Title
The impact of urbanization and climate change on ecosystem services: A case study of the city belt along the Yellow River in Ningxia, China

Permalink

Authors
Lyu, Rongfang
Clarke, Keith C
Zhang, Jianming
et al.

Publication Date
2019-09-01

DOI
10.1016/j.compenvurbsys.2019.101351

Land Use Policy 77 (2018) 163–173

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

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

Rongfang Lyu, Jianming Zhang*, Mengqun Xu, Jijun Li

College of Earth Environmental Sciences, Lanzhou University, Tianshui North Road 222, Lanzhou, China

ARTICLE INFO

Keywords:
Urbanization
Ecosystem service
Northwestern China
Temporal relationship
Urban planning

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

---

* Corresponding author.
E-mail address: jmzhang@lzu.edu.cn (J. Zhang).

https://doi.org/10.1016/j.landusepol.2018.05.022
Received 22 February 2018; Received in revised form 2 May 2018; Accepted 10 May 2018

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

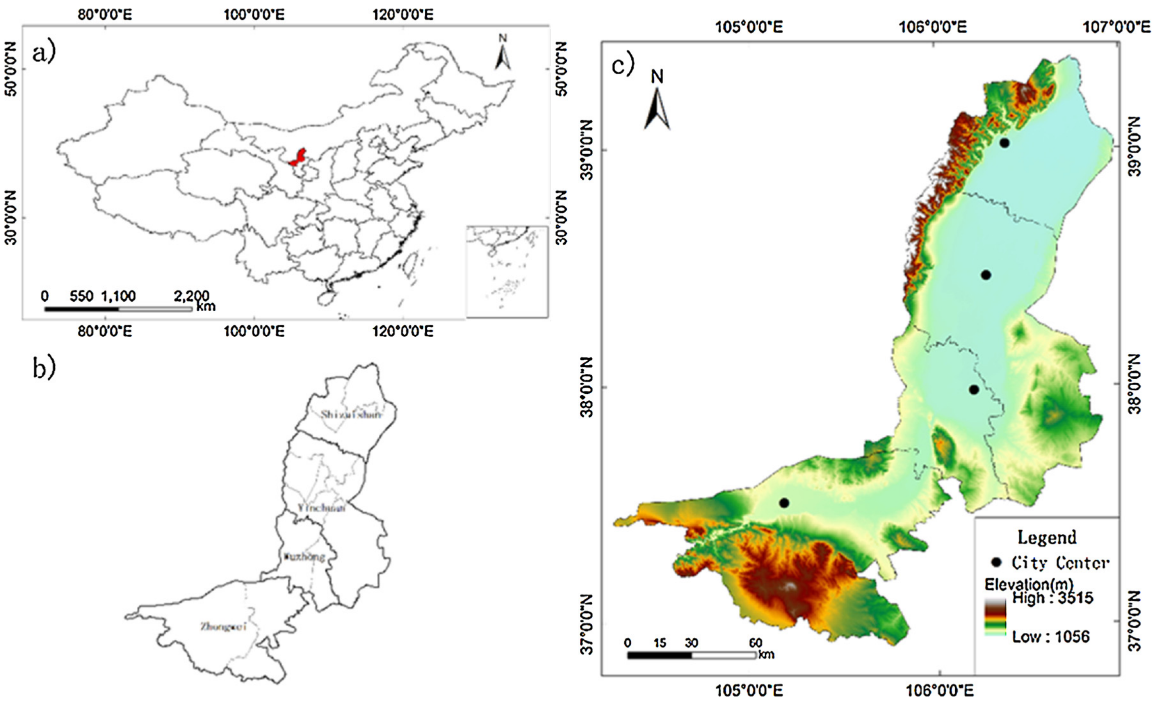

Fig. 1. Location and administrative division of the study area: a) map of China with the study area shown in red; b) political map of the Ningxia Hui Autonomous Region; and c) topographical map of the Ningxia Hui Autonomous Region with the locations of the urban centers (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 1
Data sources[a].

Types of data	Format	Sources
Landsat TM/OLI	GeoTIFF	USGS website (http://landsat.usgs.gov)
DEM	GeoTIFF	SRTM data (http://srtm.csi.cgiar.org)
Soil Data	MDB	HWSD (http://westdc.westgis.ac.cn/data)
Meteorological data	TXT	China Meteorological Data Service Center (http://data.cma.cn)
Socioeconomic data	TXT	Ningxia Statistical Yearbook (1990-2016)

[a] TM/OLI = Thematic Mapper / Operational Land Imager; DEM = digital elevation model; USGS = United States Geological Survey; SRTM = Shuttle Radar Topography Mission;, HWSD = Harmonized World Soil Database.

Table 2
Urban spatial typology in CBYN[a].

Urbanization region	Classification criteria
Developed urban area	$BD_{1989} \geq 50$ %, $BD_{2015} \geq 50$ %
Developing urban area	$BD_{1989} < 50$ %, $BD_{2015} \geq 50$ %
Rural area	$BD_{1989} < 50$ %, $BD_{2015} < 50$ %

[a] CBYN = city belt along the Yellow River in Ningxia; BD = proportion of built-up land.

preserve soil and water, and to prevent dust storms and other adverse weather (Wang et al., 2017). Habitat quality, defined as the ability of a landscape to provide suitable conditions for the persistence of living species, was selected as representative of supporting ESs (Yang et al., 2017). ES was classified into four categories: provision, regulating, supporting, and cultural ES (Assessment, 2005). As cultural ES has a higher dependence on social constructions (Paracchini et al., 2014), it was excluded from this study. Overall, five ESs of great importance for terrestrial ecosystems in arid areas were selected for analysis: crop production, carbon storage, nutrient retention, sand fixation, and habitat quality. We adapted a non-monetary approach owing to associated uncertainties and data deficiencies (Carreno et al., 2012; Seppelt et al., 2012).

2.4.1. Crop production and carbon storage simulated by CASA model

Net primary productivity (NPP) is the net carbon and remaining part of the organic substance amount gained by plants through the process of photosynthesis, which equals the difference between gross primary production and plant respiration (Chapin et al., 2011). The NPP of cropland has been used to estimate food production owing to cropland's ability to generate products (He et al., 2017; Yan et al., 2009). On the other hand, the NPP is also a direct reflection of aboveground carbon fixation by the ecosystem; thus, it can be used to estimate carbon storage (Imhoff et al., 2004). The NPP (t/ha per year) is calculated using the CASA model with the following equations:

$$\text{NPP} = \text{APAR} \times \varepsilon \tag{1}$$

$$\text{APAR} = \text{SOL} \times \text{FPAR} \times 0.48 \tag{2}$$

$$\varepsilon = T_{\varepsilon1} \times T_{\varepsilon2} \times W_{\varepsilon} \times \varepsilon_{\max}, \tag{3}$$

where, APAR is the photosynthetically active radiation absorbed by green vegetation, FPAR is the fraction of absorbed photosynthetically active radiation, SOL is the solar radiation (MJ/m^2), 0.48 is the ratio of incident photosynthetically active radiation to solar radiation, ε is the light-use efficiency, ε_{max} is the maximum value (gC/MJ), $T_{\varepsilon1}$ and $T_{\varepsilon1}$ are temperature stress coefficients, and W_{ε} is water availability. The related parameter value can be found in Zhu et al., 2007.

Crop production is crucial for food security and the social stability of society, especially in urban regions (Haase et al., 2012; Jansson and Polasky, 2010). Most previous studies preferred to calculate crop production based on statistical data; however, this cannot generate spatially precise results (Zhou et al., 2017). He et al. (2017) used the NPP of cropland (CNPP) to estimate crop production at the national scale. We collected mean grain yields from 1989 and 2015 from the Ningxia Statistical Yearbook, including rice, wheat, corn, tubers, soybeans, and other economic crops. We then performed regression analysis between CNPP and grain yield in each county using the R package. The results indicate that CNPP exhibits a good correlation with grain production at a significance level of 0.001 (R^2 = 0.804). Thus, we could use the CNPP to evaluate the spatial distribution of crop production in the CBYN in 1989 and 2015.

2.4.2. Nutrient retention simulated by the InVEST nutrient delivery ratio (NDR) model

Using the NDR model, we calculated the annual average amount of nutrients exported from each cell to the stream network, including nitrogen (N) and phosphorus (P). The model computes a nutrient mass balance that represents long-term and steady-state nutrient flow, based on: 1) nutrient sources related to different land use types, and 2) retention properties of pixels related to topography and surface vegetation (Redhead et al., 2018). Related nutrient retention coefficients and the filtering capacity of each land use type were derived from relevant literature (Yang et al., 2009). This model can be described as follows:

$$NE_i = ALV_i \times f_j \tag{4}$$

$$ALV_i = \left(\frac{\lambda_i}{\lambda_{\bar{w}}}\right) \times pol_i \tag{5}$$

where, NE_i is nutrient retention from pixel i (kg/pixel), fj is the nutrient retention capacity of land use j, ALV_i is the adjusted nutrient loading value in pixel i modified by a hydrological sensitivity score, pol_i is the exported coefficient in pixel i, λ_i is the runoff index in pixel i, and $\lambda_{\bar{w}}$ is the mean runoff index.

Records from gauging stations were derived from the Ningxia environment quality bulletin and water resources bulletin published by Ningxia water conservancy. Monthly data concentrations for nitrogen, phosphorus, and river flow were used to estimate monthly and annual nutrient retention by calculating the nutrient load difference between the inlet and outlet of the basin (Redhead et al., 2018; Terrado et al., 2014). Simultaneous nutrient concentration and river flow data were only available for 3 stations in 2015; therefore, we compared our simulation with gauge data for two sub-basins of the watershed (Fig. 2).

2.4.3. Sand fixation

Sand fixation was estimated using the model of Dong (1998) as follows:

$$\begin{aligned} \mathrm{Q} = \iiint_{txy} & \{3.9V^2 \times (1.0413 + 0.0441\theta + 0.0021\theta^2 - 0.0001\theta^3) \\ & \times (1-(8.2 \times 10^{-5})^C) \times \frac{SDR^2}{H^8 \times d^2 \times F}, x, y, t\} dxdydt \end{aligned} \tag{6}$$

where, Q is loss due to wind erosion (t), θ is the slope (°), V is wind speed (m/s), C is annual mean vegetation coverage (%), SDR is surface structural damage rate (100% in our study), H is the relative humidity of air as derived from meteorological stations, d is the soil particle size (mean of 0.2 mm), F is the hardness of the soil body (0.9 N/cm^2), t is the sand blowing time in seconds (a total of 21 and 20 days in 1989 and 2015, respectively, according to Statistical Yearbook of Ningxia), and x, y is the distance from the point to the reference point (km).

2.4.4. Habitat quality evaluated by the InVEST habitat quality model

Habitat quality is estimated using information on land use suitability and threats to biodiversity (Mansoor et al., 2013; McKinney, 2002). The computational method can be described as follows:

$$i_{rxy} = \exp\left[-\left(\frac{2.99}{d_{rmax}}\right)d_{xy}\right] \tag{7}$$

$$D_{xj} = \sum_{r=1}^{R}\sum_{y=1}^{Y}\left(\frac{W_r}{\sum_{r=1}^{R} W_r}\right) r_y i_{rxy} \beta_x S_{jr} \tag{8}$$

$$Q_{xj} = H_j\left(1 - \frac{D_{xj}^2}{D_{xj}^2 + k^2}\right) \tag{9}$$

where Q_{xj} is the habitat quality of land use type j, D_{xj} is the total threat level in cell x with land use type j, Hj is the habitat suitability of land use j, i_{rxy} is the impact of the threat r from grid cell y on habitat in cell x, d_{xy} is the linear distance between cell x and y, d_{rmax} is the maximum effective distance of the threat r, W_r is the importance of threat r compared to the others, S_{jr} is the relative sensitivity of land use j to the threat r, R is the number of threats, and Y is the number of grid cells.

2.5. Trade-offs, synergy, and bundle analysis among ESs

Relationships between ESs can be classified into three categories: synergy, trade-off, and neutral, in which: 1) synergy refers to a win-win situation of two ESs with mutual improvement; 2) trade-off is where one ES improves at the expense of another; and 3) neutral refers to one ES changing without causing an increase or decrease in another. Using ‘Create Random Points’ in ArcGIS 10.2, we randomly selected 10,000 points in the CBYN, with the distance between each point greater than 300 m to eliminate the influence of spatial autocorrelation. The changes in multiple ESs were derived using ‘Extract Multi Values to Points’ in ArcGIS 10.2. All variables were firstly standardized between 0 and 1 based on minimum and maximum values to eliminate the effects of magnitude. Correlation analysis was performed using the R package to investigate the relationships among ES changes between 1989 and 2015. Corrgram was used to illustrate the correlations among the ES changes.

Ecosystem service bundles, sets of ES that repeatedly co-occur across space or time, were analyzed to compare the correlations among ESs. Using R, principal component analysis (PCA) was used to detect ES bundles based on their change trends over time. This ordination-based technique transforms a set of ESs to uncorrelated components with concentrated information for spatial-temporal change (Marsboom et al., 2018). To express the spatial distribution of ES bundles, ES maps were

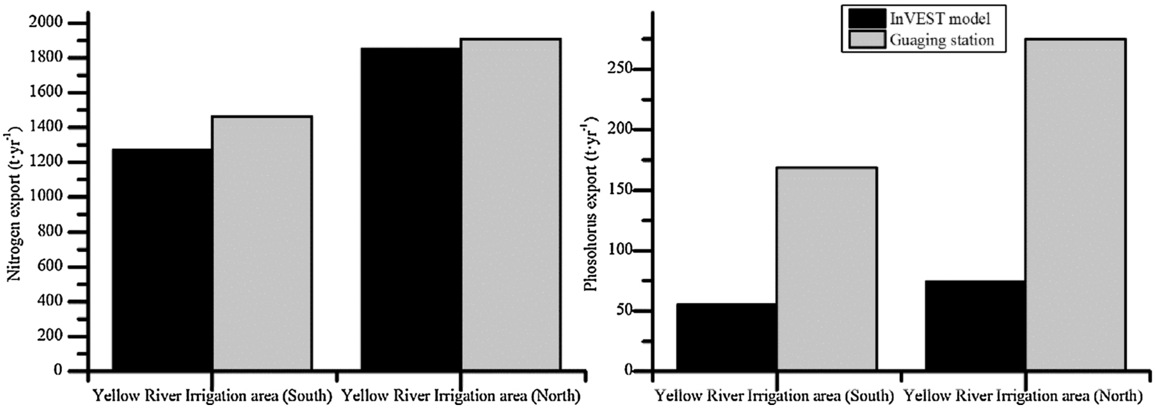

Fig. 2. Nitrogen (N) and phosphorus (P) from the InVEST nutrient delivery ratio (NDR) model (black bars) and from gauging data for two sub-basins (grey bars).

firstly standardized to 0–1, and then summed using 'Map algebra' in ArcGIS 10.2 depending on the correlation structure revealed by PCA. Summed maps were created to express the dominant changes for multiple ESs in each grid cell and represent the spatial variations in ESs change. Based on the results, specific suggestions for urban planning could be formulated for different regions.

3. Results

3.1. Urbanization in the CBYN

3.1.1. Urban expansion zoning

Urban land in CBYN increased from 179.69 km^2 in 1989 to 1113.05 km^2 in 2015 at an annual growth rate of 19.98%. In the CBYN, urban land only occupied a small part of the whole region (0.82% in 1989 and 5.06% in 2015), with 146.86 km^2 (0.67%), 977.34 km^2 (4.44%), and 20,876.72 km^2 (94.89%) accounting for developed urban areas, developing urban areas, and rural areas, respectively. The mean urban land proportion for rural areas (0.5%) was less than that for developing urban areas (88.78%) and developed areas (95.73%) in 2015. Meanwhile, the mean annual growth of urban land in developing areas was 83.42%, much larger than that for rural areas (41.35%) and developed areas (0.23%). Therefore, rapid and explosive urban expansion occurred in developing urban areas.

3.1.2. Land use change

Land use transformation analysis was performed in the three zones. In rural areas, which occupied 94.89% of the whole region, three main land use transformations occurred: grassland to cropland (1639.45 km^2), forestland to grass land (1124.54 km^2), and unused land to cropland (475.01 km^2). In comparison, urban growth was relatively low (12.36 km^2) and mainly came from the transformation of cropland. In developing urban areas, the main transformation occurred through urban expansion, which primarily came from cropland (273.39 km^2), grassland (240.74 km^2), and unused land (46.4 km^2). In developed areas, which represents the smallest area (146.86 km^2) and that with the highest built-up land proportion, urban land increased by 8.05 km^2; this change mainly came from cropland loss. Meanwhile, green infrastructure increased with urban expansion, especially in cities.

3.2. Ecosystem service changes

3.2.1. Overall ES changes

From 1989–2015, the four ESs (crop production, carbon storage, nutrient retention, and sand fixation) increased by 31.35%, 74.82%, 12.81%, and 318.32% in their total values, respectively, while the total value of habitat quality decreased by 18.46% (Table 4). Since the spatial distribution and geophysical character of soils do not change over short timescales, land use change and climate dynamics drove the ESs change (Assessment, 2005). The increases in precipitation (growth rate of 17.74%) and temperature (7.9%) between 1989 and 2015 were beneficial for access to water and growth of vegetation; thus, they contributed to nutrient filtering and growth in carbon storage. Meanwhile, according to the computational method described in Section 2.4.3, the decrease in the relative humidity of air (16.57%) would have increased sand fixation. Therefore, climate change was a contributing factor for ESs change. However, considering the coarse resolution of climate data and high spatial heterogeneity of ES change in our study (Fig. 3), land use change driven by urbanization contributed more. Besides, the mean precipitation, temperature, and humidity had almost the same values in the three sub-regions, confirming that the differences in ES changes among the different zones were mainly induced by differences in land use change.

3.2.2. ES changes in three urban expansion zones

We evaluated the mean ES values in different urban expansion zones to further compare the influence of urbanization on ESs (Table 3). Between 1989 and 2015, the mean crop production increased in developed urban areas and rural areas by 9.59 and 3.42 gC/(m^2·a), respectively, but decreased in developing urban areas by 16.93 gC/(m^2·a). The highest value was in rural areas, with 153.78 gC/(m^2·a) in 1989 and 157.2 gC/(m^2·a) in 2015. Carbon storage followed the same trend in the three zones, with values of 23.34, 43.16, and 15.46 gC/(m^2·a), respectively. Developing urban areas had the highest mean carbon storage in 1989, while t^2 a) in developed urban areas, 1746.41 t/(km^2 a) in developing urban areas, and 1729.16 t/(km^2 a) in rural areas. The highest mean value was in rural areas for both 1989 and 2015.

Nutrient retention decreased in developed and developing urban areas, by 99.76 and 379.05 kg/(m^2·a), respectively, but increased in rural area by 97.23 kg/(m^2·a). The highest mean value was for developing urban areas in 1989 and rural areas in 2015. Habitat quality decreased by 0.13 in developed urban areas, 0.31 in developing urban areas, and 0.11 in rural areas. The highest mean values of habitat quality were in rural areas for both 1989 and 2015.

3.3. Relationships among changes in ESs

3.3.1. Interactions at the regional scale

The interactions of each ES pair were analyzed to identify the relationships with respect to synergy, trade-off, and neutral at regional scale. The Kolmogorov-Smirnov test showed that the changes in five ESs were not normally distributed; thus, Spearman's correlation analysis was used to investigate the relationships among them. The results (Fig. 4) showed that only 1 in 10 pairs of ES change (carbon storage vs. nutrient retention) was not significantly correlated between 1989 and 2015 ($p < 0.01$, two tailed). The other ESs pairs had significant positive correlations, with correlation coefficients ranging from 0.044 to 0.961.

3.3.2. Interactions at a sub-region scale

To investigate the impacts of urban expansion on ES change relationships, the correlation coefficients among the changes in ESs in three urban expansion zones were analyzed and compared. The results (Table 5) showed that the correlations among ESs in rural areas were almost the same as the relationships across the whole region. The provision service of crop production was not significantly correlated with other ESs, except for carbon storage across developing areas and developed urban areas, despite 32 sample points in these two zones. In developing urban areas, there were seven significant positive correlations among ten pairs of ESs. Meanwhile, in developed urban areas, only three significant correlations occurred (nutrient retention vs. sand fixation, $r = 0.351$; nutrient retention vs. habitat quality, 0.551; and habitat quality vs. sand fixation, 0.528).

3.4. ES bundles

We used principal component analysis (PCA) to detect bundles among the five ESs based on their temporal change (Fig. 5). The first two principal components (with eigenvalues of larger than 1.0) together explained 58% of the total variance in the five ES changes. Principal component 1 had high loadings for crop production (correlation of 0.74), carbon storage (0.90) and nutrient retention (0.49); thus, these three services had higher growth in the cropland of the plain fringe, and higher loss in urban expansion area (Fig. 4a). Principal component 2 had high loadings for habitat quality (0.83) and sand fixation (0.62); thus, these two services had higher growth in the northern mountains, moderate growth in southern mountains, and higher loss in urban expansion and cropland growth areas. Using PCA, two ES bundles were identified with similar change trends over time: bundle one (crop production, carbon storage, and nutrient retention), and bundle two (sand fixation and habitat quality).

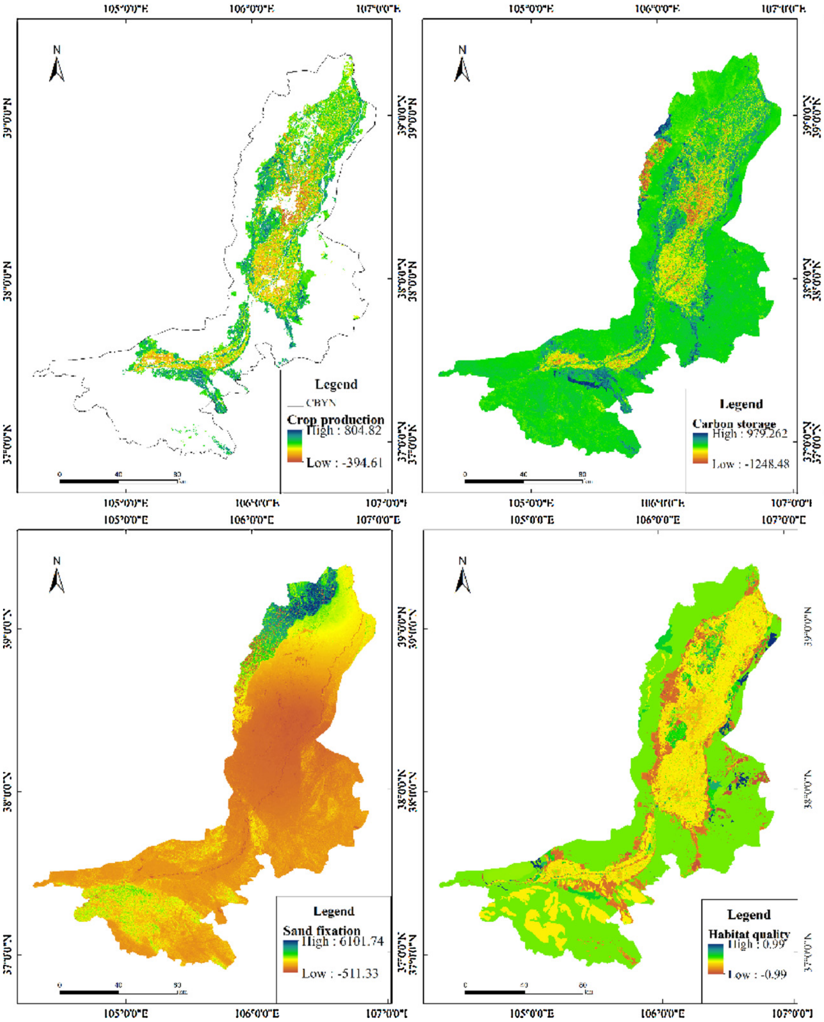

Fig. 3. Changes in the five ecosystem services between 1989 and 2015.

Table 3
Main parameters used in the InVEST habitat quality model.

Land use type	Habitat suitability	Relative sensitivity of each habitat type to each threat							
		Cropland	Rural residents	Urban residents	Unused land	Water area	Primary road	Secondary road	Light road
Cropland	0.4	1	0.2	0.3	0.1	0.1	0.2	0.1	0.1
Forest land	1	0.6	0.7	0.8	0.4	0.7	0.6	0.5	0.5
Grassland	0.8	0.2	0.35	0.5	0.25	0.2	0.3	0.2	0.1
Water	0.6	0.7	0.75	0.9	0.8	1	0.7	0.6	0.5
Unused land	0.05	0.1	0.3	0.4	1	0.1	0.4	0.3	0.2
Urban	0.1	0.4	1	1	0.6	0.7	0.8	0.7	0.6
Village	0.2	0.5	1	1	0.5	0.6	0.7	0.6	0.5
Primary road	0.07	0.4	0.7	0.8	0.75	0.7	1	0.9	0.8
Secondary road	0.08	0.5	0.6	0.7	0.65	0.6	0.9	1	0.8
Light road	0.09	0.6	0.5	0.6	0.55	0.5	0.9	0.8	1
Threat property	Maximum distance	0.9	3	6	9	2.7	3	1.8	0.9
	Relative impact	0.05	0.1	0.2	0.1	0.05	0.2	0.2	0.1
	Decay type	Linear	Linear	Exponential	Linear	Linear	Linear	Linear	Exponential

4. Discussion

Previous research suggest that climate conditions, such as precipitation, temperature, wind speed, air humidity, and land use pattern would significantly impact ESs (Assessment, 2005). In recent decades, climate has not changed significantly; despite this there is a high spatial variation in ESs. Instead, land use change driven by urbanization has been the main contributor for dynamic spatial and temporal ES changes. In detail, the total value of four ESs (crop production, carbon storage, nutrient retention, and sand fixation) increased with land use change driven by urbanization, while only habitat quality decreased with intense human activities. Meanwhile, obvious differences existed in the changes in ESs and their trade-off and synergy relationships between rural areas and urban areas, including developed areas and developing urban areas.

Table 4
Mean ES values in three urban expansion zones.

	Crop production gC/(m^2 a)		Carbon storage gC/(m^2 a)		Nutrient retention kg/(m^2 a)		Wind prevention and sand fixation t/(km^2 a)		Habitat quality	
	1989	2015	1989	2015	1989	2015	1989	2015	1989	2015
CBYN	153.04	157.77	54.02	94.44	611.79	690.17	653.47	2733.61	0.65	0.53
Developed	123.54	133.13	51.1	74.44	735.18	635.42	589.15	2318.31	0.17	0.04
Developing	147.71	130.78	100.79	85.33	988.40	690.35	597.1	2343.51	0.48	0.1
Rural	153.78	157.2	51.85	95.01	593.31	690.54	656.56	2754.78	0.66	0.55

a.ES = ecosystem services; CBYN = CBYN = city belt along the Yellow River in Ningxia.

4.1. Influence of urbanization on ESs in the CBYN

Urbanization is always characterized by converting natural landscapes into impervious surfaces, and by attracting population mobility into urban areas (Du and Huang, 2017). In the CBYN, this has not only caused large-scale urban expansion, but drove reclamation and deforestation to provide materials for urbanization. Thus, the complex change of land use pattern has contributed to the high spatial heterogeneity in ESs and their change. As concluded by previous studies (Larondelle and Haase, 2013; Radford and James, 2013), the differences in mean ES values in the three urban expansion zones also demonstrate ES gradients along an urban-suburban-rural gradient.

In rural areas, large amounts of grassland and unused land have been reclaimed to cropland for the pursuit of higher economic efficiency, such that crop production has been largely improved. Meanwhile, a part of the forestland in Helan Mountain was deforested and degraded to grassland to satisfy the demands of humans and industrial production. Chuai et al. (2013) demonstrated that LULC change from high- to low-vegetation biomass would release carbon into the atmosphere. Owing to low vegetation coverage of grassland and high-biomass quality of irrigated cropland in the CBYN, large scale reclamation in irrigated areas increased carbon storage from 89.437×10^4 tC in 1989 to 109.615×10^4 tC in 2015, and compensated for global warming caused by deforestation (1.29×10^4 tC; Schaldach and Alcamo, 2007). Nutrient pollution presents a significant threat to human health; it mainly comes from anthropogenic sources, including industrial effluent, agricultural fertilizer, residential effluent, and other emissions (Özcan et al., 2016). The high nutrient filtering function of cropland, which comes from its intensive vegetation coverage, and its critical role in non-point source pollution in the CBYN (Zhang et al., 2008), both contributed to the increase in nutrient retention caused by cropland expansion. Meanwhile, although reclamation converts previously unused bare land into vegetated areas suited for wildlife, this human activity has also inflicted great damage on regional native habitats (grassland) and species biodiversity, ultimately decreasing habitat quality.

Despite the small proportion of urban land (4.24% in 2015), its unique biophysical character and rapid expansion (annual increase rate of 19.98%) has made urbanization a critical driver for ES change, especially in developed and developing urban areas. Both of the main land use conversions in these two zones involved urban expansion onto cropland, while a large amount of green infrastructure was established in developed urban areas. Dong and Ma (2012) suggested that green infrastructure increased from 10.67 km^2 in 2001 to 53.56 km^2 in 2012 in Yinchuan city; as a result, the city changed from 'lower' to 'higher' in the national ecology garden city standard. Rapid urban expansion happened in developing urban areas, and was accompanied by a vegetation coverage decrease and impervious land surface increase. As a result, crop production and carbon storage decreased in developing and developed urban areas. Despite the increase of nutrient retention caused by green infrastructure growth (Chenoweth et al., 2018), the occupation of cropland has reduced the sources of nutrients and its ability to intercept nutrients through vegetation coverage; thus, nutrient retention had decreased in developing and developed urban areas. Densified transportation networks accompany rapid urbanization, causing habitat degradation and landscape connections, and reducing the suitability for species to live and migrate.

Jiang et al. (2016a) suggested that rapid urbanization and cropland reclamation from grassland would decrease sand fixation by the ecosystem in Inner Mongolia. However, in our study, sand fixation increased with urban expansion and reclamation in all the three subzones. This can be explained by the decreasing value of the relative air humidity in the CBYN, as caused by global climate change (Lu, 2013), suggesting that the influence of air conditions on sand fixation surpassed that of land use change. Meanwhile, the cropland difference in arid areas and irrigated areas also enhanced sand fixation, as vegetation coverage and ecological quality in the former is far lower than that in the latter.

According to the results, large scale of reclamation and urban expansion could significantly affect ecological processes (e.g., carbon cycle, water cycle, soil retention, and nutrient transformation). ES changes cannot be identified or predicted simply through land use

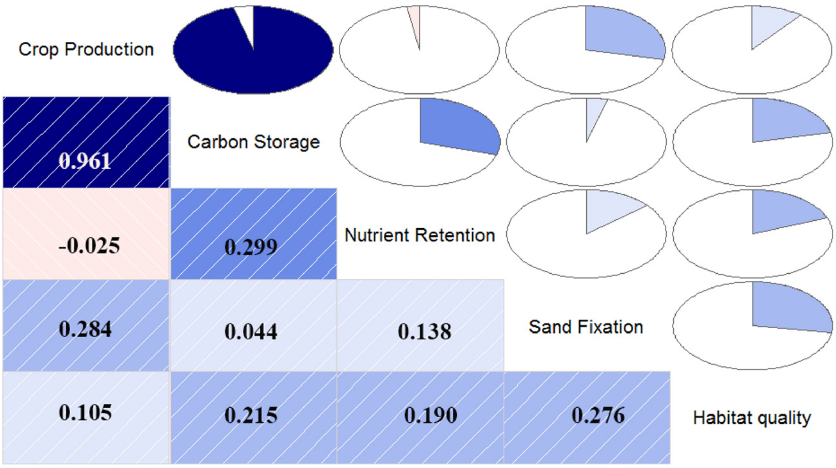

Fig. 4. Corrgram of ecosystem service (ES) pairs in the city belt along the Yellow River in Ningxia (CBYN). The values in the lower-left of each graph are the correlation coefficients of each ES pair in the whole CBYN (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 5
Correlation coefficients among ES pairs in three sub-zones[a].

		Crop production	Carbon storage	Nutrient retention	Sand fixation	Habitat quality
Crop production	Rural	1				
	Developing	1				
	Developed	1				
Carbon storage	Rural	0.963**	1			
	Developing	0.786**	1			
	Developed	–	1			
Nutrient retention	Rural	−0.023	0.266**	1		
	Developing	−0.196	0.607**	1		
	Developed	–	−0.078	1		
Sand fixation	Rural	0.288**	0.003	0.104**	1	
	Developing	−0.092	0.412**	0.411**	1	
	Developed	–	0.110	0.351**	1	
Habitat quality	Rural	0.104**	0.176**	0.14**	0.247**	1
	Developing	0.126	0.594**	0.836**	0.482**	1
	Developed	–	−0.053	0.551**	0.528**	1

** $p < 0.05$.

[a] ES = ecosystem service.

changes, although this is least true for vegetation coverage and ecological quality. High-quality vegetation coverage is beneficial for the protection and improvement of the discussed ESs, while increases in urban impervious surfaces would negatively impact all of these ESs.

4.2. Impacts of urbanization on trade-off and synergy relationships among ESs

Correlation analysis among multiple ESs could provide information for ES linkages and relationships. The magnitude and variability of correlations are governed by the temporal changes in the different ESs, which are place-based and context dependent (Gissi et al., 2016). Our study is focused on the correlations of temporal changes among ESs induced by land use transformations.

According to previous studies, a general trade-off relationship between provision services and regulating services could be suggested, especially between crop production and regulating services of carbon storage, water interception, and soil retention (Jopke et al., 2015; Zhou et al., 2017). However, in our study, crop production had a synergy relationship with carbon storage, which mainly depends on the unique geographical character of the CBYN. owing to high-biomass irrigated cropland, low coverage of high-carbon storage forest land, and a large area of sparse grassland in the CBYN, cropland was a significant contributor for carbon storage; thus, crop production was positively correlated with carbon storage in terms of temporal change among rural and urban areas.

Vegetation coverage plays an important role as a carbon sink, and can be directly altered by land use change (Chuai et al., 2013). Tian et al. (2016) suggested that vegetation coverage growth could improve carbon fixation and alter the hydrological cycle and nutrient transformation. Owing to the decrease in air humidity at a large scale, sand fixation increased for areas of the CBYN. Land use change both enhances and weakens this increase. The growth of vegetation coverage decreases the power of wind and increases the function of sand fixation (Azoogh et al., 2018). Thus, sand fixation increased more in the northern CBYN owing to the growth of vegetation coverage, as demonstrated by NDVI. Although chemical fertilizer in agricultural production surpasses nutrient degradation in the soil and vegetation filtering ability of cropland (Pickard et al., 2016), cropland of high vegetation coverage would intercept a large portion of the nutrients (Özcan et al., 2016). Therefore, large-scale reclamation has induced a synergy relationship among crop production, carbon storage, nutrient retention, and sand fixation. Cropland expansion mainly resulted from grasslands, which threatens native species and wildlife (Yang et al., 2017). For the supporting service of habitat quality and the other four ES, deforestation caused simultaneous losses, while their adverse

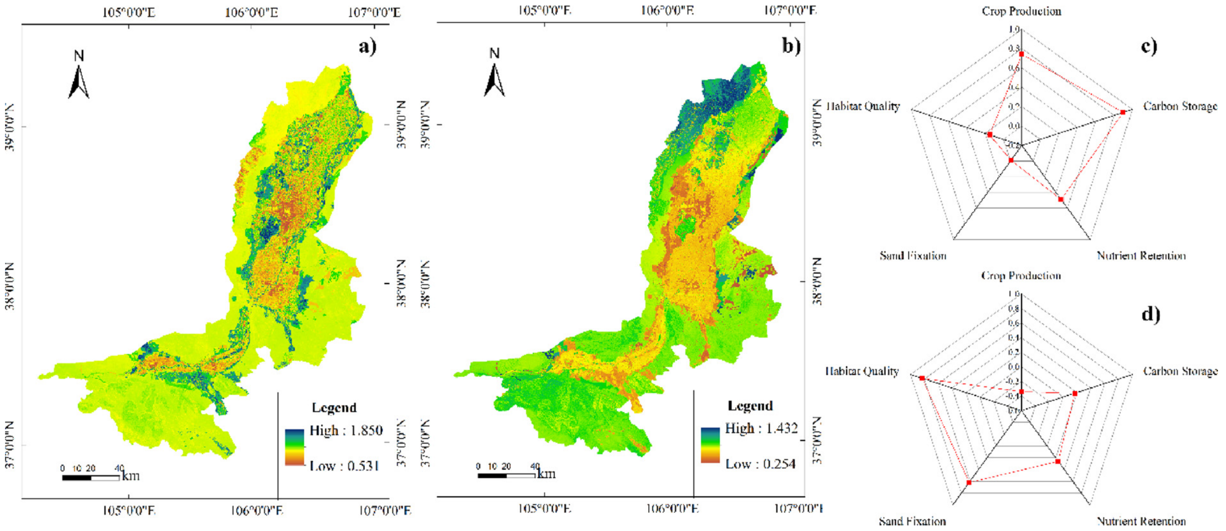

Fig. 5. Radar maps indicating the correlations between standardized ESs and the two principal components (panels c and d) derived from principal component analysis (PCA), and weighted summed maps of the two principle components (panels a and b).

changes were induced by reclamation. These two diverse correlations resulted in the weak positive correlations between habitat quality and other services.

In developing urban areas, urban expansion—the dominate land use change process—mainly came from cropland and caused simultaneous loss in the five ESs. As this land use transformation is simpler than those in rural areas, the synergy relationships among all of the services became more obvious in developing urban areas. In developed urban areas, urban land continued to occupy cropland to satisfy the demands of human living and industrial production, while green infrastructure increased with urbanization to improve landscape suitability for residents (Davies and Lafortezza, 2017). Only three significant correlations existed in developed urban area, those among nutrient retention, sand fixation, and habitat quality. This reflects the positive impacts of green infrastructure on them, and the negative impacts of cropland occupation. Thus, the establishment of green infrastructure should be encouraged in core urban areas.

4.3. Spatial distribution of ESs change

As discussed in Section 4.2, the trade-off or synergy relationships among ESs are not constant across the whole region. The converse correlations between ESs caused by different land use transformations could cumulatively result in weak correlations, such as between habitat quality and carbon storage, which has a trade-off relationship induced by reclamation, and simultaneous loss induced by deforestation. To further understand the spatial variations in the temporal relationships among ESs, PCA was used to classify ES bundles and illustrate their spatial distribution.

In our study, we defined an ES bundle as a mix of ESs having correlated temporal change at the same place, in order to further explore the relative correlations among multiple ESs. The five ESs have been classified into two bundles based on their temporal change pattern: bundle A (crop production, carbon storage, and nutrient retention), and bundle B (sand fixation and habitat quality), where ESs in the same bundle have higher correlations with each other. The multifunctionality of the landscape in providing ESs has been confirmed in previous research using cluster analysis (Queiroz et al., 2015). Our analysis also verifies the multifunctionality of land use changes in affecting multiple ESs simultaneously (i.e., the contrasting effects of reclamation on crop production and habitat quality). Driven by human activities, complex land use changes have occurred with different dominant transformation processes across space. Thus, the trade-off and synergy relationships of ES temporal changes would have high spatial heterogeneity, which should be further analyzed to formulate specific planning suggestions for different regions.

Mouchet et al. (2017) proposed that ES supply patterns could reflect the natural character of the landscape and spatial distribution of land use types simultaneously. The two principal components generated in PCA (Fig. 4) could also represent the spatial distribution of ES temporal change and the areas where their change was dominant or favored. Crop production, carbon storage, and nutrient retention showed higher increases in cropland expansion, especially on the plain fringe, and higher losses in urban expansion areas. Thus, we should pay more attention to vegetation coverage increases and to protecting landscapes from human interference. Sand fixation and habitat quality had higher increase in the northern and southern mountains, and higher losses in expansion areas of cropland and urban area. Thus, forest plantation, native habitat preservation and landscape establishment should be encouraged in these areas.

4.4. Suggestions for urban planning

Since the second stage in the Northam "S" curve of urbanization is unnecessarily long compared to the other two stages, a four-stage urbanization theory was proposed. In this proposal, the second stage is split into two stages at the 60% of urban resident percentage (Fang and Yu, 2016). Therefore, based on the metric of urban resident rate derived from the Ningxia Statistical Yearbook edited by the Statistical Bureau of Ningxia Hui Autonomous Region, we argue that there are three primary stages for the urbanization of the CBYN, namely: the initial stage (1949–1985), the middle stage (1986–2004), and the mature stage (from 2005 to now). During the study period (1989–2015), urbanization in the CBYN progressed from the middle to mature stage, with a significant GDP increase (from 5.05×10^9 to 252.63×10^9 yuan between 1990 and 2015) and population growth (from 261.70×10^4 to 439.33×10^4 persons between 1990 and 2015). As suggested by Fang and Yu (2016), economic growth and urbanization in the CBYN will continue at a lower growth rate, and more attention will be paid to living quality and environment protection.

ESs are provided to human beings at varying scales, from local to global (Power, 2010), and all of us have the responsibility to protect ecosystems. Land use allocations and patterns have been proven to have a significant influence on ESs. However, most of us tend to retain the existing land use types to generate the most profit (Paterson and Bryan, 2012). Therefore, it is critical that policymakers have the knowledge on how to constitute land use structure in a more reasonable and beneficial manner for sustainable urban development. Based on the analysis results, we propose several suggestions for future urbanization and land use planning in different regions (urban areas, irrigated croplands, and mountain areas). These suggestions would also be useful for other urban agglomerations subject to rapid urbanization, and especially for those experiencing urbanization at the middle or mature stages.

Large increases in the provision service of crop production, and in the regulating services of carbon storage and nutrient retention could be obtained by reclaiming unused land and grassland into irrigated cropland with high water accessibility. However, this activity also brings the risk of significant damage to habitat quality for native species, especially on the fringe areas of cropland. Meanwhile, lower increases in crop production and carbon storage have been observed in interior croplands near urban areas, which are affected by human disturbance with decreased vegetation coverage. Therefore, we should encourage reclamation in irrigated areas, protect existing irrigated cropland from human intervention to improve their vegetation coverage, favor utilization of sparse grassland for reclamation to protect native habitats, and improve fertilizer efficiency in agricultural production to decrease water pollution.

Sand fixation, which is largely influenced by climate change at the macro scale, showed a significant increase in the northern and southern mountains. Deforestation is harmful to carbon storage, sand fixation, and habitat quality, while forest plantation demands large amounts of water and investment of funds. Thus, we should encourage reasonable forest plantation and protection, especially in the northern and southern mountains. Vegetation coverage increases (i.e., from unused land to grassland) should be encouraged to promote environment restoration and improve habitat quality. Declining climate regulating services have been observed accompanying urban expansion, which would increase environmental stressors, such as urban heat island, air pollution, and so on. The growth of ESs in developed urban areas demonstrates the effects of green infrastructure, and thus we should encourage the establishment of green belts in urban core areas to eliminate the negative effects of increased impervious surfaces. Considering the low contribution of unused land to ESs, new urbanization sites should be first sited on unused land. In future research, we would establish a more comprehensive ES set to represent the natural and socioeconomic characters of arid ecosystems and explore the potential impacts of different policy-based scenarios on future ES flow.

5. Conclusions

This study calculated one provision service (crop production), three regulating services (carbon storage, nutrient retention, and sand fixation), and one supporting service (habitat quality) for the city belt along the Yellow River in Ningxia (CBYN). We then analyzed the impacts of urbanization on these services and their relationships (trade-off, synergy, and bundle).

Between 1989 and 2015, the CBYN experienced rapid urbanization, with demographic growth, economic development, and significant land use change. In rural areas, massive reclamation and deforestation have occurred, and comprehensively caused increases in all services, except habitat quality. Urban expansion mainly occurred in developing urban areas through the occupation of cropland, and caused decreases in these services, except for sand fixation, which was more effected by air humidity at the macro scale. In developed urban areas, urban expansion from cropland and the growth of green infrastructure have occurred and comprehensively resulted in the increase of crop production, carbon storage, and sand fixation, and the decrease of nutrient retention and habitat quality.

Based on temporal changes in the five ESs, synergy relationships exist among them, except for between crop production and nutrient retention. Urban expansion enhances the correlations among regulating services, while green infrastructure in urban core areas decreases them. Based on the correlations among ES temporal changes, the five ESs were classified into two bundles with different spatial distributions. Crop production, carbon storage, and nutrient retention show significant increases in the plain fringe owing to reclamation; higher losses in urban expansion areas are due to the decrease in vegetation coverage. Sand fixation and habitat quality had higher increases in the northern and southern parts of the CBYN owing to the increase of vegetation coverage; higher losses occurred in expansion areas of cropland and urban area. Sand fixation was largely impacted by climate change at the macro scale and showed significant increases in the northern and southern mountains. Thus, we propose several suggestions for urban expansion and land use planning in different regions.

Acknowledgements

This research was supported by the National Natural Science Foundation of China [grant No. 41371176] and the Fundamental Research Funds for the Central Universities [grant No. lzujbky_2017_it91].

References

Alam, M.Z., Carpenter-Boggs, L., Rahman, A., Haque, M.M., Miah, M.R.U., Moniruzzaman, M., Qayum, M.A., Abdullah, H.M., 2017. Water quality and resident perceptions of declining ecosystem services at Shitalakka wetland in Narayanganj city. Sustain. Water Qual. Ecol. 9–10, 53–66.

Alberti, M., 2005. The effects of urban patterns on ecosystem function. Int. Reg. Sci. Rev. 28, 168–192.

Assessment, M.E., 2005. Ecosystems and Human Well-being: Current State and Trend: Synthesis. Island Press, Washington DC.

Azoogh, L., Khalili Moghadam, B., Jafari, S., 2018. Interaction of petroleum mulching, vegetation restoration and dust fallout on the conditions of sand dunes in southwest of Iran. Aeolian Res. 32, 124–132.

Bennett, E.M., Peterson, G.D., Gordon, L.J., 2009. Understanding relationships among multiple ecosystem services. Ecol. Lett. 12, 1394–1404.

Carreno, L., Frank, F.C., Viglizzo, E.F., 2012. Tradeoffs between ecnomic and ecosystem services in Argentina during 50 years of land-use change. Agric. Ecosyst. Environ. 154, 68–77.

Chapin III, F.S., Matson, P.A., Vitousek, P., 2011. Principles of Terrestrial Ecosystem Ecology. Springer Science & Business Media.

Chenoweth, J., Anderson, A.R., Kumar, P., Hunt, W.F., Chimbwandira, S.J., Moore, T.L.C., 2018. The interrelationship of green infrastructure and natural capital. Land Use Policy 75, 137–144.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem service and natural capital. Nature 387, 253–260.

Chuai, X., Huang, X., Lai, L., Wang, W., Peng, J., Zhao, R., 2013. Land use structure optimization based on carbon storage in several regional terrestrial ecosystems across China. Environ. Sci. Policy 25, 50–61.

Cord, A.F., Bartkowski, B., Beckmann, M., Dittrich, A., Hermans-Neumann, K., Kaim, A., Lienhoop, N., Locher-Krause, K., Priess, J., Schröter-Schlaack, C., Schwarz, N., Seppelt, R., Strauch, M., Václavík, T., Volk, M., 2017. Towards systematic analyses of ecosystem service trade-offs and synergies: Main concepts, methods and the road ahead. Ecosyst. Serv. 28 (C), 264–272.

Davies, C., Lafortezza, R., 2017. Urban green infrastructure in Europe: Is greenspace planning and policy compliant? Land Use Policy 69, 93–101.

Delphin, S., Escobedo, F.J., Abd-Elrahman, A., Cropper, W.P., 2016. Urbanization as a land use change driver of forest ecosystem services. Land Use Policy 54, 188–199.

Deng, X., Huang, J., Rozelle, S., Zhang, J., Li, Z., 2015. Impact of urbanization on cultivated land changes in China. Land Use Policy 45, 1–7.

Dong, L., Ma, J., 2012. Existing problems in the urban landscaping and greening management in Yinchuan city and the coping strategies. Anhui. For. Sci. Technol. 38, 61–63.

Dong, Z., 1998. Establishing statistic model of wind erosion on samll watershed. Bull. Soil Water Conserv. 18, 55–62 (in Chinese).

Du, X., Huang, Z., 2017. Ecological and environmental effects of land use change in rapid urbanization: the case of Hangzhou, China. Ecol. Indic. 81, 243–251.

Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), 2013. Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer.

Fang, C., Yu, D., 2016. China's New Urbanization: Developmental Paths, Blueprints and Patterns. Springer, Berlin Heidelberg, Beijing, China.

Gissi, E., Gaglio, M., Reho, M., 2016. Sustainable energy potential from biomass through ecosystem services trade-off analysis: the case of the Province of Rovigo (Northern Italy). Ecosyst. Serv. 18, 1–19.

Goldstein, J.H., Caldarone, G., Duarte, T.K., Ennaanay, D., Hannahs, N., Mendoza, G., Polasky, S., Wolny, S., Daily, Gretchen C., 2012. Integrating ecosystem-service tradeoffs into land-use decisions. Proc. Natl. Acad. Sci. 109, 7565–7570.

Haase, D., Schwarz, N., Strohbach, M., Kroll, F., Seppelt, R., 2012. Synergies, trade-offs, and losses of ecosystem services in urban regions: an integrated multiscale framework applied to the Leipzig-Halle region, Germany. Ecol. Soc. 17 (3), 22.

He, C., Liu, Z., Xu, M., Ma, Q., Dou, Y., 2017. Urban expansion brought stress to food security in China: evidence from decreased cropland net primary productivity. Sci. Total Environ. 576, 660–670.

He, C., Zhang, D., Huang, Q., Zhao, Y., 2016. Assessing the potential impacts of urban expansion on regional carbon storage by linking the LUSD-urban and InVEST models. Environ. Model. Softw. 75, 44–58.

Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., Lawrence, W.T., 2004. Global oatterns in human consumption of net primary production. Nature 249, 870–873.

Jansson, A., Polasky, S., 2010. Quantifying biodiversity for building resilience for food security in urban landscapes: getting down to business. Ecol. Soc. 15, 20.

Jiang, L., Xiao, Y., Rao, E., Wang, L., Ouyang, Z., 2016a. Effects of land use and cover change (LUCC) on ecosystem sand fixing service in inner Mongolia. Acta Ecol. Sinica 36, 3734–3747.

Jiang, W., Chen, Z., Lei, X., He, B., Jia, K., Zhang, Y., 2016b. Simulation of urban agglomeration ecosystem spatial distributions under different scenarios: a case study of the Changsha–Zhuzhou–Xiangtan urban agglomeration. Ecol. Eng. 88, 112–121.

Jopke, C., Kreyling, J., Maes, J., Koellner, T., 2015. Interactions among ecosystem services across Europe: bagplots and cumulative correlation coefficients reveal synergies, trade-offs, and regional patterns. Ecol. Indic. 49, 46–52.

Kantakumar, L.N., Kumar, S., Schneider, K., 2016. Spatiotemporal urban expansion in Pune metropolis, India using remote sensing. Habitat Int. 51, 11–22.

La Notte, A., D'Amato, D., Makinen, H., Paracchini, M.L., Liquete, C., Egoh, B., Geneletti, D., Crossman, N.D., 2017. Ecosystem services classification: a systems ecology perspective of the cascade framework. Ecol. Indic. 74, 392–402.

Larondelle, N., Haase, D., 2013. Urban ecosystem services assessment along a rural-urban gradient: a cross-analysis of European cities. Ecol. Indic. 29, 179–190.

Li, B., Chen, D., Wu, S., Zhou, S., Wang, T., Chen, H., 2016. Spatio-temporal assessment of urbanization impacts on ecosystem services: case study of Nanjing City, China. Ecol. Indic. 71, 416–427.

Li, C., Zhao, J., Xu, Y., 2017. Examining spatiotemporally varying effects of urban expansion and the underlying driving factors. Sustain. Cities Soc. 28, 307–320.

Lu, A., 2013. Impacts of global warming on air humidity in China. Ecol. Environ. Sci. 22, 1378–1380.

MA, 2005. Millennium Ecosystem Assessment: Ecosystems and Human Well-being: Synthesis. Island Press, Washington DC.

Mansoor, D.K., Leh, M.D.M., Cummings, E.C., Nalley, L.L., 2013. Quantifying and mapping multiple ecosystem services change in West Africa. Agric. Ecosyst. Environ. 165, 6–18.

Marsboom, C., Vrebos, D., Staes, J., Meire, P., 2018. Using dimension reduction PCA to identify ecosystem service bundles. Ecol. Indic. 87, 209–260.

McKinney, M.L., 2002. Urbanization, biodiversity, and conservation. BioSci. 52, 883–890.

Mouchet, M.A., Paracchini, M.L., Schulp, C.J.E., Stürck, J., Verkerk, P.J., Verburg, P.H., Lavorel, S., 2017. Bundles of ecosystem (dis)services and multifunctionality across European landscapes. Ecol. Indic. 73, 23–28.

Özcan, Z., Kentel, E., Alp, E., 2016. Determination of unit nutrient loads for different land uses in wet periods through modelling and optimization for a semi-arid region. J. Hydrol. 540, 40–49.

Paracchini, M.L., Zulian, G., Kopperoinen, L., Maes, J., Schägner, J.P., Termansen, M., Zandersen, M., Perez-Soba, M., Scholefield, P.A., Bidoglio, G., 2014. Mapping cultural ecosystem services: a framework to assess the potential for outdoor recreation across the EU. Ecol. Indic. 45, 371–385.

Paterson, A., Bryan, B.A., 2012. Food-carbon trade-offs between agriculture and reforestation land uses under alternate market-based policies. Ecol. Soc. 17, 21.

Pickard, B.R., Van Berkel, D., Petrasova, A., Meentemeyer, R.K., 2016. Forecasts of urbanization scenarios reveal trade-offs between landscape change and ecosystem services. Landsc. Ecol. 32, 617–634.

Polydoros, A., Cartalis, C., 2015. Assessing the impact of urban expansion to the state of thermal environment of peri-urban areas using indices. Urban Clim. 14, 166–175.

Power, A.G., 2010. Ecosystem services and agriculture: tradeoffs and synergies. Philos. Trans. R. Soc. B 365, 2959–2971.

Xu, Q., Yang, R., Dong, Y., Liu, Y., Qiu, L., 2016. The influence of rapid urbanization and land use changes on terrestrial carbon sources/sinks in Guangzhou, China. Ecol. Indic. 70, 304–316.

Queiroz, C., Meacham, M., Richter, K., Norstrom, A.V., Andersson, E., Norberg, J., Peterson, G., 2015. Mapping bundles of ecosystem services reveals distinct types of multifunctionality within a Swedish landscape. Ambio 44 (Suppl. 1), S89–101.

Radford, K.G., James, P., 2013. Changes in the value of ecosystem services along a rural–urban gradient: a case study of Greater Manchester, UK. Landsc. Urban Plan. 109, 117–127.

Raudsepp-Hearne, C., Peterson, G.D., Bennett, E.M., 2010. Ecosystem service bundles for analyzing tradeoffs in diverse landscapes. Proc. Natl. Acad. Sci. U. S. A. 107, 5242–5247.

Redhead, J.W., May, L., Oliver, T.H., Hamel, P., Sharp, R., Bullock, J.M., 2018. National scale evaluation of the InVEST nutrient retention model in the United Kingdom. Sci. Total Environ. 610–611, 666–677.

Roberts, A.D., Prince, S.D., Jantz, C.A., Goetz, S.J., 2009. Effects of projected future urban land cover on nitrogen and phosphorus runoff to Chesapeake Bay. Ecol. Eng. 35, 1758–1772.

Seppelt, R., Fath, B., Burkhard, B., Fisher, J., Grêt-Regamey, A., Lautenbach, S., Pert, P., Hotes, S., Spangenberg, J., Verburg, P.H., Van Oudenhoven, A.P.E., 2012. Form follows function? Proposing a blueprint for ecosystem service assessments based on reviews and case studies. Ecol. Complex 7, 327–337.

Seto, K.C., Guneralp, B., Hutrra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon poold. Proc. Natl. Acad. Sci. U. S. A. 109, 16083–16088.

Seto, K.C., Gueneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. PLoS ONE 6, e23777.

Schaldach, R., Alcamo, J., 2007. Simulating the effects of urbanization, afforestation and cropland abandonment on a regional carbon balance: a case study for Central Germany. Reg. Environ. Chang. 7, 137–148.

Svirejeva-Hopkins, A., Schellnhuber, H.J., 2008. Urban expansion and its contribution to the regional carbon emissions: using the model based on the population density distribution. Ecol. Model. 216, 208–216.

Terrado, M., Acuña, V., Ennaanay, D., Tallis, H., Sabater, S., 2014. Impact of climate extremes on hydrological ecosystem services in a heavily humanized Mediterranean basin. Ecol. Indic. 37, 199–209.

Tian, Y., Wang, S., Bai, X., Luo, G., Xu, Y., 2016. Trade-offs among ecosystem services in a typical Karst watershed, SW China. Sci. Total Environ. 566–567, 1297–1308.

Wang, W., Li, B.Y., Ren, Z.Y., 2017. Ecosystem service function evaluation: a case study of the yinchuan basin in China. Ecol. Eng. 106, 333–339.

Wu, W., Zhao, S., Zhu, C., Jiang, J., 2015. A comparative study of urban expansion in Beijing, Tianjin and Shijiazhuang over the past three decades. Landsc. Urban Plan. 134, 93–106.

Wu, Y., Zhang, X., Shen, L., 2011. The impact of urbanization policy on land use change: a scenario analysis. Cities 28, 147–159.

Yan, H.M., Li, J., Huang, H.Q., Tao, B., Cao, M.K., 2009. Assessing the consequence of land use change on agricultural productivity in China. Glob. Planet. Chang. 67, 13–19.

Yang, S., Zhang, A., Yang, Z., Yang, S., 2009. Agricultural non-point source pollution in Ningxia Irrigation District and preliminary study of load estimation methods. Sci. Agric. Sinica 42, 3947–3955.

Yang, W., Jin, Y., Sun, T., Yang, Z., Cai, Y., Yi, Y., 2017. Trade-offs among ecosystem services in coastal wetlands under the effects of reclamation activities. Ecol. Indic. http://dx.doi.org/10.1016/j.ecolind.2017.05.005.

Zhang, A., Yang, S., Zhang, Q., Yang, S., Yang, Z., 2008. Influencing factors and counter measures of irrigation return pollution in Ningxia Yellow River Water Irrigation District. Chin. J. Eco-Agric. 16, 1037–1042.

Zhang, C., Tian, H., Chen, G., Chappelka, A., Xu, X., Ren, W., Hui, D., Liu, M., Lu, C., Pan, S., Lockaby, G., 2012. Impacts of urbanization on carbon balance in terrestrial ecosystems of the Southern United States. Environ. Pollut. 164, 89–101.

Zhou, Z.X., Li, J., Guo, Z.Z., Li, T., 2017. Trade-offs between carbon, water, soil and food in Guanzhong-Tianshui economic region from remotely sensed data. Int. J. Appl. Earth Obs. Geoinform. 58, 145–156.

Zhu, W., YaoZhong, P., XiaoQiong, Y., GuoBao, S., 2007. Comprehensive analysis of the impact of climatic changes on chinese terrestrial net primary productivity. Chin. Sci. Bull. 52, 3252–3260.

Zope, P.E., Eldho, T.I., Jothiprakash, V., 2016. Impacts of land use–land cover change and urbanization on flooding: a case study of Oshiwara River Basin in Mumbai. India. Catena 145, 142–154.