: 1). Tremendous amount of cultivated lands were converted to construction land, and rapidly shrank from 1990 to 2010. 2). Determined by land use, different ecosystem services had spatial heterogeneity of their strength. Ecosystem services hot spots experienced an increasing trend while cold spots showed a trend of decreasing first and then increasing from 1990 to 2010. 3). Trade-offs between provisioning services and regulating services at the 1-km^2 pixel scale changed over time. There was a new synergy between freshwater supply and aquatic production at the 1-km^2 pixel scale in 2010 with the human demand. 4). From 1990 to 2010, the changes of provisioning services led to trade-offs among provisioning services, regulating services and cultural services at two scales. Taking temporal variation and scale dependence into account, this research is helpful to the delineation of "Ecological

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Conservation Redline" and implement the project of "Grain for Green". We also provide suggestions for maintaining ecosystem services with economic growth in China's Yangtze River Economic Belt for land use policies and decision making.

1. Introduction

Understanding the spatial-temporal characteristics of trade-offs and synergies among ecosystem services is the foundation and prerequisite for sustainable ecosystem services management (Qiao et al., 2018; Raudsepp-Hearne et al., 2010). The trade-off occurs when one ecosystem service increase while other ecosystem services decrease (Rodriguez et al., 2006). For example, agricultural production increase may lead to a decrease in the water purification, which affects the fishing and water environment recreation (Tilman et al., 2002). Synergy means that two services have a consistent trend. For instance, increasing Net primary productivity (NPP) also increase the water productivity and the quantity of soil conservation (Han et al., 2017).

In recent years, trade-offs and synergies among ecosystem services at the global and regional-scale have become important topics in the study of ecosystem services (Boithias et al., 2014; Li and Wang, 2018; Qiu and Turner, 2013). The research scopes include spatial and temporal distribution characteristics of ecosystem services (Han et al., 2017; Li and Wang, 2018), spatial connections between the ecosystem service provisioning and benefiting areas and spatial flows (Serna-Chavez et al., 2014), comprehensive analysis and simulation of multi-scale effects (Mitchell et al., 2015), and natural and human driving factors of trade-offs and synergies (Li and Zhou, 2016). Diversity, complexity and uncertainty of ecosystem services, which form trade-offs and synergies, show complex interrelationships (Brauman et al., 2007). Human demands for ecosystem products might aggravate the conflict between provisioning services and other services (Dai et al., 2016). At present, statistical methods (Su et al., 2012a; Turner et al., 2014), spatial analysis mapping methods (Haase et al., 2012), scenario simulation methods (Nelson et al., 2009) and ecosystem service flow analysis methods (Johnson et al., 2014) are mainly used for the identification of trade-offs or synergies. More importantly, we could not ignore in which manner the trade-offs or synergies are affected by temporal variations and spatial scale dependency.

Trade-offs or synergies among multiple ecosystem services can mutate over time (Hou et al., 2017; Tilman, 2000). Some studies have shown that regional trade-offs or synergies increase or decrease over time. For instance, the trade-off between water yield and evapotranspiration was reduced from 2000 to 2010 in the Loess Plateau (Hou et al., 2017). Synergy between NPP, water yield and soil conservation amount increased in the Three-Rivers Headwaters region from 2000 to 2012 (Han et al., 2017). Otherwise, interactions disappeared or reversed in some places over time. Geographical factors, land use/cover changes, social economic factors were the main driving forces for the changes in trade-offs and synergies of ecosystem services.

In addition to temporal variations, trade-offs and synergies of ecosystem services can take different actions on different spatial scales. The direction of correlations changed across spatial scales between food production and water yield, food production and NPP (Hou et al., 2017). A study conducted in the floodplain of the Piedra River found that there was no significant correlation between food production and regulating services at the patch scale, but when the data were up-scaled to the municipal and landscape levels, the correlation was significantly positive (Felipelucia et al., 2014). Another study revealed that trade-off between water yield and habitat quality occurring at the pixel scale did not happen at the county scale (Hou et al., 2017).

Quantifying and exploring temporal characteristics and spatial scales in trade-offs or synergies of ecosystem services are beneficial to ecosystem management. Researchers should know that ecosystem service interactions will change over time and across spatial scales. However, only a small number of studies have considered the temporal changes and spatial scales of trade-offs and synergies so far. If spatial-temporal differences that can cause errors in the statistical analyses of some ecosystem services are neglected, it to the uncertainty for the decisions in managing trade-offs or synergies among the services might increase (Dai et al., 2016). The interactions between different services are usually multiple and non-linear, and factor analysis method can be used as a concise ecosystem service cluster to assess multiple ecological processes and services (Bennett et al., 2009). However, it is unclear whether the factor analysis output also changes over temporal variations and spatial scales. Moreover, there is a need for understanding whether the spatial interactions among disaggregated ecosystem services or among bundled ecosystem services are consistent or not.

Because of the rapid economic development, urbanization has posed a great threat to local ecological environments. The agglomeration of urban population, the expansion of urban land and farmland, the complexity of agricultural non-point source pollution, and the reduction of soil carbon stocks, which have occurred in the Yahara Watershed (Qiu and Turner, 2013), Leipzig-Halle Region (Haase et al., 2012) and Guanzhong - Tianshui economic region (Li and Zhou, 2016), are relevant examples. The Taihu Lake Basin (TLB) is located in the Yangtze River Delta in eastern China. From 1985 to 2010, it has experienced rapid changes including a rapid developing economy (annual GDP growth rate of 15.7%), population increasing (annual population growth rate of 3.0%), and urban expansion (annual urbanization growth rate of 9.2%). In recent years, ecosystem services, such as crop production (Liu et al., 2015), water purification (Xu et al., 2016), carbon sequestration (Wang et al., 2016) have significantly degraded in the TLB, posing a threat to the region's ecosystem safety and sustainability. According to the latest national urbanization plan (2014–2020) and development plan of Yangtze River Economic Belt, future urbanization of TLB will increase the demand for land resources and increase the pressure on the ecological environment carrying capacity.

Therefore, we use the Taihu Lake Basin as a case study to explore the temporal variation and spatial scale dependency of trade-offs and synergies among multiple ecosystem services in rapidly urbanizing and developing regions, and to provide decision-making for sustainable development. Our analysis is based on multi-period land use/cover data, remote sensing images and related parameters, to estimate multiple ecosystem services and their spatio-temporal characteristics at the 1-km^2 pixel scale and county scale. We used principal component analysis to reveal the temporal variations of trade-offs and synergies in the TLB, in order to show the way in which ecosystem services' trade-offs and synergies depend on spatial scale, and by comparing the interactions difference between disaggregated services and bundled services. Eight ecosystem services, including crop production, freshwater supply, aquatic production, net primary productivity, soil conservation, water retention, flood regulation and forest recreation, were used to derive key indicators that measured the trade-offs and synergies in ecosystem services. Our research can enhance the comprehension of the complex interactions among multiple ecosystem services, both over time and different scales at different periods of urbanization.