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Impacts of urbanization on ecosystem services and their temporal relations: A case study in Northern Ningxia, China

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ABSTRACT

Urbanization, an unavoidable global process, has driven land use change, impacted ecosystem services, and induced serious environmental problems. As a result, urban planning is a critical issue in sustainable development. In this study, we developed a framework to quantify how urbanization influences ecosystem services (ESs) in order to provide suggestions for urban planning during large scale urban agglomeration in northwestern China. We separated the region into three sub-regions (developed urban, developing urban, and rural areas), quantified five critical ESs (crop production, carbon storage, nutrient retention, sand fixation, and habitat quality), analyzed the relationships (trade-off, synergy, and bundle) among ES changes, and investigated the impacts of urbanization on these ESs. The results show that urbanization results in large scale reclamation and small scale deforestation in rural areas; it comprehensively results in an increase of four ESs (not habitat quality). Urban expansion mainly occurs in developing urban areas and causes a decrease in four ESs (not sand fixation). Based on temporal change in ESs, synergy relationships exist among them, except for between nutrient retention and crop production, which have an insignificant correlation. Urban expansion would strengthen the synergy relationships among regulating services, while green infrastructure in core urban areas would weaken these relationships. Based on the spatial distribution of ES change, two bundles were identified among the five ESs: 1) crop production, carbon storage, and nutrient retention; and 2) sand fixation and habitat quality. Based on these findings, several suggestions for urban expansion and land use planning are proposed to achieve an optimized balance between urbanization and ES protection. Investigating the impacts of rapid urbanization on ESs and their relationships could provide scientifically based suggestions for urban planning according to ES protection, sustainable urban development, and human well-being.

1. Introduction

Urbanization is a key anthropogenic driver affecting urban ecosystems as it can influence interactions among the atmosphere, hydrosphere, and biosphere (Polydoros and Cartalis, 2015). Unprecedented urbanization has occurred all over the world (Wu et al., 2015), with urban land having quadrupled between 1970 and 2000 (Alberti, 2005); this trend is expected to continue in the future, with triple the land and a 60% increase in the urban population by 2030 (Elmqvist et al., 2013; Seto et al., 2011). Urbanization in China is considered to be one of the two key drivers of human development in the 21 st Century (Fang and Yu, 2016), as it not only converts natural landscape into impervious surfaces, but also drives land use change away from cities, encouraging the utilization of natural resources to meet the growing demands of human population; furthermore, urbanization is accompanied by industrial production (Deng et al., 2015; Wu et al., 2011; Zope et al., 2016). Several ecological problems have emerged with rapid urbanization, including: climate warming (Xu et al., 2016); contamination of soil, air, and water (Roberts et al., 2009); and biodiversity loss (Seto et al., 2012). Ecosystem services (ES) are the goods and benefits that humans directly or indirectly obtain from ecosystems through ecological processes; for example, climate regulation, conservation of water, food supply, and leisure provision, including tourism and entertainment (Costanza et al., 1997). This concept is now widely used among scientists and policy makers to highlight the importance of the environment in global sustainable development (La Notte et al., 2017). Human activities have impacted and will continue to impact on ecosystem functions and services on a global scale (MA, 2005). Therefore, assessing the impacts of urbanization on ESs is critical and urgent for providing information and suggestions for urban planning and policy formulation that could minimize their potential negative impacts on the environment (Delphin et al., 2016; Li et al., 2017).

Complex relationships and interactions exist among ESs at regional

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to global scales; these can be classified into three types: trade-off, synergy, and neutral relationships (Jopke et al., 2015). Trade-off relationships, where one ES is elevated at the expense of another ES, are useful to investigate the impacts of strategies on different scales (Bennett et al., 2009). Goldstein et al., 2012 found that increases in carbon storage were accompanied by water quality reduction. ES bundles occur where landscapes have multifunctionality in providing multiple ESs simultaneously, with some ESs tending to repeatedly appear together across space and time (Raudsepp-Hearne et al., 2010). The spatial-temporal patterns of ESs, trade-offs, synergy, and bundle relationships among ESs have become an important topic in ES studies (Jopke et al., 2015).

A large number of studies have been conducted to investigate the impacts of urbanization and land use change on ESs, but most have only concentrated on single ESs (He et al., 2016; Zhang et al., 2012). To our knowledge, only a few studies have assessed the effects of urbanization on multiple ESs simultaneously (Jiang et al., 2016b), let alone revealed the temporal trade-offs, synergy relationships, and bundles among ESs driven by urbanization. Haase et al. (2012) proposed an analytical framework for the spatial and temporal integration of different ESs in an urban region to determine synergy and trade-offs among ESs. Li et al. (2016) compared six ESs in three urban areas and identified urbanization problems through interaction analysis. Most of the relationships analyzed are based on spatial correlations at a given time, but there is a lack of research on temporal change correlations owing to limited data (Cord et al., 2017). Moreover, how urbanization impacts multiple ESs and their changing relationships has not been considered over a large scale region, especially for large metropolitan or urban agglomerations, which have significant importance in future socioeconomic development (Kantakumar et al., 2016).

A proposed development strategy (the Silk Road Economic Belt) provides an opportunity for northwestern China to have a rapid development, but also presents a significant threat to fragile ecosystems in this arid region. Most previous studies have been applied to developed coastal cities, in which built-up land occupies the main part. To compensate for the shortage in studies with respect to large urban agglomerations, especially for less developed agglomerations, we selected the city belt along the Yellow River in Ningxia to investigate the impacts of urbanization on multiple ESs. The main objectives of our study were to: 1) assess the impacts of urbanization on ESs change; 2) detect the urbanization-driven temporal trade-offs, synergies, and bundle relationships among ESs; and 3) provide suggestions for future urban planning in large urban agglomerations.

2. Materials and methods

2.1. Study area

The city belt along the Yellow River in Ningxia (CBYN) is located in the northwestern part of the Ningxia Hui Autonomous Region, China (36°54′–39°23′N, 104°17′–106°53′E), and covers an area of ~22,000 km^2. It is located adjacent to three deserts, with the Tengger desert to the west, the Maowusu desert to the east, and the Ulan Buh desert to the north. This region has a typical continental climate and is characterized by rare precipitation, abundant sunshine, strong evaporation, and four distinct seasons: 1) late windy spring; 2) short summer; 3) early autumn; and 4) long cold winter. The CBYN is a large urban agglomeration consisting of four prefecture-level cities: Shizuishan, Yinchuan, Wuzhong, and Zhongwei (Fig. 1). The Yellow River passes through the region, providing a convenient source for an extensive agricultural irrigation system that has allowed the region to become one of the largest crop production bases in China. It is also a core area in the West Longhair-LanXin Xian economic belt; thus, its development would have significant importance for China's western development.

2.2. Data collection and process

A series of Landsat TM/ETM+/OLI images, located in row/column of 129/33, 129/34, and 130/34, were acquired on 8/24/1989 and 7/31/2015, with a horizontal spatial resolution of 30 m. These images were pretreated in ENVI 5.3, with atmospheric correction, radiation correction, geometric correction, seamless mosaic, gram-Schmidt pan sharpening, and subset via boundary. The processed data were exported into eCognition 8.7 to derive land use distribution through an object-oriented classification procedure. To facilitate spatial analysis and ES valuation simultaneously, land use was categorized into six types, including cropland (e.g., irrigable land, paddy land, and vegetable field), forest land (e.g., arbor, bush forest, and orchard), grass land, water (e.g., rivers, lakes, lagoons, and reservoirs), urban land (e.g., industrial, residential, transportation, and commercial land), and unused land (e.g., sandy areas and bare land). Subsequently, a manual correction process was undertaken to ensure the accuracy of classification based on sample points in field surveys and Google Earth. The Kappa metrics for the classification results were 0.77 and 0.81 in 1989 and 2015, respectively.

Meteorological data (e.g., rainfall, temperature, solar radiation, wind speed, and humidity) were obtained from the China Meteorological Data Service Center (http://data.cma.cn). Socioeconomic data, including demography and economic data, were acquired from Ningxia Statistical Yearbooks (1990–2016) published by China Statistics Press. The digital elevation model (DEM) was derived from Shuttle Radar Topography Mission (SRTM) images with a horizontal spatial resolution of 90 m. Soil data were derived from the Harmonized World Soil Database (HWSD) (Table 1).

2.3. Urban expansion zoning

Urban spatial typology was used to describe the type of urban distribution and expansion, which has significant importance in designing sustainable urbanization (Kantakumar et al., 2016). Larger built-up proportions are considered to represent greater levels of urbanization; thus, we classified urban land into developed urban areas, developing urban areas, and rural areas based on the proportion of built-up land (BD) (Table 2). The calculation and classification of urban expansion zoning was conducted using the block statistics tool in ArcGIS 10.2 within a neighborhood of 3*3 cells.

2.4. ES quantification and mapping

In CBYN, water is the main constraining factor for ecosystems and human uses. The Yinchuan Plain, a part of CBYN, is one of the most important grain production bases in northwestern China; thus, the provision service of crop production is critical for the CBYN and as considered in this study. Carbon storage, which has great importance in mitigating global warming and regulating the CO_2 gas cycle, has been proven to be effectively influenced by urbanization (Svirejeva-Hopkins and Schellnhuber, 2008).

Water yield and sediment retention have been analyzed in several studies owing to their importance for human life and ecosystems (Zhou et al., 2017). However, the flat topography, especially in the central plain, make the problem of soil loss unimportant in CBYN. Meanwhile, water sources for human demand mainly came from the Yellow River owing to low precipitation and high evaporation; thus, the amount of water yield is relative low compared with whole water consumption. Therefore, these two services were excluded from this study.

In the study region, precipitation mainly concentrates in July to September, when it generates strong runoff that transfers nutrients into streams (Zhang et al., 2008). Heavy water pollution caused by crop cultivation (Alam et al., 2017) in the form of nutrient retention; this was analyzed to estimate the impacts of reclamation on water quality. Sand fixation is important in arid and semi-arid areas in order to