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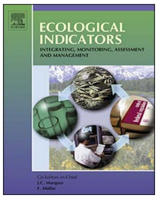

Original Articles

# Spatial trade-offs and synergies among ecosystem services within a global biodiversity hotspot

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## ABSTRACT

Managing multiple ecosystem services (ESs) in a win-win manner is a necessary and challenging task. However, our understanding of the spatial interactions among ESs is relatively limited, particularly in mountainous areas. Using the global biodiversity hotspot known as the Three Parallel Rivers Region in Southwest China as a case study, this paper systematically investigated the spatial trade-offs and synergies among 8 ESs (i.e. crop production, livestock-raising, water supply, carbon storage, carbon sequestration, soil retention, habitat support and nature recreation). We mapped the township-level distributions of the 8 ESs and measured their relationships using Spearman's rank correlation coefficients and overlap analyses of ES hotspots/coldspots. Four types of ES bundles were identified by applying the K-means clustering analysis to the 8 ESs. Our results revealed high to moderate levels of interactions among most pairs of ESs. Most provisioning services showed trade-offs with ESs of the other categories, whereas most regulating services demonstrated synergies with other ESs. The ES bundles presented a reasonable set of ecological zones that were characterized by the provisions of different ESs. The spatial patterns of ESs and their interactions corresponded well to the regional socio-ecological gradients in topography, climate and human activities. Our results should have important applications in regional decision-makings on economic development and environmental conservation. This study also provides a good case for demonstrating the complex relationships among ESs in a typical mountainous biodiversity hotspot.

## 1. Introduction

Human well-being depends on a wide range of ecosystem services (ESs) provided by nature (MA, 2005; Cardinale et al., 2012), and this dependency continues to increase with economic development (Guo et al., 2010). Despite the broad recognition of the significance of ESs (Cardinale et al., 2012; Ouyang et al., 2016; Xu et al., 2017), our understanding of the spatial trade-offs and synergies among ESs is relatively limited (Mouchet et al., 2014; Martinez-Harms et al., 2015). As a result, the management of multiple ESs in a win-win manner at regional scales is a necessary and challenging task (Raudsepp-Hearne et al., 2010; Qiu and Turner, 2013; Zheng et al., 2016). The systematic investigation of the relationships among ESs has been a research hotspot in the fields of geography and ecology over the past decade (Fu, 2013; Li et al., 2014; Guerry et al., 2015; Martinez-Harms et al., 2015).

Various ESs are simultaneously produced across landscapes, and they are interrelated in complex dynamic patterns in space, time and reversibility (MA, 2005; Bennett et al., 2009). Such relationships are commonly summarized as trade-offs and synergies, with trade-offs reflecting the opposing variation patterns among ESs, whereas synergies representing the supply of multiple ESs growing simultaneously (Bennett et al., 2009). Some interdisciplinary approaches have been recently developed to map the spatial distributions of ESs and identify the interactions among them, such as the biophysical simulation model InVEST and the scenario analysis of combining remote sensing, geographic information system and statistics (Li et al., 2014). These approaches are recognized as powerful tools for improving the efficiency and effectiveness of natural resource management and conservation and ecological restoration planning (Raudsepp-Hearne et al., 2010; Qiu and Turner, 2013; Xu et al., 2017). For instance, by applying ES trade-offs analyses, Zheng et al. (2016) put forward important management strategies on riparian grasslands for improving the regulating and provisioning services in the watershed of Miyun Reservoir, Beijing. Such analysis can also provide significant guidance on prioritizing the

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potential conservation and restoration projects that are usually subject to limited resources (Allan et al., 2015; Xu et al., 2017). Although a growing number of papers have been published over the last decade, these studies are unevenly conducted across the world with a significant lack in north Africa and Russia as well as the mountainous areas and polar regions; moreover, the ES categories that have been studied are biased towards provisioning and regulating services, and many results remain controversy among different studies (Howe et al., 2014). Therefore, our understanding on the spatial interactions among multiple ESs remains fairly dim for most ecosystems and services (Bennett et al., 2009).

Mountains are key providers of certain ESs, serving as the last refuges for many endangered and rare species (EEA, 2010). However, few studies on the relationships among multiple ESs have been conducted in high mountainous areas (see Briner et al., 2013; Crouzat et al., 2015; Locatelli et al., 2017; Wang et al., 2017; Wu et al., 2017). Mountains are also experiencing rapid changes in land use and climate (EEA, 2010; Lin et al., 2016; Locatelli et al., 2017; Lü et al., 2017). Approximately 22% of the world's population inhabits mountainous areas, with the vast majority residing in developing countries (Rodríguez-Rodríguez and Bomhard, 2012). The livelihoods of these people depend closely on the ESs provided by local ecosystems (Li et al., 2014). Moreover, mountainous areas represent some of the most fragile environments and are facing severe threats from climate change and human developments (EEA, 2010; Rodríguez-Rodríguez and Bomhard, 2012). These threats have imparted great negative effects on ESs, such as the degradation of nature recreation and water regulation services due to intensified human land uses (Locatelli et al., 2017). Studies have also revealed that the relationships among ESs in mountainous areas are extremely complex (EEA, 2010; Locatelli et al., 2017). For instance, increasing the provisioning of a focal ES in a mountainous region of southern Switzerland could bring about complex alterations in the trade-offs and synergies among ESs (Briner et al., 2013). However, due to the constraints of rugged topography and scarce datasets, such studies are very limited in mountainous areas (Howe et al., 2014), making cross-comparison difficult (Mouchet et al., 2014; Queiroz et al., 2015).

This study aimed to investigate the spatial relationships among multiple ESs within a global biodiversity hotspot, the Three Parallel Rivers Region (TPRR) in Southwest China, which is an area with extremely high mountains and deep gorges (Fig. 1). Our objectives were as follows: (1) to model the spatial distributions of 8 ESs; (2) to investigate the spatial relationships among all pairs of ESs; (3) to identify the distinct ES bundles; and (4) to discuss the implications of ES bundles in ecological management. We therefore mapped the township-level distributions of 8 ESs by building spatial biophysical models. The spatial relationships among ESs were measured using Spearman's rank correlation coefficients and overlap analyses of ES hotspots/coldspots. We analyzed the spatial variations in all 8 ESs along social-ecological gradients using Principal Component Analysis. Multiple ES bundles were then identified with the K-means clustering method. We finally discussed the implications of ES bundles in ecological management.

## 2. Methods

### 2.1. Study area

The TPRR (~67,000 km$^2$) is located in northwestern Yunnan in China, with 3 international rivers (i.e. the Lancang-Mekong, Nu-Salween and Dulong-Irrawaddy) and the Yangtze flowing parallel from north to south (Fig. 1). The TPRR is characterized by extremely high mountains and deep gorges, which greatly affect the spatial patterns of its climate, ecosystems and human activities (Wu, 2000). The northern regions have higher elevations and are cold and dry, whereas the southeastern lower areas are warm and semi-humid (Wu, 2000). The soil in the TPRR consists of 19 soil types belonging to 4 broad categories, ferrosols, alfisols, spodosols and cambisols, distributed along a clear elevational gradient (Duan and He, 2009). The TPRR holds a complete vertical spectrum of ecosystems including subtropical, temperate, cold temperate, cold mountain, dry-hot valley, wetland and aquatic vegetation types (Zhang et al., 2013). The highly diverse environments in this region provide critical habitat for great numbers of rare and endangered species, which makes the TPRR a global biodiversity hotspot (Ou and Gao, 2009). The TPRR is also a cultural hotspot inhabited by 8 major ethnic groups (Lin et al., 2016). With agriculture as the dominant industry, the TPRR is a very underdeveloped region, mainly due to the constraints of the physical environment (Wu, 2000). Notably, the spatial patterns of human activities in the TPRR are tightly linked to its topography (Duan and He, 2009). Administratively, the TPRR comprises 153 townships from 16 counties that belong to the 4 prefectures of Nujiang, Diqing, Lijiang and Dali (Fig. 1).

Despite its great significances as both a global biodiversity and cultural hotspot, the TPRR is experiencing unprecedented disturbances from economic development, including farmland expansion, urbanization, road construction, hydropower and tourism development (Ou and Gao, 2009; He et al., 2014). A systematic investigation of the complex relationships among ESs can promote the optimal management of natural resources in the TPRR and thus help to harmonize the conflicts between economic development and nature conservation.

### 2.2. Modeling the spatial distributions of ESs

Considering the significance of ESs and data availability (Queiroz et al., 2015), we selected 8 ESs belonging to 4 ES categories (MA, 2005), including 3 provisioning services (crop production, livestock-raising and water supply), 3 regulating services (carbon storage, carbon sequestration and soil retention), 1 supporting service (habitat support) and 1 cultural service (nature recreation). This paper modeled 6 ESs, using the data on water supply and soil retention from our published studies (Lin and Wu, 2015a,b).

#### 2.2.1. Crop production

The crop production service was calculated as the annual mean crop yield per hectare (t/[hm$^2$·a]; Yang et al., 2015) over 5 years (2006–2010) at the township level. The crop types included grain, beans and tubers. Data on the production and planting areas for all crop types for each township were collected from the official statistics. The areas of townships ranged from 51.95 to 2,836.34 km$^2$, with a mean of 436.06 km$^2$. Township boundaries were derived from the Yunnan Administrative Map (scale 1: 200,000; Mapping Institute of Yunnan Province, 2015).

#### 2.2.2. Livestock-raising

We considered 3 primary livestock types including pigs, cows and sheep because they accounted for 96.1% of the total number of Yunnan's livestock as of 2010 (SBYP-YSONSB, 2011). We collected livestock numbers from 2006 to 2010 for each township from the official statistics. For each livestock type, we divided the number of livestock by township area to obtain the annual mean number per hectare over 5 years. The 3 layers were then normalized as indices ranging from 0.00 to 1.00 to reduce the effects of different livestock types and data ranges. Finally, we summed the 3 indices to obtain the livestock-raising data.

#### 2.2.3. Carbon storage

Biomass carbon primarily exists in 5 forms: harvest products, aboveground biomass, belowground biomass, dead organic matter and soil organic matter (Yu et al., 2013; Chen et al., 2016). Considering the TPRR data availability, we assessed the carbon contents of aboveground biomass, belowground biomass, litter, and upper-layer (0–20 cm) soil organic matter. Using the carbon storage model in InVEST (Bai et al., 2011), we compiled the carbon density values (t/hm$^2$) for aboveground biomass, belowground biomass and litter for different vegetation types and for soil organic carbon in different soil types (see details in