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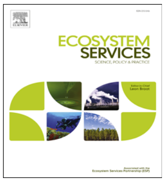

Spatial differences of the supply of multiple ecosystem services and the environmental and land use factors affecting them

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ABSTRACT

A practical knowledge of the amount or supply level of multiple ecosystem services is the key prerequisite for enhancing local ecological stability and securing the well-being of humanity. We studied the supplies of four ecosystem services: grain provisioning, meat provisioning, water conservation, and soil retention at the county level in the Jinghe watershed in northwestern China. The spatial differences of the supply of four ecosystem services were studied using two indices, the Total Ecosystem Services (TES) and Trade-Offs (TO) indices. Then, the environmental and land use factors affecting the spatial differences were also analyzed. The results show that large spatial differences exist in the supplies of multiple ecosystem services, in which the TES and TO indices varied by as much as six and 12 times from one area to another, respectively. Precipitation was the primary constraint on the total supply of multiple ecosystem services. However, environmental factors had little impact on the ecosystem service trade-offs, although the type of land use had significant impacts. An increase in the spatial extent of grassland area resulted in reduced trade-offs and enhanced the supply of multiple ecosystem services. A spatial increase in farmland had opposite effects. This case study provides a new perspective on identifying where and how to enhance multiple ecosystem services.

1. Introduction

Ecosystem services are benefits people obtain from ecosystems (Millennium Ecosystem Assessment, 2005). Globally, the intentional management of ecosystems to supply the ever-increasing needs of humanity has tremendously enhanced the provisioning ecosystem services, such as food, timber, and fiber (Foley et al., 2005). These intentional management activities may result in unexpected declines in some regulating and cultural ecosystem services, such as climate regulation, flood control, water conservation, and landscape esthetics (Raudsepp-Hearne et al., 2010a). These unexpected declines are threatening global ecosystem sustainability and stability, as well as the well-being of humanity (Foley et al., 2005; Kareiva et al., 2007).

A simultaneously provided maximal supply of all ecosystem services is the ideal target designed to enhance and guarantee ecosystem stability and the well-being of people. However, interactions occur among various ecosystem services, which have been described as synergies and trade-offs (Rodríguez et al., 2006; Bennett et al., 2009; Raudsepp-Hearne et al., 2010b). Ecosystem service synergies are described as phenomena that occur when multiple services are enhanced simultaneously. For example, retaining forest patches near coffee plantations to increase pollination that will in turn increase coffee production (Ricketts et al., 2008; Olschewski et al., 2010). Wetland restoration may simultaneously enhance water purification and flood regulation (Zedler, 2003; Moreno-Mateos and Comin, 2010). Ecosystem service trade-offs occur when the enhancement of the provision of one service causes a reduction in another ecosystem service. For example, afforestation (tree planting) enhances carbon sequestration, while simultaneously the process of tree growth increases evapotranspiration and decreases water availability (Engel et al., 2005). Therefore, avoiding or alleviating trade-offs and enhancing synergies of multiple ecosystem services could lead to a high level of supplies of multiple ecosystem services.

Understanding the patterns and factors affecting supplies of multiple ecosystem services could help us better manage ecosystems. Despite this, doubt and disagreement remain (Naidoo et al., 2008; Nelson et al., 2009). Some researchers have explored the spatial patterns of the provision of multiple services across landscapes and found simultaneously high-level supplies of multiple ecosystem services do exist; ecosystems often provide services such as carbon sequestration, soil retention, conservation of clean water resources, and forest recreational opportunities (Raudsepp-Hearne et al., 2010b) and simultaneously provide supplies of high-quality water, freshwater biodiversity, and natural riverine habitats (Holland et al., 2011). The management interventions needed to achieve high-level

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supplies of multiple ecosystem services could be land consolidation, afforestation, fertilization, and/or conservation tillage. For example, the grain production of 57 countries could be managed with a package of agricultural resource conservation technologies and practices leading to enhanced supplies of grain production, water conservation, carbon sequestration, and water quality (Pretty et al., 2006).

However, currently we do not completely understand the factors affecting the simultaneous supply of multiple ecosystem services. Will the same management interventions lead to the same situations of high-level supplies of multiple ecosystem services in different environmental situations? For example, for more than 10 years China has conducted two massive national ecological restoration programs, the Natural Forest Conservation Program (NFCP) and the Grain to Green Program (GTGP). The NFCP and GTGP are designed to conserve natural forests through logging bans and afforestation, as well as to convert cropland on steep slopes to forestland and grassland (Liu et al., 2008). The management interventions of afforestation and land use change created by these two programs caused tremendous enhancement of many ecosystem services, such as soil retention, water conservation, and carbon sequestration (Liu et al., 2008; Yin and Yin, 2010). However, some researchers have criticized the large-scale afforestation efforts because these programs have failed to solve the desertification problem in arid and semi-arid northern China by ignoring characteristics of the natural ecosystem such as low levels of annual precipitation; the planted trees simply died in some areas (Cao, 2008). Therefore, studying the factors affecting the spatial differences of supplies of multiple ecosystem services will help us to know how to adjust our management techniques to simultaneously enhance multiple ecosystem services.

Radar charts have often been used to illustrate the availability and changes in supplies of multiple ecosystem services (Foley et al., 2005; Rodríguez et al., 2006; Raudsepp-Hearne et al., 2010b). Some researchers have also used the Simpson's Diversity, Richness and Total Ecosystem Services (TES) to reflect the spatial differences of available supplies of multiple ecosystem services (Egoh et al., 2008; Raudsepp-Hearne et al., 2010b; Laterra et al., 2012). Nevertheless, this technique still lacks systematic indicators needed to qualify supplies of multiple ecosystem services and cannot connect the supplies with different environmental and anthropogenic factors at many scales.

We use the TES index and introduce another indicator to quantify patterns found in supplies of multiple ecosystem services in this case study. Then, we identify the factors affecting the spatial differences of supplies of multiple ecosystem services, including both environmental and land use aspects, to improve our understanding of how various management techniques could induce the creation of high-level supplies of multiple ecosystem services.

2. Material and methods

2.1. Research area

The Jinghe watershed study area lies in the Loess Plateau åin northwestern China (34°14′–38°11′N, 105°46′–109°12′E). This watershed includes 31 counties which belong to three provinces of Shannxi, Ningxia, and Gansu, upstream from the Yellow River. The primary land uses include farmland, forestland, grassland, and shrubland; minor land uses were barren land, urbanized land, and water. A cool semi-arid climate covers the northern part of the watershed and while the southern part is also cool, it is semi-humid. The annual precipitation ranges from 250 mm to 500 mm from northern to southern parts of the watershed. This part of the Loess Plateau of northwestern China is sensitive to water and wind erosion as a result of its unique characteristics such as having loessial soil, intensive precipitation and hilly topography. In 2000, implementation of the GTGP commenced in this region, with the goal of converting farmland on steep slopes ($>15^\circ$) into forests and afforesting sparsely vegetated areas of hilly and barren land.

2.2. Data sources

A 2005 land use map of this region was obtained from the Moderate-Resolution Imaging Spectroradiometer (MODIS) Land Cover Products (MCD12). The original MODIS land cover maps comprised 17 land types (Strahler et al., 1999). In our research, this original land cover map was reclassified by combining evergreen needleleaf forests, evergreen broadleaf forests, deciduous needleleaf forests, deciduous broadleaf forests, and mixed forests into the single category of forestland; closed and open shrublands were combined into shrublands; woody savannas, savannas, and grasslands were combined into grassland; permanent wetlands, snow and ice, and barren lands were combined into bare land; water bodies were converted into water; urban and built-up lands were combined into urbanized land; croplands and cropland/natural vegetation mosaics were combined into farmland. A land use map with 1×1 km^2 pixel size was used.

Eight-day composite maps of the Leaf Area Index (LAI) used in this study were also obtained from MODIS products (MOD15A2). Forty-five LAI maps were obtained from 1 January to 31 December every 8 days. Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) data and slope data were also used in this study, provided by the International Scientific & Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://datamirror.csdb.cn). A soil map of this region was obtained from the FAO-Harmonized World Soil Database (Fischer et al., 2008). The pixel sizes of all the maps were also 1 km × 1 km.

Daily meteorological data were obtained from 20 weather stations in and around this watershed including precipitation; average, minimum, and maximum temperature; air pressure; relative humidity; wind speed, and sunshine duration (http://cdc.cma.gov.cn) and interpolated across the landscape using the inverse distance weighted method. The interpolated maps used a 1×1 km^2 pixel size.

Economic and social statistical data for each county were obtained from yearbooks provided by each county government's statistical bureau.

2.3. Methods

2.3.1. Evaluation of the ecosystem services at the county level

Four types of ecosystem services, grain provisioning, meat provisioning, water conservation, and soil retention, were analyzed in the Jinghe watershed at the county level. Ecosystem services of grain provisioning and meat provisioning were quantified with the actual production of each county, based on the county's statistical data.

Water conservation service is defined as the ecosystem service of providing a supply of fresh water through ecosystem functions and was quantified as the amount of fresh water supplied (Egoh et al., 2008). The amount of fresh water supply was calculated by the water equation method (Eq. (1)). In this study, the 2005 water yield was calculated for each 1 km × 1 km pixel on the landscape of the watershed, and was summarized at the county level

$$FWS = P - AET, \tag{1}$$

where FWS is the fresh water supply, P is the annual precipitation, and AET is the annual evapotranspiration. Daily AET was modeled using the MODIS LAI data and the Penman–Monteith equation (Leuning