Spatial mismatch of ecosystem service demands and supplies in China, 2000–2020

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Abstract The supply capacity of ecosystem services (ES) in the past decades has shown a significant decrease globally, while ES demand capacity has increased. Identifying the spatial mismatch of ES supply and demand (ES S&D) can provide valuable knowledge about where the gaps are. Existing studies, however, lack specifics about the spatial mismatch of ES S&D—that is, few studies consider the coupling and decoupling relationship of ES S&D at the national scale. This study tries to fill the gap by examining the spatiotemporal distribution of ES S&D capacity in China from 2000 through 2020 using the land use/land cover matrix method. The spatial mismatch between ES S&D was ultimately identified by using coupling and decoupling analysis models.

A continuous increase was found in the ES demand capacity in China during the period studied, while a continuous decline was found in the ES supply capacity. The coupling degree of the ES S&D was relatively higher in the plains areas. The strong negative decoupling was the dominant relationship between ES S&D, which was widely distributed in eastern and southeastern China. The spatial mismatch of ES S&D in China has increased substantially from 2000 through 2020. The findings in this study provide important implications for ES management and effective allocation of resources.

Keywords Ecosystem services supply · Ecosystem services demand · Spatial mismatch · Ecosystem services stress · LULC matrix · Coupling analysis · Decoupling analysis · China

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Introduction

The relationships between ecosystem services (ES) supply and human demands are increasingly connected in the globalized world (Kapsar et al., 2019; Liu et al., 2013). ES enhances human well-being in the form of ES flows (Burkhard et al., 2012, 2014; Costanza et al., 1997). Establishing a spatial mismatch relationship between ES supply and demand is the foundation of the study of ES flows as well as the basis for ES payments and ecological compensation (Serna-Chavez et al., 2014; Vergara et al., 2021). An

imbalance of ecosystem services supply and demand (ES S&D) may result in a series of such issues as population stress, environmental pollution, biodiversity loss, and environmental injustice, all of which can severely threaten regional sustainability (Chen, Jiang, et al., 2019; Chi & Ho, 2018; Guan et al., 2019, 2020; Wang et al., 2019; Zhai et al., 2020). The consensus is that increasingly frequent human activities have intensified the trend of the imbalance of ES S&D in many regions of developing countries such as China (Chen, Chi, et al., 2019; González-García et al., 2020; Wang et al., 2019; Wu et al., 2019). Within this context, identifying the spatial mismatch of ES S&D is necessary in terms of the effective management of ecosystems and the rational allocation of natural resources in China.

A growing body of literature shows significant progress in the definition and assessment of ES, along with an analysis of the trade-offs, synergies, drivers, supply and demand, and mechanisms of ES (Blumstein & Thompson, 2015; Burkhard et al., 2012; Chen et al., 2020a; Cord et al., 2017; Costanza et al., 1997; Peng et al., 2020). However, integrating ES information into practice remains a challenge (Vialatte et al., 2019). More attention in the study of ES has been paid to human well-being simply because ES cannot be established without referring to humans as the beneficiaries (de Groot et al., 2010; Fisher et al., 2009).

Knowledge about ES S&D is important to policy makers. According to Burkhard et al. (2012), *ES supply* refers to the capacity to provide a specific bundle of ecosystem goods and services, while *ES demand* refers to the ecosystem goods or services currently being consumed or used within a given time period. Flow, supply, and demand are the three basic links of ES (Baró et al., 2016; Burkhard et al., 2014; Wang et al., 2019). As an essential part of the research, many studies on ES S&D have been conducted on individual ES types, such as supplying, regulating, supporting, and cultural services analysis (Burkhard et al., 2012; Chen & Chi, 2022; Egarter Vigl et al., 2017; Palacios-Agundez et al., 2015; Wu et al., 2019).

Methods such as expert experience, ecological footprint, land development indexes, ecological process simulation, and questionnaire surveys have been widely used in the existing research (Burkhard et al., 2012; Palacios-Agundez et al., 2015; Peña et al., 2015; Peng et al., 2020; Sun et al., 2020). The expert-based

semi-quantified method proposed by Burkhard et al. (2012) provides a perspective to measure regional ES potential, supply, and demand, especially at a large scale. It is a land use/land cover (LULC) method that is relatively straightforward to conduct, has low data requirements, and is based within the context of Europe and Asia (Burkhard et al., 2010, 2012; Wu et al., 2019). Although the linear and nonlinear relationships between ES S&D have been identified by mathematical analysis (Peng et al., 2020; Shi et al., 2020; Tao et al., 2018; Wang et al., 2019; Xu et al., 2022), little attention has been given to the coupling and decoupling relationship between ES S&D in consideration of the spatial mismatch (Wang et al., 2019; Wu et al., 2019). ES supply depends on the local natural capital foundation, while ES demand is directly related to socioeconomic activities (Burkhard et al., 2012). ES S&D are connected socially and ecologically, and both have significant regional spatial heterogeneity and dependence effects (Wolff et al., 2015). The existence of ES flow indicates that the supply and demand of ES do not match spatially (Schröter et al., 2018; Serna-Chavez et al., 2014). The current study attempts to construct a spatial relationship between ES S&D and explore the spatial relationship between ES supply and human well-being.

The study of the relationship between ES S&D is an important aspect of research on the relationship between human and natural systems (Alberti et al., 2011). However, the spatial relationship between ES S&D is challenging to interpret because ES S&D are ecologically and socioeconomically interconnected (Burkhard et al., 2014). Decoupling and coupling are two essential aspects of studying the relationship between human and natural systems. Decoupling theory is globally recognized as a concept of measuring sustainable development, and it has been used widely in a variety of empirical studies (e.g., economic growth, energy consumption) (Chen et al., 2017; Tapio, 2005; Von et al., 1997). The decoupling concept of the World Bank includes de-materialization and de-pollution, which is the process of gradually reducing the environmental impact of economic activities (de Bruyn & Opschoor, 1997). On the other hand, the Organisation for Economic Co-operation and Development (OECD) defines decoupling as breaking the link between environmental evils and economic goods, or breaking the linkage between environmental pressure and economic performance (Enevoldsen et al., 2007; OECD, 2001;

Zhang et al., 2021). The concept was employed in this study to decouple ES demand from ES supply. In addition, coupling analysis is also an important aspect of ES S&D research. Coupling originates from the concept of physics and refers to the phenomenon that two or more systems influence each other through various interactions (Guan et al., 2019). It can be used to measure the coupling degree and reflect the intensity of interaction and mutual influence between ES S&D (Xin et al., 2021). However, few studies have analyzed the spatial mismatch between ES S&D using the coupling and decoupling analysis framework.

The current study was conducted at the county level in China for the purpose of examining the spatial mismatch between ES S&D systems from the spatial perspective. The past 40 years of reform and opening in China have greatly promoted the country's economic growth, which increased at an average annual rate of 9.5% from 1978 to 2018. However, various problems emerged behind the economic boom, such as the continuous decline in ES supply capacity (Chen, Jiang, et al., 2019; Li et al., 2016; Song & Deng, 2017; Wu et al., 2019). Additionally, the mismatch of national spatial development and resource and environmental carrying capacity, tightening resource constraints, disorderly land development, increasing urban–rural gaps, and uneven development throughout the country is prominent in China. Accordingly, studying the spatial mismatch between ES S&D in China can help provide a basis for improved ecosystem management and national spatial policy making.

With that goal in mind, we first evaluated the spatiotemporal pattern of ES S&D in China from 2000 through 2020 using the LULC matrix method. The hotspot analysis method was then employed to identify the hotspots of changes in ES S&D. The coupling degree between ES S&D was examined to reveal the interactive coercing relationship between ES S&D. The decoupling analysis method was then used to identify ES stress zones. We seek to answer four questions:

(1) What is the spatiotemporal distribution pattern of ES S&D in China from 2000 through 2020?
(2) What is the spatiotemporal distribution pattern of the hotspots of changes in ES S&D in China?
(3) What is the spatial mismatch between changes in ES S&D in China at the county levels?
(4) Where are the ES stress zones in China?

Materials and methods

Data sources and preprocessing

The LULC dataset used in this study was sourced from the Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn). The spatial resolution was 1×1 km. The overall interpretation accuracy of the LULC dataset for 2000, 2005, 2010, 2015, and 2020 was greater than 90%, which is the most accurate land use remote-sensing monitoring data in China at present (Liu et al., 2003, 2010, 2014; Ning et al., 2018). We interpreted the LULC dataset based on the human–computer interactive method of remote-sensing satellite imagery data. We classified land use types in this study into seven primary types (cultivated land, forestland, grassland, water areas, wetland, construction land, and unused land) and 25 secondary land use types.

Complex natural conditions and uneven distribution of human activities have led to a serious mismatch between supply and demand of ES in China. To obtain more clearly spatial explanations of the coupling and decoupling relationship between ES supply and demand under the context of different regional development strategies and land use policies, we subdivided China into eight major regions on the basis of province borders (Fig. 1).

Methods

Calculation of ecosystem services supply and demand

Chen et al. (2020a) adjusted and applied the LULC matrix approach proposed by Burkhard et al. (2012) that contained 44 land cover types and 22 ES types into 25 land cover types and 22 ES types according to the land use types in this study (Burkhard et al., 2012). Three categories—provisioning services, regulating services, and cultural services—were included in the 22 ES types. We selected our LULC matrix in this study based on the study of Chen et al. (2020a), Sun, Liu, et al. (2019), and Wu et al. (2019). We assessed the LULC matrix of the ES S&D in Burkhard's study on a scale ranging from 0 to 5 based on expert knowledge. We determined the balance matrix on the basis
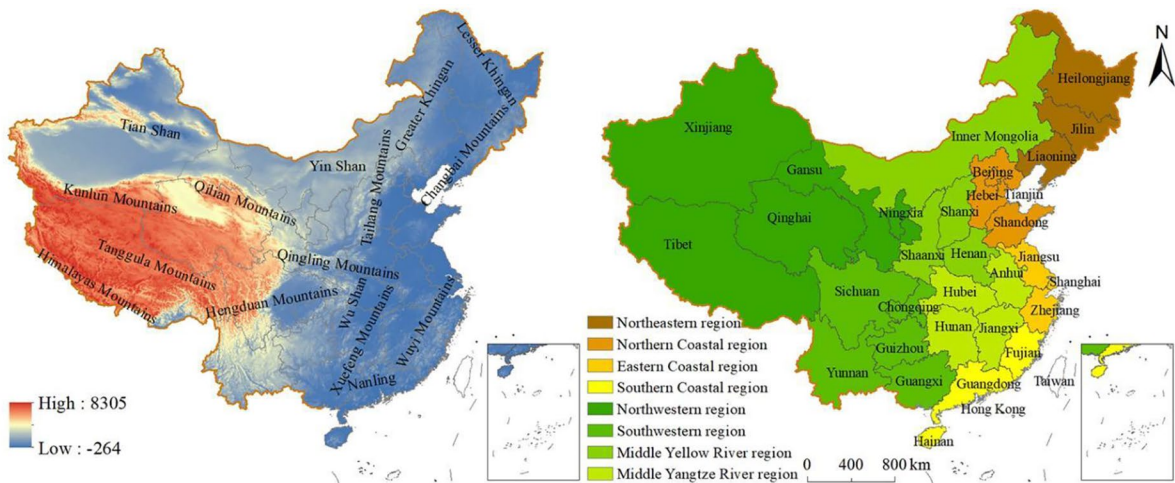
Fig. 1 Depiction of the study area. Hong Kong, Macau, Taiwan, and the South China Sea Islands are not included in the study area because there were no data available.

of the difference between the supply matrix and the demand matrix. The ES supply index (ESSI), ES demand index (ESDI), and ES balance index (ESBI) can be calculated by multiplying the proportion of these 25 land cover types by the corresponding LULC matrix. The equations are as follows:

$$ESSI_t = \sum_{j=1}^{m} \sum_{i=1}^{n} (PLUA_{i,t} \times SM_{ij,t}) \quad (1)$$

$$ESDI_t = \sum_{j=1}^{m} \sum_{i=1}^{n} (PLUA_{i,t} \times DM_{ij,t}) \quad (2)$$

$$ESBI_t = \sum_{j=1}^{m} \sum_{i=1}^{n} (PLUA_{i,t} \times BM_{ij,t}) \quad (3)$$

where $SM_{ij,t}$, $DM_{ij,t}$, and $BM_{ij,t}$ are, respectively, the matrices of ES supply, demand, and balance of the jth ES category of the ith land cover type at time t. n is the number of land cover types in this study, m is the number of ES categories, and $PLUA_{i,t}$ is the proportion of the ith land cover type at time t.

Hotspot analysis of ecosystem services supply and demand

We used hotspot analysis in ArcGIS 10.3 to examine the high-value clusters and low-value clusters in the change in ES supply, ES demand, and ES balance (Chi & Zhu, 2019; Getis & Ord, 1992). The output feature class with a Z-score, p value, and confidence level (Gi_Bin) was automatically created, and the default rendering was applied to the Gi_Bin field. Gi* statistics were Z-scores. For example, $Z(Gi^*) > 1.65$ indicates hotspots, $Z(Gi^*) < -1.65$ indicates coldspots, and $-1.65 \leq Z(Gi^*) \leq 1.65$ indicates the score is not significant. Larger statistically significant positive Z-scores indicated the clustering of high values, while the lower statistically significant negative Z-scores indicated the clustering of low values.

Coupling degree of ecosystem services supply and demand

Coupling is a concept introduced from physics, representing the degree to which two or more systems are dependent on each other (Sun, Liu, et al., 2019). The coupling degree of ES S&D can well represent the coordinated development degree of ES supply and human demand and reveal the interactive coercing relationship between ES supply and human demand (Guan et al., 2019). We calculated the coupling degree using Eq. (4):

$$SDCD_{it} = \sqrt{\left[\frac{ESSI_{it} \times ESDI_{it}}{\left((ESSI_{it} + ESDI_{it})/2 \right)^2} \right]} \quad (4)$$

Table 1 Classification of coupling degree of ES S&D

Category	Level	Degree	Function	Type
Coordinated development	$0.8 < CD \leq 1$	Highly balanced	ESSI < ESDI	ESSI lag
			ESSI ≈ ESDI	Systematically balanced
			ESSI > ESDI	ESDI lag
Transformation development	$0.6 < CD \leq 0.8$	Moderately balanced	ESSI < ESDI	ESSI lag
			ESSI ≈ ESDI	Systematically balanced
			ESSI > ESDI	ESDI lag
	$0.4 < CD \leq 0.6$	Basically balanced	ESSI < ESDI	ESSI lag
			ESSI ≈ ESDI	Systematically balanced
			ESSI > ESDI	ESDI lag
Uncoordinated development	$0.2 < CD \leq 0.4$	Moderately unbalanced	ESSI < ESDI	ESSI lag
			ESSI ≈ ESDI	Systematically balanced
			ESSI > ESDI	ESDI lag
	$0 < CD \leq 0.2$	Seriously unbalanced	ESSI < ESDI	ESSI lag
			ESSI ≈ ESDI	Systematically balanced
			ESSI > ESDI	ESDI lag

ESSI and ESDI stand for ecosystem services supply index and ecosystem services demand index, respectively; ESSI ≈ ESDI refers to |ESSI – ESDI| ≤ 0.1

where $SDCD_{it}$ represents the coupling degree between ES S&D of the ith unit at time t, and $ESSI_{it}$ and $ESDI_{it}$ are the ES supply and demand indexes of the ith unit at time t, respectively. The larger the $SDCD$, the more coordinated the $ESSI$ and $ESDI$. On the basis of SDCD values, in this study we divided county units into five first-level types, including highly balanced, moderately balanced, basically balanced, moderately unbalanced, and seriously unbalanced, along with 15 subcategories (Table 1) (Li et al., 2021).

Identification of ecosystem services stress zones

In this study, we employed the decoupling index to identify ES stress areas in China. The first systematic study of the decoupling theory was conducted by the Wuppertal Institute (Von et al., 1997). The decoupling theory was further developed and enriched (Tapio, 2005; OECD, 2001; Zhang et al., 2000). According to the definition expanded by Tapio (2005), the framework of decoupling was distinguished as eight logical possibilities (Fig. 2). We constructed the decoupling index by dividing the ES demand change ratio (%$\Delta ESDI$) by the ES supply change ratio (%$\Delta ESSI$). The equation is as follows:

$$DI_{t2-t1} = \frac{\%\Delta ESDI}{\%\Delta ESSI} = \frac{(ESDI_{i,t2} - ESDI_{i,t1})/ESDI_{i,t1}}{(ESSI_{i,t2} - ESSI_{i,t1})/ESSI_{i,t1}}$$

(5)

where DI_{t2-t1} indicates the decoupling index from the base year $t1$ to a target year $t2$. $ESSI_{i,t1}$ and $ESSI_{i,t2}$ are, respectively, the ES supply index of the ith county at $t1$ and $t2$. $ESDI_{i,t1}$ and $ESDI_{i,t2}$ are, respectively, the ES demand index of the ith county at $t1$ and $t2$.

Results

Ecosystem services supply, demand, and balance in China from 2000 through 2020

We evaluated the spatiotemporal distribution of ES S&D for three categories of ES (regulating, provisioning, and cultural services) and total ES from 2000 through 2020 at the county level in China based on the LULC matrix method. The ES supply indexes in the years 2000, 2005, 2010, 2015, and 2020 were 42.068, 42.017, 41.987, 41.899, and 40.546, respectively, and an evident decreasing tendency was observed. Regulating services contributed most of the ES supply in

Fig. 2 Decoupling degrees of ES demand index growth ($\Delta ESDI$) from ES supply index growth ($\Delta ESSI$) (modified from Tapio, 2005)
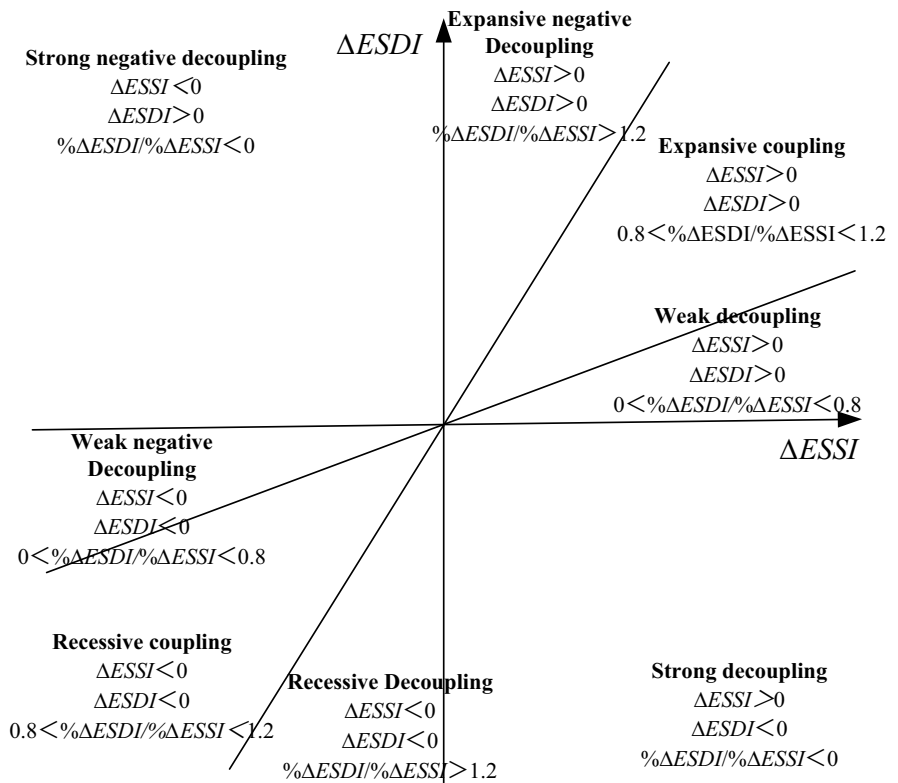
China, followed by provisioning services, and cultural services contributed the least. A high similarity in the spatiotemporal distribution pattern of ES S&D during these years was observed. Taking the ES S&D in 2020 as an example, the maps of ES S&D in 2020 are presented in Fig. 3. The ES supply capacity in the mountainous counties in the eastern monsoon zone were higher than in other regions: the ecosystems in the Greater Khingan, Lesser Khingan, Changbai, Taihang, Qinling, Hengduan, Wushan, Xuefeng, Nanling, and Wuyi mountain ranges. The low-ES supply counties were concentrated primarily in the plains area in the eastern monsoon zone and the northwestern region of China. Specifically, the low-ES supply counties were concentrated in the Chengdu Plains, North China Plains, Jianghan Plains, and Poyang Lake plains, as well as in the main capital cities in the eastern monsoon zone. The low-ES supply areas in northwestern China were located primarily in Xinjiang, Tibet, Qinghai, Gansu, Inner Mongolia, Ningxia, and Shaanxi. From the spatial distribution of ES supply, we can see that ES supply capacity was closely related to biophysical and socioeconomic factors.

The overall ES demand indexes in the years 2000, 2005, 2010, 2015, and 2020 in China were 6.958, 7.056, 7.112, 7.254, and 7.795, respectively, documenting a gradual increasing inverse tendency. We found that the overall ES supply capacity showed a decreasing trend, while the overall ES demand capacity increased continually. The spatial distribution of ES demand capacity was opposite that of the ES supply capacity. This is largely because ES supply capacity is closely related to natural capital, while ES demand capacity is closely related to human activities. Owing to increasing socioeconomic development, natural capital has been substantially exploited, consumed, wasted, degraded, or destroyed. Therefore, we found that the ES demand capacity in the plains areas was higher, with an increasing amount of ecosystem goods and services being consumed or used to meet growing needs in the key capital cities and urban agglomerations. In terms of ES balance, the spatial distribution was similar to that of the ES supply capacity. Significant ES imbalance can be found in the plains areas, the surrounding counties of large cities, and urban agglomerations. In addition, the spatial
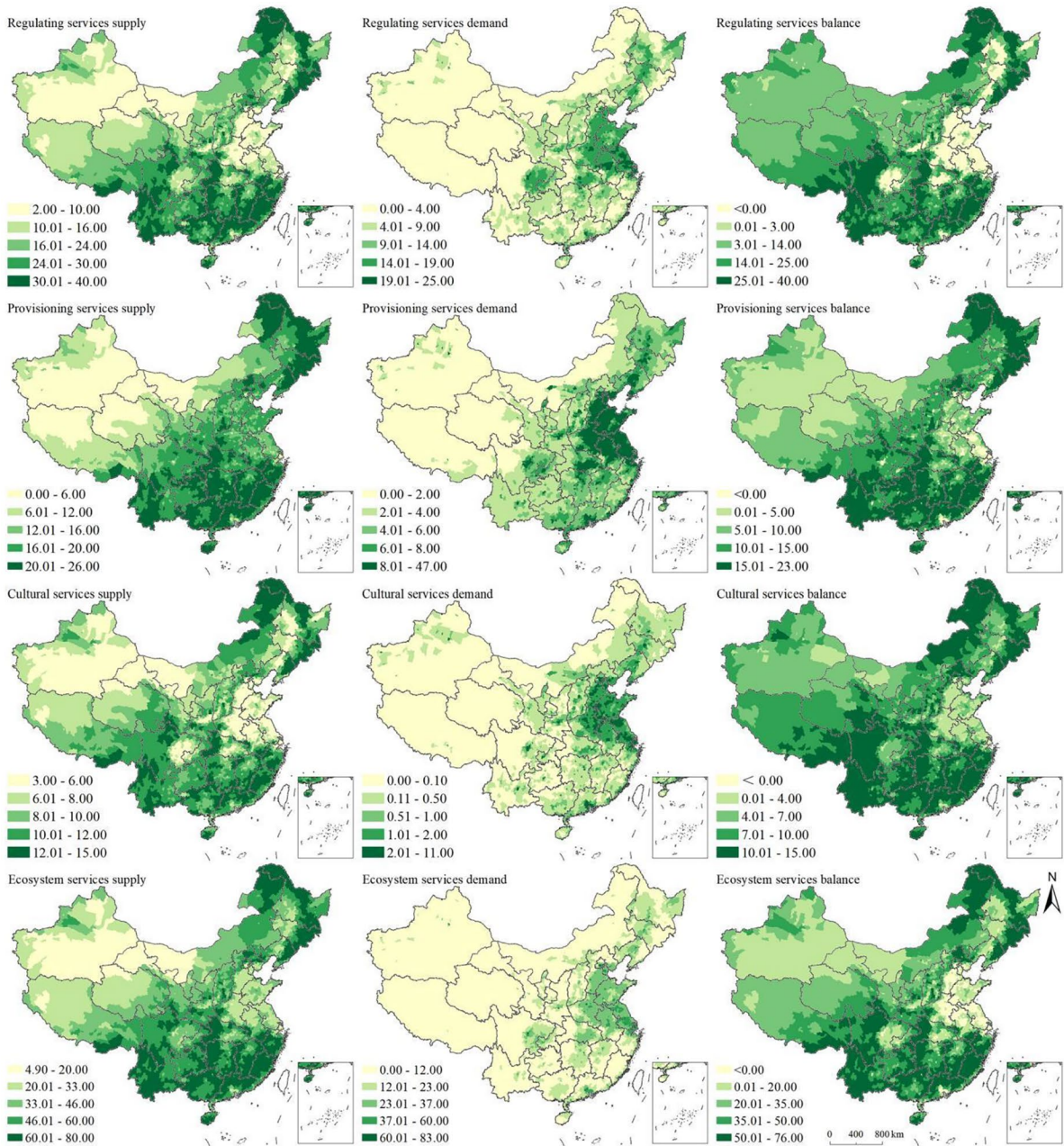
Fig. 3 ES balance supply, demand, and balance of provisioning services, regulating services, cultural services, and total ecosystem services across China in 2020

distribution pattern of the regulating services supply index, provisioning services supply index, and cultural services supply index was similar to that of ES supply index. The spatial distribution pattern of the regulating services demand index, provisioning services demand index, and cultural services demand index was similar to that of ES demand index. Furthermore, the regulating services balance index, provisioning services balance index, and cultural services balance index were similar to those of the ES balance index.

Identifying hotspots of ecosystem services supply and demand from 2000 through 2020

The hotspots and coldspots in ES S&D change varied greatly in spatial distribution and over time (Fig. 4). Comparing those hotspots and coldspots during the four study periods, we found the opposite distribution phenomenon between ES S&D—that is to say, the high-value clusters (hotspots) of ES supply change were more likely to correspond to the low-value clusters (coldspots) of ES demand change in the corresponding period. Specifically, the coldspots of ES supply change during 2000–2005 and 2005–2010 were located mainly in the eastern coastal region (Jiangsu, Shanghai, and Zhejiang), southern coastal region (Fujian and Guangzhou), the Bohai Economic Zone, and Anhui, where ES supply capacity decreased drastically because rapid socioeconomic development caused a continuous increase in ES demand. The coldspots of ES supply change during 2010–2015 were distributed mainly throughout the middle Yangtze River region and eastern coastal region (Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Zhejiang, and Shanghai) and parts of Guangdong. The coldspots of ES supply change during 2015–2020 were distributed mainly in Shandong, Henan, Shanxi, and Tibet.

The obvious hotspots of ES supply capacity change during 2000–2005 and 2005–2010 can be found on the Loess Plateau (Shanxi, Shaanxi, Gansu, Qinghai, Ningxia, Henan), the southwestern region of China (Sichuan, Guizhou, Yunnan, and Chongqing), and parts of Tibet, with coldspots of ES demand change being found in those same regions. During 2010–2015, the hotspots of ES supply capacity change were in Yunnan, the Hengduan Mountains, the southwestern part of Tibet, the Beijing–Tianjin–Hebei urban agglomeration, parts of the middle Yellow River region, and most of Heilongjiang. The obvious hotspots of ES supply capacity change during 2015–2020 were also found on the Loess Plateau. Similarly, we found that the spatial distribution of hotspots of ES demand change was consistent with the coldspots of ES supply change, and this was also the case for coldspots distribution of ES demand change. The hotspots of ES demand change were located in the northern coastal region, eastern coastal region, and southern coastal region of China, while the coldspots of ES demand change were located in the mountainous areas of the midwest of China

(Taihang, Qinling, Hengduan, Wushan, Xuefeng, Nanling, and Wuyi mountain ranges). Moreover, the hotspots (coldspots) distribution of the ES balance index change and the hotspots (coldspots) of ES supply index change were remarkably consistent.

Spatiotemporal coupling degree of ecosystem services supply and demand

The coupling degree of ES S&D in China showed an upward trend during the study period, which was 0.698, 0.702, 0.704, 0.709, and 0.736 in 2000, 2005, 2010, and 2020, respectively. Overall, we found that the coupling degree of ES S&D in China was a moderately balanced type. The dominant coupling degree type of ES S&D in China was highly balanced (> 50%), followed by moderately balanced (> 26%) and basically balanced (> 15%); only a small proportion of units were considered seriously unbalanced. We present the spatiotemporal coupling degree of ES S&D at the county level in China in Fig. 5. A spatial change pattern of SDCD in China during 2000–2020 was not evident. Overall, the SDCD in central and eastern China is evident and higher than that in northwestern China. The SDCD in the plains of central and eastern China is significantly higher than that in the mountainous areas (e.g., the North China Plain, the Northeast Plain, the Middle and Lower Yangtze Plain, Pearl River Delta, and the Sichuan Basin) (Fig. 5). We found that the characteristics of the SDCD were significantly correlated with terrain, traffic, and human activities. Therefore, the sustainable capacity of regional ES was higher in plains areas, and the relationship between ES supply and human demand was in a comparatively balanced and sustainable state.

Based on the subclassification criteria of the coupling degree of ES S&D, nine subcategories can be identified in China. ESDI lag type in the highly balanced category accounted for the most proportion of the units in China (> 35%), followed by ESDI lag type in the moderately balanced category (> 24%) and ESDI lag type in the basically balanced category (> 13%). ESSI lag type in the highly balanced category also accounted for a large proportion (> 9%). Spatially, the highly balanced ESDI lag and highly balanced ESSI lag types were mainly located in the plains, while the moderately unbalanced ESDI lag and basically balanced ESDI lag types were the dominant types in northwest China (Fig. 6).
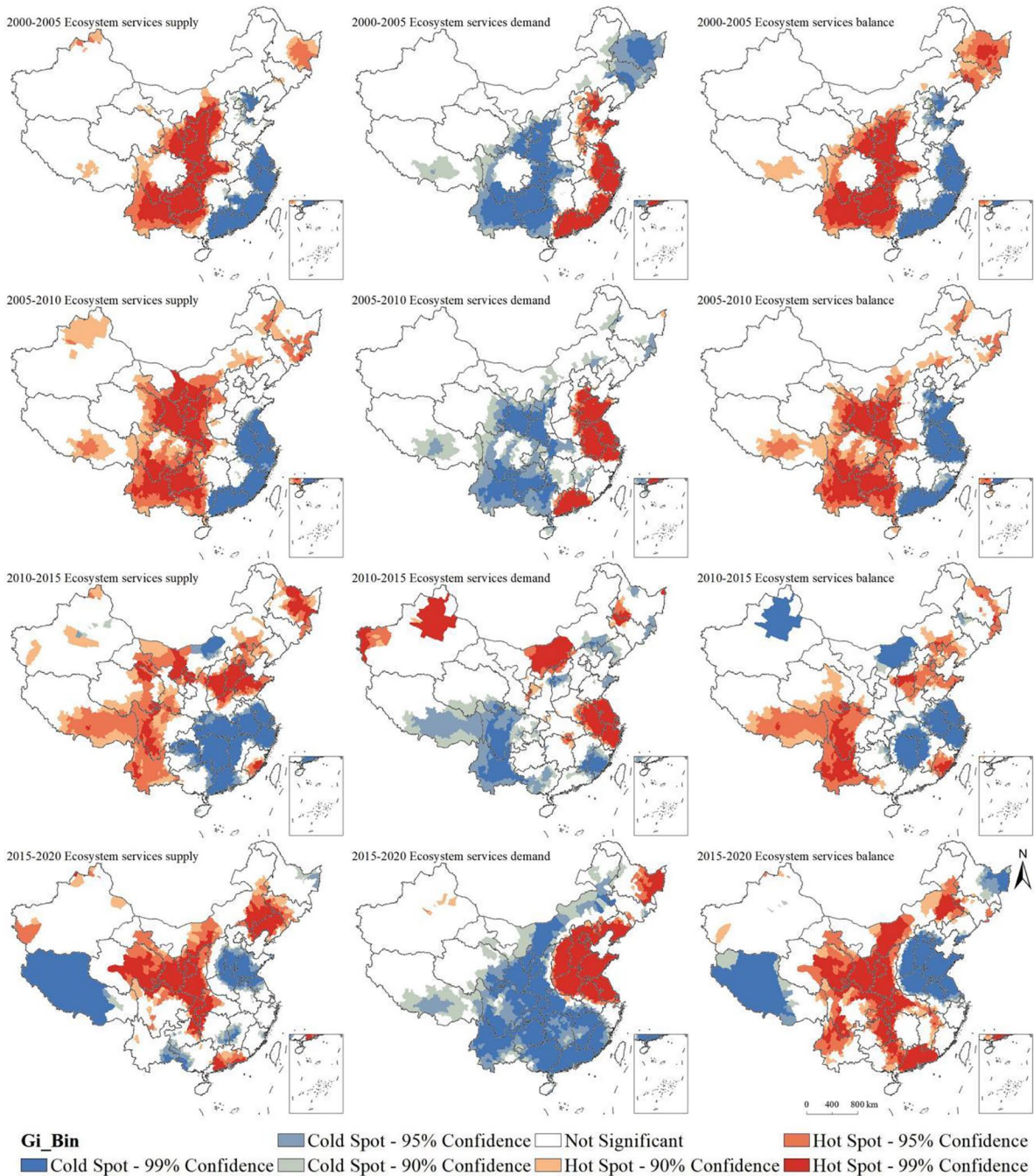
Fig. 4 Hotspots of ES S&D with different confidence levels, 2000–2020

Ecosystem services stress zones

According to the definition expanded by Tapio (2005), the framework of decoupling is distinguished by eight logical possibilities (Table 2). The decoupling indexes during 2000–2005, 2005–2010, 2010–2015, and 2015–2020 were –11.504, –10.983, –9.608, and –2.309, respectively, exhibiting a strong negative decoupling relationship. The
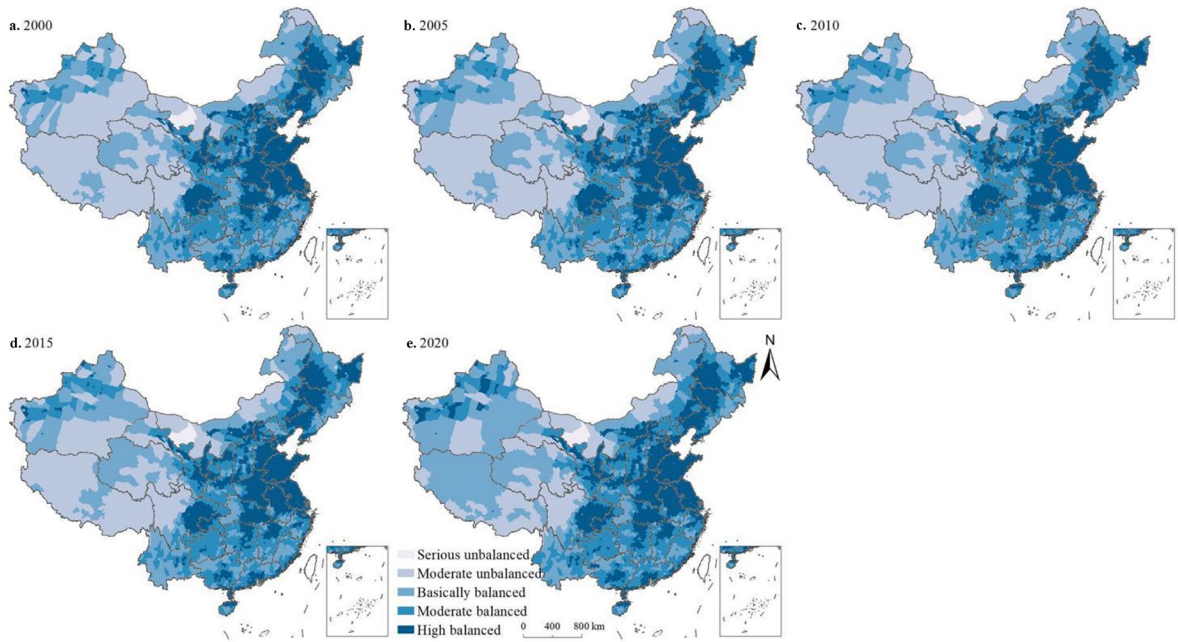
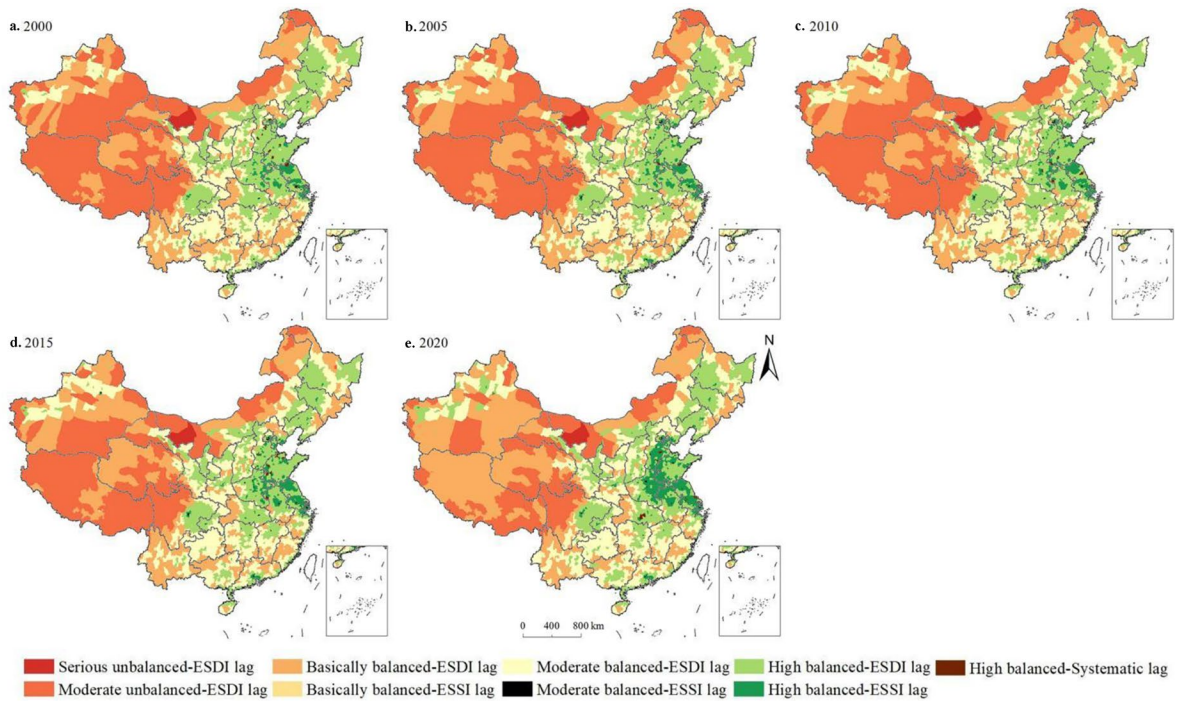**Fig. 5** Spatial distribution of SDCD in China, 2000–2020

Fig. 6 Spatial mismatch of ES S&D in China, 2000–2020

strong negative decoupling, expansive negative decoupling, and strong decoupling were the primary relationships between ES S&D. As shown in Table 2, the counties exhibiting a strong negative decoupling relationship were defined as the dilemma type, accounting for 58.898%, 54.081%, 80.981%, and 67.951% of the counties in China during the four respective periods (2000–2005, 2005–2010, 2010–2015, and 2015–2020). The counties exhibiting a strong negative decoupling relationship that experienced significant ES demand increase and ES supply decrease were distributed mainly in the eastern monsoon zone of China, especially in the eastern coastal region, southern coastal region, major urban agglomerations, provincial capitals, and surrounding counties (Fig. 7). During the period of 2010–2015 and 2015–2020, strong negative decoupled zones covered almost of China except some counties in Tibet, Xinjiang, and Inner Mongolia. The economic base and population in China are concentrated mainly in the central and eastern and southern coastal regions of China. Rapid economic development and urbanization consume a considerable amount of natural capital and led to a rapid and simultaneous increase in ES demand. The proportion of strong decoupling of ES supply increase and ES demand decrease was 15.061%, 13.25%, 4.483%, and 11.489%, respectively, during the four periods. We found a gradually decreasing tendency in the proportion of strong decoupled counties for 2000–2015, while there was a big rebound for 2015–2020. The strong decoupled counties are concentrated primarily in the northwestern region and the mountain range of the eastern China, but some of those counties are in Tibet and a few are discretely distributed in the eastern region. With an expansive decoupling negative status, ESSI and ESDI increased synchronously, with the growth rate of the former being far lower than that of the latter. The expansive decoupling negative counties were located mainly in northwestern China. Compared with expansive coupling, the expansive negative decoupling is a much worse decoupling status. The weakly decoupled counties that experienced faster ES supply growth than ES demand are defined as win–win types. However, the weakly negative decoupled counties that experienced faster ES supply decline than ES demand were in the most unfavorable situation for regional sustainability, not only in the decoupling relationship but also in the coupling relationship that existed in the relationship between ES S&D. Expansive coupling and recessive coupling exemplified the coupling relationships between ES S&D.

The decoupling pattern of ES S&D in this study changed significantly across the different periods. The most significant transition happened between strong decoupling and strong negative decoupling during the periods in the study (Tables 3, 4, and 5). Specifically, 5.534% of the counties changed from strong decoupling to strong negative decoupling, while 5.464% of the counties changed from strong negative decoupling to strong decoupling in the periods 2000–2005 and 2005–2010. However, 11.454% of the counties changed from strong decoupling to strong negative decoupling, while only 2.627% of the counties changed from strong negative decoupling to strong decoupling from the periods 2005–2010 and 2010–2015. For the periods 2010–2015 and 2015–2020, the proportion of the counties changing from strong decoupling to strong negative decoupling was the highest, reaching 9.081%, followed by the counties changing from expansive negative decoupling to strong negative decoupling (8.196%).

Table 2 Proportion of eight logical possibilities of decoupling types in China

| Decoupling types	2000–2005 (%)	2005–2010 (%)	2010–2015 (%)	2015–2020 (%)
No change	9.947	15.902	3.993	0.350
Expansive negative decoupling	9.072	7.846	6.410	11.629
Expansive coupling	0.701	0.981	0.105	1.121
Weak decoupling	3.222	2.907	0.736	2.697
Strong decoupling	15.061	13.275	4.483	11.489
Recessive decoupling	2.767	2.452	2.067	2.732
Recessive coupling	0.420	0.806	0.350	0.525
Weak negative decoupling	0.911	1.751	0.876	1.506
Strong negative decoupling	57.898	54.081	80.981	67.951
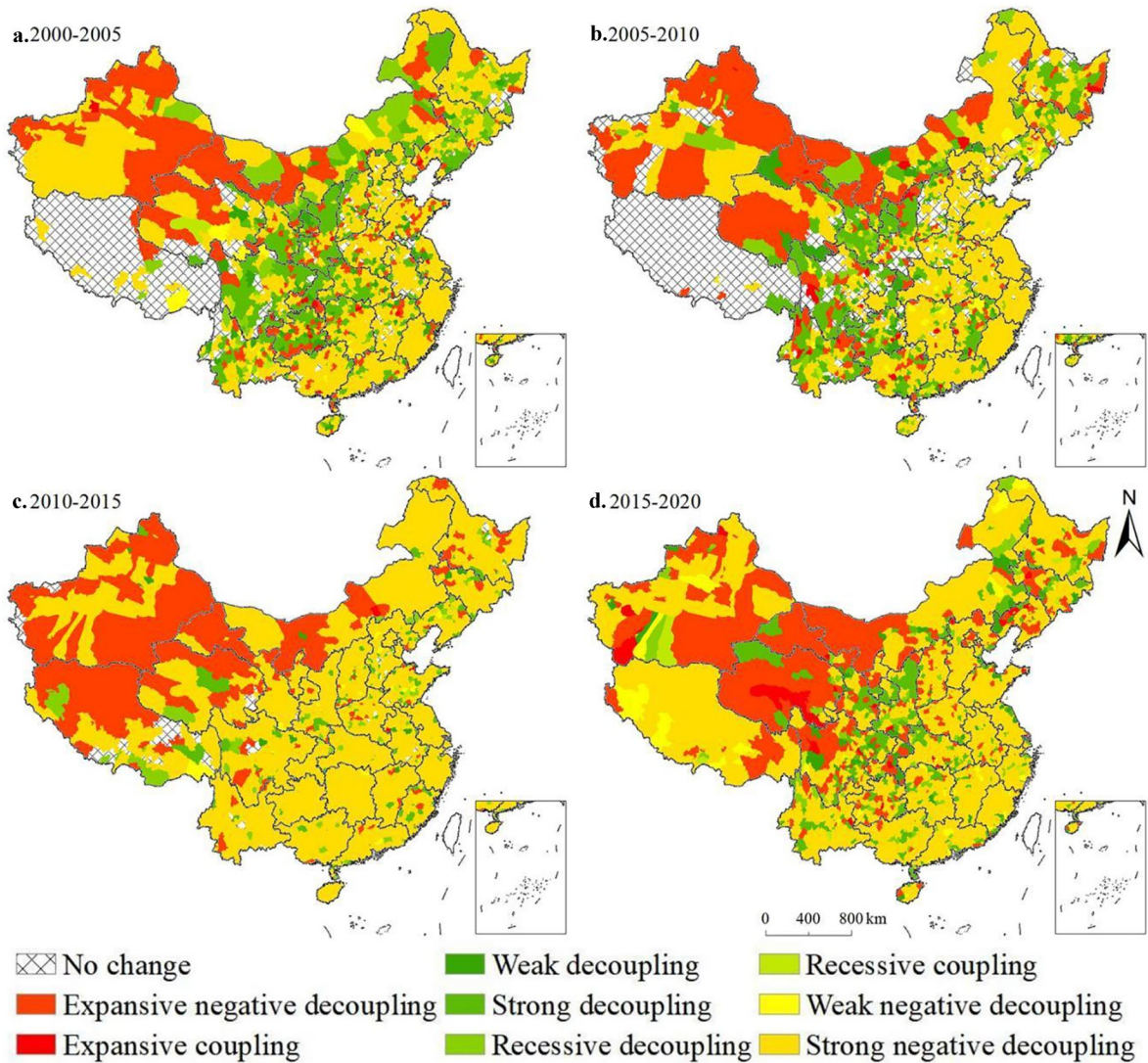
Fig. 7 Spatial distribution of eight logical possibilities of decoupling types in China, 2000–2020

Discussion

Spatial mismatch of ecosystem services supply and demand

ES flows from natural ecosystems to human social systems in the form of service flows (Burkhard et al., 2014). ES supply is the source of ES, while ES demand is the consumption of ES (de Groot et al., 2010; Fisher et al., 2009). The analysis of supply–demand mismatches in ES can help inform environmental management and produce useful

information for planning and integrating ES frameworks into decision-making processes. Our results showed that ES supply was not completely aligned with ES demand with respect to spatial distribution. The ES supply capacity in the mountainous counties of the eastern monsoon zone was higher than in other regions, while the ES demand capacity in the plains areas was relatively higher. The coupling degree of the ES S&D was relatively higher in the North China Plain, the Northeast Plain, the Middle–Lower Yangtze Plain, and the Sichuan Basin. This indicates that the ES S&D in the plains were basically in a state

Table 3 Transformation matrix of logical possibilities of decoupling types for the periods 2000–2005 and 2005–2010 in China

Logical possibilities	No change	Expansive negative decoupling	Expansive coupling	Weak decoupling	Strong decoupling	Recessive decoupling	Recessive coupling	Weak negative decoupling	Strong negative decoupling	Total
No change	137	24	3	7	69	7	2	1	204	454
Expansive negative decoupling	15	55	1	1	37	16	2	4	93	224
Expansive coupling	2	6	0	0	6	1	1	0	12	28
Weak decoupling	5	16	2	3	19	4	1	3	30	83
Strong decoupling	30	36	6	21	114	14	1	1	156	379
Recessive decoupling	7	7	1	3	15	5	1	2	29	70
Recessive coupling	1	3	1	2	5	2	1	0	8	23
Weak negative decoupling	5	6	0	4	7	0	0	1	27	50
Strong negative decoupling	82	106	6	51	158	30	3	14	1094	1544
Total	284	259	20	92	430	79	12	26	1653	2855

Rows show logical possibilities 2005–2010, and columns show logical possibilities 2000–2005

Table 4 Transformation matrix of logical possibilities of decoupling types for the periods 2005–2010 and 2010–2015 in China

Logical possibilities	No change	Expansive negative decoupling	Expansive coupling	Weak decoupling	Strong decoupling	Recessive decoupling	Recessive coupling	Weak negative decoupling	Strong negative decoupling	Total
No change	80	2	0	0	2	1	0	0	29	114
Expansive negative decoupling	26	54	1	7	25	9	4	4	53	183
Expansive coupling	0	0	0	1	1	0	0	0	1	3
Weak decoupling	5	3	0		2	1	0	2	8	21
Strong decoupling	28	11	0	2	10	1	0	1	75	128
Recessive decoupling	16	6	1	0	7	3	0	2	24	59
Recessive coupling	0	0	0	0	1	0	1	0	8	10
Weak negative decoupling	7	0	0	0	4	0	0	1	13	25
Strong negative decoupling	292	148	26	73	327	55	18	40	1333	2312
Total	454	224	28	83	379	70	23	50	1544	2855

Rows show logical possibilities 2010–2015, and columns show logical possibilities 2005–2010

Table 5 Transformation matrix of logical possibilities of decoupling types for the period 2010–2015 and 2015–2020 in China

Logical possibilities	No change	Expansive negative decoupling	Expansive coupling	Weak decoupling	Strong decoupling	Recessive decoupling	Recessive coupling	Weak negative decoupling	Strong negative decoupling	Total
No change	10	0	0	0	0	0	0	0	0	10
Expansive negative decoupling	10	60	1	3	14	7	2	1	234	332
Expansive coupling	2	5	0	1	2	1	0	0	21	32
Weak decoupling	0	5	0	2	7	2	1	0	61	78
Strong decoupling	23	15	0	6	19	5	0	0	259	327
Recessive decoupling	0	5	0	1	5	1	0	1	65	78
Recessive coupling	1	1	0	0	0	1	0	0	12	15
Weak negative decoupling	2	6	0	2	6	3	0	0	24	43
Strong negative decoupling	66	86	2	6	75	39	7	23	1636	1940
Total	114	183	3	21	128	59	10	25	2312	2855

Rows show logical possibilities 2015–2020, and columns show logical possibilities 2010–2015

of equilibrium. The strong negative decoupling relationship was the dominant type during the study period in China. Increasing human activities in China resulted in considerable increase in ES demand and led to severe degradation of the ES supply capacity.

Several other studies had similar results (Feurer et al., 2021; Jiang et al., 2022; Wei et al., 2018). For example, Feurer et al. (2021) noted a very high ES demand in urban areas of China because of economic development and population growth. Jiang et al. (2022) selected the karst area in southwest China as their study case and found an evident imbalance between ES S&D (i.e., demand exceeding supply), particularly in the surrounding areas of urban agglomerations. This finding shows that the moderately balanced ESSI lag type can be found in economically developed areas, especially provincial capital cities. The spatial mismatch between ES S&D was caused mainly by a variety of anthropogenic factors and natural conditions (Geijzendorffer et al., 2015; Sun, Li, et al., 2019; Wang et al., 2019). Specifically, anthropogenic factors (i.e., population density, economic development, built-up area, and land use intensity) were commonly considered to be closely related to ES demand (Chen et al., 2020a; Pan & Wang, 2021; Wang et al., 2019; Xu et al., 2022; Zhai et al., 2020). To the contrary, physical factors were usually closely related to ES supply capacity (Wei et al., 2018). Previous studies have shown that topographic factors, vegetation biomass, and climate factors have significant impact on ES supply capacity (Chen et al., 2020b; Zhang et al., 2021).

Policy implications

Rapid urbanization and economic growth increase the consumption of natural capital, which leads to an increase in ES demand and inevitably results in a decline in ES supply (Wang et al., 2019). The existence of a win–win mode (ES supply increase with an increase in ES demand) proves that reasonable land use can meet human needs for ES without compromising the capacity of ES supply (Goldstein et al., 2012). However, only a small proportion of counties in China experienced the increase in both ES S&D capacity, indicating that this kind of development model was difficult to achieve—but that does not mean it did not exist. The widely implemented ecosystem conservation programs in China have, to a certain extent, improved the ES supply capacity (Bryan et al., 2018). Moreover, the zoning of China's main functional areas has promoted the orderly development of national

land space and alleviated the rapid deterioration of ES caused by excessive pressure (SC, 2010). Since the 18th National Congress in China, a series of central conferences and documents have repeatedly been proposed for use in developing a spatial planning system—for example, promoting multiple planning integration and scientifically delineating the "three spaces" (ecological, agricultural, and urban) and "three lines" (ecological protection red line, permanent basic farmland protection red line, and urban development boundary). Currently, the evaluation of resource and environmental carrying capacity and land suitability are the prerequisites and foundations for national spatial planning. Delineating "three spaces and three lines" has important implications for monitoring and assessing national spatial planning and ES conservation, as well as providing early warning about potential ES stress areas.

Our study results can provide valuable information to assist policy makers and practitioners in maintaining a particular ES or improving human well-being. For regions with a high coupling degree between ES S&D, it is necessary to further achieve "win–win" outcomes through effective supply and demand management strategies (Guan et al., 2019). Policy makers in regions with a low coupling degree between ES S&D should focus on the improvement of ES and coordinate the relationship between ES S&D, ensuring that the relationship between ES supply and human demand is in a healthy cycle and sustainable state (Guan et al., 2019).

Strong negative decoupling, expansive negative decoupling, and strong decoupling were the primary relationships between ES S&D. In a strong decoupling zone, ESSI increased while ESDI decreased. Therefore, it is essential to preserve the ES supply and achieve a balance between ES S&D. In a strong negative decoupling zone, ESSI decreased but ESDI increased, so attention should be given to increasing the supply of ES and reducing the demand for ES. In an expansive negative decoupling zone, ESSI and ESDI increased synchronously, but the growth rate of ESSI was far lower than that of ESDI. Special attention should be paid to controlling the consumption of ES and controlling ESDI—thus promoting a decoupling between ESDI and ESSI. Specifically, for a supply–demand mismatch, it is necessary to reconcile the differences in both the supply and the demand sides of the equation to maintain ecological sustainability (Feurer et al., 2021). Moreover, ES supply can be increased by creating more protected areas, expanding existing protected areas, restoring vegetation in degraded landscapes

(González-García et al., 2020), and creating more urban and peri-urban parks (Baró et al., 2016; González-García et al., 2020). Accordingly, in future urban landscape planning, it is essential to retain an appropriate proportion of forestland to maintain sufficient ES (Jiang et al., 2022; Kehoe & Rhodes, 2013; Schirpke et al., 2019; Xu et al., 2021).

Limitations and future directions

This study used a land use/land cover (LULC) matrix to quantify ES S&D. This is a semi-expert-based method used within the context of Europe and Asia; therefore, the implications for using this LULC matrix for China may lead to some deviation, but it still provides useful perspectives on overall patterns and trends. A future study is being considered to modify the LULC matrix by adding more local expert knowledge based on China's context. The issues of ES S&D varied spatially. The LULC matrix method cannot recognize the key issue of ES S&D in a specific region. Specific categories of ES S&D and their driving factors can be thoroughly analyzed in future research to address specific ES issues. Furthermore, geographers and ecologists have been struggling with the complex relationship between pattern and scale for decades. Future research can also test the differences in the ES supply, demand, and balance at different research scales.

Conclusion

In this study, we quantified and mapped the ES supply, demand, and balance in China based on the LULC matrix approach, from 2000 through 2020. Continuing increases were found in ES demand in those years, while declines were found in ES supply. The results of the hotspot analysis method indicate that ES supply capacity in the eastern coastal provinces experienced a significant decrease and that ES demand capacity increased significantly in those areas. The coupling degree of ES S&D was higher in the plains areas. The decoupling relationships between ES S&D were zoned into eight logical possibilities. A strong negative decoupling relationship covered the most counties in the study area, indicating that ES in China faces increasing stress from human activities. The findings in this study provide practical guidance for resource allocation and ecosystem management.

Availability of data and material Not applicable.

Code availability Not applicable.

Declarations

Ethics approval This is an observational study. The Research Ethics Committee has confirmed that no ethical approval is required.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The participant has consented to the submission of this case report to the journal.

Conflict of interest The authors declare no competing interests.

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