Valuing natural capital amidst rapid urbanization: assessing the gross ecosystem product (GEP) of China’s ‘Chang-Zhu-Tan’ megacity

Ziying Zou, Tong Wu, Yi Xiao, Changsu Song, Kelin Wang and Zhiyun Ouyang

1 Key Laboratory of Agro-ecological Processes in Subtropical Region, Institute of Subtropical Agriculture, Chinese Academy of Sciences, Changsha, People’s Republic of China
2 State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, People’s Republic of China
3 College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, People’s Republic of China

E-mail: zyouyang@rcees.ac.cn and kelin@isa.ac.cn

Keywords: ecosystem services, urbanization, gross ecosystem product, natural capital, China, Yangtze River

Abstract

Gross Ecosystem Product (GEP) is an aggregate measure of the monetary value of final ecosystem services, or the direct benefits that people derive from nature. In this study, we focus on the ‘Chang-Zhu-Tan’ (CZT) urban agglomeration—an emerging megacity of over 15 million people situated on the Yangtze River—as a case study of the dynamics of ecological production amidst rapid urbanization. In this study, we couple a spatial-temporal analysis of regional ecological change based on remote-sensing data with economic valuation methods (e.g. travel cost method) using official statistics and survey data. We find that while the land cover of natural ecosystems decreased slightly between 2000 and 2015, their quality—and therefore economic value—greatly improved. From 2000 to 2015, the GEP of CZT increased by 56.77%. In particular, the value of regulating services grew by 7.43% (calculated using inflation-adjusted prices). GEP can reflect nature’s contribution to human well-being. At the same time, its long-term trends can serve as an indicator of the extent and quality of local and regional ecosystems, thereby providing a corrective or complement to more conventional measures of development. Although urbanization increases spatial constraints on the management of natural capital, progress in ecological protection and restoration can still improve the quality of ecosystems and the services they provide. Our study shows how GEP, and the value of natural capital it reflects, can grow amidst the pressures of rapid urbanization.

1. Introduction

Ecosystems and their processes not only create and maintain earth’s life support system, but also form the conditions necessary for human well-being. People and the biophysical environments in which they live constitute complex ‘economic-social-natural’ or ‘socio-ecological’ systems, in which anthropogenic impacts alter the conditions of the ecosystems that sustain human wellbeing [1–4]. It follows that a key goal of socioeconomic development is ensuring the quality and quantity of ecosystem services, which depend on the structure, processes, and functions of the surrounding natural landscape [5–7]. Studies of ecosystem services have become increasingly popular in the evaluation of environmental change and resource management [8]. Ecosystem services are the benefits people obtain from ecosystems [9], and can be classified into the supply of material services (e.g. food, water supply, hydro-electric power generation), regulating services (e.g. carbon sequestration, flood mitigation, soil retention), and nonmaterial services (e.g. eco-tourism, mental health). This has been a crucial concept linking nature to human wellbeing, providing a compelling rationale for the sustainable management of the biophysical environment.

Correspondingly, assessing the value of ecosystem services using market prices or non-market valuation
methods has been incorporated into urban, landscape, and regional planning [10, 11]. Urbanization has advanced economic, social, and cultural development, but at the same time, its processes have changed the structure of ecosystems [12]. Land use change such as built cover expansion and deforestation (as well as afforestation) constitute a major driver of the distribution of ecosystem services [13]. Urbanization not only influences the supply and use of ecosystem services but also the number, behavior, and distribution of the beneficiaries of those services through its demographic and economic impacts (e.g. growing populations with higher incomes).

In addition to being used at the national level to track macroeconomic progress, the Chinese government also uses gross domestic product (GDP) at the local (including provincial, prefecture, and county) level to track development and as an indicator of administrative performance. Unfortunately, a narrow focus on GDP growth has led to widespread ecological degradation. The adoption of GEP as another indicator is meant to help remedy this problem. Gross ecosystem product (GEP) is a concept similar to GDP, but does not claim to be a measure of social welfare. Rather, it is meant to be a practical accounting tool for benchmarking policies. Ouyang et al. first defined the concept of GEP as a measure that translates the value of ecological production into monetary terms, aggregating the monetary value of final ecosystem goods and services in a given region over an accounting period, typically one year [14, 15].

Traditional ecosystem service valuation usually focuses on evaluating a single service or a small set of services. GEP accounting aims to provide a comprehensive valuation of all relevant services that directly contribute to human wellbeing using an aggregate indicator. GEP is the sum of the monetary value of final ecosystem services (without intermediate or ‘supporting’ services to avoid economic double-counting). At present, there are numerous projects that have been carried out in China to explore GEP accounting across provinces, cities, and counties, and as a policy metric it is being tested in pilot programs by numerous local governments [16]. Focusing GEP accounting in urban agglomerations in particular can provide scientifically important as well as administratively instructive insights into managing ecosystems for human wellbeing amidst rapid urbanization—a process that will continue in China for decades, likely adding another 150 million city-dwellers over the coming decade [17]. In this study, we aim to explore how rapid urbanization impacts ecological production—as measured by GEP—at the regional scale, and the ways in which natural capital can be sustainably managed under such conditions. We answer these questions within an interdisciplinary framework, using a spatial-temporal analysis of land cover change coupled with economic valuation.

Our study focuses on the Chang-Zhu-Tan urban agglomeration (CZT). CZT is located in the central and eastern part of China’s Hunan Province and is comprised of three major cities: Changsha, Zhuzhou, and Xiangtan. China’s economic geography is usually divided into four major regions: East, West, Northeast, and Central. ‘The Rise of Central China’ is an important strategy adopted by the national government to promote the development of the six provinces belonging to this region (e.g. Hubei, Hunan, Jiangxi, Anhui, Henan, and Shanxi). The goal is to enhance economic competitiveness by stimulating new industries, as well as to promote sustainable development, of these core inland provinces. The strategy was first laid out in 2005, and as of 2015, the central region’s total economic output accounted for 20.3% of the country’s total economy (compared to 18.8% in 2005) [18].

As an ‘engine’ of ‘The Rise of Central China’ strategy, CZT is an emerging megacity (an urban area with a population greater than 10 million people) located at the intersection of the Beijing-Guangzhou Economic Belt, the Pan-Pearl River Delta Economic Zone, and the Yangtze River Economic Belt; this is a highly advantageous geographical position from the standpoint of future development. In 2007, CZT was selected for the first batch of Chinese cities to implement a reform program for the construction of a resource-saving and environment-friendly urban society. Protecting and enhancing the value of the natural capital is crucial to this aim. Analyzing the dynamics of GEP in this important, emerging megacity can make a contribution to understanding and managing CZT’s sustainable development, and also that of other fast-developing urban regions in China.

2. Methodology

2.1. Study area

The CZT urban agglomeration is located in the central-eastern part of Hunan Province, a central province in China, (figure 1) and straddles the Xiang River, one of the principal tributaries of the Yangtze River. Its geographical coordinates are 111°53′–114°15′ E, 27°53′–28°01′ N, and cover a total area of 28,000 km². CZT’s permanent resident population at the end of 2018 was 15.04 million people. The terrain surrounding the urban agglomeration is defined by diverse landforms and extensive surface water. The study area has a subtropical monsoon climate, with long summers and winters and short springs and autumns. The average annual temperature is 17.4 °C, and the average annual rainfall is 1475.8 mm. The natural ecosystems are predominately forests and shrublands land cover, with urban and farmland being the predominant anthropogenic land cover.

2.2. Data acquisition

Ecosystem classification data was based on a land cover dataset with 30 m resolution taken from...
Chinese environmental disaster monitoring satellites (HJ-1A/B) and U.S. terrestrial satellites (Landsat OLI). An object-oriented multi-scale segmentation change detection method was used to classify this remote sensing data into relevant categories. We conducted random sampling verification on remote sensing classification results, and the results showed that the accuracy of the first class reached 95% and that of the second class reached 89%. Aboveground biomass and vegetation coverage data came from the database of the Chinese Academy of Sciences and has been used in others studies of ecosystem services dynamics in the country [19]. Socio-economic data, hydrological data, meteorological monitoring data, and pollution monitoring data came from publicly available, official statistical sources maintained by the associated provincial and national government departments. Data on the biophysical and economic (e.g. prices and inflation) parameters of ecosystem services were also taken from official data sources as well as the relevant literature [20, 21]. The questionnaire data used to estimate the value of nonmaterial services came from Xiao et al (2016), which estimated the value of natural landscapes in China by choosing 29 natural landscapes (including landscapes in CZT) to conduct a questionnaire survey [22].

2.3. Ecosystem pattern and quality assessment method

The ecosystems of CZT can be divided into 8 primary types and a further 18 secondary types (table 1) [23, 24]. Using ArcGIS 10.3 for spatial data cutting, grid calculation, spatial analysis and statistics, the distribution and area composition of ecosystems, as well as their extents and rates of change, were calculated. Based on these calculations, we aimed to assess the spatiotemporal changes in the ecological structure of CZT between 2000 and 2015.

We calculated ecosystem area using the equation:

\[ P_{ij} = \frac{A_{ij}}{TA} \]

where \( P_{ij} \) presents the area proportion of type \( i \) ecosystem in \( j \) year, \( A_{ij} \) is the area of type \( i \) ecosystem in \( j \) year, and \( TA \) is the total area.

Ecosystem type transfer matrix can be used to analyze the composition of regional ecosystem changes and the direction of each type of transformation. It can reflect not only the composition of ecosystem types at the beginning and end of the study period, but also the changes in the transfer between ecosystem types. We used the Zonal Histogram tool in the ArcGIS10.3 Spatial Analyst module to get the ecosystem type transfer matrix.

We select above-ground biomass and vegetation coverage as the quality evaluation factors of the natural ecosystem in this study. The quality of forests and shrubs is evaluated by pixel-based relative biomass density, and the quality of grassland is evaluated by vegetation coverage [24]. Ecosystem quality classification standards are given by table 2.

\[ EQ_{ij} = \frac{B_{ij}}{CCB_j} \times 100\% \]
\[ EQ_{ij} = \frac{C_{ij}}{CCC_j} \times 100\% \]

Where \( EQ_{ij} \) is the ecosystem quality of pixel \( i \) in ecosystem \( j \), \( B_{ij} \) is the biomass of pixel \( i \) in ecosystem \( j \) (g/m\(^2\)), \( CCB_j \) is the biomass of the
Table 1. Ecosystem types.

| Primary types                | Secondary types                | Primary types                | Secondary types                |
|-----------------------------|--------------------------------|-----------------------------|--------------------------------|
| Forest                      | broadleaf forest               | Constructed wetland         | Reservoir                      |
|                             | needleleaf forest              |                             | Canal/Channel                   |
| Broadleaf and needleleaf mixed forest |                     |                             | Paddy field                     |
| Shrub                       | Evergreen broadleaf shrub     | Cropland                    | Dry farmland                    |
|                             | Deciduous broadleaf shrub     |                             | Orchard                         |
| Grassland                   | Tussock                        | Urban                       | Settlement                      |
| Natural wetlands            | Lake                           |                             | Urban green land                |
|                             | River                          |                             | Transportation and Mining field |

climax communities in ecosystems \( j \) \((g/m^2)\), \( C_{ij} \) is the vegetation coverage of pixel \( i \) in ecosystem \( j \), \( CCC_j \) is the coverage of the climax communities in ecosystems \( j \). \( B_{ij} \) and \( C_{ij} \) obtained by remote sensing retrieval. \( CCB_i \) and \( CCC_j \) obtained from the data of the long-term positioning observation station of the ecosystem and the survey of sample plots [25].

2.4. GEP accounting method

According to the characteristics of CZT’s ecosystem services, we applied different evaluation methods (table 3) [10, 14, 26]. Ecosystem services are closely related to their biomass, and the value of ecosystem services in different regions also change with their biomass [27]. Based on the correlation between biomass and coverage, along with the differences in biomass and coverage between different ecosystem types, we made amendments on the corresponding biophysical parameters of the various ecosystem services we modeled.

3. Results

3.1. Ecosystem structure and change

There is a diversity of ecosystems in the CZT region (figure 1), of which forests had the greatest coverage at 1047.35 km\(^2\), accounting for 36.6% of the region’s total area. Forests are mainly distributed in the eastern and southern areas of CZT. The forests in this area account for 76.12% of the total forests in CZT. Shrublands accounted for 22.65% of the total area of CZT, are mainly distributed in the surrounding areas of the main urban zone.

The municipal district of Changsha, Zhuzhou, Xiangtan constituted CZT’s urban core. The proportion of urbanized land in Changsha is up to 62.03%, followed by Xiangtan (37.87%), and Zhuzhou (27.09%). The proportion of urban land in other counties is less than 10%.

While farmlands accounted for 31.16% of CZT’s total area, they were mainly distributed to the east and west. The proportion of land covered by surface water and wetlands was 2.31%. Among these ecosystems, the largest area of natural wetland ecosystems (e.g. rivers, lakes, swamps) was located in the northern part of CZT, adjacent to Dongting Lake, and assorted artificial surface water and wetlands (e.g. reservoirs) were relatively evenly distributed across the region.

From 2000 to 2015, there were significant land cover changes in CZT (table 4). Urbanized land with an increase of 42.22%, the area covered by forests, grasslands, and wetlands also increased, but all by less than 2%. The coverage of shrubland and farmland decreased by 4.22% and 3.92%, respectively. Throughout the study area, a total of 1425.63 km\(^2\) underwent ecological change (figure 2), mainly due to the conversion of farmlands and forests into urbanized land and thickets into forests. The sum of these three types of transformations accounted for 55.6% of the total ecosystem change.

Additionally, the quality of ecosystems changed, with natural ecosystems showing an overall trend improvement from 2000 to 2015 (figure 3). The amount of area covered by ecosystems of good-quality and above increased by 1515.38 km\(^2\). 3495 km\(^2\) of inferior-quality and poor-quality ecosystems improved to intermediate quality. From the perspective of ecosystem types, in 2000, forest ecosystems were mainly of poor quality (30.26%) and inferior-quality (47.72%), the excellent-quality and good-quality were only 0.02% and 2.42%. By 2015, the area of poor-quality and inferior-quality forests had declined, and the area covered by excellent-quality (0.97%), good-quality (12.04%), and intermediate-quality (36.75%) forests had increased significantly. The change in shrubland ecosystem quality exhibited the same characteristics as forests. In 2000, CZT’s grasslands were dominated by good-quality (47.87%) and excellent-quality (45.93%) ecosystems. By 2015, the percentage of excellent-quality grassland had reached 69.23%.
Table 3. GEP accounting index and methods.

| Types of service               | Category of ecosystem services                                                                 | Biophysical value accounting methods                                                                 | Monetary value accounting methods                                                                 |
|-------------------------------|--------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Material services             | Production of forestry, agricultural, animal husbandry, and fishery goods                       | $E_{pro} = \sum_{i=1}^{n} Y_i$<br>where $E_{pro}$ is the total yield of ecosystem products (t/a), $Y_i$ is the yield of the $i$th product (t/a), $n$ is the products category. | Market value method<br>$V_m = \sum_{i=1}^{n} Y_i \times P_i$<br>where $V_m$ is the monetary value of material services (CNY), $P_i$ is the price of category $i$ ecosystem products (CNY/t). |
|                               | Water retention                                                                                   | Water balance equation<br>$C_{wr} = \sum_{i=1}^{j} A_i \times (P_i - R_i - ET_i) \times 10^{-3}$<br>Where $C_{wr}$ represents the water retention capacity (m$^3 \cdot$ y$^{-1}$), $P_i$ is the average annual rainfall (mm), $R_i$ is the surface runoff (mm), $ET_i$ is the evapotranspiration (mm), $A_i$ is the area of $i$-type ecosystem (m$^2$), $i$ is the type of ecosystem in the study area, $j$ is the total number of ecosystem types in the study area [24]. | Shadow engineering method Simulate the construction of water conservancy facilities with the same water storage capacity as the corresponding ecosystems.<br>$V_{wr} = C_{wr} \times C_{wr}$<br>Where $V_{wr}$ represents the accounting value of water retention (CNY/year), $C_{wr}$ is the average cost of reservoir construction. |
|                               | Soil retention                                                                                   | Universal soil loss equation (USLE)<br>$Q_s = R \times K \times LS \times (1 - C \times P)$<br>where $Q_s$ represents the soil retention capacity (t $\cdot$ ha$^{-1}$ $\cdot$ y$^{-1}$), $R$ is the rainfall erosivity factor, $K$ is the soil erodibility factor, $LS$ is the topographic factor representing the effect of the length of slope, $C$ is the vegetation cover factor, and $P$ is the practice factors of soil erosion control (e.g. terraced fields) [28, 29]. | Replacement cost method<br>$V_s = V_{sd} + V_{dpd}$<br>Where $V_s$ represents the accounting value of soil retention (CNY/year), $V_{sd}$ is the reduced cost of dredging (Yuan/year), $V_{dpd}$ is the reduced cost of non-point source pollution treatment (CNY/year).<br>$V_{sd} = \lambda \times (Q_s / \rho) \times c$<br>Where $\lambda$ is the sediment deposition coefficient [30], $\rho$ is the soil bulk density (t/m$^3$), $c$ is the cost of reservoir dredging per unit (CNY/m$^3$).<br>$V_{dpd} = \sum_{i=1}^{j} Q_s \times c_i \times p_i$<br>Where $c_i$ is the content of $N$ and $P$ in sediment, $p_i$ is the cost to treat waste water of nitrogen and phosphorus (CNY/t) [31]. |
Table 3. (Continued)

| Types of service    | Category of ecosystem services | Biophysical value accounting methods | Monetary value accounting methods |
|---------------------|---------------------------------|--------------------------------------|----------------------------------|
| **Flood mitigation**| The flood mitigated service provided by ecosystems includes runoff retention by vegetation and runoff retention by lakes. | $C_{fm} = C_{nc} + C_{ke}$ | **Shadow project method** |
|                     | $C_{nc} = \sum_{i=1}^{j} (P_i - R_i) \times A_i \times 1000$ | Where $C_{nc}$ is the total storage of flood water ($m^3$), $C_{ke}$ is the storage of flood water from natural vegetation ($m^3$), $C_{ke}$ is the storage of flood water by lakes ($m^3$) [32]. | $V_{fm} = C_{fm} \times C_{ave}$ |
|                     | Where $P_i$ is the average annual storm rainfall (mm), $R_i$ is the stormwater runoff (mm), $A_i$ is the area of $i$-type ecosystem ($m^2$), $j$ is the type of ecosystem in the study area, $A$ is the lake area [33, 34]. | | Where $V_{fm}$ represents the accounting value of flood mitigation (CNY/year), $C_{ave}$ is the average cost of reservoir construction. |
| **Air purification**| $C_{ap} = \sum_{i=1}^{m} \sum_{j=1}^{n} Q_{ij} \times A_i$ | Where $C_{ap}$ is the ecosystem air purification capacity (kg a$^{-1}$), $Q_{ij}$ is the purification amount per unit area of the $j$th air pollutant in the $i$-type ecosystem (kg km$^{-2}$ a$^{-1}$), $A_i$ is the area of type $i$ ecosystem ($km^2$) [35–39]. | We used the treatment cost of reducing air pollution to calculate the accounting value of air purification from vegetation. |
|                     | Where $C_{ap}$ represents the ecosystem water purification capacity (kg a$^{-1}$), $Q_{ij}$ is the purification amount per unit area of the $j$th air pollutant in the $i$-type ecosystem (kg km$^{-2}$ a$^{-1}$), $A_i$ is the area of type $i$ ecosystem ($km^2$). | $V_{ap} = \sum_{i=1}^{m} \sum_{j=1}^{n} C_{ij} \times c_j$ | Where $C_{ij}$ is the purification amount of the $j$th air pollutant in the $i$-type ecosystem (kg a$^{-1}$), $c_j$ is the cost of treating $j$-type air pollutants [40, 41]. |
| **Water purification** | $C_{wp} = \sum_{i=1}^{n} Q_i \times A$ | Where $C_{wp}$ represents the ecosystem water purification capacity (kg a$^{-1}$), $Q_i$ is the purification amount per unit area of type $i$ water pollutants [42–44], $i$ is the pollutant category, $A$ is wetland area ($km^2$). | We used water treatment costs for removing COD, ammonia nitrogen and total phosphorus to assess the accounting value of the water purification service. |
|                     | $V_{wp} = \sum_{i=1}^{n} Q_i \times c_i$ | Where $c_i$ is the unit treatment cost of type $i$ water pollutant (CNY/t) [40, 41]. | Where $c_i$ is the unit treatment cost of type $i$ water pollutant (CNY/t). |
| **Carbon sequestration** | We examined the dynamics of biomass carbon storage in ecosystems and estimated the average annual carbon sequestration of ecosystems. | $Q_{ce} = MCO_2 / MC \times A \times C_C \times (AGB_2 - AGB_3)$ | We set price equal to the cost of sequestering carbon via afforestation or reductions in industrial emissions. |
|                     | Where $Q_{ce}$ is the amount of carbon sequestration in ecosystems (tCO$_2$/y), $A$ is the ecosystem area ($km^2$), $C_C$ is the biomass-carbon conversion coefficient, $AGB_2$ and $AGB_3$ are the biomass levels at $t_2$ and $t_1$ years (t/km$^2$), $MCO_2 / MC = 44 / 12$ is the coefficient for C to CO$_2$ [45]. | Where $Q_{ce}$ is the amount of carbon sequestration in ecosystems (tCO$_2$/y), $A$ is the ecosystem area ($km^2$), $C_C$ is the biomass-carbon conversion coefficient, $AGB_2$ and $AGB_3$ are the biomass levels at $t_2$ and $t_1$ years (t/km$^2$), $MCO_2 / MC = 44 / 12$ is the coefficient for C to CO$_2$ [45]. | Where $Q_{ce}$ is the amount of carbon sequestration in ecosystems (tCO$_2$/y), $A$ is the ecosystem area ($km^2$), $C_C$ is the biomass-carbon conversion coefficient, $AGB_2$ and $AGB_3$ are the biomass levels at $t_2$ and $t_1$ years (t/km$^2$), $MCO_2 / MC = 44 / 12$ is the coefficient for C to CO$_2$ [45]. |
Table 3. (Continued)

| Types of service | Category of ecosystem services | Biophysical value accounting methods | Monetary value accounting methods |
|------------------|---------------------------------|-------------------------------------|---------------------------------|
| Climate regulation | The climate regulation service provided by ecosystems includes temperature retention by vegetation transpiration and temperature retention by water surface evaporation [24, 47]. |
| | $E_{cr} = E_{pt} + E_{we}$ |
| | $E_{pt} = \sum EPP_i \times A_i \times D \times \frac{10^6}{3600 \times r}$ |
| | $E_{we} = E_w \times q \times \frac{10^3}{(3600)}$ |
| | Where $E_{cr}$ represents the energy consumed by ecosystems to regulate climate (kWh), $E_{pt}$ is the energy consumed by ecosystem transpiration (kWh), $E_{we}$ is the energy consumed by ecosystem water evaporation (kWh), $EPP_i$ is the energy consumption per unit area of $i$-type ecosystem, $A_i$ is the area of $i$-type ecosystem (km$^2$), r is the air conditioning energy efficiency ratio: 3.0, D is the number of days the air conditioner is operated (d), $i$ is the type of ecosystem (forest, shrub, grassland), $E_w$ is the amount of water surface evaporation, q is the evaporation latent heat of water (J/g). |

Nonmaterial service | ecotourism |
|-----------------|-----------------|
| (i) The numbers of tourists that visited CZT between 2000 and 2015 was determined based on official statistics kept by Hunan Province [48, 49]. |
| (ii) The Yuelu Mountain scenic spot was identified as a representative sample point for questionnaire surveys [22]. |

Replacement cost method

The accounting value of climate regulation can be assessed using the power consumption required for artificial temperature adjustment (kWh), measured by electricity price (CNY/kWh).

$V_{cr} = E_{cr} \times P_e$

Where $P_e$ is the residential electricity price (CNY/kWh).

Zonal consumer cost model (the simplest implementation of the expenditure method, EM)

(i) Definition of geographical zones where visitors to the site come from.

(ii) Data collection concerning the number of visitors to the site in question from each defined zone and estimation of the visitation rates from each zone.

(iii) Calculation of the average consumer cost of the round trip from each zone to the recreation site, which includes direct travel cost and time cost, which comes from the questionnaire. [14]

*Due to data limitations, this water purification model focuses on wetlands and does not consider the potential purification services provided by other ecosystems such as forests. Additionally, we do not factor in the potential additional pollution caused by urban land cover transitions. Therefore, the value generated should be considered an underestimate.
Table 4. Changes in the areas of ecosystem types in CZT (2000–2015).

| Ecosystem types     | 2000     | % of total area | Area (km^2) | % of total area | Amount of change (km^2) | % change |
|---------------------|----------|-----------------|-------------|-----------------|------------------------|----------|
| Forest              | 10 184.12| 36.28           | 10 247.35   | 36.50           | 63.23                  | 0.62     |
| Shrub               | 6622.74  | 23.59           | 6343.14     | 22.60           | −79.6                  | −4.22    |
| Grassland           | 235.11   | 0.84            | 239.63      | 0.85            | 4.52                   | 1.92     |
| Natural wetland     | 453.7    | 1.62            | 460.61      | 1.64            | 6.91                   | 1.52     |
| Constructed wetland | 185.1    | 0.66            | 187.3       | 0.67            | 2.2                    | 1.19     |
| Cropland            | 9081.47  | 32.35           | 8725.91     | 31.08           | −355.56                | −3.92    |
| Urban               | 1261.88  | 4.50            | 1794.66     | 6.39            | 532.78                 | 42.22    |
| Bare land           | 48.51    | 0.17            | 74.04       | 0.26            | 25.53                  | 52.63    |

Figure 2. Ecosystem conversions in CZT from 2000 to 2015.

Figure 3. Changes in ecosystem quality in CZT from 2000 to 2015.
3.2. GEP values and changes
In 2015, the GEP of CZT was 466.04 billion Yuan (CNY), or approximately 66.61 billion USD at year-end exchange rates. Among them, the value of regulating services was the largest, accounting for 59.67%, and the value of material services and nonmaterial services accounted for 21.81% and 18.53%, respectively.

The region's GEP increased from 250.96 billion CNY in 2000–466.04 billion CNY. After accounting for inflation and comparing values based on inflation-adjusted prices, the actual growth rate over the 15 years was 56.77%. Among the three types of ecosystem services that constitute GEP, the biggest increase was the value of nonmaterial services. In 2000, the nonmaterial service value of CZT was 3.629 billion CNY, which accounted for only 1.47% of that year's GEP. Fifteen years later, the value of nonmaterial services had increased to 86.350 billion CNY, accounting for 18.53% of that year's GEP, an increase of 2279.56%. Secondly, the value of material services increased from 24.5 billion CNY to 101.62 billion CNY, an increase of 192.01% after adjusting for inflation. Finally, the value of regulating services increased by 7.43% from 2000 to 2015 (figure 4, table 5).

3.3. Regulating services value and changes
As the main component of GEP, we conducted a more detailed analysis of regulating ecosystems services. In 2015, the value of regulating services in CZT was 273.73 billion CNY, accounting for 59.29% of GEP. Of this value, climate regulation accounted for the largest share at 28.39%. This was followed by the value of water retention and flood mitigation, accounting for 20.77% and 5.91%, respectively. The largest increase came from carbon sequestration (increased by 53.04%), followed by the water retention (18.72%). The value of soil retention, flood mitigation, air purification, and water purification all increased, but the value of climate regulation decreased slightly (0.05%) over the 15-year period. Please find the spatial distribution for the above described regulating services in figure 5.

From the perspective of spatial distribution (figure 5(a)), the areas in CZT with the highest regulating services value in 2015 were in the east and south, including Luiyang City in Changsha and the three southern counties of Zhuzhou; these areas were also where forests were primarily distributed. The areas with the lowest value were mainly located in the central urban zone. According to our calculations, the spatial pattern and changes in the value of regulating services bear significant spatial relation to changes in the pattern and quality of the region's natural ecosystems.

Calculating the disaggregated regulating services value and their changes in each district and county, we found that those with the highest growth were distributed in the eastern and southern parts of CZT. These were also the areas with the most significant improvements in the quality of natural ecosystems (figure 6).

The changes in regulating services value were affected by changes in the area and quality of natural ecosystems. This study compared regulating services value changes caused by changes in those biophysical dimensions. The results show that from 2000 to 2015, the region's regulating services value recorded a net growth of 19.23 billion CNY. In aggregate, there was a 1.02 billion CNY increase due to the growth in the area of the natural ecosystems and a further 18.21 billion CNY increase due to improvements in ecosystem quality. However, in the six counties that compromised the most urbanized area, an increase of 2.39 billion CNY from increased ecosystem quality was somewhat offset by a 1.45 billion CNY shortfall caused by the shrinkage of ecosystem coverage.
| Type of services                  | Category of ecosystem services | Accounting items                      | 2015 | 2000–2015 (2015 constant price) | 2000–2015 (current price) |
|----------------------------------|---------------------------------|---------------------------------------|------|---------------------------------|---------------------------|
|                                  |                                 | Monetary value | % of total value | Amount of change | % change | Amount of change | % change |
| Material services                | Production of ecosystem goods   | Agricultural production                | 55.67 | 11.95 | 38.14 | 217.49 | 43.3 | 350.04 |
|                                  |                                 | Forestry production                    | 6.02  | 1.29  | 4.67  | 347.04 | 5.07 | 533.68 |
|                                  |                                 | Animal husbandry production            | 35.85 | 7.69  | 21.75 | 154.18 | 25.9 | 260.30 |
|                                  |                                 | Fishery production                     | 4.08  | 0.88  | 2.27  | 124.87 | 2.8  | 218.75 |
| Water retention                  |                                 | Water retention                        | 95.90 | 20.58 | 15.12 | 18.72 | 38.86 | 78.12 |
|                                  |                                 | Retained soil                          | 6.12  | 1.31  | 0.35  | 6.03  | 2.05 | 50.32 |
| Soil retention                   |                                 | Retained N                             | 2.44  | 0.52  | 0.14  | 6.03  | 1.29 | 112.06 |
|                                  |                                 | Retained P                             | 1.14  | 0.24  | 0.06  | 6.03  | 0.06 | 60.3 |
| Flood mitigation                 |                                 | Flood mitigation of lake               | 0.63  | 0.14  | 0.03  | 4.20  | 0.20 | 47.55 |
|                                  |                                 | Flood mitigation of vegetation         | 26.64 | 5.72  | 0.85  | 3.32  | 8.43 | 46.3 |
|                                  |                                 | SO2 purification                       | 0.41  | 0.09  | -0.0010 | -0.23 | 0.2040 | 99.53 |
| Regulating services             |                                 | NOx purification                       | 0.01  | 0.00  | -0.0001 | -0.74 | 0.0067 | 98.51 |
|                                  |                                 | Dust purification                      | 5.73  | 1.23  | 0.0218 | 0.38  | 0.0218 | 0.38  |
|                                  |                                 | COD purification                      | 0.10  | 0.02  | 0.0014 | 1.43  | 0.0508 | 102.85 |
|                                  |                                 | NH-N purification                     | 0.01  | 0.00  | 0.0001 | 1.43  | 0.0049 | 102.85 |
|                                  |                                 | TP purification                       | 0.02  | 0.00  | 0.0002 | 1.43  | 0.0002 | 1.43  |
| Water purification (wetland)     |                                 | Carbon sequestration                   | 7.86  | 1.69  | 2.72  | 53.04 | 4.24 | 116.94 |
|                                  |                                 | Vegetation transpiration               | 101.37 | 21.75 | -0.49 | -0.48 | -0.49 | -0.48 |
|                                  |                                 | Water surface evaporation              | 29.69 | 6.37  | 0.42  | 1.43  | 0.42 | 1.43  |
| Nonmaterial services            |                                 | Ecotourism                             | 86.35 | 18.53 | 82.72 | 2279.56 | 82.66 | 2240.64 |
| Grand Total                     |                                 | Ecotourism                             | 466.04 | 100   | 168.77 | 56.77 | 215.08 | 85.7 |

Table 5. GEP accounting in CZT urban agglomeration (Billion CNY).
4. Discussion

Urbanization has been the most important driver of changes in the composition and pattern of CZT’s ecosystems. China’s 10th Five-Year Plan (FYP), which started in 2001, proposed the implementation of a national urbanization strategy and 2015 was the end year of the 12th FYP. Our study period corresponded to this timeframe. Over this 15-year period between 2000 and 2015, the contribution of urbanized land expansion to the changes in the region’s ecosystems reached 43.36%. These changes were, to a degree, counteracted by ecological protection and restoration projects, such as returning farmland to forests through reforestation and afforestation, which accounted for 30.92% of the ecosystem transitions over the study period. A number of major ecological protection construction projects in China (e.g. Grain-for-Green Project, Non-Commercial Forest Construction Project) were implemented around the year 2000. The period from 2000 to 2015 was one of significant change in China’s economy and ecological protection. The large amount of farmland that has been lost has prompted the government to implement policies such as ‘Permanent Basic Farmland’. This policy aims to reduce further farmland loss and ensure agricultural production by delimiting rural areas that cannot be used for other purposes and by

Figure 5. Accounting values for CZT based on the spatial distribution of regulating ecosystem services.
promoting farmland reclamation. In CZT, the ecosystem structure changes due to farmland reclamation likely reflects this policy emphasis, with farmland reclamation accounting for 12.34% of total land cover change in the region.

Studies of other urban agglomerations in China (such as the Beijing-Tianjin-Hebei agglomeration and the Yangtze River Delta agglomeration) [50–52] have found that most of these burgeoning megacities have experienced land use/cover changes in which significant amounts of farmland have been converted to urbanized land (e.g. impervious surfaces). But in the process of CZT’s rapid urbanization, the area that changed from forests to urbanized land accounted for more than 20% of the total urbanized area, much higher than in other Chinese urban agglomerations. This is likely related to the topographical differences of the region where the processes of urban agglomeration are taking place. Most other major urban agglomerations in China are located in flatter terrain, whether plains (e.g. Beijing-Tianjin-Hebei) or deltas (e.g. the Yangtze River Delta and Pearl River Delta). CZT is nestled in a hilly region, with surrounding pockets of settlement and mostly low-quality and fragmented forests.

Urbanization also promotes the transfer of rural population into urban zones, which reduces anthropogenic pressures on natural ecosystems and is therefore conducive to the restoration of forests, grasslands, and wetlands. Between 2000 and 2015, CZT’s urban share of total population increased from 30.57% to 71.65% [48, 49]. In light of the results of this study, it can be seen that with the increase in urban population density and the decline in rural population density, synergy with ecological protection and restoration projects
increased the area and quality of natural ecosystems, which in turn led to the growth of regional GEP. Urbanization can also cause ecological problems such as biodiversity loss and environmental pollution. However, not all of these problems are captured by GEP because it is an economic approximation of the positive contribution of ecosystems to human well-being. The purpose of GEP is not to measure potential offsets to negative externalities of development, but to evaluate the effectiveness of ecosystem protection in generating socially-relevant benefits. Nonetheless, if problems such as environmental pollution and biodiversity loss were to reach an intensity and scale sufficient to measurably affect the pattern and quality of ecosystems in a given landscape or region, GEP would likely decrease.

The effectiveness of ecological protection is not only reflected in the area changes of natural ecosystems (e.g. forests, shrub, grassland and natural wetland), but also in the improvement of their quality. Due to the spatial constraints imposed by rapid urbanization, it is difficult to expand the area of natural vegetation, but ecosystem services can be improved by improving the quality of existing ecosystems. The results of this study show that the area of natural ecosystems in CZT decreased during the 15 years of the study period, but the quality of natural ecosystems improved significantly. Changes in the region's GEP show that under circumstances that limit the coverage of restoration, improving the quality of existing ecosystems can still increase the total value of natural capital.

The composition of CZT's GEP changed over the 15 years. In 2000, the value of regulating services accounted for a large proportion of GEP, reaching 88.75%, while the value of material services and nonmaterial services accounted for only 9.78% and 1.47%. Fifteen years later, the value of nonmaterial services increased greatly, accounting for 18.53% of GEP. This was mainly because of economic development brought about by rapid urbanization improved the living standards of local residents as well as visitors from other parts of the country, and the demand for recreational tourism increased accordingly. In the process of rapid urbanization, the addition and upgrading of infrastructure made tourism much more accessible, and the corresponding growth of regional traffic led to a significant growth in the number of tourists to natural landscapes.

China's government now requires that ecological benefits be included in the assessment of local government performance. In parallel with assessing economic development using GDP, the addition of GEP as a benchmark for development and administrative performance can promote investments in natural capital. The growth of GDP and decline of GEP (Figure 7) in a given region indicates that economic development has come at the cost of ecological damage; if GDP declines and GEP grows, this may mean that ecological protection has unduly constrained economic development. Based on this hypothesis, many local governments in China have adopted GEP as an exploratory policy.

Calculating the value of ecosystem services has become a growing field of research, with important practical corollaries. Previous studies have calculated ecosystem service values based on the unit area value of different types of ecosystems, but this method cannot clarify the value differences of the same type of ecosystem in different regions. GEP accounting is still at an early stage of development, but it has absorbed previous research experience in accounting methods (such as the Millennium Ecosystem Assessment and the United Nation's System of Environmental Economic Accounts). The results of this study indicate that it is feasible to produce an estimate of GEP with available data and methods in a rapidly urbanizing region, but there remains space for improvement.

First, the comprehensive value of regional ecological production, which GEP aims to capture, should include the value of material and nonmaterial services. Although both of these have been included in this study, they are relatively coarse approximations due to the limitation of data. The value of material services uses the reported estimates of official statistics for agriculture, forestry, animal husbandry and fishery products, while the value of cultural services is reflected in the value generated by ecotourism. The difficulty of integrating these accounts into GEP analysis is to separate the contribution of natural ecological processes from valued-added by artificial inputs (e.g. fertilizers, machinery). Additionally, we used the annual tourist arrivals from official statistics to estimate the value of nonmaterial services, in conjunction with data from a previously published study. However, the current statistics do not have a detailed classification of visitor numbers or intention (i.e. if it was the 'natural' part of the site that drew their visit). Nor do these statistics tell us the value-added from non-natural infrastructure at the tourist sites, for instance facilities. Filling these data gaps will require thorough site-specific data gathering and survey work, preferably done on a regular basis using consistent empirical standards.

Therefore, this study focuses on the core part of the region's GEP, which is the value of regulating services. In urbanized areas, these regulating services together form 'green infrastructure' that protects human well-being, particularly from environmental shocks such as extreme weather events as well as progressive stresses such as the climate change exacerbated urban heat island effect. At the same time, the quantity and quality of regulating services are good indicators of ecosystem functioning and resilience.
Finally, some of the data and models used in the current GEP biophysical calculations have shortcomings, mainly due to the limitations of the relevant ecological-environment monitoring system in terms of the frequency and resolution of data collection. For example, the same vegetation cover may have different biomass levels in different years and under different climatic conditions. However, the biomass data we used did not incorporate the impact of climate change. Nonetheless, this is an increasingly important phenomenon that may have significant implications for GEP and therefore merits further research. However, with additional case studies and further advances in relevant technologies, these restrictions will gradually slacken and calculations of GEP will more accurately reflect the value of natural capital in this and other regions.

5. Conclusions

The improvement and degradation of a landscape’s or region’s ecosystems directly affect their ability to provide the and services necessary for human well-being. In the long run, protecting and investing in natural capital will be crucial to sustainable development, or ensuring that the opportunities of future generations are not compromised by the activities of current generations. Ecosystem protection and restoration are essentially processes of safeguarding and increasing ecosystem area, improving ecosystem quality, and improving the ability of the ecosystem to provide relevant goods and services. In terms of management, GEP can be used to evaluate the effectiveness of policies and the performance of administrators, as a reference for urban planning, and as an economic baseline to determine the amount of eco-compensation (i.e. monetary transfers to incentivize stakeholders to engage in environmentally-beneficial activities).

The results of our study of the CZT megacity show that GEP can reflect the contribution of a region’s ecosystems to human well-being and economic development, and that the trend of GEP over a medium-term horizon can reflect changes in the area and quality of a region’s ecosystems—even amidst rapid urbanization that places spatial limitations on the protection and restoration of natural ecosystems. Our results show that despite these limitations, GEP, and therefore the value of nature-based contributions to human wellbeing, can still improve if the quality of its existing ecosystems is enhanced. These findings may be instructive not only for CZT’s future development, but also for policies that aim to advance the sustainability of other rapidly urbanizing regions as well.

Acknowledgments

This research was funded by grants from the State Key Program of National Natural Science Foundation of China (71533005) and the National Key Research and Development Program of China (2016YFC0503400).

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iD

Ziying Zou https://orcid.org/0000-0003-1729-364X

References

[1] Ma S J and Wang R S 1984 The social-economic–natural complex ecosystem Acta Ecol. Sinica 4 1–8
[2] Levin S, Xepapadeas T, Crépin A S, Norberg J, Zeeuw A D, Folke C and Daily G 2013 Social-ecological systems as complex adaptive systems: modeling and policy implications Environ. Dev. Econ. 18 111–32
[3] Folke C 2006 RESILIENCE: THE EMERGENCE OF A PERSPECTIVE FOR SOCIAL-ECOLOGICAL SYSTEMS ANALYSES Glob. Environ. Change-Human and Policy Dimensions 16 253–67
[4] Gunderson L H and Holling C S 2003 Panarchy: Understanding Transformations in Human and Natural Systems Biological Conservation 114 2
[5] De Groot R S, Wilson M A and Boumans R M J 2002 A typology for the classification, description and valuation of ecosystem functions, goods and services Ecol. Econ. 41 393–408
[6] Tschamntke T, Klein A-M, Krauss A, Steffan-Dewenter I and Thies C 2005 Landscape perspectives on agricultural intensification and biodiversity – ecosystem service management Ecol. Lett. 8 837–47
[7] Wu J 2013 Landscape sustainability science: ecosystem services and human well-being in changing landscapes Landscape Ecol. 28 999–1023
[8] Troy A and Wilson M A 2007 Mapping ecosystem services: practical challenges and opportunities in linking GIS and value transfer Ecol. Econ. 60 435–49
[9] Millennium Ecosystem Assessment 2001 Ecosystems and Human Well-being: A Framework for Assessment (The Millennium Ecosystem Assessment Washington, DC: Island Press)
[10] Boyer T and Polasky S 2004 Valuing urban wetlands: A review of non-market valuation studies Wetlands 24 744–55
[11] Groot R S, De, Alkemade R, Braat I, Hein I. and Willemsen L 2010 Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making Ecol. Complexity 7 260–72
[12] Eigenbrod F et al 2011 The impact of projected increases in urbanization on ecosystem services Proc. Biol. Sci. 278 3201–8
[13] Millennium Ecosystem Assessment 2005 Ecosystems and Human Well-being: Scenarios: Findings of the Scenarios Working Group (The Millennium Ecosystem Assessment Washington, DC: Island Press)
[14] Ouyang Z et al 2020 Using gross ecosystem product (GEP) to value nature in decision making Proc. Natl Acad. Sci. USA 117 1493–601
[15] Ouyang Z, Zhu CQ, Yang GB, Xu WH, Zheng H, Zhang Y and Xiao Y 2013 Gross ecosystem product: concept, accounting framework and case study Acta Ecol. Sinica 33 6747–61
[16] IUCN Gross Ecosystem Product (GEP) (Available at: http://www.iucn.org/asia/countries/china/gross-ecosystem-product-gep%EF%BC%89)
[17] United Nations 2018 World Urbanization Prospects: The 2018 Revision World Urbanization Prospects: The 2018 Revision (Department of Economic and Social Affairs, Population Division, United Nations New York)

[18] National Development and Reform Commission 2016 The 13th five-year plan for promoting the rise of Central China

[19] Ouyang Z Y et al 2016 Improvements in ecosystem services from investments in natural capital Science 352 1455–5

[20] National Forestry Administration 2008 LYT 1721–2008 Forest Ecosystem Service Function Evaluation Specification (Beijing: China Standard Press)

[21] Ministry of Water Resources of the People's Republic of China 2002 Water Resources Construction Project Budget Quota (Zengzhou: Yellow River Water Conservancy Press)

[22] Xiao Y et al 2016 Evaluating value of natural landscapes in China China. Geog. Sci. 26 244–55

[23] Glenn E, Neuenwander A, Vierling L A, Spaele L, Li A, Shinneman D J, Pilliod D S, Arkle R S and McIlroy S K 2016 Landsat 8 and ICESat-2: performance and potential synergies for quantifying dryland ecosystem vegetation cover and biomass Remote Sens. Environ. 185 233–42

[24] Ouyang Z et al 2013 China's Ecological Environment Evolution and Evaluation: China's Ecosystem Patterns, Quality, Service and Evaluation (Beijing: Science Press)

[25] China ecosystem assessment and ecological security database (http://www.ecosystem.csdb.cn)

[26] Polasky S, Nelson E, Pennington D and Johnson K A 2011 Evaluation of land-use change on ecosystem services, biodiversity and returns to landowners: a case study in the state of Minnesota Environ. Resour. Econ. 48 219–42

[27] Li B 2000 Course Materials for the 21st Century, Ecology (Beijing: Higher Education Press)

[28] Wischmeier W H and Smith D D 1978 Predicting Rainfall Erosion Losses: A Guide to Conservation Planning (Washington, DC: U.S. Department of Agriculture)

[29] Rao E M, Ouyang Z, Yu X and Xiao Y 2014 Spatial patterns and impacts of soil conservation service in China Geomorphology 207 64–70

[30] Ouyang Z et al 1999 A primary study on Chinese terrestrial ecosystem services and their ecological-economic values Acta Ecol. Sinica 19 607–13

[31] Zha L 2009 Study on the Soil Losses and Eutrophication in the Songhua Lake Basin (http://cdmd.cnki.com.cn/Article/CDMD-10183-2009051559.htm) (Changchun: Jilin University)

[32] Xiao Y, Ouyang Z, Xu W, Xiao Y, Zheng H and Xian C 2016 Improvements in ecosystem services Green Growth that Works: Natural Capital Policy and Finance Mechanisms around the World (http://www.cbnrn.com.cn/article/CDDM-10183-2009051559.htm)

[33] Rao E M et al 2014 Status and dynamics of China's lake water regulation Acta Ecol. Sinica 34 6225–31

[34] Wang S M and Dou H S 1998 Records for Chinese Lakes (Beijing: Science Press)

[35] Ma X H et al 2002 The value of vegetation purified air and its measure in Xi'an City J. Arid Land Resour. Environ. 16 85–86

[36] Feng C Q 1992 Study on Green Environment Effect (Beijing: China Environmental Science Press)

[37] Yuan Z K et al 2005 Research on SO2 cleansing ability of the air of forest biology system and S absorbed potential Human Forestry Sci. Technol. 32 1–4

[38] Xiao J W et al 2011 Evaluation for service functions of urban forest ecosystem in Guangzhou Chin. Agric. Sci. Bull. 27 27–35

[39] Liu X J et al 2015 Evaluation of the grassland ecosystem services of Wutai Mountain Area J. Arid Land Resour. Environ. 29 24–29

[40] National Development and Reform Commission Notice on the adjustment of pollution discharge fee collection standards and other related issues (http://zcfg/201410/201410016_629060.html)

[41] National Development and Reform Commission Notice on the adjustment of pollution discharge fee collection standards and other related issues (http://www.ndrc.gov.cn/ zcfg/20140903_624939.html)

[42] Zhao Y et al 2002 The effect of greenland on absorbed dust and its assessment method. J. Huauchong Agric. 24 582–586

[43] Xin F N 2004 A study on the function of Lake Dongting's Wetland in removing pollutants FUJIAN Geogr. 19 1–5 12–12

[44] He J N et al 2008 Purification function and value of Dongting Lake Journal. Central South Univ. For. Technol. 28 24–28 34–34

[45] Keith H, Mackey B G and Lindenmayer D B 2009 Re-evaluation of forest biomass carbon stocks and lessons from the world’s most carbon–dense forests Proc. Natl Acad. Sci. 106 11635–40

[46] Lu F et al 2018 Effects of national ecological restoration projects on carbon sequestration in China from 2001 to 2010 Proc. Natl Acad. Sci. USA 115 4039–44

[47] Zhang B, Gao JX, Xie GD and Wang YP 2012 Preliminary evaluation of air temperature reduction of urban green spaces in Beijing Acta Ecol. Sinica 30 7698–705

[48] Hunan Provincial Bureau of Statistics 2001 Hunan Statistical Yearbook (Beijing: China Statistics Press)

[49] Hunan Provincial Bureau of Statistics 2016 Hunan Statistical Yearbook (Beijing: China Statistics Press)

[50] Li Z, Sun Z, Tian Y, Zhong J and Yang W 2019 Impact of land use/cover change on Yangtze river delta urban agglomeration ecosystem services value: temporal–spatial patterns and cold/hot spots ecosystem services value change brought by urbanization Int. J. Environ. Res. Public Health 16 123

[51] Zhang Y S, Zhao L, Liu J, Liu Y and Li C 2015 The impact of land cover change on ecosystem service values in urban agglomerations along the coast of the Bohai Rim, China Sustainability 7 10365–87

[52] Gao J, Yu Z, Wang L and Vejre H 2019 Suitability of regional development based on ecosystem service benefits and T losses: A case study of the Yangtze River Delta urban agglomeration China Ecol. Ind. 107 105379

[53] Ouyang Z Y et al 2019 China: designing policies to enhance ecosystem services Green Growth that Works: Natural Capital Policy and Finance Mechanisms around the World (http://www.cbnrn.com.cn/article/CDDM-10183-2009051559.htm)

[54] Costanza R et al 1997 The value of the world's ecosystem services and natural capital Nature 387 253–60

[55] Costanza R et al 2011 Valuing ecosystem services and natural capital: a spatially explicit benefit transfer approach Environ. Manage 45 1271–85

[56] Xie G D et al 2005 Ecological assets valuation of the Tibetan Plateau J. Nat. Resour. 18 189–96

[57] Xie G D et al 2003 The economic evaluation of grassland ecosystem services in Qinghai - Tibet Plateau J. Mt. Sci. 20 50–55

[58] National Development and Reform Commission Notice on the adjustment of pollution discharge fee collection standards and other related issues (http://zcfg/201410/201410016_629060.html)

[59] System of Environmental-Economic Accounting 2012 Experimental ecosystem accounting-white cover publication

[60] Andersson E, Barthel S, Borgström S, Colding J, Elmquist T, Folke C and Gren Å 2014 Reconnecting cities to the biosphere: stewardship of green infrastructure and urban ecosystem services AMBIO 43 445–53

[61] Lovell S T and Taylor J R 2013 Supplying urban ecosystem services through multifunctional green infrastructure in the United States Landscape Ecol. 28 1447–63

[62] Schaffler A and Swilling M 2013 Valuing green infrastructure in an urban environment under pressure — the Johannesburg case Ecol. Econ. 86 246–57