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Quantifying ecosystem services supply and demand shortfalls and mismatches for management optimisation

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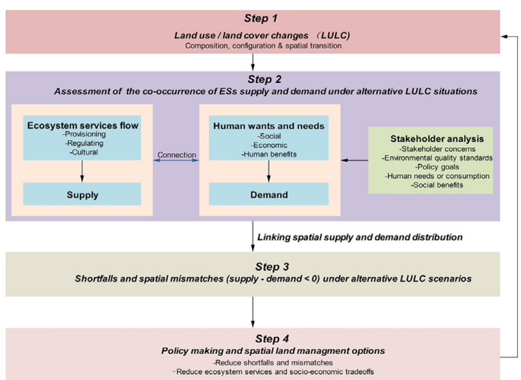
HIGHLIGHTS

- Framework for linking ecosystem services supply and demand is presented.
- PM_{10} removal service is in a state of surplus while the other three have shortfalls.
- The ecosystem services assessed had spatial heterogeneity in supply and demand.
- The balance thresholds of ecosystem services supply and demand were derived.
- Countermeasures to help reduce shortfalls and mismatches are suggested.

GRAPHICAL ABSTRACT



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ABSTRACT

Research on ecosystem services (ESs) has increased substantially in recent decades, but the findings have been slow to affect actual management, perhaps because most studies to date have neglected ESs supply and demand coupling mechanisms. Human reliance on ESs is due to the capacity of the landscape to supply services, but also to a societal need for these services. Sustainable land management requires supply and demand mismatches to be reconciled and the needs of different stakeholders to be balanced. Explicit spatial mapping of ESs supply and demand associated with land use changes can provide relevant insights for enhancing land management in urban areas. The emphasis is now shifting to enhancing sustainable land use, to ensure that supply meets or exceeds demand. In this study, a comprehensive framework comprising four core steps for quantifying ESs supply and demand changes associated with land use changes was developed and applied in a case study on Shanghai municipality, on the basis of environmental quality standards and policy goals. The balance thresholds of ESs supply and demand were derived by regression analysis between ESs and land use/land cover types. The results revealed large spatial heterogeneity in supply and demand for four key ESs tested: carbon sequestration, water retention, particulate (PM_{10}) removal and recreation. Carbon sequestration, water retention and recreation

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services all showed major shortfalls in supply that changed dramatically with urban land use change. This is valuable empirical evidence and has timely policy implications for management in a rapid urbanising world.

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1. Introduction

With the continuing rise in the global population, simultaneous urban expansion is omnipresent (Haas and Ban, 2014). The main effects of urban expansion on the environment include land use and resulting land cover changes. By converting natural ecosystems to impervious urban areas, urbanisation in the past century has changed landscapes more rapidly than at any other time in the history of mankind (Foley et al., 2005; Wang, 2018). While the impacts of rapid land use and land cover changes in urbanising areas on ecosystems are being increasingly recognised, landscapes continue to be converted and used in unsustainable ways (Euliss et al., 2010). Land management is one of the most important factors affecting land cover directly or indirectly. Policy and environmental planning decisions largely influence how land is managed (Carpenter et al., 2009; Maring and Blauw, 2017). At the landscape level, the main challenge is determining the optimal management of alternative land use options (de Groot et al., 2010; Bai et al., 2018).

Assessments of ecosystem services (ESs) are seen by many as a promising tool for supporting land management decisions, because they seek to highlight the multiple contributions of ecosystems to society and associated trade-offs between different land use options (Goldstein et al., 2012). This is especially important for urbanising regions, as they must accommodate an increasing population and depend on ESs to sustain human wellbeing (Gómez-Baggethun and Barton, 2013). By understanding the effect of land use and land cover changes in urbanising regions on ESs, different land management decisions to optimise ESs supply could be enabled (Logsdon and Chaubey, 2013).

The ESs concept has now gained importance at the land management level (van Oudenhoven et al., 2012), and ESs assessments are increasing in number (Seppelt et al., 2011; Abson and Hanspach, 2014). Many studies have shown that land use and land cover changes (e.g. urbanisation) can decrease various ESs, such as pollination service (Ricketts et al., 2008), carbon storage service (Tao et al., 2014), water retention service (Jia et al., 2014) and soil conservation service (Bai et al., 2012). However, the majority of ESs assessments have not yet been effectively incorporated into land management decisions in the public and private sector (Ruckelshaus et al., 2015). It has been suggested that such studies are not meeting the information needs of decision makers (Martinez-Harms et al., 2015; Förster et al., 2015). Due to the spatial peculiarity of ESs, mapping changes in ESs under alternative land uses has the potential to aggregate complex information (Burkhard et al., 2012). Therefore, explicit quantification and mapping of ESs is one of the main requirements for implementation of the ESs concept into landscape planning, management and decision-making (Bai et al., 2011a, b; Wolff et al., 2017).

Great progress has been made on mapping and quantifying ESs supply and demand in the past decade (Burkhard et al., 2012; Stürck et al., 2014; Wolff et al., 2017; Nikodinoska et al., 2018). Information on ESs supply reflects the capacity of ecosystems to supply particular ESs that are actually used or delivered, while ESs demand represents the other side of ESs equation and is related to the social beneficiaries (Yahdjian et al., 2015). Demand for specific ESs varies among stakeholders (the individuals or groups who benefit from ESs delivery) in terms of the location, type and intensity of ESs required (Lamarque et al., 2011). Inclusion of both ESs supply and demand in ecosystem assessment can increase the policy relevance and practical application of the ESs concept in land management (Honey-Rosés and Pendleton, 2013). Maps and spatial presentations of data can assist in visualisation of complex phenomena (Malinga et al., 2015). Therefore, mapping the heterogeneity of ESs supply and demand can help analyse the spatial configuration and provide a basis for accounting to ensure supply meets or exceeds demand (Crossman et al., 2013).

There is often an ambition to maximise ESs supply to reduce mismatches and shortfalls through land management, but a major challenge is integrated analysis to avoid unwanted trade-offs in ESs (Feng et al., 2017). Within this context, exploring the spatial mismatch between ESs supply and demand associated with urbanisation-related land use is crucial in appropriate incorporation of ESs into land management strategies. Many ESs studies have accounted for both ESs supply and demand in order to identify potential mismatches in urban regions (Baró et al., 2016). The challenge is that the majority of ESs assessments have not yet effectively influenced land management decisions (Bai et al., 2018).

The city of Shanghai is made of constructed land, arable land, woodland, grassland, lakes, reservoirs, rivers, garden plots and coastal wetlands. Among these, constructed land and arable land are the two major land use types in Shanghai, accounting for 40.88% and 30.3% of the total terrestrial area, respectively (Bai et al., 2018). Shanghai's rapid urbanisation has resulted in enormous change in the spatial pattern of land use, resulting e.g. in lack of green space for recreation, air and water pollution, urban heat island effects, climate impacts and biodiversity loss (Li et al., 2017). For example, 47% of Shanghai's freshwater ecosystems are worse than Grade V (Shanghai Municipal Government, 2013). It is claimed that disorderly urban expansion can aggravate the deficit and mismatch between ESs supply and demand (Baró et al., 2015). Therefore Shanghai government wants to optimise land use to improve ESs such as water quality etc.

The hypothesis tested in this study was that optimal land management can reduce ESs deficit and mismatches. The overall aim of the work was to quantify ESs supply and demand changes associated with land use changes, in order to inform future land management options. Specific objectives were to: 1) select appropriate environmental quality standards (EQS) and policy goals for a test case (Shanghai municipality) in order to assess ESs supply and demand coupling mechanisms; 2) examine land cover changes in Shanghai during the period 2000–2014 and quantify co-occurrence of ESs supply and demand under these land cover situations using spatially explicit models; 3) identify ESs mismatches on the basis of ESs supply and demand results; and 4) suggest future spatial land management approaches to address ESs mismatches and reduce shortfalls. Shortfall in this instance refers to deficiency in both amount and spatial distribution between ESs supply and demand.

To fulfil these objectives, a modified operational framework was developed based on environmental quality standards and policy goals (Baró et al., 2015) to quantify ESs supply and demand coupling mechanisms associated with land use changes in Shanghai municipality. The methodological approaches described by Baró et al. (2015) include three main steps: (1) selection of EQS; (2) definition and quantification of ESs supply and demand indicators; and (3) identification and assessment of ESs mismatches on the basis of EQS, considering certain additional criteria. These three steps were incorporated to step 2 in the modified framework.

Using the modified framework, ESs supply and demand in Shanghai municipality were mapped by linking land cover information from e.g. remote sensing, land surveys and GIS with data from monitoring, statistics, modelling, EQS and policy goals. Four types of ESs were selected based on stakeholder concerns and data availability.

The years 2000, 2008 and 2014 were selected to best reflect Shanghai's urban expansion process (Li et al., 2017). The quantitative information obtained was used to suggest potential strategies to minimize the mismatch between ESs supply and demand associated with rapid urbanisation and thus to contribute to sustainable urban planning in metropolises.

2. Materials and methods

2.1. Study area

Shanghai covers about 6340 km^2 (land area, Fig. 1) and the vast majority of this area is flat, with an average elevation of 4 m. The region has a subtropical monsoon climate, with mean annual temperature of 15.5 °C and mean annual precipitation of 1200 mm (Li et al., 2017). From 1961 to 2017, Shanghai's surface temperature increased significantly, and annual precipitation showed a weak increasing trend and obvious intergenerational changes (Shanghai Climate Change Monitoring Bulletin, 2017). In recent decades Shanghai has experienced mean annual population growth of 2.76%, from 16.09 million in 2000 to 24.26 million in 2014. In the same period, the nominal gross domestic product (GDP) of Shanghai municipality has increased from 477 billion RMB in 2000 to 2357 billion RMB in 2014 (Shanghai Statistical Yearbook, 2001, 2009, 2015). In fact, considerable socioeconomic development in the past 40 years has resulted in Shanghai becoming one of the internationalised metropolises with the highest urbanisation level in China.

Shanghai city government has long recognised the multiple roles played by urban green spaces and has implemented several master plans to optimise green spaces in integration with an environmental sustainability agenda. The most well-known plans influencing Shanghai urban land management are the general land use plan for Shanghai (1997–2010) and the Shanghai urban master plan (1999–2020). Following the implementation of these plans, woodland and grassland area increased, by 396.44 km^2 (455.84% increase) and 153.75 km^2 (457.05% increase), respectively, from 2000 to 2014 (Table S1). Quantification of green space patterns in Shanghai municipality is necessary in understanding green space changes and is essential for assessing and mapping the mismatches of ESs supply and demand in response to these changes, in order to inform future landscape and urban planning.

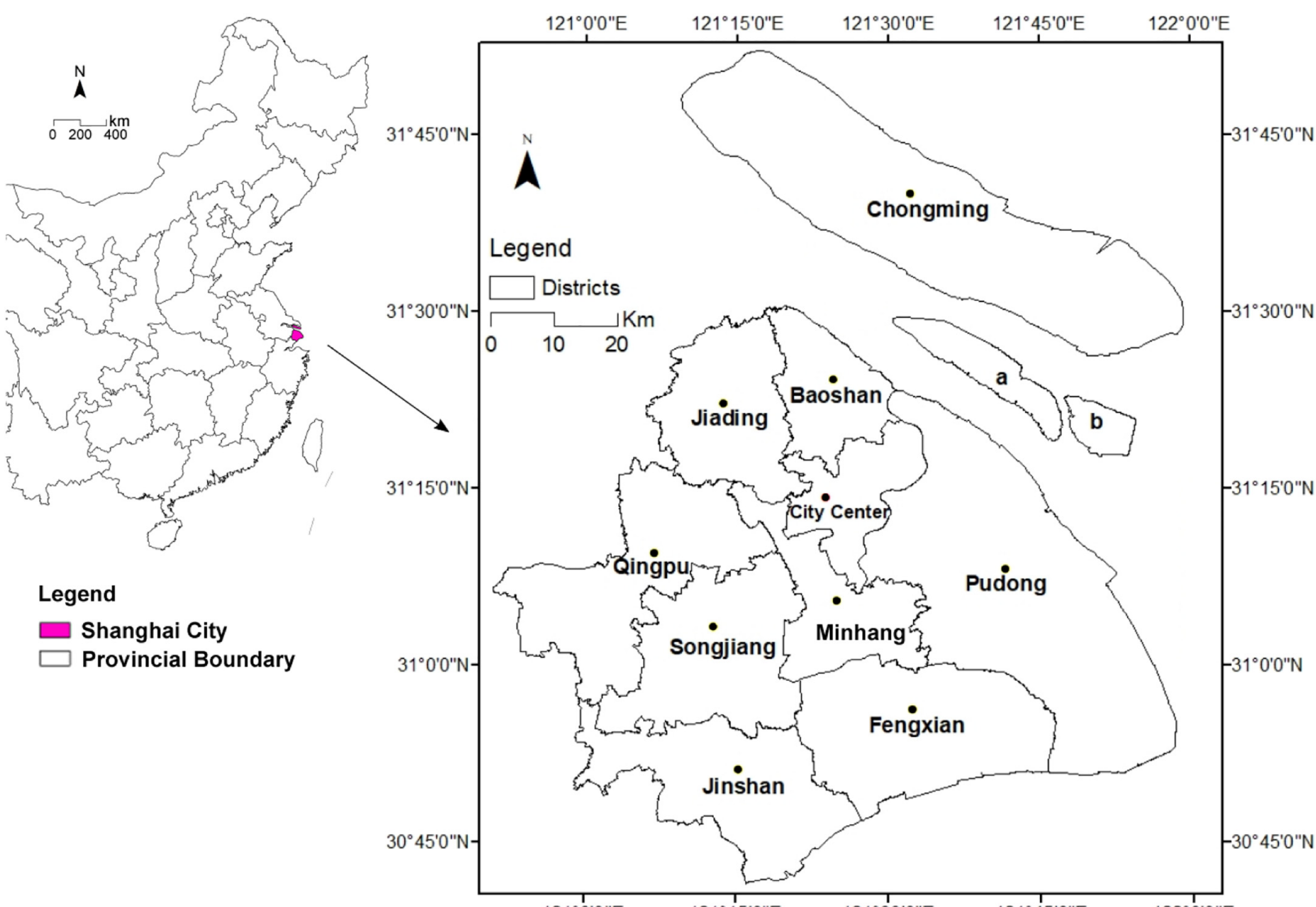

Fig. 1. Geographical location of (left) Shanghai and (right) its administrative divisions (a and b are two outlying islands governed by Chongming district).

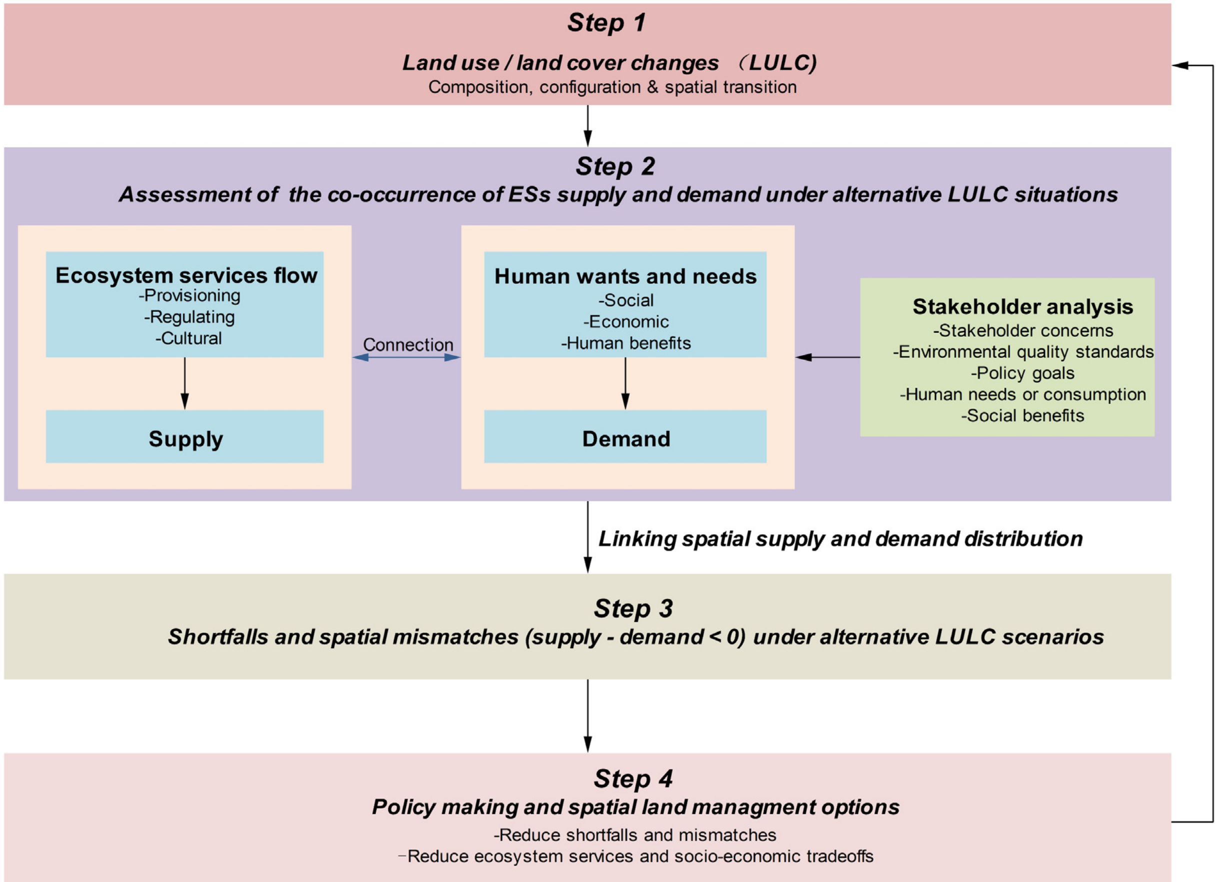

Fig. 2. Linking ecosystem services (ESs) supply and demand mismatches in Shanghai to land use changes for spatial land management. This framework includes four main steps: (1) urbanisation related LULC (e.g. land composition, configuration and spatial transition), (2) selection of appropriate indicators reflecting stakeholder concerns and appropriate EQS and policy goals based on policy documents to assess the co-occurrence of ESs supply and demand under alternative land use situations using spatially explicit models, (3) assessment of ES mismatches and shortfalls on the basis of spatial visual results, and (4) inform future land management options.

2.2. Framework for quantifying ESs supply and demand mismatches

The methodological approach devised by Baró et al. (2015) assumes that EQS can provide a common minimum threshold value to assess mismatches across different contexts. The approach was used by Baró et al. (2015) to assess mismatches between ESs supply and demand across five European cities on the basis of EQS and to discuss the actual and potential contribution of urban green infrastructure to address mismatches between ESs supply and demand. An operational framework was developed based on that of Baró et al. (2015) to assess the contribution of ESs supply to societal demand associated with land use changes for optimal land management in Shanghai municipality. However, the developed framework advanced the existing methodology by quantifying the mismatches between ESs supply and demand associated with land use changes for optimal land management.

Four core steps were conducted to integrate scientific methodologies in quantifying ESs supply and demand within analyses of policies to meet EQS and policy goals for practical implementation (Fig. 2). In step one, remote sensing and GIS were used to analyse land composition, configuration and spatial transition in Shanghai during the period 2000–2014. This step aims to examine LULC changes in Shanghai during the period 2000–2014 and set different LULC situations for spatial explicit modelling. In step two, co-occurrence of ESs supply and demand under alternative land use situations was quantified using spatially explicit models and policy goals. This comprised two tasks: selection of appropriate indicators reflecting stakeholder concerns (e.g. government and local residents); and selection of appropriate EQS and policy goals based on policy documents to assess ESs supply and demand. This step aims to select appropriate indicators and related-EQS and policy goals to quantify co-occurrence of ES supply and demand under the LULC situations using spatially explicit models. In step three, mismatches and shortfalls between ESs supply and demand were assessed and identified based on the spatial visual results. This step aims to identify ESs supply and demand mismatches. In step four and final step in the framework, future spatial land management plans to reduce shortfalls were addressed. This step aims to inform future land management options.

2.2.1. Step 1: Land composition, configuration and spatial transition

In step one, multi-temporal aerial images (0.5 m) were used to quantify land use and land cover (LULC) for 2000, 2008 and 2014 in Shanghai municipality. The images were merged together in ERDAS Imagine 9.3 by adjusting the projection system to UTM (Universal Transverse Mercator), and used manual visual interpretation via ArcGIS 10.0 to delineate polygons for 10 LULC classes, namely lake, reservoir, grassland, garden plot, coastal wetland, aquaculture, woodland, river, constructed land and arable land. Overall classification accuracy is 94% for the 2014 LULC map based on LULC ground truth samples collected with a handheld Global Positioning Systems (GPS). The LULC layers were converted to grid format with spatial resolution of 100 m for ESs supply and demand analysis.

2.2.2. Step 2: Occurrence of ESs supply and demand under alternative land use situations

(1) Selection of ESs

High-priority ESs for use in the assessment of supply and demand for Shanghai in step two were selected based on four criteria: i) ESs classification framework: The ESs subjected to this analysis were defined based on types in the Millennium Ecosystem Assessment (MA, 2005) and Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin-Young, 2018) classification frameworks, of which regulating, supporting and cultural services were included. ii) Stakeholder concerns: ESs that reflect the particular interests and concerns of government and local residents. For example, Shanghai aims to reduce its peak carbon emissions by 15% by 2020 to help meet the national carbon emissions reduction target. To reduce the negative social impacts of climate change – the Shanghai government wants to invest in ecosystems to enhance local carbon sequestration. iii) Supply-demand connection: ESs that can reflect coupling mechanisms between ESs suppliers and beneficiaries, representing co-occurrence of ESs supply and demand for quantifying mismatches. iv) Good data availability. Four key ESs were selected based on these criteria, namely: 1) water retention; 2) particulate matter (PM_{10}) removal; 3) carbon sequestration; and 4) recreation. These four ESs are important for urban areas mainly because most urban areas face local pollution problems (e.g., contaminated air), regional depletion of natural resources (e.g., water scarcity), global environmental change (e.g., climate change) and has demand for recreation space. The water retention service benefits city residents by sustaining water supplies and improving water quality; the PM_{10} removal service benefits residents by providing cleaner and safer living environments through absorption of particulate organic matter; the carbon sequestration service helps fulfil the global responsibility of mitigating carbon emission; and the recreation service can help residents enjoy good spirits and high-quality lives (Baró et al., 2015; Larondelle and Lauf, 2016; Bai et al., 2018).

(2) ESs supply and demand quantification

Water retention service is defined as the ability of ecosystems to intercept or store water resources from rainfall, while mitigating surface runoff. The water balance equation (Eq. (1)) was used to quantify the water retention service supply for the case of Shanghai, while the water consumption for agricultural, industrial, domestic and ecological purposes was summarised to quantify the water demand (Eq. (2)). Ecological water consumption refers to the irrigation water for green spaces in urban area. Precipitation and runoff were taken from Water Resources Bulletin of Shanghai (2000, 2008 and 2014). Evapotranspiration (ET) was downloaded from MODIS Global Evapotranspiration Project (MOD16) (Mu et al., 2011). Data on water consumption for different purposes were also taken from Water Resources Bulletin of Shanghai (see Table S2). For Shanghai at city scale, in spatial mapping of water demand the amount of agricultural water consumption was equally allocated to agricultural land; the amount of industrial water consumption was equally allocated to industrial land; the amount of domestic water consumption was equally allocated to residential land; and the amount of ecological water consumption was equally allocated to urban green spaces.

$$\text{Supply}: \quad S_{wp} = P - ET - Runoff \tag{1}$$

$$\text{Demand}: \quad D_{wp} = D_{agricultural} + D_{industrial} + D_{domestic} + D_{ecological} \tag{2}$$

where S_{wp} is water retention service supply, m^3; P is annual average precipitation, mm; ET is annual average evapotranspiration, mm; $Runoff$ is annual average runoff, mm; D_{wp} is water demand, which in this case equates to water consumption, m^3; and $D_{agricultural}$, $D_{industrial}$, $D_{domestic}$ and $D_{ecological}$ is water consumption for agricultural, industrial, domestic and ecological purposes, respectively, in m^3.

PM_{10} removal service supply is conditional, which was quantified by considering the PM_{10} absorption capacity of four main types of contributing vegetation (woodland, grassland, garden plots and arable land) and the PM_{10} concentration of each sub-district (Larondelle and Lauf, 2016) (Eq. (3)). If PM_{10} absorption capacity by vegetation exceeds the PM_{10} concentration, the PM_{10} removal service supply is equal to the PM_{10} concentration. However, if PM_{10} absorption capacity by vegetation is smaller than the PM_{10} concentration, the PM_{10} removal service supply equals the PM_{10} absorption capacity.

PM_{10} removal demand is also conditional, which was calculated as the difference between the PM_{10} concentration of each sub-district and the permitted PM_{10} concentration set by the local government target. The demand is the discrepancy between the actual concentration and the permitted concentration if the actual concentration exceeds the permitted PM_{10} concentration. Otherwise, the demand would be zero (Eq. (4)).

$$\text{Supply}: \quad S_{pm} = \begin{cases} R_{LULC_i} \times A_{LULC_i} & \text{if } R_{LULC_i} \times A_{LULC_i} \le \rho_{pm,district} \times H \times A_{district} \\ \rho_{pm,district} \times H \times A_{district} & \text{if } R_{LULC_i} \times A_{LULC_i} > \rho_{pm,district} \times H \times A_{district} \end{cases} \tag{3}$$

$$\text{Demand}: \quad D_{pm} = \left\{ \left(\rho_{pm,district} - PM_{10}, permitted\right) \times H \times A_{district} \quad if\, \rho_{pm,district} > PM_{10}, permitted \quad 0, if\, \rho_{pm,district} \le PM_{10}, permitted \right. \tag{4}$$

where S_{pm} is PM_{10} removal service supply, kg; $LULC_i$ is index of land use and land cover; R_{LULUi} is PM_{10} absorption capacity of $LULC_i$, kg/ha (value taken from Escobedo and Nowak, 2009; see Table S3); A_{LULCi} is area of $LULC_i$; D_{pm} is demand for PM_{10} removal service, kg; $\rho_{pm,\ district}$ is PM_{10} concentration of each district, kg/m^3 (value taken from Shanghai Environmental Bulletin, 2000, 2008 and, 2014); H is estimated air column, where 200 m was selected as the boundary layer (Larondelle et al., 2016); $A_{district}$ is area of district, ha; and $PM_{10,\ permitted}$ is the permitted PM_{10} concentration set by air quality guidelines from World Health Organization, which is 20 μg/m^3 (WHO, 2005).

Carbon sequestration service supply and demand are both conditional. The absorbed carbon capacity was estimated considering carbon sequestration by vegetation and soils within woodland, grassland, arable land and wetland, which was evaluated as net primary production (NPP) based on the photosynthesis process and soil carbon sequestration rate (Bai et al., 2011a, 2011b). Carbon sequestration service demand was estimated as the difference between actual carbon emissions and permitted CO_2 emissions set by local government (Eq. (6)). Carbon emissions from industrial, service industry and household sources were summarised. For spatial mapping, the amount of industrial carbon emissions was equally allocated to industry land; the amount of service industry carbon emissions was equally allocated to commercial land; and the amount of household carbon emissions was equally allocated to residential land.

$$\text{Supply}: \\ S_{cs} = \begin{cases} 1.63 \times NPP_{LULC_i} \times A_{LULC_i} + SCS_{LULC_i} \times A_{LULC_i} & \text{if } 1.63 \times NPP_{LULC_i} \times A_{LULC_i} + SCS_{LULC_i} \times A_{LULC_i} \le \left(E_{industry} + E_{services} + E_{living}\right) \times C_t \\ \left(E_{industry} + E_{services} + E_{living}\right) \times C_t & \text{if } 1.63 \times NPP_{LULC_i} \times A_{LULC_i} + SCS_{LULC_i} \times A_{LULC_i} > \left(E_{industry} + E_{services} + E_{living}\right) \times C_t \end{cases} \tag{5}$$

$$\text{Demand}: \\ D_{cs} = \begin{cases} \left(E_{industry} + E_{services} + E_{living}\right) \times C_t - C_{target} & \text{if } \left(E_{industry} + E_{services} + E_{living}\right) \times C_t > C_{\text{target}} \\ 0 & \text{if } \left(E_{industry} + E_{services} + E_{living}\right) \times C_t \le C_{\text{target}} \end{cases} \tag{6}$$

where S_{cs} is supply of carbon sequestration service, ton; $LULC_i$ is index of land use and land cover; NPP_{LULCi} is net primary production of $LULC_i$, ton/ha/yr (which was derived from Chen et al. (2011), Wang et al. (2010) and Xu et al. (2011); Table S4); A_{LULCi} is area of $LULC_i$, ha; SCS_{LULCi} is soil carbon sequestration rate of $LULC_i$, ton/ha (which was derived from Han et al. (2008) and Duan et al. (2008); Table S5); the constant of 1.63 refers to the absorbed carbon capacity by vegetation based on photosynthesis process, where for every unit of NPP accumulated by the vegetation, 1.63 units of carbon can be sequestrated (Bai et al., 2011a, 2011b). D_{cs} is demand for carbon sequestration, ton; $E_{industry}$, $E_{services}$ and E_{living} is carbon emissions from industry, services and households, respectively (values taken from Water Resources Bulletin of Shanghai, 2000, 2008 and 2014; Table S6); C_t is the conversion rate of carbon, 0.68 according to National Development and Reform Commission; and C_{target} is calculated based on the permitted CO_2 emissions set by Shanghai government. Based on the target CO_2 emissions level stated in the "13th Five-year Plan for Energy Conservation and Climate Change of Shanghai", an emissions reduction target for carbon of 39% by 2020 was set (FPE, 2017).

Recreation service supply was measured as the average fraction of urban green space, which was calculated as total area of urban green space divided by the area of the corresponding sub-district. Recreation service demand was multiplied by the population density and the local government guidance on green space provision per capita during the study period.

$$\text{Supply}: \\ S_r = A_{greenspace,subdistrict} / A_{subdistrict} \tag{7}$$

$$\text{Demand}: \\ D_r = \rho_{pop} \times A_{guided\ \ greenspace} \tag{8}$$

where S_r is recreation service supply, ha/ha; and $A_{greenspace,\ subdistrict}$ is area of green space in each sub-district, ha. There are 236 sub-districts in Shanghai (Fig. S1); $A_{subdistrict}$ is area of each sub-district; D_r is recreation service demand, ha/ha; ρ_{pop} is population density, person/ha (Fig. S2); and $A_{guided\ greenspace}$ is the government guidance on green space provision, which is 13.5×10^{-4} ha/person (Shanghai's Urban Construction and Management "Twelfth Five-year Plan", 2012).

2.2.3. Step 3: ESs supply and demand mismatches and shortfalls

Ecological supply-demand ratio (ESDR) links the actual supply of ESs and human demand, which can be used to reveal the nature of surpluses or shortfalls (Li et al., 2016):

$$ESDR = \frac{S - D}{(S_{\max} + D_{\max})/2} \tag{9}$$

where S and D refers to the actual supply and demand for a specific ES, respectively; and S_{max} and D_{max} indicates the maximum value of supply and human demand, respectively, for a specific ES in the three periods, which are extracted from the corresponding S and D spatial layers. The denominator in Eq. (9) for the three periods is the same for each ES. A positive ESDR value indicates an ES surplus, a value of zero indicates supply-demand balance and a negative value indicates that supply does not meet demand, i.e. there is a shortfall.

In step three of the framework, comprehensive supply-demand ratio (CESDR) was used to determine the status of ESs at the integral level, calculated as the arithmetic mean of ESDR:

$$CESDR = \frac{1}{n} \sum_{i=1}^{n} ESDR_i \tag{10}$$

where n is number of estimated ESs, with $n = 4$ in this case; and $ESDR_i$ is supply-demand ratio for each ES type, where $i = 1$ refers to water retention service, $i = 2$ refers to PM_{10} removal service, $i = 3$ refers to carbon sequestration service and $i = 4$ refers to cultural service.

2.2.4. Step 4: Spatial land management plans to reduce shortfall

The ESDR of the four key ESs assessed and the corresponding constructed land ratio/urban green space ratio for the 236 sub-districts in Shanghai in 2000, 2008 and 2014 were derived via ArcGIS 10.0. Constructed land in this case refers to all impervious surfaces, which includes transportation land, industrial land, residential land etc. Constructed land ratio was calculated as those areas of constructed land divided by the total land area. Urban green space refers to natural vegetated area, which includes woodland grassland and garden plots. Urban green space ratio was calculated as the area of urban green space divided by the total land area. Least squares regression analysis via SPSS was then used to draw trend lines between ESDR and constructed land ratio/urban green space ratio for 2000, 2008 and 2014, to indicate a negative or positive influence and also the level of significance. A similar regression analysis was used to draw trend lines between CESDR and constructed land ration/urban green space ratio.

The threshold of spatial land management (constructed land ratio and green space ratio) to reduce shortfall and achieve balance was then calculated based on the regression analysis results. When supply equals demand, balance is achieved and there is no shortfall.

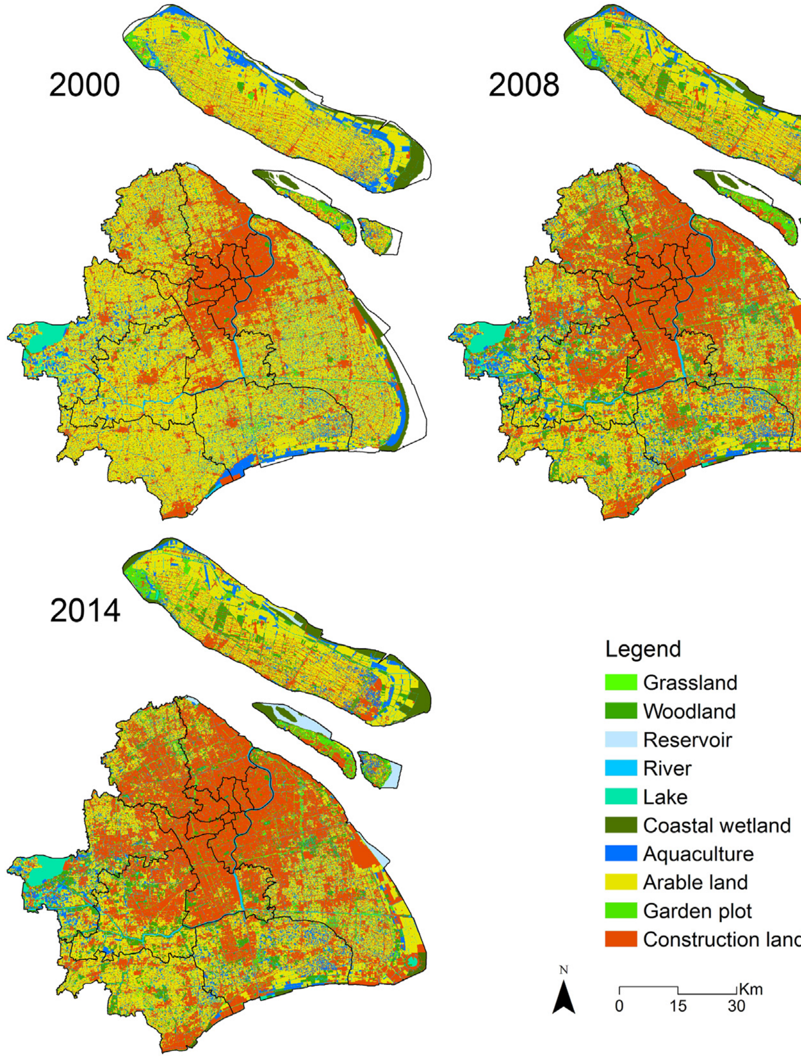

Fig. 3. Spatial distribution of land use and land cover (LULC) in Shanghai in 2000, 2008 and 2014.

2.3. Data requirements and preparation

The above models and analysis require multiple gridded datasets, together with specific biophysical data, as inputs. Mean annual precipitation and water demand data were extracted from Water Resources Bulletin of Shanghai (2000, 2008 and 2014). Carbon emissions and population density

Table 1
Dynamic land use and land cover (LULC) change in Shanghai and transition from 2000 to 2014 (units: km^2).

	Types	Grassland	Woodland	Reservoir	River	Lake	Coastal wetland	Aquaculture	Arable land	Garden plot	Constructed land
2000–2008	Grassland	21.92	1.96	0	0.91	0	0.01	0.12	0.39	0.03	8.16
	Woodland	2.83	37.66	0	2.39	0.07	0.01	2.13	18.50	3.41	19.49
	Reservoir	0	0	3.77	0	0	0	0	0	0	0.01
	River	5.84	10.18	0	338.79	1.34	1.58	12.31	49.19	2.92	73.17
	Lake	0.03	0.15	0	0.77	59.70	0	0.26	0.11	0	0.29
	Coastal wetland	1.81	1.77	2.84	3.08	0	106.74	8.73	32.97	0.06	30.34
	Aquaculture	6.62	27.15	0	11.13	0.34	3.03	199.40	93.51	4.56	86.26
	Arable land	77.29	384.17	0	57.46	0.67	1.28	164.63	1980.67	104.96	820.23
	Garden plot	0.61	8.42	0	1.56	0	0	0.88	18.93	67.56	9.38
	Constructed land	43.54	28.95	0.03	20.19	0.38	1.14	8.57	84.03	3.84	1574.48
2008–2014	Grassland	145.83	1.29	0	0.50	0	0.25	0.13	0.80	0.01	11.95
	Woodland	3.81	417.12	0	1.64	0	0.08	0.91	22.71	21.10	34.03
	Reservoir	0	0	27.96	0.00	0	0	0	0	0	0
	River	0.66	0.74	0	415.88	0	0.06	0.39	3.47	0.08	16.88
	Lake	0	0.01	0	0.01	68.38	1.34	0	0.02	0	0.01
	Coastal wetland	0.31	0.03	3.56	1.52	0	154.71	0.30	37.10	0	14.39
	Aquaculture	1.19	3.05	0	2.71	0	0.07	297.25	61.36	0.75	40.25
	Arable land	10.48	40.44	0.01	8.90	0	0.14	24.09	1970.41	12.45	230.29
	Garden plot	0.17	2.93	0	0.30	0	0.01	0.52	8.85	165.76	8.80
	Constructed land	24.62	16.66	0.34	7.48	0.47	0.04	2.91	46.74	1.07	2541.64

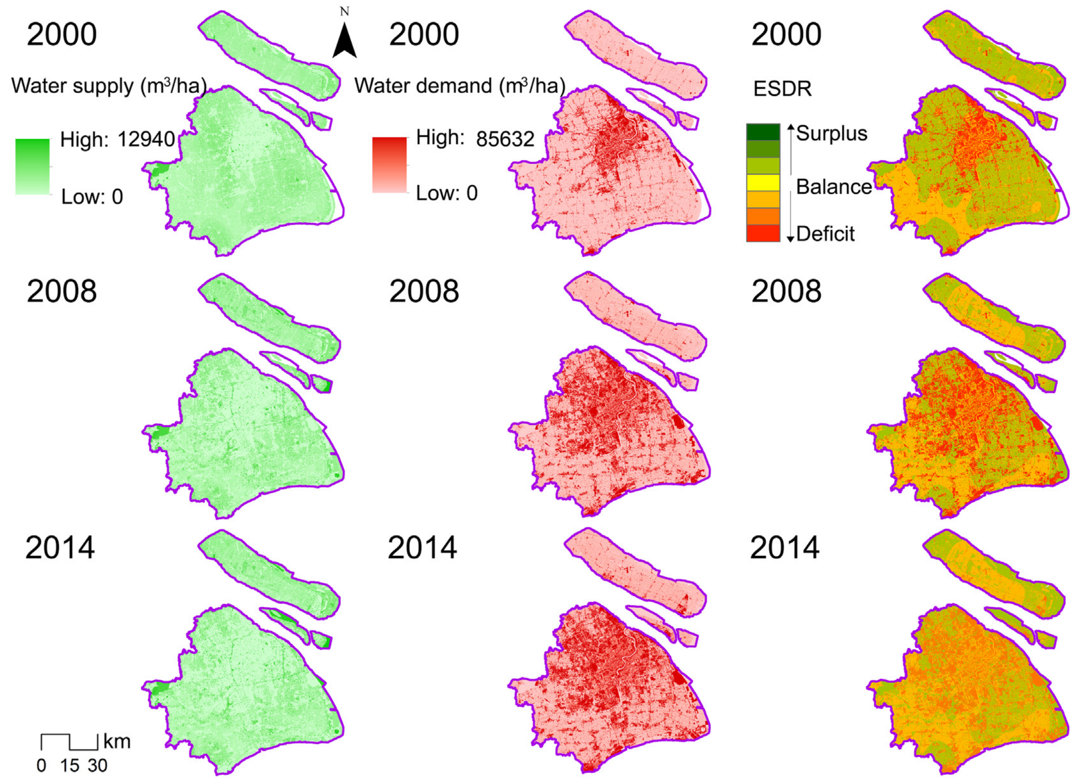

Fig. 4. Distribution of water retention supply (left column), water demand (middle column) and supply-demand ratio (right column) in Shanghai in 2000, 2008 and 2014.

data were extracted from Water Resources Bulletin of Shanghai (2000, 2008 and 2014) (Fig. S1). The collected spatial data for Shanghai and other relevant crucial data are listed in Table S7, which summarises each dataset by its sources, a short introduction and the associated models. Tables S2–S6 list key parameters required by those models. All spatial layers were re-sampled to 100 m resolution and assigned the same spatial references in Universal Transverse Mercator.

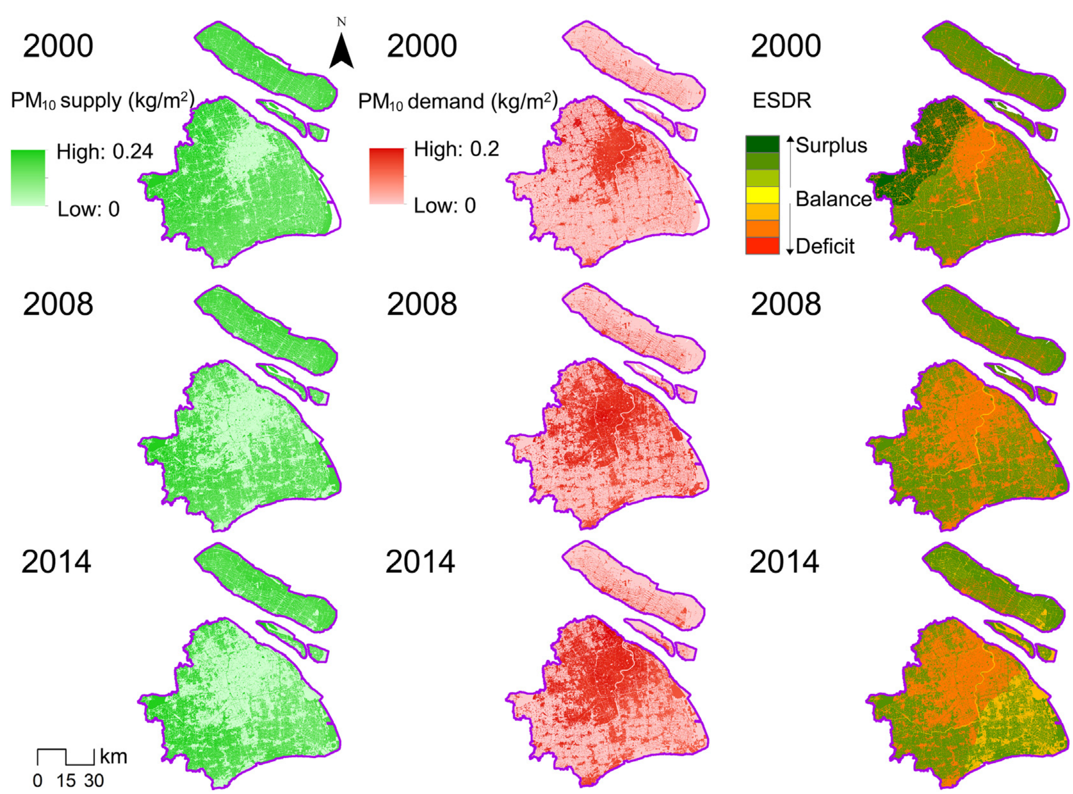

Fig. 5. Distribution of PM_{10} removal supply (left column), PM_{10} removal demand (middle column) and supply-demand ratio (right column) in Shanghai in 2000, 2008 and 2014.

3. Results

3.1. LULC change

Shanghai experienced enormous temporal change in LULC during the study period. From 2000 to 2014, constructed land area showed an increasing trend, expanding from 1768.13 km^2 in 2000 to 2909.09 km^2 in 2014, mainly due to conversion of arable land (1113.02 km^2) and aquaculture (101.08 km^2). Arable land area showed the greatest decrease (31.88%), from 3606.21 km^2 in 2000 to 2456.55 km^2 in 2014. Both woodland and grassland areas showed increasing trends, mainly through conversion of arable land and constructed land. The area occupied by lakes, reservoirs, rivers, garden plots and coastal wetlands showed minor changes over the period (Fig. 3 and Table 1). Compared with the second half of the period (2008–2014), LULC change was more intense in the first half (2000–2008), especially for arable land and constructed land. The rate of change in constructed land and arable land was 110.68 km^2 and −160.65 km^2 per year, respectively, in 2000–2008 and 42.59 km^2 and −27.41 km^2 per year, respectively, in 2008–2014.

3.2. ESs supply and demand change and mismatches

3.2.1. Water retention service

Water retention service supply showed an increasing trend, from 0.83 billion m^3 in 2000 to 1.07 billion m^3 in 2014, a 28.92% increase (Fig. 4). However, the overall increase in water retention service supply does not mean that it exceeded demand (water consumption). Water demand in 2000, 2008 and 2014 was 10.23 billion m^3, 11.36 billion m^3 and 9.82 billion m^3, respectively. Despite the decrease per unit area from 2008 to 2014, water demand during the whole period 2000–2014 greatly exceeded the water retention service supply. The shortfall for 2000, 2008 and 2014 was 9.4 billion m^3, 10.31 billion m^3 and 8.75 billion m^3, respectively.

Besides the shortfall in amount, the spatial distribution of water retention service supply and demand showed a mismatch according to the supply-demand ratio map (Fig. 4). The sub-districts had clearly higher water supply than the city centre, since the reservoirs and lakes in the sub-districts can store more water resources. In comparison, water demand was more clustered in the city centre because of the higher population numbers and density. However, over time water demand also expanded to the other sub-districts. Lower water supply and higher water demand in the city centre led to a shortfall and negative supply-demand ratio.

3.2.2. PM_{10} removal service

The PM_{10} removal service supply exceeded demand in the total amount considering the whole period, with a surplus in 2000, 2008 and 2014 of 26.88 tons, 27.51 tons and 27.72 tons, respectively (Fig. 5). PM_{10} removal service supply decreased markedly from 132.69 tons in 2000 to 91.11 tons in 2014, a decrease of 31.34%. The PM_{10} removal service demand also showed a decreasing trend, from 105.81 tons in 2000 to 63.39 tons in 2014, a decrease of 40.09%.

The spatial distribution of PM_{10} removal supply and demand exhibited diverse patterns (Fig. 5). Though surplus in amount, the spatial distribution of PM_{10} removal service supply and demand also showed a mismatch according to the supply-demand ratio map. The suburban area had clearly higher PM_{10} removal service supply than the city centre area. In comparison, the city centre showed high PM_{10} removal service demand. This caused the surplus areas to be mainly distributed in the suburbs and the shortfall areas to be mainly distributed in the city centre.

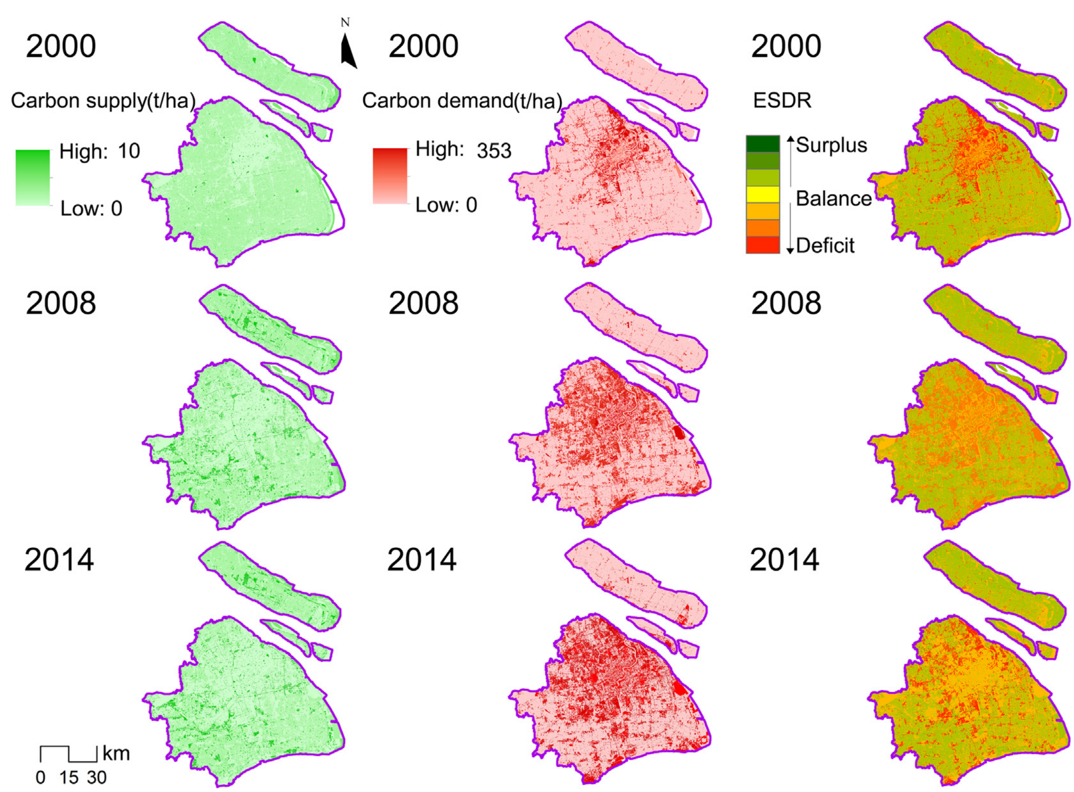

Fig. 6. Distribution of carbon sequestration supply (left column), carbon sequestration demand (middle column) and supply-demand ratio (right column) in Shanghai in 2000, 2008 and 2014.

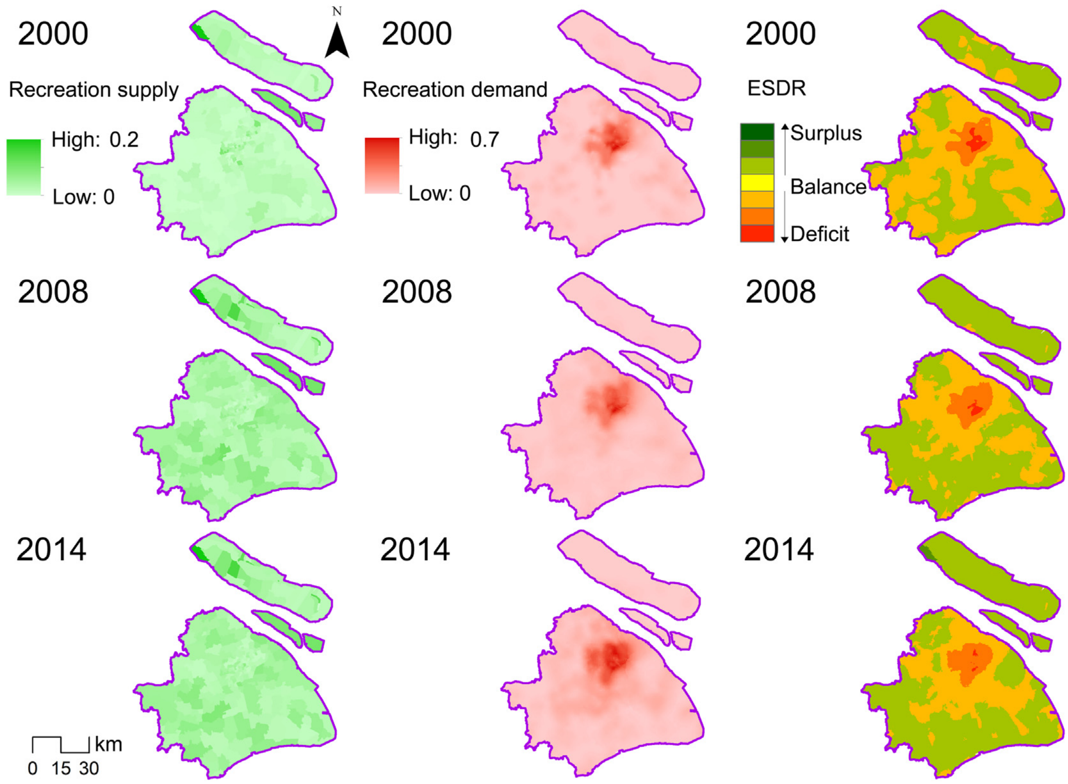

Fig. 7. Distribution of recreation supply (left column), recreation demand (middle column) and supply-demand ratio (right column) in Shanghai in 2000, 2008 and 2014.

3.2.3. Carbon sequestration service

Carbon sequestration service supply increased from 0.24 million tons in 2000 to 0.57 million tons in 2014, an increase of 137.5%. In the same period, carbon sequestration demand exhibited an increase of 35.2%, from 21.82 million tons in 2000 to 29.51 million tons in 2014 (Fig. 6). There was thus a marked shortfall between supply and demand and this shortfall showed an increasing trend, from 21.58 million tons in 2000 to 28.94 million tons in 2014.

Despite the spatial distribution of carbon sequestration supply and demand showing a mismatch, the surplus area exceeded the shortfall area during the whole period from 2000 to 2014 (Fig. 6). Higher carbon sequestration service demand was mostly distributed in the city centre in 2000, but demand also spread rapidly throughout the sub-districts,

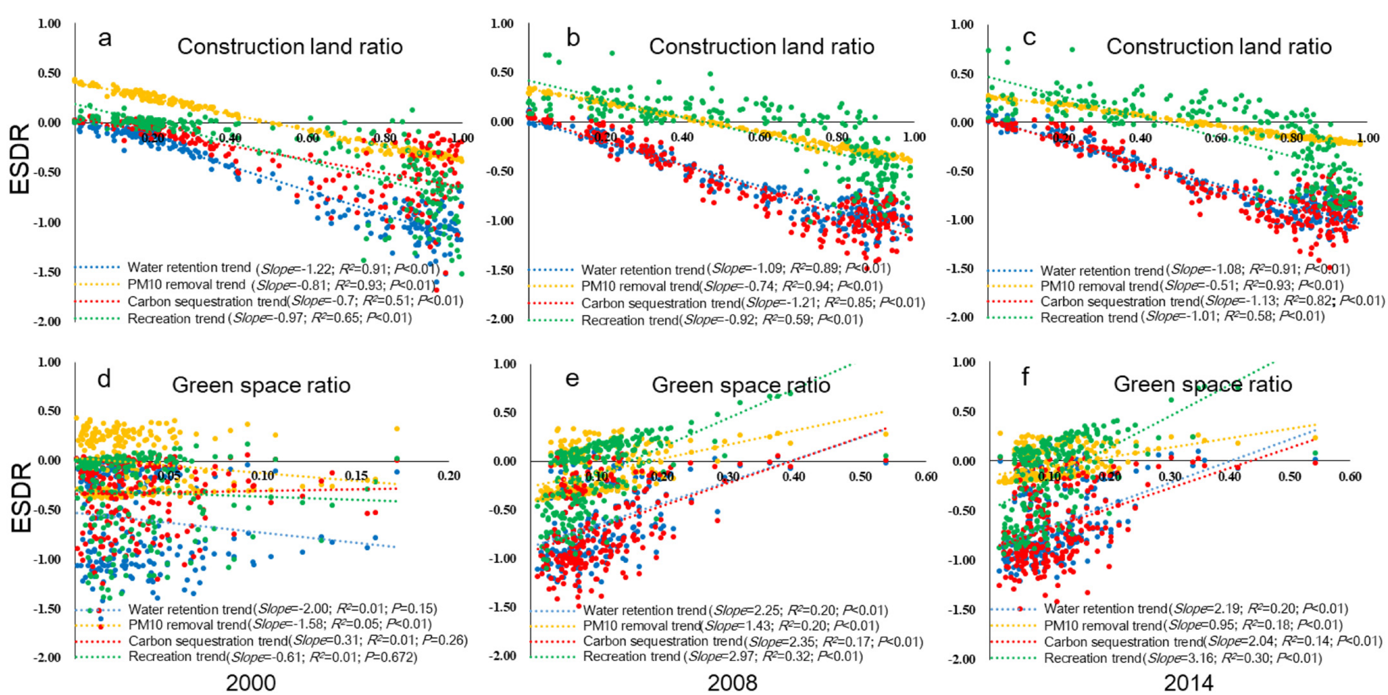

Fig. 8. Influence of constructed land ratio on ecological supply-demand ratio (ESDR) in Shanghai in (a) 2000, (b) 2008 and (c) 2014; and influence of green space ratio on ESDR in Shanghai in (d) 2000, (e) 2008 and (f) 2014.

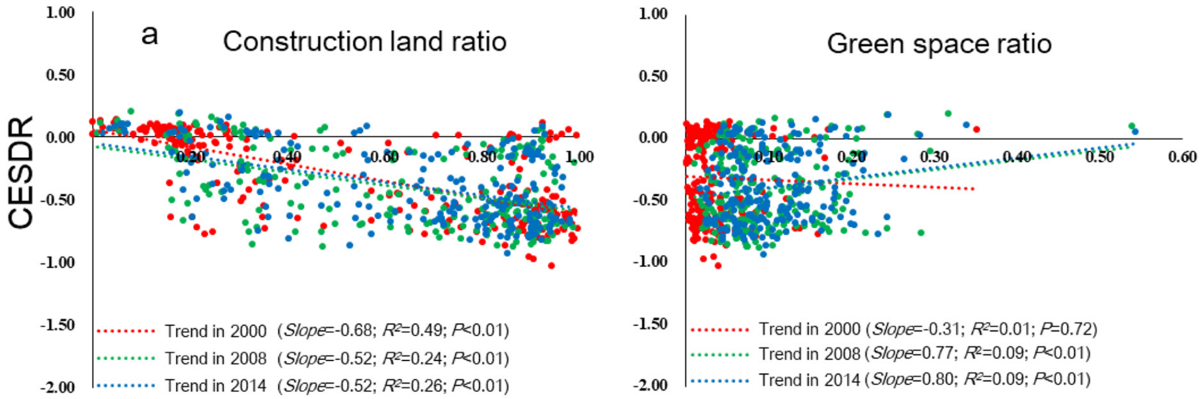

Fig. 9. Influence of (a) constructed land ratio and (b) green space ratio on comprehensive supply-demand ratio (CESDR) in Shanghai in 2000, 2008 and 2014.

which led to the increase in the shortfall area from 2000 to 2008 and 2014 (Fig. 6).

3.2.4. Recreation service

Recreation service supply and demand both showed increasing trends from 2000 to 2014, but overall the supply did not meet the demand (Fig. 7). The shortfall greatly decreased from 14.42 thousand ha in 2000 to 1.89 thousand ha in 2008 and 0.15 thousand ha in 2014.

According to the spatial distribution of recreation service supply-demand ratio, the shortfall areas were originally in the city centre (Fig. 7). The overall change in the spatial distribution of recreation service supply area was because: i) with the rapid expansion in constructed land area from 2000 to 2014, the recreation service supply area was greatly reduced in the city centre; and ii) sub-districts with much newly planted vegetation coverage played an important role in providing residents with comfortable places to relax, which increased the recreation service supply area. In comparison, recreation service demand was more population density-dependent, decreasing from the city centre to the sub-districts.

3.3. Influence of LULC on ESDR and CESDR

3.3.1. Influence of constructed land ratio on ESDR

Constructed land ratio had a significant negative influence on ESDR of water retention service, PM_{10} removal service, carbon sequestration service and recreation service during 2000–2014 ($p < 0.01$) (Fig. 8).

Constructed land ratio explained most of the variance in ESDR of water retention service, i.e. 91%, 89% and 91% in 2000, 2008 and 2014, respectively. Constructed land ratio also explained a significant proportion of the variance in ESDR of carbon sequestration service, PM_{10} removal service and recreation service. The proportion of variance explained by constructed land ratio increased changed from 51% in 2000 to 82% in 2014 for carbon sequestration service, it was 93% in both 2000 and 2014 for PM_{10} removal service, and it decreased from 65% in 2000 to 58% in 2014 for recreation service (Fig. 8).

Table 2
Thresholds to inform future landscape and urban planning in Shanghai.

Indicators		Constructed land ratio	Green space ratio
Threshold	Water retention	0.60%	40.21%
	Carbon sequestration	2.43%	53.34%
	Recreation	19.86%	15.78%
Range		0.60%–45.80%	14.77%–53.34%
Mean		21.84%	35.15%

3.3.2. Influence of green space ratio on ESDR

Green space ratio had a significant positive influence on ESDR of water retention service, carbon sequestration service and recreation service during 2008–2014 ($p < 0.01$) (Fig. 8), but a non-significant influence on ESDR of these services in 2000 ($p > 0.05$). Green space ratio had a significant positive influence on ESDR of PM_{10} removal service during 2000–2014 ($p < 0.01$).

Green space ratio explained only a small fraction of the variance in ESDR of the water retention, carbon sequestration and recreation services in 2000, and none of the variance in the ESDR of PM_{10} removal service. The coverage of green space in 2000 was relatively low and it was mostly distributed in the city centre, which is why green space ratio explained only a small fraction of the variance in three of the key ESs. However, with increasing green space in suburban areas, the supply of water retention service and recreation service also increased significantly, resulting in a significant level of variance being explained by the green space ratio in 2014.

3.3.3. Influence of constructed land ratio and green space ratio on CESDR

Constructed land ratio had a significant negative influence on CESDR during 2000–2014 ($p < 0.01$). In contrast, green space ratio had a significance positive influence on CESDR in 2008 and 2014 ($p < 0.01$), and a non-significant influence in 2000 ($p > 0.05$). The significant change between 2000 and 2008/2014 was due to the increasing green space in suburban areas. The proportion of variance in CESDR explained by constructed land ratio decreased from 49% in 2000 to 26% in 2014. Constructed land ratio explained more variance in CESDR than green space ratio, which indicated that it had a greater impact on the ESs balance than green space ratio (Fig. 9).

3.4. Balance thresholds of ESs supply and demand

For water retention service, when constructed land ratio exceeds 0.60% or green space ratio is <40.21% of the total land area, water retention service supply in the study area will be in deficit (Table 2). This means that supply will meet demand only when constructed land ratio is lower than 0.60%, or green space ratio is >40.21% of the total land area. Currently, constructed land accounts for 40.88% of the total area and green space accounts for 9.43%, meaning that constructed land ratio must decrease by 98.53% or green space ratio must increase by 326.61% to meet the local demand for water retention service.

For carbon sequestration service, when constructed land ratio is <2.43% or green space ratio is >53.34%, carbon sequestration service supply will be in surplus. This means that supply will meet demand only if constructed land ratio is lower than 2.43%, or green space ratio is >53.34% of the total land area. Constructed land ratio must decrease by 94.06% or green space ratio must increase by 465.92% to reach the local government targets on CO_2 emissions. Increasing the direct carbon sequestration service supply from green space is not likely to be an effective land management strategy, and government must also control the CO_2 emissions from industries.

For recreation service, when constructed land ratio is <19.86% and green space ratio is >15.78%, recreation service supply will be in surplus. The mean threshold of constructed land ratio is 21.84%, while the mean threshold of green space ratio is 35.15% (Table 2). This means that supply will meet demand only if constructed land ratio is lower than 19.86%, or green space ratio is >15.78% of the total land area. Constructed land ratio must decrease by 51.41% or green space must increase by 67.42% to meet the requirement for recreation service demand. Green space would be an effective land management strategy to meet the demand for this service.

4. Discussion

4.1. Contribution of ESs supply to societal demand

There is often an ambition among policymakers to maximise ESs supply in order to reduce mismatches and shortfalls through land management. However, without clear clarification on whether ESs supply meets societal demand, ESs assessments cannot effectively change land management decisions (Abson and Hanspach, 2014; Ruckelshaus et al., 2015). In this study, the contribution of ESs supply to societal demand associated with urbanisation-related land use changes was identified for the case of Shanghai municipality. The findings suggest that Shanghai municipality is meeting the required level for PM_{10} removal service, but is incurring shortfalls in other ESs studied, namely water retention, carbon sequestration and recreation.

For water retention service, despite the total increase in supply and total decrease in demand, the water retention supply in the study period (2000–2014) was far from meeting the demand. In fact, the results suggest that water retention service supply met less than approximately 10% of demand. The ESs supply relative to water demand was low temporally and spatially, suggesting limited effectiveness to address mismatches by increasing local water retention service supply unless water demand decreases. On the other hand, government should consider multiple ways to increase water supply, such as external input for water supply from upstream areas.

For carbon sequestration service, a number of studies have assessed the role of green space in offsetting urban CO_2 emissions (Escobedo et al., 2010; Liu and Li, 2012; Yoon et al., 2016). Escobedo et al. (2010) estimated that net CO_2 sequestration offsets 3.4% of annual city CO_2 emissions in Gainesville, USA, while Liu and Li (2012) found that it offsets only 0.26% in Shenyang, China. The present study went one step further by considering local government targets on CO_2 emissions. The results show very low contribution of carbon sequestration service supply to demand (1.1% in 2000 and 1.93% in 2014). Compared with 2000, carbon sequestration service demand maintained an increasing trend, suggesting that any increase in direct carbon sequestration service delivered by green space alone is not likely to be an effective land management strategy for reaching local government targets on CO_2 emissions. In addition to increasing the green space for delivering carbon sequestration, government must also control CO_2 emissions from industries in order to reach the management targets.

For recreation service, both supply and demand increased from 2000 to 2014. Overall, the shortfall between recreation supply and demand decreased and although still in shortfall in 2014, the amounts of recreation supply and demand were at comparable levels. In recent years, subdistricts in Shanghai with much newly planted vegetation coverage have played an important role in increasing the recreation service supply area. The results suggest that recreation service delivered by green space would be an effective land management strategy to meet the requirement for population density dependent-recreation service demand. Government can keep increasing the area of green space to increase the supply of recreation service.

4.2. Spatial pattern of ESs supply and demand mismatches

In this study, fine-resolution data were used to assess the variation in supply and demand for the four key ESs across urban spatial scales. The findings suggest that PM_{10} removal service is in a state of surplus for Shanghai municipality as a whole (amount), but that all ESs have major mismatches between supply and demand in spatial, particularly in the city centre because of higher demand. Urban expansion from 2000 to 2014 aggravated these mismatches between supply and demand for these ESs. Spatially explicit mapping of ESs supply and demand showed the specific location of ESs mismatches at the Shanghai municipality level, hence informing land planners and managers about ESs surplus and deficit areas.

4.3. Management implications to reduce shortfalls

It has been shown that urban green spaces can increase urban ESs (Lovell and Taylor, 2013), but only a few studies have measured ESs outcomes under alternative green space scenarios (Pataki et al., 2011). The Shanghai government introduced the general land use plan for Shanghai (1997–2010) and the Shanghai urban master plan (1999–2020) to improve ESs supply. Those plans worked, but lacked of a solid scientific basis for management strategies. Policymakers need measurements connecting land management to ESs supply and demand in order to design green spaces for multiple ESs. In this study, the influence of land use change on ESDR and CESDR and thresholds of ESs supply and demand were demonstrated. According to regression analysis and threshold analysis, constructed land ratio and green space ratio both have a significant influence on water retention service, carbon sequestration service and recreation service.

The results suggest that there are trade-offs between constructed land and ESs. To obtain desired ESs in the form of water retention, carbon sequestration and recreation services, constructed land ratio needs to be decreased by 98.53%, 94.06% and 51.41%, respectively. However, according to the Shanghai urban master plan (2016–2040) on constructed land area (controlled within 3200 km^2) and green space ratio (165.22% increase compared with 2014), it is impossible to decrease the constructed land ratio to obtain the desired ESs. Although the planned green space ratio will exceed the threshold requirement for recreation service, it cannot reach the threshold requirement for water retention and carbon sequestration services. Besides, the spatial pattern of green space area cannot guarantee rebalancing of the spatial mismatches for recreation service. This study therefore suggest that newly increased green space be placed in recreation service deficient areas, such as the city centre, Minhang district and Pudong district, Shanghai (Fig. 8). It should take the form of corridors to increase the connectivity of urban green spaces.

Increasing green space by 165.22% could help regulate the deficit in water retention and carbon sequestration services to some extent, but it would still not meet the requirement for matching ESs supply and demand. For carbon sequestration service, this study suggests that policymakers should set a strict CO_2 emissions target to control carbon sequestration service demand. For water retention service, this study suggests that policymakers should consider both supply-side measures (paying for water from upstream sources such as Yangtze River and Lake Taihu, to compensate for the low water retention service supply) and demand-side measures (advocate saving and reusing water by industries and households).

Since different regions have different ESs mismatches, policymakers should also decide which ESs should be protected in a given region. Thus, the data obtained in this study suggest that policymakers should establish appropriate planning units to regulate the mismatches between ESs supply and demand. The specific planning unit, which refers to the minimum planning area, could be a sub-watershed, a block or even a spatial grid, to guarantee the feasibility of policy implementation.

4.4. Main limitations

This study provides some important lessons for ESs management, but also has some limitations and uncertainties. It makes a novel contribution to ESs research through the use of EQS or policy goals to assess mismatches between ESs supply and demand, with the focus on carbon sequestration service, PM_{10} removal service and recreation service. Established EQS or policy goals are generally meaningful, as they provide a benchmark representing the minimum desirable environmental quality condition or policy goal (Baró et al., 2015). However, CO_2 emissions goals are often not based on scientific evidence about the impacts of possible changes (Baró et al., 2015). The ESDR index is a relative indicator, which might not be accurate for comparisons over different years. However, the maximum values of supply and demand in the whole time periods for each specific ES were used to overcome/minimize this uncertainty. Moreover, due to lack of fine data, this study only evaluated supply and demand for the four ESs. For complete ESs management, there is a need to evaluate the influence of alternative management scenarios on trade-offs between multiple ESs, in order to permit adaptive management.

5. Conclusions

Co-occurrence of supply and demand and mismatches in four types ESs were quantified for Shanghai municipality by linking land cover information from e.g. remote sensing, land surveys and GIS with data from monitoring, statistics, modelling, EQS and policy goals. The findings suggest that Shanghai municipality is meeting desired levels for PM_{10} removal service amount, but has shortfalls in the amount of other ESs. The findings also suggest that all four ESs have a major mismatch between supply and demand in spatial, particularly in the city centre because of higher demand. Urban expansion from 2000 to 2014 was one of the important factors aggravating the mismatch between ESs supply and demand. The results also demonstrate that optimal land management might reduce ESs mismatches by considering their specific location, but cannot reach the threshold requirement for water retention and carbon sequestration services. Three countermeasures are suggested to help reduce shortfalls and mismatches in the future: 1) Optimise the spatial pattern of green space area to regulate spatial mismatches in recreation service; 2) control CO_2 emissions; and 3) pay for water provision from upstream areas. The suggested method includes both standardized parts that are globally applicable and policy goals that are flexible, making it possible to quantify shortfalls and mismatch problems in ESs supply and demand.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.09.126.

References

13th Five-Year Plan for Energy Conservation and Climate Change of Shanghai (FPE), 2017. Shanghai Municipal Development & Reform Commission. http://www.shdrc.gov.cn/gk/zcjd/sswzxghjd/27893.htm.

Abson, D.J., Hanspach, J., 2014. Response to Turnhout et al.'s rethinking biodiversity: from goods and services to "living with". Conserv. Lett. 7, 334–335.

Bai, Y., Ouyang, Z.Y., Zheng, H., Xu, W.H., Jiang, B., Fang, Y., 2011a. Evaluation of the forest ecosystem services in Haihe River Basin, China. Acta Ecol. Sin. 31 (7), 2029–2039.

Bai, Y., Zhuang, C.W., Ouyang, Z.Y., Zheng, H., Jiang, M.B., 2011b. Spatial characteristics between biodiversity and ecosystem services in a human-dominated watershed. Ecol. Complex. 8 (2), 177–183.

Bai, Y., Ouyang, Z.Y., Zheng, H., Li, X.M., Zhuang, C.W., Jiang, B., 2012. Modeling soil conservation, water conservation and their tradeoffs: a case study in Beijing. J. Environ. Sci. 24 (3), 419–426.

Bai, Y., Wong, C.P., Jiang, B., et al., 2018. Developing China's Ecological Redline Policy using ecosystem services assessments for land use planning. Nat. Commun. 2018 (9), 3034.

Baró, F., Haase, D., Gómez-Baggethun, E., et al., 2015. Mismatches between ecosystem services supply and demand in urban areas: a quantitative assessment in five European cities. Ecol. Indic. 55, 146–158.

Baró, F., Palomo, I., Zulian, G., et al., 2016. Mapping ecosystem service capacity, flow and demand for landscape and urban planning: a case study in the Barcelona metropolitan region. Land Use Policy 57, 405–417.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply, demand and budgets. Ecol. Indic. 21 (3), 17–29.

Carpenter, S.R., Mooney, H.A., Capistrano, A.J., et al., 2009. Science for managing ecosystem services: beyond the millennium ecosystem assessment. Proc. Natl. Acad. Sci. 106, 1305–1312.

Chen, F.J., Shen, Y.J., Li, Q., Guo, Y., Xu, L.M., 2011. Spatio-temporal variation analysis of ecological systems npp in China in past 30 years. Sci. Geogr. Sin. 31 (11), 1409–1414.

Crossman, N., Burkhard, B., Nedkov, S., et al., 2013. A blueprint for mapping and modelling ecosystem services. Ecosyst. Serv. 4, 4–14.

de Groot, R.S., Alkemade, R., Braat, L., et al., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecol. Complex. 7, 260–272.

Duan, X.N., Wang, X.K., Lu, F., Ouyang, Z.Y., 2008. Carbon sequestration and its potential by wetland ecosystems in China. Acta Ecol. Sin. 28 (2), 463–469.

Escobedo, F.J., Nowak, D.J., 2009. Spatial heterogeneity and air pollution removal by an urban forest. Landsc. Urban Plan. 90, 102–110.

Escobedo, F.J., Varela, S., Zhao, M., et al., 2010. Analyzing the efficacy of subtropical urban forests in offsetting carbon emissions from cities. Environ. Sci. Pol. 13, 362–372.

Euliss, N.H., Smith, L.M., Liu, S.G., et al., 2010. The need for simultaneous evaluation of ecosystem services and land use change. Environ. Sci. Technol. 44, 7761–7763.

Feng, Q., Zhao, W.W., Fu, B.J., et al., 2017. Ecosystem service trade-offs and their influencing factors: a case study in the loess Plateau of China. Sci. Total Environ. 607–608, 1250–1263.

Foley, J.A., DeFries, R., Anser, G.P., et al., 2005. Global consequences of land use. Science 309, 570–574.

Förster, J., Barkmann, J., Fricke, R., et al., 2015. Assessing ecosystem services for informing land-use decisions: a problem-oriented approach. Ecol. Soc. 20 (3), 31.

Goldstein, J.H., Caldarone, G., Duarte, T.K., et al., 2012. Integrating ecosystem-service tradeoffs into land-use decisions. Proc. Natl. Acad. Sci. 109 (19), 7565–7570.

Gómez-Baggethun, E., Barton, D.N., 2013. Classifying and valuing ecosystem services for urban planning. Ecol. Econ. 86, 235–245.

Haas, J., Ban, Y., 2014. Urban growth and environmental impacts in Jing-Jin-Ji, the Yangtze, River Delta and the Pearl River Delta. Int. J. Appl. Earth Obs. Geoinf. 30, 42–55.

Haines-Young, R., Potschin-Young, M., 2018. Revision of the common international classification for ecosystem services (CICES V5.1): a policy brief. One Ecosyst. 3, e27108.

Han, B., Wang, X.K., Lu, F., Duan, X.N., Ouyang, Z.Y., 2008. Soil carbon sequestration and its potential by cropland ecosystems in China. Acta Ecol. Sin. 28 (2), 612–619.

Honey-Rosés, J., Pendleton, L.H., 2013. A demand driven research agenda for ecosystem services. Ecosyst. Serv. 5, 160–162.

Jia, X., Fu, B., Feng, X., Hou, G., Liu, Y., Wang, X., 2014. The tradeoff and synergy between ecosystem services in the grain-for-green areas in northern Shaanxi, China. Ecol. Indic. 43 (1), 103–113.

Lamarque, P., Tappeiner, U., Turner, C., Steinbacher, M., Bardgett, R.D., Szukics, U., et al., 2011. Stakeholder perceptions of grassland ecosystem services in relation to knowledge on soil fertility and biodiversity. Reg. Environ. Chang. 11 (4), 791–804.

Larondelle, N., Lauf, S., 2016. Balancing demand and supply of multiple urban ecosystem services on different spatial scales. Ecosyst. Serv. 22, 18–31.

Larondelle, N., Frantzeskaki, N., Haase, D., 2016. Mapping transition potential with stakeholder- and policy-driven scenarios in Rotterdam City. Ecol. Indic. 70, 630–643.

Li, J., Jiang, H., Bai, Y., Alatalo, J.M., Li, X., Jiang, H., et al., 2016. Indicators for spatial–temporal comparisons of ecosystem service status between regions: a case study of the Taihu river basin, China. Ecol. Indic. 60, 1008–1016.

Li, J.H., Fang, W., Wang, T., Qureshi, S., Alatalo, J.M., Bai, Y., 2017. Correlations between socioeconomic drivers and indicators of urban expansion: evidence from the heavily urbanised Shanghai Metropolitan Area, China. Sustain. For. 9, 1199.

Liu, C., Li, X., 2012. Carbon storage and sequestration by urban forests in Shenyang, China. Urban For. Urban Green. 11, 121–128.

Logsdon, R., Chaubey, I., 2013. A quantitative approach to evaluating ecosystem services. Ecol. Model. 257, 57–65.

Lovell, S.T., Taylor, J.R., 2013. Supplying urban ecosystem services through multifunctional green infrastructure in the United States. Landsc. Ecol. 28, 1447–1463.

MA, 2005. Millennium Ecosystem Assessment. World Resources Institute, Washington, DC.

Malinga, R., Gordon, L.J., Jewitt, G., et al., 2015. Mapping ecosystem services across scales and continents – a review. Ecosyst. Serv. 13, 57–63.

Maring, L., Blauw, M., 2017. Asset management to support urban land and subsurface management. Sci. Total Environ. 615, 390–397.

Martinez-Harms, M.J., Bryan, B.A., Balvanera, E.A., et al., 2015. Making decisions for managing ecosystem services. Biol. Conserv. 184, 229–238.

Mu, Q., Zhao, M., Running, S.W., 2011. Improvements to a MODIS global terrestrial evapotranspiration algorithm. Remote Sens. Environ. 115, 1781–1800.

Nikodinoska, N., Paletto, A., Pastorella, F., Granvik, M., Franzese, P.P., 2018. Assessing, valuing and mapping ecosystem services at city level: the case of Uppsala (Sweden). Ecol. Model. 368, 411–424.
Pataki, D.E., Carreiro, M.M., Cherrier, J., Grulke, N.E., Jennings, V., Pincetl, S., et al., 2011. Coupling biogeochemical cycles in urban environments: ecosystem services, green solutions, and misconceptions. Front. Ecol. Environ. 9, 27–36.
Ricketts, T.H., Regetz, J., Steffan-Dewenter, I., Cunningham, S.A., Kremen, C., Bogdanski, A., 2008. Landscape effects on crop pollination services: are there general patterns? Ecol. Lett. 11 (5), 499–515.
Ruckelshaus, M., McKenzie, E., Tallis, H., et al., 2015. Notes from the field: lessons learned from using ecosystem service approaches to inform real-world decisions. Ecol. Econ. 115, 11–21.
Seppelt, R., Dormann, C.F., Eppink, F.V., Lautenbach, S., Schmidt, S., 2011. A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. J. Appl. Ecol. 48 (3), 630–636.
Shanghai Climate Change Monitoring Bulletin, 2017. Shanghai Meteorological Service. China Meteorological Press.
Shanghai Environmental Bulletin, 2000, 2008, 2014. Shanghai Environmental Protection Bureau.
Shanghai Municipal Government (SMG), 2013. Half of Shanghai's rivers and lakes heavily polluted. Retrieved from. http://www.shanghai.gov.cn/shanghai/node27118/node27818/u22ai73035.html (Aug. 9, 2013).
Shanghai Statistical Yearbook, 2001, 2009, 2015. Shanghai Municipal Statistics Bureau, Survey Office of The National Bureau of Statistics in Shanghai.
Shanghai's Urban Construction and Management, 2012. Twelfth Five - Year Plan. Shanghai Government http://www.shanghai.gov.cn.
Stürck, J., Poortinga, A., Verburg, P.H., 2014. Mapping ecosystem services: the supply and demand of flood regulation services in Europe. Ecol. Indic. 38, 198–211.
Tao, Y., Li, F., Wang, R., Zhao, D., 2014. Effects of land use and cover change on terrestrial carbon stocks in urbanized areas: a study from Changzhou, China. J. Clean. Prod. 103 (1), 651–657.
van Oudenhoven, A.P.E., Petz, K., Alkemade, R., et al., 2012. Framework for systematic indicator selection to assess effects of land management on ecosystem services. Ecol. Indic. 21, 110–122.
Wang, Z., 2018. Evolving landscape-urbanization relationships in contemporary China. Landsc. Urban Plan. 171, 30–41.
Wang, Y., Huang, M., Wang, X.R., 2010. Impacts of land use and climate change on agricultural productivity in Shanghai. Acta Sci. Circumst. 30 (3), 641–648.
Water Resources Bulletin of Shanghai, 2000, 2008, 2014. Shanghai Water Authority. http://www.shanghaiwater.gov.cn.
Wolff, S., Schulp, C.J.E., Kastner, T., Verburg, P.H., 2017. Quantifying spatial variation in ecosystem services demand: a global mapping approach. Ecol. Econ. 136, 14–29.
World Health Organization (WHO), 2005. Air quality guidelines. Global update. Particulate Matter, Ozone, Nitrogen Dioxide and Sulfur Dioxide.
Xu, X.B., Yang, G.S., Li, H.P., 2011. Impacts of land use change on net primary productivity in the Taihu basin, China. Resource. Sci. 33 (10), 1940–1947.
Yahdjian, L., Sala, O.E., Havstad, K.M., 2015. Rangeland ecosystem services: shifting focus from supply to reconciling supply and demand. Front. Ecol. Environ. https://doi.org/10.1890/140156.
Yoon, T., Seo, K., Park, G., Son, Y., Son, Y., 2016. Surface soil carbon storage in urban green spaces in three major South Korean cities. Forest 7 (6), 115.