Identification of Ecosystem Service Bundles and Driving Factors in Beijing and its Surrounding Areas

Identification of Ecosystem Service Bundles and Driving Factors

Research Paper

Abstract

In high-intensity human activity areas, such as metropolises, rapid changes in land use, agricultural intensification, and population urbanization have resulted in profound and complex transformations in socio-economic ecosystems. The study of ecosystem service (ES) bundle is conducive to various aspects, such as determination of the variation characteristics of ES; identification of the mechanism of interdependence within ES; and driving mechanism of socio-economic-ecological factors to ES to maintain the sustainable development of the region. The research areas include Beijing and its surrounding areas. Ten ES, including grain providing (GP), water yield (WY), carbon sequestration (CS), soil retention (SEC), purified water service, cultural services, and habitat quality (HQ) were selected for valuing and mapping. The ES paired trade-offs and synergetic relationship, bundle was determined, and the bundles’ service types and spatial distribution characteristics were analyzed. Subsequently, GeoDetector was used for detecting the factors affecting the bundles’ distribution. Results showed that WY, CS, SEC, and HQ were bounded by Tai-hang and Yanshan Mountains. Among the 45 pairs of ES, 38 pairs bore significant correlation. Multiple services had different degrees of positive and negative correlations with other services. For example, GP had a high positive correlation with WY while bearing a high negative correlation with HQ. Seven bundles include SEC, culture, urban, HQ, agriculture, water supply and purification, and water purification. Various factors played decisive roles in the bundles’ spatial distribution. Among them, the investment capacity and demand for ecological protection depend on the level of GDP and POP. The formulation of agricultural planting plans is inseparable from Tadem. ASL is directly related to species richness. Results indicate that bundle research can identify the areas of the formation of co-occurrence of trade-offs and synergies and support the formulation of ES optimal management plans for different regions through further research of the driving mechanism.

Keywords

Ecosystem Service Bundle; GeoDetector; Principal Component Analysis; Trade-offs and Synergies

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Abstract: In high-intensity human activity areas, such as metropolises, rapid changes in land use, agricultural intensification, and population urbanization have resulted in profound and complex transformations in socio-economic ecosystems. The study of ecosystem service (ES) bundle is conducive to various aspects, such as determination of the variation characteristics of ES; identification of the mechanism of interdependence within ES; and driving mechanism of socio-economic-ecological factors to ES to maintain the sustainable development of the region. The research areas include Beijing and its surrounding areas. Ten ES, including grain providing (GP), water yield (WY), carbon sequestration (CS), soil retention (SEC), purified water service, cultural services, and habitat quality (HQ) were selected for valuing and mapping. The ES paired trade-offs and synergetic relationship, bundle was determined, and the bundles' service types and spatial distribution characteristics were analyzed. Subsequently, GeoDetector was used for detecting the factors affecting the bundles' distribution. Results showed that WY, CS, SEC, and HQ were bounded by Tai-hang and Yanshan Mountains. Among the 45 pairs of ES, 38 pairs bore significant correlation. Multiple services had different degrees of positive and negative correlations with other services. For example, GP had a high positive correlation with WY while bearing a high negative correlation with HQ. Seven bundles include SEC, culture, urban, HQ, agriculture, water supply and purification, and water purification. Various factors played decisive roles in the bundles’ spatial distribution.
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**Keywords:** Ecosystem Service Bundle; GeoDetector; Principal Component Analysis; Trade-offs and Synergies

1 Introduction

Ecosystem services (ES) indicate the benefits that humans directly or indirectly receive from the ecosystem (Costanza et al., 1997). Any of these ES is associated with other services (Bennett and Balvanera, 2007) and constitutes “trade-offs and synergies” among the services (Rodriguez et al., 2006). Trade-offs represent the supply of certain types of ES, which will decrease with the increase in other types of ES (or increase with the decrease in another ES). Conversely, synergies are formed when the supply of the two services simultaneously increases or decreases. Trade-offs and synergies are typical spatiotemporal features presented by ES, usually between supply and regulating services, because both types of ES support different targets (Bennett et al., 2009). The changes in trade-offs and synergies among ES can be based on the driving mechanism of ES (Bennett et al., 2009). Determining the drivers and driving mechanisms of ES is key to understanding the possibility of forming trade-offs and synergies (Dade et al., 2018). Most current studies provide a simple description of trade-offs and synergies among ES and lack an in-depth exploration of the drivers and mechanisms.

Bundle constitution refers to the repetitive spatiotemporal appearance of trade-offs and synergies of ES (Cord et al., 2017; Raudsepp-Hearne et al., 2010). Such constitution is primarily used to identify trade-offs and synergies among multiple ES (Turner et al., 2014). The formation, spatial distribution and temporal evolution of bundles are influenced by a combination of drivers (Raudsepp-Hearne et al., 2010; Kong et al., 2018). Research on bundle contributes to the presentation of the internal connection among various ES and in deepening the understanding of supply, demand, and transport mechanism of ES (Bai et al., 2011; Bennett et al., 2009). Given the influence of variational drivers and the mechanism to relate these drivers to ES results, trade-offs and
synergies among ES are directly manifested in differences in the spatial distribution of bundles and in the intrinsic composition of ES. Leaving these drivers and mechanisms out of consideration is likely to result in ill-informed management decisions and reduction of ES supply (Dade et al., 2018).

Numerous studies showed that climate, vegetation types, and biodiversity are important driving factors for bundles (Lamarque et al., 2014; Feng et al., 2017; Liu et al., 2017). In high-intensity human activities such as cities and surrounding areas, socio-economic factors also strongly influenced the spatial distribution of service clusters (Hamann et al., 2015; Baró et al., 2017). Dittrich et al. (2017) used an artificial neural network to identify ecosystem service bundles and social environment indicator bundles and calculated the coincidence degree to identifying their intrinsic links by overlapping methods. Yang et al. (2015) conducted a qualitative analysis of 12 ecosystem services in 22 prefecture-level cities in the lower reaches of the Yangtze River, which pointed out that compared with environmental factors, socio-economic factors could explain the formation of the bundle at the scale of urban agglomerations. Bundle recognition and spatial mapping have many research achievements at present; however, research on the time evolution and the driving factors of bundles are still limited (Turner et al., 2014). Thus, further research is needed.

Intensive human activities cause profound and complicated transformations in land use and landscape pattern (Bryan et al., 2016), among which the intensification of agricultural production and the urbanization of population have dramatically changed the intensity and nature of ES supply and demand, thereby cutting off the direct relations between human beings and the ecosystem (Cumming et al., 2014). Management and optimization from the ES perspective should be conducted (Yang et al., 2018). The bundle, which refers to the production combination of ES, can reflect the requirements of stakeholders on ES (Simpson et al., 2016), which can serve as important bases for ES management and optimization.

Beijing and its surrounding areas, which are China’s “capital economic circle,” are the country’s crucial populated region and economic growth pole that bear intense and frequent human activities, drastic change in land use, and evident trend in agricultural intensification and population urbanization. Environmental problems, such as air pollution, soil erosion, water scarcity, and biodiversity loss, occur in the region (Li et al., 2017; Yang et al., 2019), thereby resulting in severe ES losses (Zhang et al., 2017). In China, the coordinated development of the Beijing-Tianjin-Hebei region has been lifted to a national strategy. The construction of ecological
civilization has become a social consensus. The requirements for alleviating ecological pressure and solving environmental problems in the region are becoming increasingly urgent. Consequently, research on bundle evolution mechanism and the driving factors in Beijing and its surrounding areas is indispensable and imperative.

In view of the limitations of the current bundle research, Beijing and its surrounding areas, which are China’s capital economic circle, are selected as the research areas for analyzing trade-offs and synergies of ES and the driving mechanism of their bundles in high-intensity human activity areas. Specifically, such research needs to determine: (1) the spatial distribution, trade-offs of ES; (2) further partition of various bundles based on the trade-offs and synergies of ES; (3) the bundle driving mechanism, which primarily embodies the identification of the driving factors, and the analysis of the direction and intensity of the driving factors. The results are expected to provide reference for equilibrating the economic development and ecological protection in megacities and surrounding areas.

2 Materials and methods

2.1 Study area

The total area of Beijing and its surrounding areas (42°37′–38°14′, 113°45′–119°18′) is approximately 140,000 km². It includes two municipalities (e.g., Beijing and Tianjin) that are directly under the Central Government and five prefecture-level cities (e.g., Hebei Province, Zhangjiakou, Baoding, Langfang, Tangshan, and Chengde) (Fig. 1). The research area, which is located in the northwest of the North China Plain, holds intricate and various ecological system types and landscape patterns. Coastal tidal flats, coastal wetlands, paddy fields, cities, shrubs, forests, forest grasslands, and grasslands are distributed from southeast to northwest. The main land-use type in the study area is dry land, which accounts for 37.88% of the total area. Such value is more than 10% of the coverage rate of forest, bush, and forest grassland. The area comprises a certain number of paddy fields, sparse woodland, other woodlands, grassland, degraded grassland, river, lake, reservoirs and ponds, beach land, town, country, other built-up lands, sandy land, salina, wetland, bare land, and exposed rock land.

With the two megacities of Beijing and Tianjin and the concentrated destitute areas of counties and cities of the Yanshan-Taihang region, the research area holds intensive and frequent human activities, divergent economic development level, and evident spatial differentiation of supply and demand of ES. This region is the prime area for practicing the major national strategy of “the coordinated development of Beijing–Tianjin–Hebei,”
with Xiongan New Area under construction in the southern region and targeted poverty alleviation of the concentrated destitute area of Yanshan-Taihang in the northern region. Central city Beijing is undergoing non-capital function reconciliation and urban sub-center construction. With the rapid urban expansion of the study area in the previous decades, the land use types, such as wetland, woodland, grassland, and arable land, have been transformed into construction land, and the mass population has been gathering toward cities. The region has implemented a series of ecological projects, such as returning farmland to forest and grassland, replacing paddy fields with dry land, and afforestation of million acres of plain, to mitigate environmental pressure.

Fig. 1 Land use and cover in the study area

2.2 Data sources

The following datasets were used in this study:

(1) The National Catalogue Service for Geographic Information (http://www.webmap.cn/) provided the
vector data of basic geographic information, such as water bodies and roads.

(2) The National Earth System Science Data Center (http://www.geodata.cn/) provided rainfall erosion data.

(3) The Resource and Environment Data Cloud Platform (http://www.resdc.cn/DataList.aspx) provided land-cover information, population distribution data, gross domestic product (GDP) spatial distribution data, and annual meteorological data.


(5) The National Science & Technology Infrastructure (http://www.cnern.org.cn/) provided the dataset of carbon density in Chinese terrestrial ecosystems (the 2010s).

(6) The National Meteorological Information Center (http://data.cma.cn/) provided the Daily Data Set of Surface Climate Data in China (V3.0).


(8) Baidu Map API (http://lbsyun.baidu.com/) provided latitude and longitude data of A-level scenic spots.

(9) NASA EARTH SCIENCE DATA (https://earthdata.nasa.gov/) provided evapotranspiration data (ET0).

(10) CGIAR - Consortium for Spatial Information (http://srtm.cgiar.org/srtmdata/) provided the SRTM 90-m digital elevation data (DEM).


<table>
<thead>
<tr>
<th>Data</th>
<th>Time resolution</th>
<th>Spatial resolution</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food production</td>
<td>1 year</td>
<td>District</td>
<td>T</td>
</tr>
<tr>
<td>Normalized difference vegetation index (NDVI)</td>
<td>1 year</td>
<td>1 km × 1 km</td>
<td>–</td>
</tr>
</tbody>
</table>
DEM – 90 m × 90 m M

Precipitation 1 year 1 km × 1 km Mm

Evapotranspiration 8 days 500 m × 500 m Mm

Harmonized World Soil Database – 1 km × 1 km –

Land-Use and Land-Cover Change(LUCC) 1 year 30 m × 30 m –

Rainfall erosion 16 days 1 km × 1 km MJ/mm/(ha/h/a)

Population 1 year 1 km × 1 km One people

GDP 1 year 1 km × 1 km 10,000 Yuan

Temperature 1 year 500 m × 500 m °C

Dryness 1 year 500 m × 500 m –

Humid index 1 year 500 m × 500 m –

2.3 Mapping ES supply

This work computes ES from four aspects, namely, provisioning, regulating, cultural, and supporting services, in accordance with the ES classification of Millennium Ecosystem Assessment (MA) of the United Nations (MA, 2015) (Table 2). The spatial resolution of ES is 1 km × 1 km, and China Lambert Conformal Conic is the projection coordinate system.

Table 2 ES entries and their data requirements, spatial resolution, and units

<table>
<thead>
<tr>
<th>ES</th>
<th>Data required</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain providing (GP)</td>
<td>Grain production and NDVI</td>
<td>t/pixel</td>
</tr>
<tr>
<td>Water yield (WY)</td>
<td>DEM, annual rainfall, annual steaming, soil data, and LUCC</td>
<td>mm/pixel</td>
</tr>
<tr>
<td>Carbon sequestration (CS)</td>
<td>Carbon density and LUCC</td>
<td>Mg/pixel</td>
</tr>
</tbody>
</table>
2.3.1 Grain providing (GP)

GP is a direct manifestation of ecosystem provisioning services, and the vegetation index derived from remote sensing data serves as a good indicator of grain yield (Potdar et al., 2007). In the study, the farmland in Beijing and its surrounding areas produced three main types of food: grain, vegetables, and fruits. The grain, vegetable, and fruit supply data of the districts and counties were obtained through the statistical yearbook officially published by Beijing Municipal Bureau of Statistics, Tianjin Municipal Bureau of Statistics, and Hebei Provincial Bureau of Statistics. The grain output data were then spatialized and rasterized on the foundation of the NDVI distribution.

\[
GP_{ij} = \frac{NDVI_{ij}}{NDVI_i} GP_i \quad \cdots \quad (1)
\]

where \( GP_{ij} \) is the \( j \)th pixel of GP in the \( i \)th county, \( NDVI_{ij} \) is the \( j \)th pixel of NDVI in the \( i \)th county, \( NDVI_i \) is the NDVI in the \( i \)th county, and \( GP_i \) is the GP in the \( i \)th county.

2.3.2 Water yield (WY)

Water directly or indirectly contributes to various services that support human well-being, and WY is a vital ES supply (Aznar Sanchez et al., 2019). The annual WY model version 3.6.0 of the integrated valuation of ES and trade-offs (InVEST) is applied to estimate the total and average volume of water of each sub-basin in the
research area (Sharp et al., 2018). The model is based on the Budyko curve and the annual average precipitation. Formula 2 shows the basic principle.

The sub-watershed is generated by DEM through the hydrologic analytical toolset of ArcGIS, evapotranspiration data stems from NASA public datasets, and root depth originates from HWSD Formula 3 shows the calculation method of water content of plants with the adoption of the international classification standard of soil texture (Zhou, 2013). LUCC includes six types, namely, crop, forest, grass, developed land, water, and undeveloped land; the maximum root depth in the biophysical table is determined in consideration of the current studies (Schenk and Jackson, 2002); the plant transpiration and evaporation coefficient $k_c$ is computed using the $k_c$ calculator provided by FAO. The statistical analysis of daily rainfall data from 121 meteorological stations in the research area is analyzed to verify whether the annual rainfall event number is approximately 55.18, and $Z$ is 11.04. This task is undertaken to calculate $Z$ using Formula 4 (Donohue et al., 2012).

$$Y(x) = \left(1 - \frac{A(x)}{P(x)}\right) \times P(x), \ldots \quad (2)$$

where $Y(x)$ is the annual water volume of each pixel, $A(x)$ is the annual evapotranspiration per pixel, and $P(x)$ is the amount of precipitation per year of each pixel.

$$PAWC = 54.509 - 0.132 \times SAND - 0.003 \times SAND^2 - 0.055 \times SILT - 0.006 \times SILT^2 - 0.738 \times CLAY + 0.007 \times CLAY^2 - 2.688 \times OM + 0.501 \times OM^2, \ldots \quad (3)$$

where $PAWC$ is the water content available to plants, $SAND$ is the percentage content of soil sand, $SILT$ is the percentage content of soil silt, $CLAY$ is the percentage content of soil clay, and $OC$ is the percentage content of soil organic matter.

$$Z = 0.2 \times N \ldots \quad (4)$$

where $Z$ is the empirical constant related to the local precipitation model and hydrogeological characteristics with its value ranging from 1 to 30; and $N$ is the number of annual rainfall events.
2.3.3 Carbon sequestration (CS)

CS is a primary regulating service that is directly related to the carbon content of the four major carbon pools in the ecosystem, namely, aboveground biomass, underground biomass, soil carbon, and dead matter (Ouyang et al., 2016). The carbon storage and sequestration model version 3.6.0 InVEST is used to calculate the total amount of CS in the light of the corresponding carbon density and land use/cover (Sharp et al., 2018). The model can be simply expressed as the sum of the four carbon pools of aboveground biomass, belowground biomass, soil, and dead organic matter using Formula 5. The “2010s China terrestrial ecosystem carbon density data set” is taken for reference to determine the carbon density data in this research (Xu et al., 2018).

\[
CS = \sum_{i=1}^{5} S_i \times (C_{\text{above}i} + C_{\text{below}i} + C_{\text{soil}i} + C_{\text{dead}i}), \quad \cdots \quad (5)
\]

where \( i \) is the code of LUCC; and \( C_{\text{above}i} \) is carbon density in aboveground biomass (megagrams/hectare); \( C_{\text{below}i} \) is carbon density in belowground biomass (megagrams/hectare); \( C_{\text{soil}i} \) is carbon density in soil (megagrams/hectare); and \( C_{\text{dead}i} \) is carbon density in dead matter (megagrams/hectare)

2.3.4 Soil retention (SEC)

Soil erosion is an ecological destruction phenomenon that causes not only huge economic losses but also irreversible damage to the NL. SEC services can be quantified by the universal soil loss equation that is widely used by the academic community (Wischmeier and Smith, 1978). Formulas 6–8 show that various factors are involved. The long-term average annual erosion rate is predicted in line with rainfall pattern, soil type, terrain, crop system, and management practice. With the prediction of the annual amount of soil erosion, the difference between the results of the amount of the potential soil erosion and the actual amount of erosion is the quantity of soil conservation.

\( R \) comes from the National Earth System Science Data Sharing Platform. With the application of the international classification standard of soil texture and the percentage content of soil sand, silt, and clay, \( K \) can be computed in light of Formula 9 by utilizing the EPIC model proposed by Williams and Arnold (1903). \( LS \) can be acquired through terrain analysis of ArcGIS. \( C \) is acquired by utilizing the NDVI data, Cai et al.’s (2000) calculation method, and Formulas 10–11. The \( P \) factor was calculated through Wenner method (Lufafa et al.,
2003) (Formula 12).

\[ A_C = A_p - A_r, \ldots \ldots (6) \]

\[ A_p = R \times K \times LS, \ldots \ldots (7) \]

\[ A_r = R \times K \times LS \times C \times P, \ldots \ldots (8) \]

where \( A_C \) is the amount of SEC (t/(ha/yr)), \( A_p \) is the potential amount of SEC (t/(ha/yr)), \( A_r \) is the actual amount of SEC (t/(ha/yr)), \( R \) is the rainfall erosion index (MJ/mm/(ha/h/a)), \( K \) is the soil erosion factor, \( LS \) is the slope length-gradient factor, \( C \) is the crop/vegetation and management factor, and \( P \) is the support practice factor.

\[ K = \left( 0.2 + 0.3 \exp \left( -0.0256 \times SAND \times (1 - \frac{SILT}{100}) \right) \right) \times \left( \frac{SILT}{CLAY + SILT} \right)^{0.3} \times \left( 1 - \frac{0.25 \times OM}{OM + \exp (3.72 - 2.95 \times OM)} \right), \ldots \ldots (9) \]

where \( SAND, SILT, CLAY, \) and \( OM \) are the percentages of sand, silt, clay, and organic carbon in the soil, respectively.

\[ f = \frac{(NDVI - NDVI_{min})}{(NDVI_{max} - NDVI_{min})}, \ldots \ldots (10) \]

\[ C = \begin{cases} 0.6508 - 0.3436 \log f, & 0 < f \leq 78.3\% \, , \ldots \ldots (11) \\ 1, & f > 78.3\% \end{cases} \]

where \( NDVI_{min} \) is the minimum of NDVI, \( NDVI_{max} \) is the maximum of NDVI, \( f \) is the degree of vegetation coverage, and \( C \) is the crop/vegetation and management factor.

\[ P = 0.2 + 0.03 \alpha, \ldots \ldots (12) \]

where \( \alpha \) is slope steepness (%), and \( P \) is the support practice factor.

**2.3.5 Water purification service**

NEs and PEs are typical representatives of water purification services. The nutrient delivery ratio (NDR)
model version 3.6.0 InVEST is used to calculate the regulating service (Sharp et al., 2018).

The model calculates the pixel-level output data based on the nutrient load \( (\text{load}_i) \) and NDR of each pixel \( i \) and then merges into the total output of the basin range. The nutrient load is determined by referring to Harmel et al. (2006) and Pärn et al. (2012). The NatCap nutrition parameter database is used as reference to determine the retention efficiency. The maximum pixel is applied for retention lengths.

### 2.3.6 Cultural services

The intangible benefits that humans obtain from the ecosystem are called cultural service, and people’s access to non-material benefits is realized mainly through human perception. The measurement of cultural services is regarded as a difficult point in academic research. However, the grading of scenic spots implemented in China facilitates the measurement of cultural services. The scene is divided into five levels (from AAAAA to A) according to the classification criteria of the quality level of tourist attractions in the People’s Republic of China. Level 5A is the highest level of China’s tourist attractions. Such level represents the country’s world-class boutique tourist attractions. Given the existing research and study area situation, this work adopts the accounting data of the maximum daily carrying capacity of each A-level scenic spot implemented in China since 2014 to represent the cultural service and calculates through the inverse distance weight interpolation method. Cultural services can be divided into three types, namely, NL, HC, and EN, on account of the service categories of scenic spots. Among the data, in which the A-level scenic list was obtained from the Ministry of Culture and Tourism of the People’s Republic of China, the longitude and latitude of the scenic spot are crawled through Baidu API.

<table>
<thead>
<tr>
<th>District</th>
<th>Name of the scenic spot</th>
<th>Longitude</th>
<th>Latitude</th>
<th>ES</th>
<th>Daily carrying capacity (10,000 people)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beijing</td>
<td>Palace Museum, Beijing</td>
<td>39.91</td>
<td>116.39</td>
<td>HC</td>
<td>8.0</td>
</tr>
<tr>
<td>Beijing</td>
<td>Temple of Heaven Park</td>
<td>39.88</td>
<td>116.41</td>
<td>EN</td>
<td>17.5</td>
</tr>
</tbody>
</table>
Beijing  Summer palace  39.99  116.27  EN  18.0
Beijing  Badaling–Mutianyu Great Wall Tourist Area  40.38  116.53  HC  14.3
Beijing  Ming XIII Mausoleum Scenic Area  40.25  116.22  HC  11.7
Beijing  King’s Palace Scenic Area  39.93  116.38  HC  4.0
Beijing  Beijing Olympic Park  40.00  116.39  EN  50.0
Tianjin  Tianjin Ancient Culture Street Tourist Area  39.14  117.19  HC  16.0
Tianjin  Panshan Scenic Area, Tianjin  40.09  117.28  NL  5.2
Hebei  The Imperial Summer Villa of Chengde  41.01  117.95  EN  15.3
Hebei  Qingdong Mausoleum Scenic Area, Tangshan City  40.13  117.70  NL  11.2
Hebei  Palace Scenic Area  36.64  113.61  EN  11.2
Hebei  Baoding An Xin Baiyangdian Scenic Area  38.93  115.98  NL  5.0
Hebei  Baoding Sushui County Wild Three Slope Scenic Area  39.66  115.38  NL  2.8
Hebei  Xibaipo Scenic Area, Shijiazhuang Pingshan County  38.34  113.94  NL  3.2

*In the research area, 15 AAAAA, 217 AAAA, 196 AAA, 149 AAA, and 16 A scenic spots are present, totaling 347.

2.3.7 Habitat quality (HQ)

In the MA’s classification system, supporting service indicates a service function necessary for the ecosystem to provide other services, such as provisioning, regulating, and cultural services. Habitat quality refers to the ability of ecosystems to provide sustainable conditions for individuals or groups (Hall et al. 1997). Habitat quality depends on the proximity to human land use and the intensity of land use. The relative impact of threat sources on different habitats is determined by the relative impact of threats, the distance between habitats and threat sources, and the relative sensitivity of habitats to threats. The HQ model version 3.6.0 of InVEST is selected to calculate HQ (Sharp et al., 2018) by combining the relevant information of land use/cover and the diverse threat to ecology to constitute an HQ map.
2.4 Trade-offs and synergies

The trade-off and synergy analysis bears the following edges: First, such approach will determine the relationship among ES provided by the ecosystem for human society as the guideline of the protection of the ecosystem. Second, trade-offs and synergies of supply and demand can be analyzed to achieve sustainable ES outputs and deliver benefits to mankind. Pearson correlation analysis was applied to determine the correlation coefficient between the two ES. The graph can be drawn through R Performance Analytics package to intuitively display the correlation of multiple ES values in Beijing and its surrounding areas.

2.5 Identification of bundle

Bundle indicates the ES aggregation that repetitively occurs in space (Raudsepp-Hearne et al., 2010) and can recognize the clustering pattern of multiple ES. In this study, R princomp is used for principal component analysis, which is a data dimensionality reduction technique. The scheme aims to convert a set of possible correlation variables into a set of linearly unrelated ones through orthogonal transformation. As a consequence, the principal components obtained in the analysis are linear combinations of ES. The first few principal components with cumulative contribution rate that reaches 80% are generally selected for subsequent calculation. After the dimension reduction via principal component analysis, Calinski criterion is applied for the optimal number of classifications, and k-mean clustering is performed to identify bundles with different ES, trade-offs, and synergies. The spatial distribution of bundles and ES characteristics within each bundle are analyzed.

2.6 Driving factors that affect bundle formation and spatial distribution

The spatiotemporal changes in bundles may be closely associated with a certain environmental/economic factor. In the research area, the bundle formation is the result of the superposition of multiple factors. The interaction effects in the superposition process are difficult to distinguish. GeoDetector is used to provide technical support for the identification of the bundle’s influencing factors given its advantages in the study of spatial stratification heterogeneity and categorical variables.

GeoDetector has unique advantages in dealing with categorical variables. Such application has been gradually applied to land use, landscape pattern, rural residential areas, and other fields in recent years. The core
idea suggests: if a significant spatial consistency exists between independent variable $X$ and dependent variable $Y$, then an association is present between them. The exploration of the correlation between $X$ and $Y$ can be demonstrated as follows:

$$q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2}, \ldots (13)$$

where $\sigma^2$ is the variance of variable $Y$, and $N$ is the size of $Y$, such as the geographical area and total population; the superposition of $X$ and $Y$ variables forms $L$ layers in $Y$ and is indicated by $h = 1, 2, \ldots, L$; $N_h$ and $\sigma_h^2$ represent the scale and variance of layer $h$, respectively; $q$ signifies the degree of explanation of factor $X$ to factor $Y$, with its values ranging from 0 to 1, that is, 0 for no correlation between the two and 1 for $Y$'s complete dependence on $X$.

GeoDetector consists of risk, factor, ecological, and interaction detectors. The research primarily utilizes factor and ecological detectors. The factor detector mainly quantitatively detects the degree of interpretation of different factors of $X$ for $Y$. Specifically, the larger the $q$ (the $q$ value in the above formula), the stronger the explanatory ability. The ecological detector examines and compares the $p$ through $F$ to determine whether one of the factors $X_1$ is more influential than the other factor $X_2$:

$$F = \frac{n_{x_1p}(n_{x_1p} - 1)\sigma_{x_1p}^2}{n_{x_2p}(n_{x_2p} - 1)\sigma_{x_2p}^2}, \ldots (14)$$

where $F$ is the test value of $F$; $n_{x_1p}$ and $n_{x_2p}$ are the sample quantities of influencing factors $X_1$ and $X_2$ in unit $p$, respectively; $\sigma_{x_1p}^2$ and $\sigma_{x_2p}^2$ are the variances of $X_1$ and $X_2$, respectively. The null hypothesis of the model is $H_0: \sigma_{x_1p}^2 = \sigma_{x_2p}^2$. If the null hypothesis is rejected, and the $p$ value reaches the significance level of 0.05, then the effect of influencing factor $X_1$ on the dependent variable is prominently greater than that of $X_2$.

In this research, with the application of the developed GeoDetector software (http://www.geodetector.org/), some indexes are selected to detect factors that may affect the driver of the spatial distribution of the bundle, including social economic index (e.g., population density (POP) and GDP), landscape indicators (e.g., altitude (ASL) and Ground roughness (GR)), climate indicators (e.g., annual average temperature ambient (TADEM),
annual average precipitation (PRE), humid index (IM), and dryness (ARI), soil quality index, percentage of sand in soil (sand), percentage of silt in soil (silt), and percentage of clay in soil (clay).

\[
q = 1 - \frac{\sum_{h=1}^{L} N_h \sigma_h^2}{N \sigma^2}
\]

Fig. 2 Principle of GeoDetector

Bottom map: distribution of variable Y. Top map: Y is divided into multiple units. Variable q is in between the two maps (Wang et al., 2010).

3 Result

3.1 Spatial distribution characteristics of ES supply

As shown in Fig. 3, ES selected for the research is clustered in the research zone (Moran’s I > 0.24, p < 0.01). GP is mainly concentrated in Baoding City, Langfang City, Tangshan City, and other places, belongs to the northwest of the north China plain, and is rich in arable land resources. WY is bounded by the Taihang Mountain - Yanshan Mountain Range, with the water supply to the southeast side of the boundary significantly higher than the northwest side of the boundary. CS, SEC, and HQ, bearing the similar distribution characteristics, are mainly distributed in groups in Taihang Mountain - Yanshan Mountains and its northwest side, with high forest coverage and reduced human activities. CS in urban areas, such as Beijing, is evidently at a low level. The distribution of NE and PE in water purification services is roughly the same, with high values in Tianjin, Tangshan, and Zhangjiakou. The distribution of NL, HC, and EN are discrepant, among which, the supply of ecosystem cultural services in Beijing is always at a high level. Overall, the ES distribution in the study area is differentiated. The differences between the Taihang-Yanshan Mountains range, urban and non-urban areas, plains and non-plain areas are obvious.
Fig. 3 ES in Beijing and its surrounding areas
Including, GP, WY, CS, SEC, NE, PE, NL, HC, EN, and HQ. GP: Grain Providing; WY: water yield; CS: carbon storage; SEC: soil retention; NE: purified water service (N export); PE: purified water service (P export); NL: cultural service (natural landscape (NL)); HC: cultural services (historical culture (HC)); EN: cultural services (entertainment (EN)); HQ: habitat quality.

3.2 Trade-offs and synergies between ES

As shown in Figs. 4 and 5, in 2015, 38 significant correlations are found among 45 pairs of ES (Pearson correlation coefficient $p<0.05$; $-1<r<1$), with 18 and 20 pairs of positive and negative correlations, respectively. GP, which is prominently correlated with other ES ($p<0.05$), has a high positive correlation with WY and a high negative one with HQ. WY is negatively correlated with CS and HQ to a great extent. CS and HQ show a high positive correlation, and areas with few human activities, high forest cover, or high species abundance tend to hold high CS and HQ. SEC is negatively correlated with GP and WY. NE and PE in water purification services manifest a high positive correlation. A high positive correlation between NL and EN indicates that a good NL is still the guarantee of high EN.

Fig. 4 Relationship between 10 ES

The number of * in the figure is positively correlated with the degree of significance. GP: Grain Providing; WY: water yield; CS:
carbon storage; SEC: soil retention; NE: purified water service (N export); PE: purified water service (P export); NL: cultural service (natural landscape (NL)); HC: cultural services (historical culture); EN: cultural services (entertainment); HQ: habitat quality.

3.3 Spatial distribution and characteristics of bundles

Taking pixel (1000 m × 1000 m) as the basic unit for principal component analysis, Beijing and its surrounding areas hold the standard deviation, contribution rate, and cumulative contribution rate of 11 components shown in Table 4 with the first six components with a cumulative contribution rate of 80% chosen for clustering. The recognition of the optimal cluster number lies on Calinski criterion, which is a quantitative evaluation index. The larger the value, the better. As shown in Fig. 6, the cluster number corresponding to Calinski’s larger value is 7.

Table 4 Information of principal component analysis
The following seven bundles were identified by the K-means method (Figs. 7 and 8) and named after the ES (Table 5) and LUCC in the bundle.

(1) Soil retention bundle (SECB): This bundle covers 24.25% of the study area. In addition to the southwestern part of the study area, many SEBC co-occurrences can be found in other areas. The corresponding land use is mainly forest land. SECB provides a wealth of SEC, NL, HC, and EN, of which SEC has a high functional capacity, accounting for 45.31% of the total.
(2) Cultural service bundle (CSB): This bundle covers 25.50% of the research area. CSB is mainly situated in Zhangjiakou and Baoding, with a variety of the corresponding land uses embodying grassland, farmland, and water body. The NL, HC, and EN contributions are 26.35%, 25.92%, and 22.87%, respectively.

(3) Urban bundle (CB): This bundle covers 9.07% of the research area. CB is chiefly distributed in urban areas. The wetlands in Beijing and its surrounding areas are concentrated in Beijing, Tianjin, and Tangshan. Therefore, CB offers approximately 50% WY of SECB and CSB with an area of less than half that of SECB and CSB, up to 10.92%, which is the highest proportion of all CB services.

(4) Habitat quality bundle (HQB): This bundle covers 15.98% of the research area. HQB is principally located in the northwest of Yanshan–Taihang Mountains in the areas of deciduous broad-leaved forest, closed shrub, forested grassland, grassland, and farmland. HQ is the service component of the main cluster.

(5) Agricultural bundle (AB): 22.34% of the research areas are covered, which are mainly distributed in Savannas, Open Shrublands, and Evergreen Broadleaf Forests. The corresponding land uses are cultivated land and grassland with most of them in the northwest of the North China Plain. AB has an outstanding GP service supply capacity, accounting for 45.93% of all GP services;

(6) Water supply and purification bundle (WWB): this bundle covers 2.40% of the research area, primarily in large-scale waters of non-urban areas, with the coexistence of WWB outside Zhangjiakou and Chengde and in Beijing, Tianjin, Baoding, Langfang, and Tangshan. WWB has prominent water purification capacity, especially NE. Moreover, WWB produces certain WY, accounting for 3.95% of all WY in the study area.

(7) Water purification bundle (WB): This bundle covers 0.46% of the research area. WB is mostly distributed in urban and built-up areas. ES supply of WB is noticeably lower than other bundles, but it has striking NE and PE.

Table 5 Proportion of ES in each bundle (%)

Soil retention bundle (SECB); Cultural service bundle (CSB); Urban bundle (CB); Habitat quality bundle (HQB); Agricultural bundle (AB); Water supply and purification bundle (WWB); Water purification bundle (WB).
<table>
<thead>
<tr>
<th></th>
<th>SECB</th>
<th>CSB</th>
<th>CB</th>
<th>HQB</th>
<th>AB</th>
<th>WWB</th>
<th>WB</th>
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</thead>
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<tr>
<td>GP</td>
<td>28.36</td>
<td>14.43</td>
<td>4.49</td>
<td>5.63</td>
<td>45.93</td>
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<tr>
<td>WY</td>
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<td>28.32</td>
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<td>SEC</td>
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<td>16.23</td>
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<td>NE</td>
<td>6.73</td>
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<td>4.46</td>
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<td>7.55</td>
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</tr>
<tr>
<td>PE</td>
<td>3.54</td>
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<td>3.19</td>
<td>0.77</td>
<td>68.66</td>
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<tr>
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Different bundles have distinct ES components, and the corresponding scales vary. The bundles with large ES variances in the graph indicate that the key lines are dense. Soil retention bundle (SECB); Cultural service bundle (CSB); Urban bundle (CB); Habitat quality bundle (HQB); Agricultural bundle (AB); Water supply and purification bundle (WWB); Water purification bundle (WB).

Fig. 7 Radar diagrams for ES distribution within each bundle
3.4 Result of driving factor identification

In the research, 11 possible driving force factors, including POP, GDP, ASL, GR, TADEM, PRE, IM, ARI, SAND, SILT, and CLAY, are selected. The driving factors that may affect the spatial distribution of the bundle and their degree of interpretation are obtained through the factor and ecological detectors of GeoDetector. Tables 6 and 7 illustrate the detection results. The study regions are divided into several sub-regions to examine the close relation between bundles and social-ecological indicators through the GeoDetector application. The results
still suggest prominent differences behind the spatial differentiation of bundles. Table 6 shows the output of the ecological detector, and significant differences are observed among the 11 variables in terms of the effect of different variables on the spatial distribution of bundles. Table 7 demonstrates the detection results of factor detector, including the q and p values of 11 independent variables. The q values are distributed as follows: POP (0.141542) > GDP ASL (0.118844) > GR (0.001816) > TADEM (0.140291) > PRE (0.035797) > IM (0.051321) > ARI (0.051806) > SAND (0.072666) > SILT (0.035306) > CLAY (0.03273). The results show that GDP, POP, TADEM, and ASL have the maximum q value. The GDP and POP are regarded as socio-economic factors, TADEM as meteorological indicators, and ASL as landscape indicators. Accordingly, GDP, POP, TADEM, and ASL play a decisive role in the spatial pattern of bundles.

Beijing and its surrounding areas, as megacities, hold intensive human activities. GDP is the optimal indicator of local economic conditions. Economically developed areas can invest substantial manpower, material resources, and financial resources in ecological governance and protection, such as the subsidy tariff policy after the implementation of coal reform in Beijing. The areas where POP is highly centralized are political, economic, and cultural centers. When human demands, such as food supply, for ES are uncoordinated with ES cannot meet human needs, the emergence of food crisis forces humans to upgrade planting techniques and expand planting area. The technological upgrading will take a long time to accumulate. However, land settlement where human beings will engage in work for thousands of years can rapidly expand the planting area in a short period of time. Such condition directly causes changes in land use/covering and has a short-term irreversible impact on the original ecosystem.

In practice, certain positive behaviors are observed when the supply and demand for services are not in harmony. For instance, China is currently advocating the comprehensive rehabilitation of “mountains, rivers, forests, fields, lakes, and grasses”, which primarily improves the comprehensive rehabilitation from the ES supply perspective, to coordinate the ES supply and demand. The area is mainly one harvest a year and two harvests a year. TADEM is also an important controlling factor with a direct impact on crop growth. Identifying the key driving force factor of TADEM, combined with the increasing distribution of the factor from northwest to southeast, can adjust the planting plan of food and oil crops in the region and effectively use the land. The
change of the proportion of different species is consistent with the change of the regional vegetation perpendicular band spectrum. Accordingly, species richness may have a different pattern of elevation gradient. The ES and its trade-off and synergy relationship provided by the ecosystem manifest differences. Thus, ecological environmental protection schemes at different ASLs must be studied and formulated to reasonably maintain the habitat quality.

Table 6 Ecological detector results (Y for a difference, N for no difference, and f-test: 0.05)

POP: population density; GDP: Gross National Product; ASL: altitude; GR: Ground roughness; TADEM: Annual average Temperature Ambient; PRE: Annual average precipitation; IM: Humid index; ARI: Dryness; SAND: Percentage of sand in soil; SILT: Percentage of silt in soil; CLAY: Percentage of clay in soil.

<table>
<thead>
<tr>
<th>Factor</th>
<th>POP</th>
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<th>ASL</th>
<th>GR</th>
<th>TADEM</th>
<th>PRE</th>
<th>IM</th>
<th>ARI</th>
<th>SAND</th>
<th>SILT</th>
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<td>N</td>
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<td>Y</td>
<td>N</td>
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<td>Y</td>
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<tr>
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</table>

Table 7 Factor detector results
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<th>No.</th>
<th>Variable</th>
<th>q-Statistic</th>
<th>p Value</th>
</tr>
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<tr>
<td>1</td>
<td>POP</td>
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<td>**</td>
</tr>
<tr>
<td>2</td>
<td>GDP</td>
<td>0.159264</td>
<td>**</td>
</tr>
<tr>
<td>3</td>
<td>ASL</td>
<td>0.118844</td>
<td>**</td>
</tr>
<tr>
<td>4</td>
<td>GR</td>
<td>0.001816</td>
<td>**</td>
</tr>
<tr>
<td>5</td>
<td>TADEM</td>
<td>0.140291</td>
<td>**</td>
</tr>
<tr>
<td>6</td>
<td>PRE</td>
<td>0.035797</td>
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<tr>
<td>7</td>
<td>IM</td>
<td>0.051321</td>
<td>**</td>
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<tr>
<td>8</td>
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<td>SAND</td>
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</tr>
<tr>
<td>11</td>
<td>CLAY</td>
<td>0.03273</td>
<td>**</td>
</tr>
</tbody>
</table>

The larger the q value is, the stronger the degree of interpretation of the dependent variable on the independent variable is. The p value indicates the degree of significance, requiring that it is significant at least at the 10% level (p < 0.1), of which only the independent variable ARI does not match the requirements. The other variables are extremely significant, and they are labeled as **.

4 Discussion

4.1 Relationship between ecosystem service bundles and LUCC

The spatial co-occurrence of bundles corresponds to the co-occurrence of ES and its tradeoffs under different longitudes, latitudes, ASLs, and climate or socio-economic conditions. In this co-occurrence relationship, bundles have a certain degree of association with specific landscape patterns. Bundles are relevant to specific landscape patterns, and they often simultaneously occur in space and time, thereby creating a co-occurrence relationship (Hamann et al., 2016; Hu et al., 2019). Such relationship forms a bridge between ES and the landscape pattern and can provide references for ecosystem management and landscape planning (Li et al.,
Bundles and land use distribution patterns are used to construct bridges between ES and landscape models. At the same time, important "bundle-landscape" pairs are identified by co-occurrence frequency statistics. Besides, it provides a spatial basis for the development of management plans.

Certain progress of the current research has been made in this field. Lamy et al. (2016) analyzed the landscape composition and structure of 130 cities and pointed out that both had an influence on bundles. However, the composition and structure of various bundles had different contributions. In the course of the bundle study of an urban–rural gradient in the Barcelona metropolitan area, Baro et al. (2017) found that bundles are not only associated with a certain type of land use. Mixed types of land use have co-occurrence with certain types of bundles in the urban boundary areas. A study of Denmark by Turner et al. (2014) suggests that suburban leisure landscapes around large cities also co-exist with unique bundles. There are many studies on the co-occurrence relationship between bundles and a specific type of land-use (Yao et al., 2016). However, current models or indicators of land-use change, ecological footprint, etc. do not perform well in interpreting and predicting bundles (Meacham et al., 2016). Therefore, there is still a lack of co-occurrence relationship with specific composite land-use or complex landscape patterns.

A spatial combination of bundle and LUCC in the research area is conducted. The results are shown in Figs. 9 and 10. Thirty-seven combinations in total are determined, among which combinations numbered 20, 2, 5, 8, 1, and 7 are the six categories with the highest co-occurrence frequency. Number 20 signifies a high degree of correlation between AB and cropland, that is, cropland type landscape provides most of AB. Numbers 5 and 8 reveal that cropland also offers a larger proportion of CSB and SECB. Numbers 2 and 1 suggest the substantial provision of SECB and HQB from woodland. This finding indicates the significance of woodland protection in maintaining the normal supply of regulating services. Substantial SECB is provided by number 7 of grassland. Accordingly, woodland and grassland correspond to many bundles, which mainly supply regulating service, and are of great importance to the ecosystem.
The left side of the figure refers to the spatial expression of 37 combinations. The right side shows the co-occurrence frequency of 37 combinations (1 time per unit area in km$^2$) and the mapping between bundles of different combinations and land use/cover.
4.2 Verification of the model

There are two main methods for mapping ecosystem services: one is the simple conversion of official public release data, such as GP, culture services; the other is a model constructed by ecological mechanisms, such as multiple modules of InVEST model, the Universal soil loss equation, etc. The data foundation of the first method is derived from an authoritative organization and has a good quality control system. The second approach has been widely used for ecosystem service assessments, providing relatively accurate estimates of water yield (WY), carbon storage (CS), soil retention (SEC), purified water service, cultural services, habitat quality (HQ). However, the accuracy depends on the selection of appropriate model parameters and input data, so parameter calibration is required to make it more suitable for specific research areas (Wang et al. 2019).

To calibrate the model, the parameters are selected and calculated according to the unique geographical conditions and socio-economic conditions of Beijing and the surrounding areas. Parameters have been described in Materials and methods including precipitation, evapotranspiration, depth of root restricting layer, plant available water fraction, etc.

To verify the validity of the model, the model results are compared with other model results, and the allocation disagreement (AD) and Quantity disagreement (QD) are used as important indicators for model verification. The comparison is as follows:

(1) Comparison of CS and NPP. Calculating carbon fixation based on the NPP of biodiversity is an effective and widely used method.

(2) Annual water yield calculated by the water balance equation is named as WY*. WY is compared with WY*. The principle of water balance means that the difference between the input and output of the water quantity is consistent with the change of the water storage in a timed space. The unified unit after the calculation is (mm).

\[
WY^* = \sum_{i=1}^{i} (P_i - R_i - ET_i) \times A_i, \ldots \ldots (15)
\]

where \( WY^* \) is water conservation (m3); \( P_i \) is annual precipitation (mm); \( R_i \) is storm runoff; \( ET_i \) is evapotranspiration (mm); \( A_i \) is the area of the \( i \)-th ecosystem.
(3) Ecosystem services dataset of China (2010) includes the measurement results of various ecosystem services in China (Zhang et al., 2017). The habitat quality and soil erosion from this dataset are named as HQ* and SEC*. HQ and SEC are compared with HQ* and SEC*.

As shown in fig.11, the charting result AD is low, and some ES have QD in the high-value or low-value part. In the study, low AD and QD are enough to guarantee the validity of the model. Specifically, CS and NPP have similar spatial distribution, and the difference between the two sides of the Taihang-Yanshan Mountains is obvious, but the value of CS is higher than that of NPP. The carbon storage and sequestration model version 3.6.0 InVEST considers four carbon pools to calculate carbon sequestration (Sharp et al., 2018), but NPP considers the carbon sequestration of plants. WY and WY* exhibit the same distribution characteristics, and the water volume in Beijing and its southeast is significantly higher than that in the northwest. The basic principle of the annual water yield model version 3.6.0 InVEST and water balance equation is water balance. However, it can be seen from the histogram that the distribution of the high-value areas of the two is uniform, but the distribution of the low-value areas of WY is more coordinated. The minimum mapping units of HQ and HQ* are different, but the spatial distribution is consistent. The high-value part of Taihang-Yanshan Mountain and the low-value part of Beijing-Tianjin are obvious. In the median area, the quantity distribution of the two is highly uniform. The spatial distribution of SEC and SEC* is also consistent. The boundary line between Taihang-Yanshan Mountain is very prominent, and the quantity distribution is highly uniform.
Fig. 11 Comparison of ecosystem services and histograms calculated by different models

5 Conclusion

These 11 significant ES ranging from provisioning and cultural services to supporting service embody GP,
WY, CS, SEC, NE, PE, NL, HC, EN, and HQ, and are applied for mapping and depiction of their correlation. Bundles composed of different trade-offs and synergistic relationships, which are recorded in pixel and directly manifested as spatial co-occurrence, are obtained through dimensionality reduction by PCA and cluster analysis, respectively. SECB, which is a supply of high soil conservation services, should minimize the conversion of woodland to arable land in these areas. AB provided 45.93% of the GP, and the cultivated land in this area should be reduced as much as possible. The protection of WWB and WB should be given high priority, and pollutant emissions in the region should be supervised. The research demonstrates that a negative correlation intrinsically exists between the large supply of service and the regulating service and the supporting service, which can be interpreted as the competition of land-use type. In the study of driving force mechanism, the high degree of interpretation of various factors, such as GDP, POP, TADEM, and ASL, indicate that in the areas where human activities are highly concentrated, the bundle distribution is strongly interfered by human socio-economic behaviors. Apart from these socio-economic factors, the prominent degree of interpretation of TADEM and ASL manifests that these two factors deserve to be adopted by decision makers as a reference factor for ES management policies in different regions.

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Acknowledgement

This research was financially supported by the National Natural Science Foundation of China (No. 41901261, U1810107) and Beijing Social Science Fund Project (18GLB043).
Fig. 1 Land use and cover in the study area
Fig. 2 Principle of GeoDetector

Bottom map: distribution of variable Y. Top map: Y is divided into multiple units. Variable q is in between the two maps (Wang et al., 2010).

\[ q = 1 - \frac{\sum_{h=1}^{k} N_h \sigma_h^2}{N \sigma^2} \]
Fig. 3 ES in Beijing and its surrounding areas
Including, GP, WY, CS, SEC, NE, PE, NL, HC, EN, and HQ. GP: Grain Providing; WY: water yield; CS: carbon storage; SEC: soil retention; NE: purified water service (N export); PE: purified water service (P export); NL: cultural service (natural landscape (NL)); HC: cultural services (historical culture (HC)); EN: cultural services (entertainment (EN)).
Fig. 4 Relationship between 10 ES

The number of * in the figure is positively correlated with the degree of significance.
Fig. 5 Correlation heat map

Blue indicates a positive correlation, while red indicates a negative. The graph expands as the color becomes dark, thereby indicating high correlation.
The graph on the left exhibits the abscissa number of objects and the ordinate number of groups in each partition. The graph shows the number of objects under different grouping numbers. The red dot on the right is the corresponding maximum.
Fig. 7 Radar diagrams for ES distribution within each bundle
Fig. 8 Spatial distribution of bundles in Beijing and its surrounding areas
Fig. 9 Spatial combination of CL and LUCC

The left side of the figure refers to the spatial expression of 37 combinations. The right side shows the co-occurrence frequency of 37 combinations (1 time per unit area in km$^2$) and the mapping between bundles of different combinations and land use/cover.
Fig. 10 Details of the first six combinations in the co-existence frequency

The CL, on the left, denotes the codes and names of all bundles. The middle com-code is the number of the top six combinations in the co-occurrence frequency, which is arranged from top to bottom on the basis of the frequency from high to low. LUCC, on the right, represents the codes and names of six LUCC.
Fig. 11 Comparison of ecosystem services and histograms calculated by different models
### Table 1 Details on important data

<table>
<thead>
<tr>
<th>Data</th>
<th>Time resolution</th>
<th>Spatial resolution</th>
<th>Unit</th>
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<td>Food production</td>
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<td>Normalized difference vegetation index(NDVI)</td>
<td>1 year</td>
<td>1 km × 1 km</td>
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<td>DEM</td>
<td>–</td>
<td>90 m × 90 m</td>
<td>M</td>
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<td>Precipitation</td>
<td>1 year</td>
<td>1 km × 1 km</td>
<td>Mm</td>
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<td>Evapotranspiration</td>
<td>8 days</td>
<td>500 m × 500 m</td>
<td>Mm</td>
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<tr>
<td>Harmonized World Soil Database</td>
<td>–</td>
<td>1 km × 1 km</td>
<td>–</td>
</tr>
<tr>
<td>Land-Use and Land-Cover Change(LUCC)</td>
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<td>30 m × 30 m</td>
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<td>Rainfall erosion</td>
<td>16 days</td>
<td>1 km × 1 km</td>
<td>MJ/mm/(ha/h/a)</td>
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<tr>
<td>Population</td>
<td>1 year</td>
<td>1 km × 1 km</td>
<td>One people</td>
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<tr>
<td>GDP</td>
<td>1 year</td>
<td>1 km × 1 km</td>
<td>10,000 Yuan</td>
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<tr>
<td>Temperature</td>
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<td>Dryness</td>
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<td>500 m × 500 m</td>
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<tr>
<td>Humid index</td>
<td>1 year</td>
<td>500 m × 500 m</td>
<td>–</td>
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### Table 2 ES entries and their data requirements, spatial resolution, and units

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<th>Data required</th>
<th>Unit</th>
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<td>Grain providing (GP)</td>
<td>Grain production and NDVI</td>
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<tr>
<td>Water yield (WY)</td>
<td>DEM, annual rainfall, annual steaming, soil data, and LUCC</td>
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<tr>
<td>Carbon sequestration (CS)</td>
<td>Carbon density and LUCC</td>
<td>Mg/pixel</td>
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<tr>
<td>Soil retention (SEC)</td>
<td>World Soil Database, rainfall erosion factor, DEM, and NDVI</td>
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<tr>
<td>Purified water service (nitrogen export (NE))</td>
<td>DEM, LUCC, rainfall, nutrient load, and retention efficiency and length</td>
<td>kg/pixel</td>
</tr>
<tr>
<td>Purified water service (phosphorus export (PE))</td>
<td>DEM, LUCC, rainfall, nutrient load, and retention efficiency and length</td>
<td>kg/pixel</td>
</tr>
<tr>
<td>Cultural services (natural landscape (NL))</td>
<td>Maximum daily carrying capacity in scenic areas</td>
<td>10,000 people</td>
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</tbody>
</table>
Habitat quality (HQ) LUCC, threat data, and sensitive data –

Table 3 Detailed information of 15 AAAAA scenic spots in Beijing and its surrounding areas

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<th>District</th>
<th>Name of the scenic spot</th>
<th>Longitude</th>
<th>Latitude</th>
<th>ES</th>
<th>Daily carrying capacity (10,000 people)</th>
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<tbody>
<tr>
<td>Beijing</td>
<td>Palace Museum, Beijing</td>
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<td>116.39</td>
<td>HC</td>
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<td>Temple of Heaven Park</td>
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<td>116.41</td>
<td>EN</td>
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<td>Beijing</td>
<td>Summer palace</td>
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<td>116.27</td>
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<td>King’s Palace Scenic Area</td>
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<td>Beijing Olympic Park</td>
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<td>116.39</td>
<td>EN</td>
<td>50.0</td>
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<td>Tianjin Ancient Culture Street Tourist Area</td>
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<td>HC</td>
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<td>Tianjin</td>
<td>Panshan Scenic Area, Tianjin</td>
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<td>Hebei</td>
<td>The Imperial Summer Villa of Chengde</td>
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*In the research area, 15 AAAAA, 217 AAAA, 196 AAA, 149 AAA, and 16 A scenic spots are present, totaling 347.*

Table 4 Information of principal component analysis

<table>
<thead>
<tr>
<th>Index</th>
<th>Com1</th>
<th>Com2</th>
<th>Com3</th>
<th>Com4</th>
<th>Com5</th>
<th>Com6</th>
<th>Com7</th>
<th>Com8</th>
<th>Com9</th>
<th>Com10</th>
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<td>Standard deviation</td>
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<td>Proportion of variance</td>
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<td>0.06</td>
<td>0.03</td>
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<tr>
<td>Cumulative proportion</td>
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<td>0.59</td>
<td>0.69</td>
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<td>0.95</td>
<td>0.97</td>
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Table 5 Proportion of ES in each bundle (%)

Soil retention bundle (SECB); Cultural service bundle (CSB); Urban bundle (CB); Habitat quality bundle (HQB); Agricultural bundle (AB); Water supply and purification bundle (WWB); Water purification bundle (WB).

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>SECB</th>
<th>CSB</th>
<th>CB</th>
<th>HQB</th>
<th>AB</th>
<th>WWB</th>
<th>WB</th>
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<td>GP</td>
<td>28.36</td>
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<td>WY</td>
<td>19.28</td>
<td>25.53</td>
<td>10.92</td>
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<td>28.32</td>
<td>3.95</td>
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<td>16.23</td>
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<td>14.78</td>
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Table 6 Ecological detector results (Y for a difference, N for no difference, and f-test: 0.05)

POP: population density; GDP: Gross National Product; ASL: altitude; GR: Ground roughness; TADEM: Annual average Temperature Ambient; PRE: Annual average precipitation; IM: Humid index; ARI: Dryness; SAND: Percentage of sand in soil; SILT: Percentage of silt in soil; CLAY: Percentage of clay in soil.

<table>
<thead>
<tr>
<th>Factor</th>
<th>POP</th>
<th>GDP</th>
<th>ASL</th>
<th>GR</th>
<th>TADEM</th>
<th>PRE</th>
<th>IM</th>
<th>ARI</th>
<th>SAND</th>
<th>SILT</th>
<th>CLAY</th>
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*The larger the q value is, the stronger the degree of interpretation of the dependent variable on the independent variable is. The p value indicates the degree of significance, requiring that it is significant at least at the 10% level (p < 0.1), of which only the independent variable ARI does not match the requirements. The other variables are extremely significant, and they are labeled as **.*
Highlights:

- the spatial distribution characteristics of several ES were bounded by Tai-hang and Yanshan Mountains.
- Among the 45 pairs of ES, 38 pairs bore significant correlation.
- Multiple services had different degrees of positive and negative correlations with others.
- Seven bundles were identified. GDP, population density, annual average temperature ambient, and altitude played decisive roles in the spatial distribution of the bundle.
- Bundle research can identify the areas of the formation of co-occurrence of trade-offs and synergies and support the formulation of ES optimal management plans.