Identifying Hotspots and Management of Critical Ecosystem Services in Rapidly Urbanizing Yangtze River Delta Region, China

Journal of Environmental Management, 191, pp. 258-267.

Wenbo Cai[a], David Gibbs[a], Lang Zhang[b], Graham Ferrier[a], Yongli Cai[c,*]

[a] Geography, School of Environmental Sciences, University of Hull, Cottingham Road, Hull, HU6 7RX, U.K.

[b] Shanghai Academy of Landscape Architecture Science and Planning, No. 899, Longwu Road, Xuhui District, Shanghai, China

[c] Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Sciences, East China Normal University, Dongchuan Rd. 500, Shanghai, 200241, China

Highlights

- A comprehensive framework to identify hotspots of critical ecosystem services was developed.
- The framework comprised five core steps.
- The framework was applied in the Yangtze River Delta Region.
- Regionalization and management strategies of the YRD Region were suggested.

A B S T R A C T

Rapid urbanization has altered many ecosystems, causing a decline in many ecosystem services, generating serious ecological crisis. To cope with these challenges, we presented a comprehensive framework comprising five core steps for identifying and managing hotspots of critical ecosystem services in a rapid urbanizing region. This framework was applied in the case study of the Yangtze River Delta (YRD) Region. The study showed that there was large spatial heterogeneity in the hotspots of ecosystem services in the region, hotspots of supporting services and regulating services aggregately distributing in the southwest mountainous areas while hotspots of provisioning services mainly in the northeast plain, and hotspots of cultural services widespread in the waterbodies and southwest mountainous areas. The regionalization of the critical ecosystem services was made through the hotspot analysis. This study provided valuable information for environmental planning and management in a rapid urbanizing region and helped improve China's ecological redlines policy at regional scale.

Keywords: Ecosystem Services, Hotspot, Rapid Urbanization, Yangtze River Delta Region

1. Introduction

*Corresponding author. Shanghai Key Lab for Urban Ecological Processes and Eco-Restoration, School of Ecological and Environmental Sciences, East China Normal University, Dongchuan Rd. 500, Shanghai, 200241, China

E-mail address: ylcai@geo.ecnu.edu.cn (Prof. Yongli Cai).

With the continuous rise in global population, a simultaneous growth of urban areas is omnipresent (Haas et al., 2014). Urban populations are projected to reach nearly 60% of the human population by 2030; while urban areas will grow twice as fast as urban populations (Elmqvist et al., 2013). Rapid urbanization has altered many ecosystems, causing a decline in many ecosystem services, generating ecological crisis such as water shortages and pollution, air pollution, soil pollution and so on (Li, et al 2016). The ecological crisis has become a great threat to global and regional sustainable development. In order to address the challenges resulting from rapid urbanization, it is urgent to identify and protect endangered ecosystems.

Ecosystem services (ESs) are the benefits that people obtain from ecosystems, including food, natural fibers, a steady supply of clean water, regulation of pests and diseases, medicinal substances, recreation, and protection from natural hazards such as floods (MA., 2005; Costanza & Folke, 1997; Daily, 1997). ESs were considered as a bridge between environment and human well-being (Van et al., 2014), which provide an important framework for linking ecological infrastructure to social infrastructure in the city, with the potential to benefit humans and ecosystems (Timon et al., 2014). The term 'ES hotspot' is increasingly used for the purpose of informing spatial prioritization of ES (Cimon-Morin et al. 2013). Despite this growing use of the term, an ES hotspot is not clearly defined in the literature yet (Schröter et al., 2016). The term ES hotspot often refers to areas where high amounts of one particular service are present (Cimon-Morin et al. 2013), but other studies have defined hotspots as areas where multiple ESs overlap (e.g., Gos and Lavorel 2012).

To facilitate financial incentives for the responsible management of land and habitat, assessments and mapping of ESs provide quantitative information to initiate sustainable ecosystem management (Robinson et al., 2013). Alessa et al. (2008) reported that output from hotspot mapping were dependent on the assumptions underlying the methodology. Mola-Yudego and Gritten (2010) used kernel-based hotspot analysis to study forest management conflict clusters based on the number of reported conflicts. Other studies have identified areas for conservation efforts, as well as mapping ESs such as water supply, soil quality, and carbon in South Africa (Timilsina et al., 2013). Such assessments help identify which services are declining because of urbanization. Researches on the identification and mapping of 'hotspots' are relatively recent and little formal guidance in the current literature (Karimi et al., 2015).

Several methodologies and frameworks using ESs to support environmental management and decision making have been discussed (Müller et al., 2007; de Groot et al., 2010; Kroll et al., 2012; Crossman et al., 2013; Albert et al., 2014). Van Jaarsveld et al. (2005) presented a practical application of ESs mapping at the subcontinental scale for Africa. Troy et al. (2006) developed a decision framework or spatially explicit value transfer to estimate ESs flow values and to map results for three case studies that represented a diversity of spatial scales and locations. Paetzold et al. (2010) developed a framework for the assessment of ESs. Kroll et al. (2012) provided a method to quantify and map the ecosystem service supply at the regional scale for a rural-urban region in eastern

Germany. Burkhard’s framework made a great improvement. Burkhard’s ESs matrixes were useful in providing statistical and spatial information and illustrations (maps) in environmental planning and management (Burkhard et al., 2012; 2013). However, these researches failed to provide a complete and systematic framework from problems to management and cannot target to multiple ESs management.

China is one of the developing countries with rapid urbanization. Over the past 30 years, China has experienced rapid urbanization and an immense growth in population as the consequence of economic and political reforms in 1978 (Haas et al., 2014). The Yangtze River Delta (YRD) Region is one of the most rapidly urbanized regions in China and has experienced a remarkable period of population growth (at an annual growth rate of 3.0%), and urbanization (at an annual growth rate of 9.2%) (Xu et al., 2014). Rapid urbanization has dramatically changed land use/land cover patterns and ecosystems in the region, causing widespread environmental problems such as water shortages and decline in water quality, and serious air pollution (Zhang et al., 2011, Wang et al., 2012). These environmental problems have posed great threats to the regional eco-safety, adding new challenges to sustainable development in the region.

To overcome management conflicts and secure ESs, China has proposed a new ‘ecological redline policy’ (ERP) using ESs as a way to meet its targets (Bai et al., 2015). To carry out this policy, it is fundamental and necessary to identify hotspots of critical ESs. Thereupon, the aims of this study are (1) to present a comprehensive framework to identify and manage hotspots of critical ESs in a rapid urbanizing region, (2) to apply the framework to the Yangtze River Delta (YRD) region’s environmental management.

2. Methods

We present a comprehensive framework (Fig.1) for identifying and managing critical ESs hotspots in rapid urbanizing regions. This framework comprises five core steps:

2.1. Identification of major environmental problems and definition of ecosystems conservation objectives

Combining analysis of regional professional materials at different spatial and temporal scales, e.g. environmental assessment reports, land cover/ land use, with fieldwork and local experts’ consultation, regional major environmental problems can be defined.

Through the socio-ecological context analysis, causal relationships between the environmental problems related to urbanization and the decline of ESs caused by deterioration of ecosystems should be understood, and then objectives of management and priority conservation of critical ecosystems and their services in a region can be defined.

2.2. Classification of ecosystem types combining CORINE with local expert knowledge

The CORINE (Co-ordinated Information on the Environment) data series were established by the European Community (EC) as a means of compiling geo-spatial environmental information in a standardized and comparable manner across the European continent. Although the CORINE focuses on the European continent, it provides a good reference for land cover classification of other continents. To address the difference of land cover in different regions, local land cover or ecosystem classification may be used to adjust the names and types of land cover or ecosystems of CORINE classification.

2.3. Identifying and Scoring critical ESs

Firstly, identification of critical ESs should be Millennium-Ecosystem Assessment-based. The MA presented the most-widely used classification system of ESs which grouped ESs into four major categories: provisioning services (PS) consisting of the commodities that people use such as fiber, food, timber, and water; regulating services (RS) affecting climate, disease, floods, wastes, and water quality; cultural services (CS) providing recreational, aesthetic, and spiritual benefits; and supporting services (Ecological integrity: EI) assisting in soil formation, photosynthesis, and nutrient cycling (MA., 2005).

Secondly, for scoring critical ESs, the Burkhard's method constructs an ESs matrix combining land cover information in assessment of the state of ecosystems and their capacities to supply ESs based on MAs' ESs classification system (Burkhard et al., 2012).

Thirdly, the score adjustment of each critical ecosystem service will be made by using local expert knowledge. The local experts familiar with the environment of a study area will be chosen and be invited to score the ESs of the study area. They will firstly be given the explanation of the definition and classification of ESs, and be provided with Burkhard's original supply scores table and the relevant explanation. Next, each expert adjusts the original score of each ecosystem service based on his own expertise. Then, the final scores of critical ESs will be discussed together and determined by all experts.

In addition to using local expert knowledge, ecosystem quality or deterioration grade map may also be used to adjust the original scores of ESs. For example, land cover/land use maps are used for the classification of urban areas, waterbodies and other ecosystems, and water environmental assessment maps can be used to adjust the scores of the different quality grades of waterbodies.

2.4. Defining and mapping hotspot and coldspot of critical ESs

The Critical ESs Hotspot and Coldspot Formulation are designed as follow:

If, $V_{max} \le 5$, $H = V_{max}$, $C = V_{min}$;

If, $V_{max} > 5$, $H > \bar{x} + \delta$, $C < \bar{x} - \delta$;

H: hotspot; C: coldspot;

Vmax: the maximum of ESs values;

Vmin: the minimum of ESs values;

Range: the maximum of ESs values - the minimum of ESs values (Range = Vmax-Vmin);

Average $\bar{x}$: the mean of ESs values; the mean stands for the score of the average-level capacity of each of the four integrated services: EI, RS, PS, and CS;

STDEV (δ): the standard deviation of ESs values. (STDEV = $\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$).

From the data distribution, the highest-level of the twenty-three individual ESs were all rate 5, but the maximum level of the four integrated ESs were all above 5. For each of the individual ecosystem service, the score of 5 represented the maximum level of a very high relevant capacity which has been defined in Burkhard's score matrix.

But for the four integrated ESs, the range and the fluctuation of the scores of the four integrated ESs are different from each other, thus the same score cannot be used as the threshold to define the hotspot. So, the mean and the standard deviation were used to define the scores of hotspots and coldspots.

The mean of the four integrated ESs represented the score of average capacity of services, which is provided by relevant ecosystems. The standard deviation represented the fluctuation of the score of capacities for each of the integrated ESs.

In order to compare with the average level in each of the four integrated ESs and define how much the score of capacities deviate from the average level, both of the mean and the standard deviation are applied. If the score is higher than the mean plus a standard deviation of ESs values, the area with such a score has a high relevant capacity of ecosystem service or the hotspot. On contrast, if the score is lower than the mean minus a standard deviation of ESs values, the area with such a score has a low relevant capacity of ecosystem service or the coldspot.

2.5. Regionalization of Critical ESs

The first step is to map hotspot areas where multiple chosen critical ESs overlap by GIS, and the chosen ESs for overlaping should to be determined by the priority conservation objectives defined above. Then, critical ecosystems services zones are delineated by synthesizing same kinds of critical ESs, land use and physical features. Finally, the ESs zones are characterized with major environmental problems, related ecosystems and their critical services, their social driving forces correlated with urbanization, and management strategies.

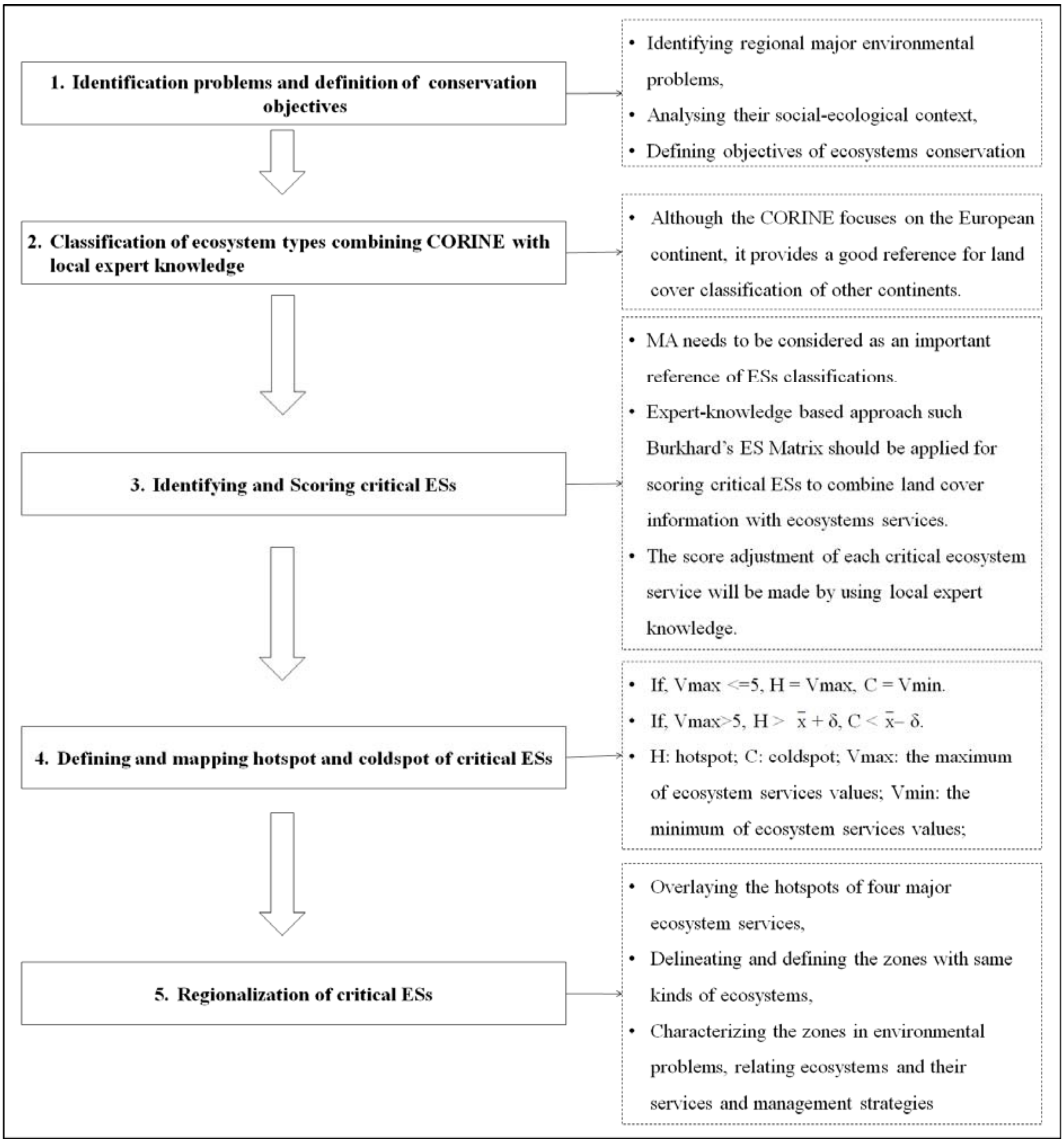

Fig.1. The Framework of Hotspots Identification and Management for Critical Ecosystem Service

3. Case Study

3.1. Study Area

The Yangtze River Delta Region (28.03° 28to 33.42° 42to 3.32° 32to 33t.83° E) is located in the coastal region of Eastern China (Fig 2). It encompasses fifteen prefecture-level cities in two provinces (Jiangsu, Zhejiang) and one municipality (Shanghai). This region is located in China's biggest estuarine delta alluvial plain of the subtropical monsoon climate zone, which has warm, humid weather and abundant rainfall. It has an area about 116,171 km^2 and a population of

102,176,131 inhabitants in 2010, resulting in a high population density (915 inhabitants per km^2). The region has 1.2% of the total land area of China but supports 8.1% of the nation's population (1.34 billion) according to the 2010 Chinese census (Xu et al., 2014).

This region is both an ecologically fragile area and economically developed region: high population densities, low forest cover rates, less per capita green spaces, poor air quality and serious water pollution (Luo and J, 2009; Reidsma et al., 2011; Tian et al., 2011; Zhao and Chen, 2011; Reidsma et al., 2012; Wang et al., 2012;Su et al., 2013; Zhang et al., 2013; Zhang et al., 2010., Zhou et al., 2013).

3.2. Identify problems and define objectives of critical ecosystem service conservation

The rapid urbanization has greatly changed natural ecosystems in the region since the reform and opening in China. The urban sprawling occupied species' habitat such as natural forest and wetlands, brought about habitat fragmentation and reduction of biodiversity, and thus decreased the supporting services of forest and wetlands. The decline of regulating services of forest and aquatic ecosystems have caused heavy fog and haze and serious water pollution in the region. Therefore, the priority should be given to the protection of supporting and regulating services of regional ecosystems in the Yangtze River Delta region.

There is large spatial heterogeneity in landforms and land cover of this region. There are twelve land cover types in this region (Fig.2). Urban areas and cultivated land mainly distributed in the northeast plain region. Forest and grassland mainly distributed in the southwest mountainous region.

3.3. Classify the ecosystem types based on combining CORINE with local expert knowledge

The raster land cover dataset used in this study is available from the National Geomatics Center of China (NGCC) and can be transferred and digitized in GIS format. The images that are utilized for GlobeLand30-2010 classification are multispectral images with 30 m resolution, including the TM5 and ETM + of America Land Resources Satellite (Landsat) and the multispectral images of China Environmental Disaster Alleviation Satellite (HJ-1) in baseline year of 2010 (GLC30, 2010). The Yangtze River Delta Region covered four satellite images: N50_25_2010LC030, N50_30_2010LC030, N51_25_2010LC030, and N51_30_2010LC030, and all of them are projected to the same coordinate system (WGS_1984_UTM_Zone_51N) to facilitate the spatial analysis.

The land cover and ecosystem types of this case are identified by combining local expert knowledge in the Yangtze River Delta Region with the CORINE land cover system. The land cover and ecosystem types are: rainfed croplands, mosaic croplands/vegetation, mosaic vegetation/croplands, closed to open broadleaved evergreen or semi-deciduous, closed broadleaved deciduous forest, closed needle leaved evergreen forest broadleaved and needle leaved forest, mosaic forest-shrubland/grassland, mosaic grassland/Forest-shrubland, closed to open shrubland, closed to open grassland, sparse vegetation, closed broadleaved forest permanently flooded, closed to open vegetation regularly flooded, discontinuous urban fabric, continuous urban fabric, bareland, beaches, dunes and sand plains, Taihu Lake, Qiandao Lake, ponds, Yangtze River, Qiantang River, river courses, inland marshes, salt marshes, shallow sea wetlands.

3.4. Identify critical ESs and score them

Twenty-three ESs that derived respectively from ecological integrity (supporting services), regulating services, provisioning services and cultural services were classified according to MA, and were scored by Burkhard's method. The matrix linking twenty-three ESs (on the x-axis) to twenty-eight different land cover types (on the y-axis) was constructed in this paper (Table 1). Local expert knowledge was used to adjust the scores of the ESs in Yangtze River Delta Region. In the case of the Yangtze River Delta Region, fourteen experts were interviewed and asked to score each ecosystem service in the region. The scoring adjustment process was completed according to the methods section discussed before.

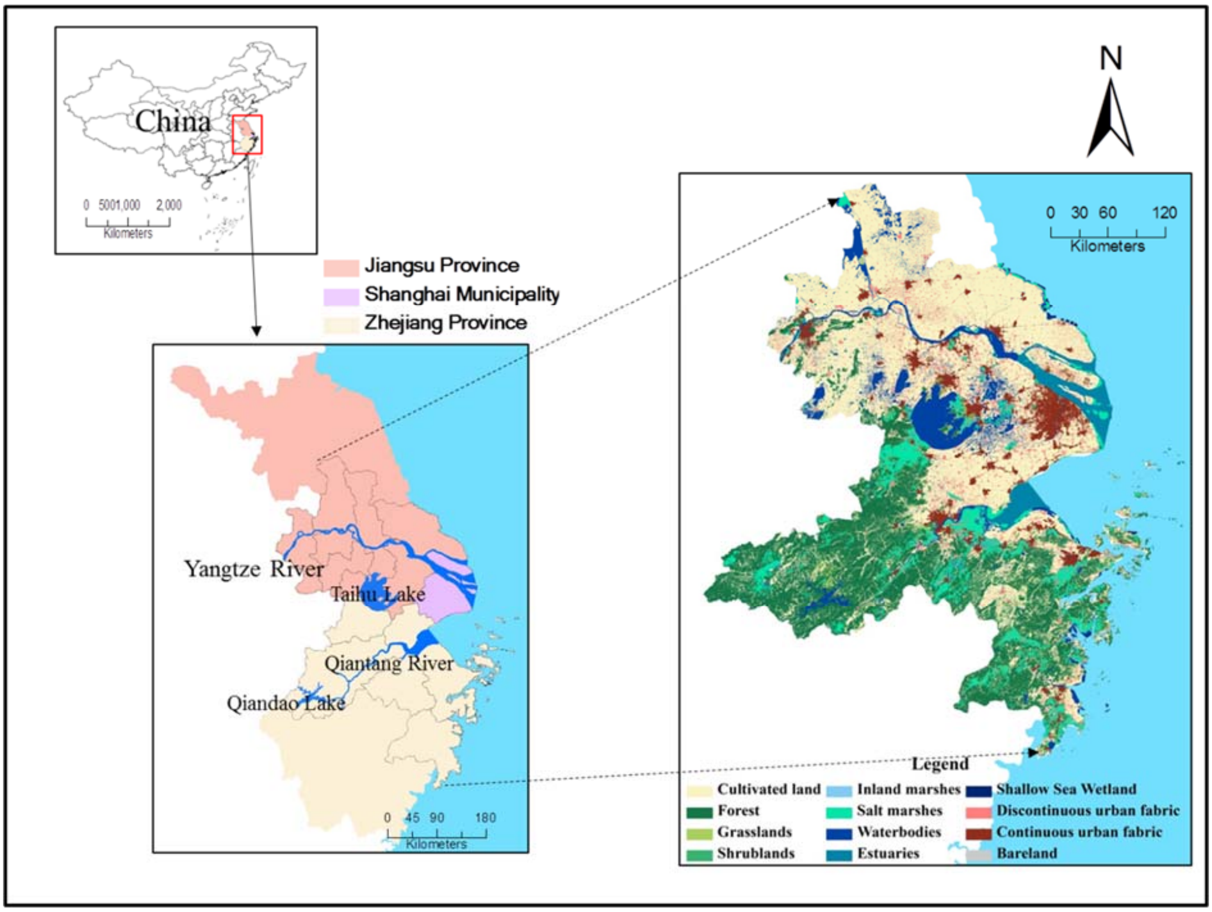

Fig.2. Location of the Yangtze River Delta Region

In the case of the Yangtze River Delta Region, among fourteen experts, seven from government bodies (one from Shanghai, two from Jiangsu Province, two from Zhejiang Province, and two from Anhui Province in the upstream watershed of Hangzhou in Zhejiang Province), three from East China Normal University, one from Nanjing University, one from Jiangsu University, one from an environmental institution employed by government in Zhejiang Province and one from a green enterprise in Jiangsu Province) were interviewed and asked to score each ecosystem service in the region. All experts were familiar with the environmental issues in the Yangtze River Delta Region.

In the case study, we adjusted the score of each ecosystem service depending only on local expert knowledge, because there were not usable ecosystem quality or deterioration grade maps in the whole region.

3.5. Identify and map hotspots and coldspots of critical ESs

In this case, we defined the critical ESs hotspots and coldspots by calculating supply capacity scores from Table 1. According to the methods we presented in section 2.4, we defined and mapped the hotspots and coldspots of twenty-three ESs in Fig.3 and four integrated ESs in Fig.4.

3.5.1. Natural Causes are decisive factors for the following pattern

B, F-H, L-N, O-P, V: Hotspots were widespread in southwest mountainous areas, while coldspots of B, F-H were scattered in northeastern urban area, of L-M, O-P were widespread in the northeastern plain, and of N, V coldspots were widespread in the northeastern plain except the waterbodies areas.

K, W: Hotspots were widespread in waterbodies areas and southwest mountainous areas, while coldspots scattered in the northeastern plain.

A, N: Hotspots only distributed in the waterbodies areas of the region.

S-T, D: Hotspots were only in the estuaries areas in the region.

3.5.2. Human activities are decisive factors for the following patterns

Q-R: Contrary to the A-L's distribution, hotspots were widespread in northeast plain, while coldspots were widespread in southwest mountainous areas.

I-J: Hotspots only distributed in the wetlands of the coastal areas, while coldspots were in the urban areas of the region.

C, E: Hotspots were widespread in the whole region, while coldspots distributed in the urban areas of the region.

3.5.3. The spatial pattern of the hotspots and coldspots of ecological integrity (EI), regulating services (RSs), provisioning services (PSs) and cultural services (CSs)

The hotspots of four major ESs were defined according to the results got from the calculation of the equations in the method section. The thresholds of scores of four integrated ESs' hotspots and coldspots were used to determine hotspots by combining the mean and the standard deviation (Table.2).

Using CSs as an example, since the standard deviation was 3 and average was 4, therefore the hotspots values were the one exceeding 7, while the coldspost values were lower than 1.

For EI and RSs, hotspots were widespread in the southwest mountainous areas, while coldspots scattered in the urban areas of the region.

For PSs, hotspots were widespread in the northeast plain including cultivated land areas, waterbodies and estuaries areas, while coldspots distributed in the southeast mountainous areas. For cultural services, hotspots were widespread in the waterbodies and southwest mountainous areas, while coldspots scattered in urban areas and rural residential areas in the region.

3.6. Regionalization and Management Strategies of Critical ESs

In this case study, the regionalization of critical ESs was completed through overlapping the hotspots of the four integrated ESs (Fig. 5). Six functional zones or types were defined as follow:

3.6.1. Ecological Integrity Conservation Zone (I)

The zone only included the hotspot of EI and scattered in the whole area except the urban area (Fig.5). Since EI represented the base for the provision of regulating, provisioning and cultural ESs, this zone was vital to support and preserve the processes and structures that were essential prerequisites of the ecological ability for self-organization of ecosystems such as biodiversity (Barkmann et al., 2001).

3.6.2. Southwest Mountainous and Hilly Forest Ecological Zone(II):

The southwest mountainous and hilly forest ecological zone was the one with most various types of ESs that included three integrated types (EI, RS and CS) and twelve individual types in which the supporting service(EI) included Biodiversity (B), Storage capacity (G and Reduction of nutrient loss(F),. The regulating service included Local climate regulation (H), Water purification (O), Erosion Regulation (M), Air Quality Regulation (L), Pollination (P), Nutrient regulation (N) and Groundwater recharge (K) the cultural service included Intrinsic Value of Biodiversity (V and Recreation & Aesthetic Values (W).

In this zone, Local climate regulation (H) and Air Quality Regulation (L) offer assistance in decreasing regional air pollution as fog and haze. Water purification (O), Erosion Regulation (M) and Groundwater recharge (K) offer assistance in reducing water pollution and floods. Intrinsic Value of Biodiversity (V), Recreation &Aesthetic Values (W) help to meet the demand of leisure activities and tourism from large increasing population.

For environmental conservation, the administrative boundary should be broken to unify the management and conservation of the forest in the region. Further study in ESs hotspots should be done to assist delineation of ecological redline for protected areas.

PES (payment for ESs) mechanism should be done for forest conservation in southwest mountainous and hilly forest ecological zone. The establishment of payment criteria and identification of ecosystem service flow are core questions in payment for critical ecological services. These need to be done on the basis of a precise quantitative assessment and flow simulation of ESs.

For socioeconomic development, ecological development that matches local resources such as ecological agriculture and ecological forestry should be built by making full use of natural resources in this zone. Mountain forest area in this zone is rich in natural scenery tourism resources. Developing tourism forms with ecological characteristics will improve human and natural coupling relationship and enhance the sustainable utilization of landscapes in this zone.

3.6.3. Northeast Plain Agriculture Ecological Zone (III)

This zone included the hotspots of two provisioning services: Crops provisioning (Q) and livestock provisioning (R), and mainly distributed in the northeast plain. The conservation of the two provisioning services was directly related to food safety for the huge population of the region.

The main landforms of northeast areas were lowland plain. Cultivated lands such as irrigated croplands were dominant ecosystem types in this zone. Habitat fragmentation caused by urban expansion and urban rainstorm floods were serious in this zone. The city sprawling and developing residential areas occupied or destroyed many species habitats and largely decreased the services provided by ecosystems of this region. Therefore, the restriction of urban expansion will be an arduous management task in this region.

Sub zones of ESs should further be delineated and connected with each other to build an ecosystem service network based on the deep analysis of hotspots of multiple ecosystems: ecological integrity sub eco-zone for conservation of biodiversity, storage capacity and reduction of nutrient loss; regulating services sub-zone for regulation of local climate, water purification, erosion, air quality, etc.; cultural services sub-zone for conservation of intrinsic value of biodiversity and recreation & aesthetic values.

3.6.4. Aquatic ESs Conservation Zone (IV):

Four hotspots of ESs distributed in the zone were Abiotic heterogeneity (A), Groundwater recharge (K), Freshwater (U) and Recreation & Aesthetic Values (W). Not only the water supply for regional residents' living relied on the rivers and lakes, but the huge demand of entertainment and leisure activities of regional residents also relied on the conservation of the waterbodies in this zone. This zone could be divided into two subzones: the Qiandao Lake subzone in the south and the Taihu Lake subzone in the north. These two subzones were the main sources of water supply for the whole region.

Aquatic ecosystems such as lakes and rivers were dominant ecosystem types in this zone. Water pollution and flood were main ecological risks in this zone.

Table 1 Assessment matrix illustrating the capacities of different land cover classes to support ecological integrity (column at the left side), to supply ESs (the three columns at right) and statistic indicators: The mean, standard deviation, range (column at the bottom left side). The values/colors indicate the following capacities: 0 = no relevant capacity; 1 = low relevant capacity; 2 = relevant capacity; 3 = medium relevant capacity; 4 = high relevant capacity; and 5 = very high relevant capacity (after Burkhard et al., 2012; Burkhard et al., 2009). The total score of each of the EI, RS, PS and CS means the total capacity of each of the four integrated services. The mean, standard deviation and range were explained in section 2.4.

land cover types:	**Ecological integrity**	Abiotic heterogeneity	Biodiversity	Biotic waterflows	Metabolic efficiency	Exergy Capture(Radiation)	Reduction of Nutrient loss	Storage capacity (SOM)	**Regulating services**	local climate regulation	Global climate regulation	Flood protection	Groundwater recharge	Air Quality Regulation	Erosion Regulation	Nutrient regulation	Water purification	Pollination	**Provisioning services**	Crops	Livestock	Capture Fisheries	Aquaculture	Freshwater	**Cultural services**	Recreation&Aesthetic Value	Intrinsic Value of Biodiversit
Irrigated croplands	21	3	2	5	2	5	1	3	5	3	1	1	0	0	0	0	0	0	10	5	5	0	0	0	1	1	0
Rainfed croplands	22	3	2	3	4	5	1	4	5	2	1	1	1	0	0	0	0	0	10	5	5	0	0	0	1	1	0
Mosaic Croplands/Vegetation	25	3	3	3	4	5	3	4	12	2	2	1	1	0	2	2	2	0	7	3	4	0	0	0	3	2	1
Mosaic Vegetation/Croplands	27	3	4	4	4	4	3	5	15	2	2	1	1	0	3	3	3	0	6	2	4	0	0	0	4	2	2
Closed to open broadleaved evergreen or semi-deci	32	3	5	5	4	5	5	5	39	5	4	3	2	5	5	5	5	5	0	0	0	0	0	0	10	5	5
Closed broadleaved deciduous forest	31	3	4	5	4	5	5	5	39	5	4	3	2	5	5	5	5	5	0	0	0	0	0	0	10	5	5
Closed needleleaved evergreen forest	30	3	4	4	4	5	5	5	39	5	4	3	2	5	5	5	5	5	0	0	0	0	0	0	10	5	5
broadleaved and needleleaved forest	31	3	4	5	4	5	5	5	39	5	4	3	2	5	5	5	5	5	0	0	0	0	0	0	10	5	5
Mosaic Forest-Shrubland/Grassland	25	3	4	3	3	3	4	3	11	1	1	0	0	0	2	2	2	1	2	0	2	0	0	0	5	2	2
Mosaic Grassland/Forest-Shrubland	26	3	5	3	4	4	5	4	14	2	2	1	1	0	3	3	3	1	3	0	3	0	0	0	5	3	3
Closed to open shrubland	21	3	4	2	3	3	4	2	3	1	0	0	0	0	0	0	0	2	2	0	2	0	0	0	4	2	2
Closed to open grassland	30	3	5	4	4	4	5	5	22	2	3	1	1	0	5	5	5	0	3	0	3	0	0	0	6	3	3
Sparse vegetation	9	2	3	1	0	1	1	1	3	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Closed broadleaved forest permanently flooded	9	1	1	2	1	2	2	2	12	2	1	1	1	2	2	2	2	2	0	0	0	0	0	0	3	2	2
Closed to open vegetation regularly flooded	6	1	2	1	0	1	1	1	2	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Discontinuous urban fabric	7	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
Continuous urban fabric	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bareland	6	3	3	0	0	0	0	0	3	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	4	4	0
Beaches, dunes and sand plains	10	3	3	1	1	1	0	1	6	0	0	5	1	0	0	0	0	0	0	0	0	0	0	0	7	5	2
Taihu Lake	23	4	4	0	4	4	3	4	7	2	1	1	2	0	0	1	0	0	8	0	0	3	0	5	9	5	4
Qiandao Lake	12	2	2	0	2	2	2	2	4	1	1	1	1	0	0	1	0	0	4	0	0	2	0	3	5	3	2
Ponds	7	1	1	0	1	1	1	1	2	1	0	0	1	0	0	0	0	0	2	0	0	1	0	2	3	2	1
Yangtze River	30	5	5	1	5	5	4	5	8	3	2	2	3	1	1	2	1	1	8	0	0	3	0	5	9	5	4
Qiantang River	15	3	3	1	3	3	2	3	4	2	1	1	2	1	1	1	1	1	4	0	0	2	0	3	5	3	2
River Courses	9	2	2	0	2	2	1	2	2	1	1	1	1	0	0	1	0	0	2	0	0	1	0	2	3	2	1
Inland marshes	25	3	2	4	4	4	3	5	14	2	2	4	2	0	0	4	0	0	2	0	2	0	0	0	0	0	0
Salt marshes	23	2	3	4	3	3	3	5	8	1	0	5	0	0	0	2	0	0	2	0	2	0	0	0	3	3	0
Shallow sea welands	15	2	2	0	3	3	4	1	13	3	5	0	0	0	0	5	0	0	10	0	0	5	5	0	6	4	2
Average	19								12										3						4		
Standard Deviation	10								12										3						3		
Range	32								39										10						10		

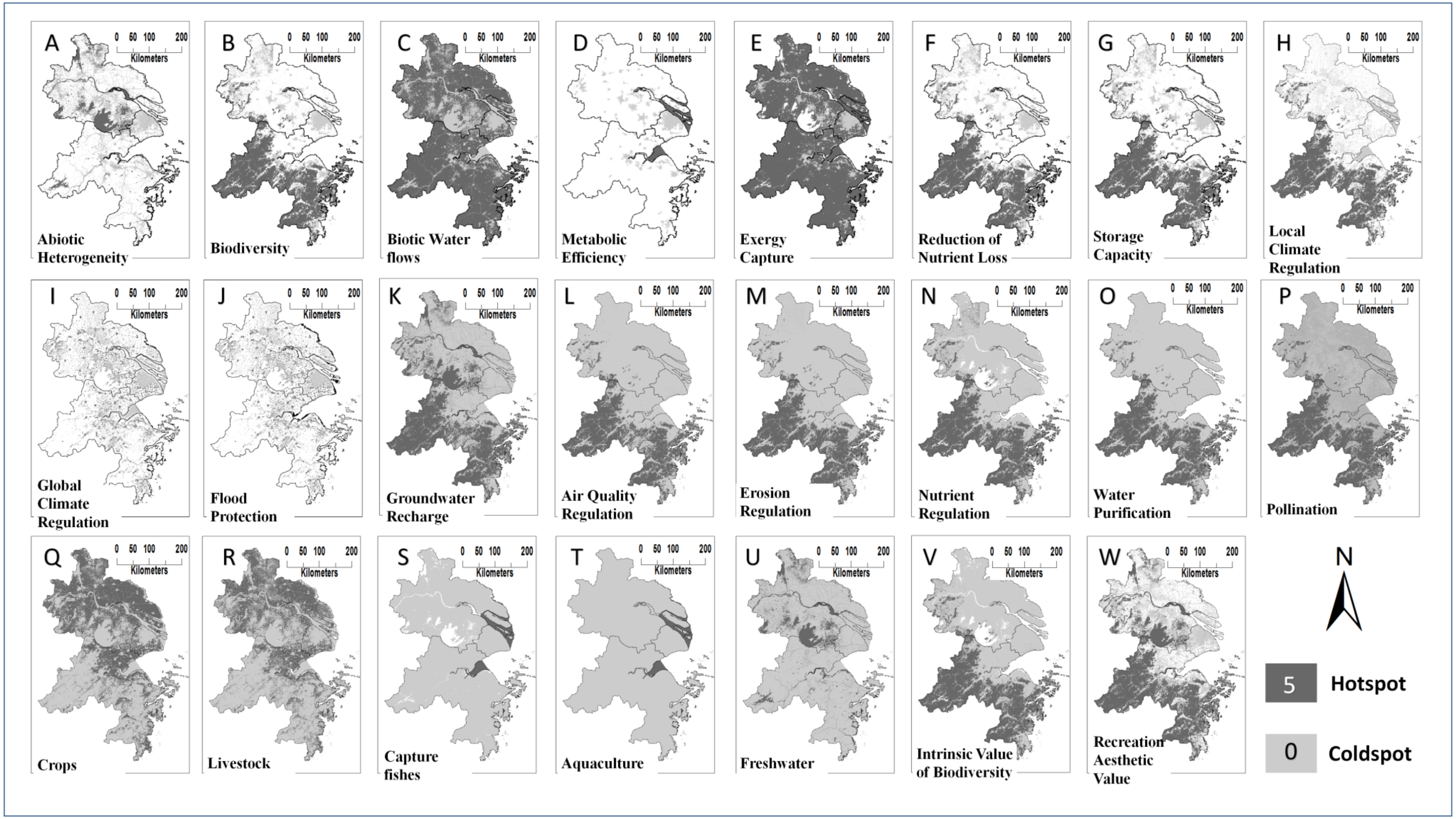

Fig.3. The map of multiple ESs hotspots and coldspots in the Yangtze River Delta Region. The values/colors indicate the capacities of different ESs supply: (from 0/grey（coldspot）= demand exceeds supply significantly = undersupply; to 5/black （hotspot）= supply exceeds the demand significantly = oversupply)

Table 2 The table of hotspots and coldspots of ecological integrity, regulating services, provisioning services and cultural services in the Yangtze River Delta Region:

(If Vmax>5, H>X+δ, C <X-δ;H: hotspot; C: coldspot;

Average $\bar{x}$: the mean of ESs values;

STDEV (δ): the standard deviation of ESs values.

STDEV = $\sqrt{\frac{\sum (x-\bar{x})^2}{(n-1)}}$).

	Ecological integrity	Regulating services	Provisioning services	Cultural services
Standard Deviation	10	12	3	3
Average	19	12	3	4
H>(Average+Standard Deviation)	29	24	6	7
C<(Average-Standard Deviation)	9	0	0	1

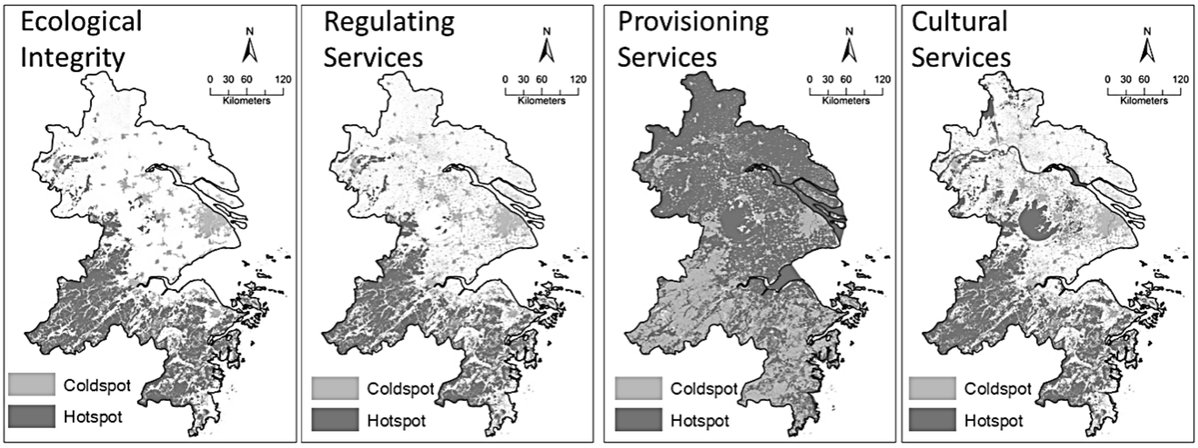

Fig.4. The map of hotspots and coldspots of ecological integrity, regulating services, provisioning services and cultural services in the Yangtze River Delta Region according to Table 3. The black color indicates the hotspots of the four integrated ESs supply; the grey color indicates the coldspots of the four integrated ESs.

The discharge of urban domestic sewage and industrial waste water in these areas should be strictly controlled. Artificial wetlands should be built in these regions for assistant sewage treatment. Low-impact eco-tourism could be developed in these areas to meet the huge increasing demand of tourism and leisure activities of urban residents.

For environmental conservation, PES mechanisms between upstream and downstream of rivers and lake pollution control should be launched Trans-boundary environmental conservation cooperation mechanisms in the lake watersheds should be developed.

3.6.5. Eastern Coastal Estuaries Ecological Zone (V)

The zone included four services hotspots distributed in the eastern coastal areas: Metabolic efficiency (D), Flood Protection (J) Capture fisheries (S), and Aquaculture (T). The main landforms of eastern coastal areas are river estuarine plains. Estuaries, salt marshes and shallow sea wetlands are dominant ecosystem types in this zone. Water pollution and habitat fragmentation are major ecological risks in this zone. Therefore, the protection of coastal wetland and restoration of deteriorated wetland ecosystems will be main objectives in this zone.

3.6.6. Urban Development Area (VI)

The zone was the coldspots of critical ESs in the region. With urban expansion, this zone will have greater demand for ESs. Therefore, the future task is to negotiate the relationship between urban development and ecological protection, and decrease the pressure on natural ecosystem. Thus, constructing eco-city should be taken into serious and urgent consideration for regional sustainable development.

4. Discussion

4.1. The relationship between the rapid urbanization and the pattern of critical ESs:

Rapid urbanization and cultivation in the northeastern plain is the main reason of significant spatial heterogeneity in the Yangtze River Delta Region. The urban area has expanded continuously in this plain area in the past 30 years. Due to the rapid urbanization, the world's sixth largest urban agglomeration including Shanghai, Nanjing, Suzhou, Wuxi, Changzhou, Hangzhou, and Ningbo has formed in this northeastern plain(Zhang et al., 2010; Zhao et al., 2011; Wang et al., 2012; Su et al., 2013; Zhang et al., 2013; Zhou et al., 2013). Large amounts of immigrants from other parts of China moved to this area every year (Zhao et al., 2011; Wang et al., 2012; Su et al., 2013; Zhang et al., 2013). In order to meet the huge grain demands from large population, other parts of the northeastern plain have been developed into rural settlements and cultivated land in the past 30 years (Zhao et al., 2004; Huang et al., 2006; Zhang et al., 2010; Zhang et al., 2013). So, the urban and cultivated lands have become the most main land cover types in the northeastern plain. However, the southwestern part does not catch the pace of the development of the northeastern part. The expansion of urban areas is quite slower in the southwestern part than the northwestern part. But, the southwestern part does better in forest conservation and water resource protection than the northeast part.

4.2. Measurable factors of ecosystem are quantified in proportion to increasing pace of urbanization under the chosen region of study

If we have ecosystem quality data for the entire region, we can use measurable factors such as the changes of water quality classification to reveal how rapid degradation of waterbody ecosystems corresponds to the rapid urbanization in the cases in the Yangtze Region Delta Region. Ren et al., (2003) examined the water quality at five sampling sites along the course of Shanghai's Huangpu

River between 1947 and 1996. The analysis revealed that there was a strong positive correlation between proportion of urban land use (e.g., residential and industrial) and worsening water quality classifications. The water quality at each sampling site was classified according to the Chinese Government standard for water quality issued in 1988 (GB 3838-88). This standard includes the following five water classifications (Ren et al., 2003).

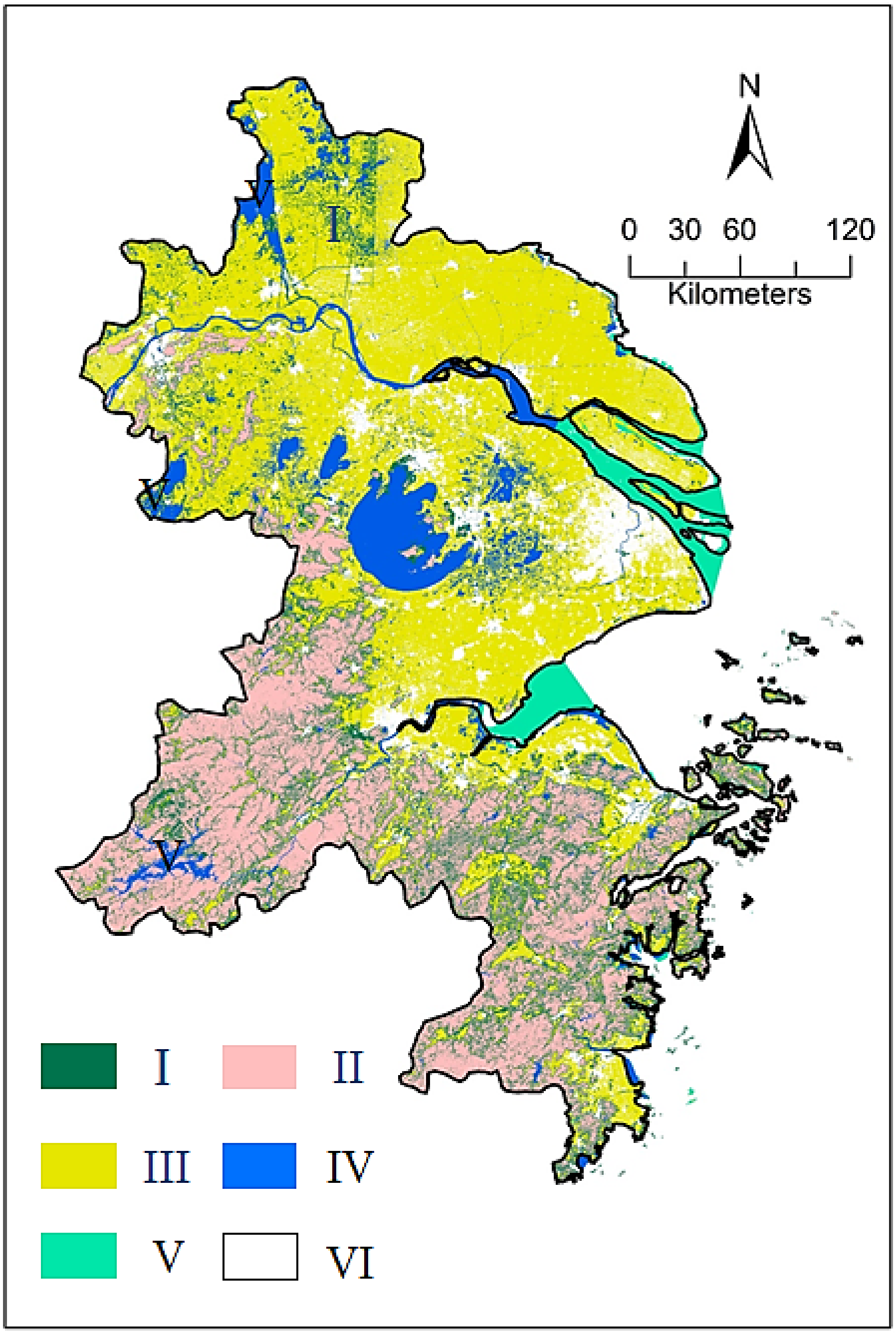

Fig.5. The overlap map of the integrated ESs in the Yangtze River Delta Region. *I: Ecological Integrity Conservation Zone, II: Southwest Mountainous and Hilly Forest Ecological Zone III: Northeast Plain Agriculture Ecological Zone, IV: Aquatic Ecosystem service Zone, V: Eastern Coastal Estuaries Ecological Zone, VI: Urban Development Area (coldspots).*

For example, in a period of rapid urban growth (1979–1996), the annual rate of urbanization was at its highest with over 6.5 km^2 of land per year converted to urban uses. The proportion of urban land increased from 72% at the start of the 1980s to over 96% by the mid-1990s. Corresponding to the rapid urban rapid growth, the increment in index scores of water quality classifications of five monitoring sites are: Site 1 (+0.5), Site 2 (+1.5), Site 3 (+1), Site 4 (+2), and Site 5 (+1). The sampling sites located in the City Proper (e.g., Sites 4) consistently scored higher, i.e., poorer, water classifications than the sites located outside, indicating the strong influence of intense urban activity on the water quality within the lower reaches of the Huangpu River.

4.3. The Method and Hotspots

Some of the previous studies can be considered as part of the comprehensive of modern hotspots identification and management of critical ESs:

First, incorporation of land use and land cover data in ecosystem service assessments for identifying and scoring critical ESs, for example, Burkhard et al., (2009, 2012) presented an approach to evaluate ecosystem service provisions of different landscapes (ecosystems) in relation to human activities by using quantitative and qualitative assessment data in combination with land cover and land use information originated from remote sensing and GIS. Second, identification of environmental problems, for instance, Gregory et al., (2012) proposed a structured decision-making process for the use of species distribution models (SDMs) which was increasingly proposed to address environmental problems (Wintle et al., 2011; Addison et al., 2013; Guisan et al., 2013). Third, threshold methods for delineating an ES hotspot according to an expert-based threshold value, for example, Egoh et al. (2008) set thresholds of a soil depth C0.8 m and C70 % litter cover for the ES soil accumulation in a specific case study.

However, few studies synthesized these studies for hotspot identification and management of critical ESs. Adapted from previous research, we synthesize them into a comprehensive framework for priority conservation. In practice, the case study used detailed local land cover classification systems that made the new framework more suitable for the practical. situation in the Yangtze River Delta Region.

The 'ES hotspots calculated by local expert knowledges scores' can be considered as a new index that should be evolved. Since the local expert knowledge scores can be adapted to different contexts globally, and they are easier to obtain than observed results by field work, this index would simplify the complexity involved in priority conservation of critical ecosystem services within an international context.

Moreover, the 'local expert knowledges scores area' may be used as a new index to further quantify the amount of supply in hotspot areas and demand of cotspots areas at different scales. Since this new index can provide relative amounts of supply, demand and budget of ES, it will be easier than calculating monetary values for environmental planning and urban cooperation in different counties at different scales.

5. Limitations and contributions of the research

It is undeniable that the method put forward in this paper had some limitations. Firstly, although this framework included local environmental reading and preliminary score adjustment process, it could not completely avoid the subjectivity of expert scoring method. Secondly, Burkhard' scoring method only helped to define the potential but not actual scores of ESs.

In order to improve the scoring accuracy of services that present ecosystems provide, we need ecosystem quality or deterioration grade map and water environmental grade map in the regional scale. However, it is difficult to get these data from the rapid urbanization area. For example, some of the natural forests have changed to artificial forests for years. So, it is likely that the services provided by artificial forests are much lower than the natural forests. For another, the water quality of some parts of Taihu Lake in this region was spoiled by industrial and domestic pollution for a long time (Luo et al., 2011; Jiao et al., 2015). Thus, the ESs of these parts were worse than other area of Taihu Lake because of the decline of biodiversity and water eutrophication. In the case study, since we only had the data about ecosystem qualities of a few number of local areas instead of the data of the entire region, experts could not gave different scores according to the variation of ecosystem qualities in the regional scale.

Despite the limitations, this framework is undeniably suitable for environmental management in large-scale, data-scare region. For a rapidly urbanized area with urgent demand of overall regional guidance for environmental management, it will be a great help for decision makers to quickly identify crucial spatial points and effectively decide protection priority areas.

6. Conclusions

In this paper, a new comprehensive framework for critical ESs regionalization and management was presented. This framework is targeted to regional-scale critical ESs regionalization and management by identifying ESs hotspots in rapid urbanization areas. It also will help to delineate Ecological Redline at regional scale in China.

The application of the comprehensive framework in case study revealed the spatial heterogeneity of hotspots and coldspots of critical ESs, which will be helpful for critical ESs conservation in this region. The regionalization of the critical ecosystem service zones was the first step of Ecological Redline delineation in the Yangtze River Delta Region.

Despite its limitations and uncertainty, the framework can globally be used for identifying hotspots of critical ecosystem service and provides valuable information for environmental management in a rapid urbanization area.

Acknowledge

The authors gratefully acknowledge the project supported by National Natural Science Foundation of China (Grant No. 31670474) & the National Key Research Program of China (Grant No.2016YFC0502701). The author would like to thank Dr Daryl Burdon, Dr Benjamin Burkhard, Professor Ruishan Chen for reviewing the manuscript. Field research was partially funded through a grant from the School of Geographic Sciences, East China Normal University and Department of Geography, Environment and Earth Sciences, University of Hull.

References

Albert C., Aronson J., Furst C., Opdam P., 2014. Integrating ecosystem services in landscape planning: requirements, approaches, and impacts. Landscape Ecol 29, 1277–1285 DOI 10.1007/s10980-014-0085-0

Alessa, L., Kliskey, A., & Brown, G. , 2008. Socialeecological hotspots mapping: a spatial approach for identifying coupled socialeecological space. Landscape and Urban Planning, 85(1), 27-39.

Bai, Y., Jiang B, Wang M, Li H, M.Alatalod J, Huang S., 2015. New ecological redline policy (ERP) to secure ecosystem services in China. Land Use Policy, http://dx.doi.org/10.1016/j.landusepol.2015.09.002

Barkmann, J., Baumann, R., Meyer, U., Müller, F. & W. Windhorst 2001. Ökologische Integrität: Risikovorsorge im Nachhaltigen Landschaftsmanagement. GAIA 10/2, 97-108.

Brase, C.H. and Brase, C.P., 2016. Understanding Basic Statistics, Enhanced. Cengage Learning, 33-36

Burkhard, B., Crossman, N., Nedkov, S., Petz, K., Alkemade, R., 2013. Mapping and modeling ecosystem services for science, policy and practice. Ecosyst. Serv. 4,1–3

Burkhard, B., Krolla, F., Nedkovb S., Müllera F., 2012. Mapping ecosystem service supply, demand and budgets. Ecological Indicators 21, 17–29

Burkhard, B., Kroll, F., Müller, F., Windhorst, W., 2009. Landscapes' capacities to provide ecosystem services – a concept for land-cover based assessments. Landscape Online 15, 1–22.

China City Statistical Yearbook , Shanghai Statistical Yearbook , Statistical Yearbook of Jiangsu Province , Zhejiang Province Statistical Yearbook , China 's economic and social development of China's regional economic statistical databases and statistical yearbook., 2001-2013

Cimon-Morin, J., Darveau, M. and Poulin, M., 2013. Fostering synergies between ecosystem services and biodiversity in conservation planning: a review. Biological Conservation, 166, pp.144-154.

Crossman, N. D., Burkhard, B., Nedkov, S., Willemen, L., Petz, K., Palomo, I., ... &Maes, J. (2013). A blueprint for mapping and modeling ecosystem services. Ecosystem Services, 4, 4-14.

Costanza, R., & Folke, C. (1997). Valuing ecosystem services with efficiency, fairness, and sustainability as goals. Nature's services: societal dependence on natural ecosystems. Island Press, Washington, DC, 49-70.

Cowling R M, Egoh B, Knight A T. An operational model for mainstreaming ecosystem services for implementation. Proceedings of the National Academy of Sciences of the United States of America, 2008, 105(28): 9483-9488.

Daily, G. 1997. Nature's services: societal dependence on natural ecosystems. Island Press.

de Groot, R.S., Alkemade, R., Braat, L., Hein, L., Willemen, L., 2010. Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity 7, 260–272.

GlobeLand30, 2010. National Geomatics Center of China, http://www.globeland30.org/GLC30Download/download.aspx

Gregory, R., Failing, L., Harstone, M., Long, G., McDaniels, T. and Ohlson, D., 2012. Structured decision making: a practical guide to environmental management choices. John Wiley & Sons.

Gos, P. and Lavorel, S., 2012. Stakeholders' expectations on ecosystem services affect the assessment of ecosystem services hotspots and their congruence with biodiversity. International Journal of Biodiversity Science, Ecosystem Services & Management, 8(1-2), pp.93-106.

Guisan, A., Tingley, R., Baumgartner, J.B., Naujokaitis‐Lewis, I., Sutcliffe, P.R., Tulloch, A.I., Regan, T.J., Brotons, L., McDonald‐Madden, E., Mantyka‐Pringle, C. and Martin, T.G., 2013. Predicting species distributions for conservation decisions. Ecology letters, 16(12), pp.1424-1435.

Haas, J. and Ban, Y., 2014. Urban growth and environmental impacts in Jing-Jin-Ji, the Yangtze, River Delta and the Pearl River Delta. International Journal of Applied Earth Observation and Geo-information, 30, pp.42-55.

Haines-Young R. 2009. Land use and biodiversity relationships. Land Use Policy, 26:S178-S186

Hilde, T., & Paterson, R. 2014. Integrating ecosystem services analysis into scenario planning practice: Accounting for street tree benefits with i-Tree valuation in Central Texas. Journal of environmental management, 146, 524-534.

Huang, B., Shi, X., Yu, D., Öborn, I., Blombäck, K., Pagella, T. F., ... & Sinclair, F. L. 2006. Environmental assessment of small-scale vegetable farming systems in peri-urban areas of the Yangtze River Delta Region, China. Agriculture, Ecosystems & Environment, 112(4), 391-402.

Jiao, W., Min, Q., Fuller, A. M., Yuan, Z., Li, J., Cheng, S., & Li, W. 2015. Evaluating environmental sustainability with the Waste Absorption Footprint (WAF): An application in the Taihu Lake Basin, China. Ecological Indicators,49, 39-45.

Karimi, A., Brown, G. and Hockings, M., 2015. Methods and participatory approaches for identifying social-ecological hotspots. Applied Geography,63, pp.9-20.

Kroll, F., Müller, F., Haase, D., Fohrer, N., 2012. Rural-urban gradient analysis of ecosystem services supply and demand dynamics. Land Use Policy 29 (3),521–535.

Li, B., Chen, D., Wu, S., Zhou, S., Wang, T. and Chen, H., 2016. Spatio-temporal assessment of urbanization impacts on ecosystem services: Case study of Nanjing City, China. Ecological Indicators, 71, pp.416-427.

Li, J., Jiang, H., Bai, Y.,M. Alatalo, J., Li, X., Jiang H., Liu, G., Xu J. 2016. Indicators for spatial–temporal comparisons of ecosystem service status between regions: A case study of the Taihu River Basin, China. Ecological Indicators,60, 1008-1016

Li, J., Li, C., Zhu, F., Song, C., & Wu, J. 2013. Spatiotemporal pattern of urbanization in Shanghai, China between 1989 and 2005. Landscape ecology, 28(8), 1545-1565.

Landuyt, D., Lemmens, P., D'hondt, R., Broekx, S., Liekens, I., De Bie, T., & Goethals, P. L. 2014. An ecosystem service approach to support integrated pond management: A case study using Bayesian belief networks–Highlighting opportunities and risks. Journal of environmental management, 145, 79-87.

Luo, X. and J. Shen., 2009. A study on inter-city cooperation in the Yangtze river delta region, China. Habitat International, 33(1), p. 52-62.

Luo, X. J., Qu, F. T., Feng, S. Y., Shi, X. P., & Jiang, H. 2011. Ecological compensation mechanism in Taihu Lake Basin: Based on theory and experience of watershed ecological compensation in and out of China. Journal of Nanjing Agricultural University (Social Sciences Edition), 1, 014.

MacDonald, D.H., Bark, R.H., Coggan, A., 2014. Is ecosystem service research used by decision-makers? A case study of the Murray-Darling Basin, Australia. Landscape Ecol 29, 1447–1460, doi: 10.1007/s10980-014-0021-3

Mascarenhas, A., Ramos, T. B., Haase, D., & Santos, R. 2014. Integration of ecosystem services in spatial planning: a survey on regional planners' views. Landscape Ecology, 29(8), 1287-1300.

MA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being: Synthesis. Island Press/World Resources Institute, Washington, DC.

Mola-Yudego, B., Gritten, D., 2010. Determining forest conflict hotspots according to academic and environmental groups. For. Policy Econ. 12, 575-580.

Müller, F., Burkhard, B., 2007. An ecosystem based framework to link landscape structures, functions and services. In:

Mander, Ü., Wiggering, H., Helming, K. (Eds.), Multifunctional Land Use –Meeting Future Demands for Landscape Goods and Services. Springer, pp. 37–64.

Paetzold, A., Warren, P.H., Maltby, L.L., 2010. A framework for assessing ecological quality based on ecosystem services. Ecological Complexity 7, 273–281.

Reidsma, P.; Feng, S.; van Loon, M., 2012. Integrated assessment of agricultural land use policies on nutrient pollution and sustainable development in Taihu Basin, China. Environmental Science & Policy, 18(0), 66-76

Reidsma, P.; K Nig, H.; Feng, S., 2011. Methods and tools for integrated assessment of land use policies on sustainable development in developing countries. Land Use Policy, 28(3), 604-617

Ren, W., Zhong, Y., Meligrana, J., Anderson, B., Watt, W.E., Chen, J. and Leung, H.L., 2003. Urbanization, land use, and water quality in Shanghai: 1947–1996. Environment International, 29(5), 649-659.

Robinson, D., Jackson, B., Clothier, B., Dominati, E., Marchant, S., Cooper, D., Bristow, K., 2013. Advances in soil ecosystem services: concepts, models, and applications for earth system life support. Vadose Zone J. 12 (4).

Schröter, M. and Remme, R.P., 2016. Spatial prioritisation for conserving ecosystem services: comparing hotspots with heuristic optimisation. Landscape ecology, 31(2), pp.431-450.

Su, S., Li, D., Xiao, R., & Zhang, Y. 2014. Spatially non-stationary response of ecosystem service value changes to urbanization in Shanghai, China. Ecological Indicators, 45, 332-339.

Tian, G., et al., 2011. The urban growth, size distribution and spatio-temporal dynamic pattern of the Yangtze River Delta megalopolitan region, China. Ecological Modeling, 222(3), p. 865-878.

Timilsina, N., Escobedo, F.J., Cropper, W.P., Abd-Elrahman, A., Brandeis, T.J., Delphin, S. and Lambert, S., 2013. A framework for identifying carbon hotspots and forest management drivers. Journal of environmental management, 114, pp.293-302.

Troy, A., & Wilson, M. A. 2006. Mapping ecosystem services: practical challenges and opportunities in linking GIS and value transfer. Ecological economics, 60(2), 435-449.

Turner cal economics, 60(2), 435-449.J et al. 2003. Illustrating the coupled human-environment system for vulnerability analysis: Three ease studies. PNAS, 2003, 100(14): 8080-8085.

Van Jaarsveld, A.S., Biggs, R., Scholes, R.J., Bohensky, E., Reyers, B., Lynam, T., Musvoto,C., Fabricius, C., 2005. Measuring conditions and trends in ecosystem services at multiple scales: the Southern African Millennium Ecosystem Assessment (SAfMA) experience. Philosophica Transactions of the Royal Society B 360,425–441.

Van Riper, C. J., & Kyle, G. T. 2014. Capturing multiple values of ecosystem services shaped by environmental worldviews: A spatial analysis. Journal of environmental management, 145, 374-384.

Viglizzo F, Frank F C. 2006. Land-use options for Del Plata Basin in South America: tradeoffs analysis based on ecosystem service provision. Ecological Economics, 57: 140-151.

Wackernagel, M., &Yount, J. D. 1998. The ecological footprint: an indicator of progress toward regional sustainability. Environmental Monitoring and Assessment, 51(1-2), 511-529.

Wang, T., et al., 2012.Urban air quality and regional haze weather forecast for Yangtze River Delta region. Atmospheric Environment, 58(0), p. 70-83.

Xu, X., Tan, Y., Chen, S. and Yang, G., 2014. Changing patterns and determinants of natural capital in the Yangtze River Delta of China 2000–2010. Science of the Total Environment, 466, pp.326-337.

Zhang, Y. 2010. Yangtze River Delta's System Integration: Institutional Barriers and Countermeasures. Social Sciences in Nanjing, 11, 006.

Zhou, F., et al., 2013. Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. Journal of Hydrology, 485(0), p. 113-125.

Zhao, M. and C. Chen., 2011.Polycentric Network Organization of Mega-City Regions in Yangtze River Delta. Procedia Earth and Planetary Science, 2(0), p. 309-314.

Zhao, B., Kreuter, U., Li, B., Ma, Z., Chen, J., & Nakagoshi, N. 2004. An ecosystem service value assessment of land-use change on Chongming Island, China. Land Use Policy, 21(2), 139-148.

Zhang, Y.; Wu, Y.; Yu, H., 2013. Trade-offs in designing water pollution trading policy with multiple objectives: A case study in the Tai Lake Basin, China. Environmental Science & Policy, 33(0), 295-307