Land use management based on multi-scenario allocation and trade-offs of ecosystem services in Wafangdian County, Liaoning Province, China

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Abstract

15   Developing effective methods to coordinate the trade-offs among ecosystem services (ES)
16 is important for achieving inclusive growth and sustainable development, and has been the focus
17 of scholars and ecosystem managers globally. Using remote sensing and geographic information
18 system (GIS) data, our study examined Wafangdian County of Liaoning Province as a case study
19 to reveal the spatiotemporal evolution of four ES (food supply [FS], net primary productivity
20 [NPP], water yield [WY], and soil conservation [SC]) and changes among their interactions.
21 Then, an ordered weighted averaging model was introduced to simulate the optimal scenario of
22 ES allocation. Results showed that: 1) The spatial and temporal changes in ES were significant
23 over 14 years. All ES presented an inverted U-shaped growth curve from 2000–2014. 2)
24 Synergies were observed within provisioning services, and there were trade-offs between
25 provisioning services and regulating services, as well as provisioning services and supporting
26 services. 3) The optimal scenario for Wafangdian was scenario 5 (trade-off coefficient, 0.68).
27 The allocation of FS, NPP, WY, and SC in scenario 5 were 0.187, 0.427, 0.131, and 0.063,
28 respectively. Implementing each ES weight of optimal scenario in land use management
29 contributed to achieving intercoordination of ES. We propose to coordinate land and sea
30 management to restore natural habitats that were expanded into in the high ES area. It is our
31 anticipation that this study could provide a scientific basis for optimizing the allocation of ES
32 and improving land use structure of coastal zones in the future.

Introduction

34   Ecosystem services (ES) can be considered to be natural capital assets, which provide
35 various benefits to human society (Daily, 2008; Zheng et al., 2019). Managing ES is intended to
36 achieve both environmental sustainability and socioeconomic benefits (Bohnke-Henrichs et al.,
37 2013; Granek et al., 2010). Its essence is to enhance regional integration of ES through science-
38 based management, which is also the purpose of China's 'Ecological Civilization Construction'
39 (Li et al., 2019). The Millennium Ecosystem Assessment of the United Nations classifies these
40 services into four categories: provisioning services, regulating services, supporting services, and
41 cultural services (Alcamo et al., 2002). The specific interactions among different ES are complex
42 (Barbier et al., 2008; Brauman et al., 2007); however, they can be abstracted as competing trade-
43 offs and synergies of mutual gains (Dai et al., 2016; Rodrguez et al., 2006). They have become
44 hot topics in geography and ecology to understand these trade-offs and synergies among various
45 ES; to identify their types, characteristics, and spatiotemporal patterns; and to maximize the
46 benefits to human society from multiple interconnected ES (Fu and Yu, 2016; Queiroz et al.,
47 2015; Rodríguez et al, 2006).

48   Land use change is one of the most important factors affecting ES by changing the
49 structure, processes, and functions of the ecosystem (Ceschia et al., 2010; Chen et al., 2019).
50 Human intervention in land use is an effective way to manage negatively affected in ES. Under
51 increasing human development, the depletion of natural resources and rapid changes in land use

52 have resulted in unbalanced ES (Zheng et al, 2019). In the past decade, ES trade-offs have been
53 widely evaluated and studied, and have been reported to occur between provisioning services
54 (e.g., agricultural production) and regulating services (e.g., soil conservation, carbon storage), as
55 well as between cultural services (e.g., aesthetic, recreation) and provisioning services (Lorilla et
56 al, 2018; Rodrguez et al, 2006; Zheng et al, 2019). There is no doubt that the trade-offs among
57 ES will continue to intensify owing to the increasing demand for natural resources from an
58 increasing human population (Alcamo et al, 2005). In response to such global trends, scientific
59 land use management can minimize the loss of alternative services and facilitate the management
60 of ES (Schroter et al, 2018; Wong et al, 2015). However, previous research on land use
61 management focused on case descriptions and analysis based on trade-offs and synergies of ES
62 (Butler et al, 2013; Lorilla et al, 2018; Rodrguez et al, 2006). Few studies have focused on the
63 allocation and trade-off of ES. Effective methods for transforming scientific understanding of ES
64 trade-offs into policy are still lacking. Ordered weighted averaging (OWA) can effectively
65 reflect the effect of decision-makers' subjective perception on evaluation results by simulating
66 different preference decision-making scenarios combining order weight and criterion weight
67 (Yager, 1988). Previous studies have demonstrated the ability of the OWA model to balance the
68 internal conflicts among ES, and it has been widely used in land suitability appraisals, geological
69 disaster prevention, and ecological security assessments (Malczewski & Rinner, 2005; Delgado
70 et al., 2013; Zhang et al., 2015). However, few studies have applied OWA to land use decision
71 management based on ES allocation and trade-off.

72   Wafangdian is at the node of the Northeast Asia Economic Circle. After 2010, the
73 Changxing Island Economic and Technological Development Zone and Taiping Bay Port Area
74 were established successively, and a large-scale reclamation campaign was launched. In addition,
75 industrial effluent from petrochemical factories has polluted coastal waters. In particular, the
76 establishment of Hengli Petrochemical Company, the world's largest PTA petrochemical
77 company, has exacerbated this threat. Therefore, the present study was carried out in Wafangdian
78 County with the aim to explore land use management based on ecosystem services. Specifically,
79 the objectives of our study were, (1) to evaluate the four typical ES and their interrelationships,
80 (2) to optimize ES allocation and trade-off based on the OWA-GIS model, and (3) to recommend
81 land use management strategies. Our research can not only further our understanding of the
82 complex interactions among typical ES but also provide scientific reference for land use
83 planning for decision makers and stakeholders.

Materials & Methods

Study area

86   The ES analysis was developed for Wafangdian County of Liaoning Province (121°13E–
87 122°16′E, 39°20′N–40°07′N), in northeast China (Fig. 1). Wafangdian covers 3881 km^2 and its
88 western region is near the Bohai Sea with a coastline of 461.2 km. Altitude ranges from sea level
89 to ~800 m. With its beneficial geographical position and strong industrial foundation,

90   Wafangdian has become the leading county-level economy in Liaoning Province, and is known
91   as the "bearing capital" of China. However, the geographical advantages of land and sea not only
92   bring great opportunities for development but also cause ecological problems for Wafangdian.
93   As for the marine ecological environment, with the advancement of macrocosm urbanization
94   strategies, urban construction and industrial development in Wafangdian turn to the coastal zone,
95   and the ecological pressure increases year by year. Natural ecosystems, such as estuaries and
96   beaches, have been encroached on a large scale. The sewage discharged from petrochemical
97   factories into the sea has deteriorated water quality in sea area, and the disorderly development
98   of mariculture has gradually reduced the ecological balance of the sea. In addition, terrestrial
99   ecological problems are also serious. A large number of chemical enterprises in Dalian have
100 been transferred to aggravate air pollution. Furthermore, seasonal drying of major rivers
101 increases the pressure on the water supply. Wafangdian urgently needs to co-ordinate land and
102 sea, strengthen land use management, and improve integrated ES.

Data source

104 The study data are from 2000, 2007, and 2014. Five data types were used in this study: (1)
105 The land use data of the three years were interpreted from remote sensing images (Landsat7
106 ETM and Landsat8 OLI) with a spatial resolution of 30 m. According to the actual situation of
107 the study area, the land use types of Wafangdian were interpreted into seven categories: forest,
108 grassland, cropland, settlement, inland water, mariculture area, and unused land. (2) The
109 normalized difference vegetation index (NDVI) data were obtained from the MODIS13Q1
110 dataset on the NASA website (https://www.nasa.gov/), with a spatial resolution of 250 m.
111 Bilinear interpolation was used to improve the resolution accuracy of the NDVI to 30 m to
112 ensure that all raster data was at the same resolution. (3) A 30-m resolution digital elevation
113 model was provided by Geospatial Data Cloud Site, Computer Network Information Center,
114 Chinese Academy of Sciences (http://www.gscloud.cn/). (4) The meteorological data were
115 collected from the China Meteorological Data Network (http://data.cma.cn/). We obtained
116 monthly precipitation, evaporation, and average temperature; and total and net solar radiation
117 pertaining to Wafangdian and 13 surrounding counties. ArcGIS 10.2 software was used to
118 interpolate the monthly meteorological data by inverse distance weighting, so that the
119 meteorological point data could be converted into 30 m resolution raster data. (5) Soil property
120 data came from the China Soil Map-Based Harmonized World Soil Database version 1.1
121 (http://westdc.westgis.ac.cn).

Quantifying ecosystem services

123 Ecological problems should be considered, such as water shortage and soil erosion caused
124 by rapid urbanization in Wafangdian. At the same time, the government's decision-making
125 tendency in dealing with ecological problems is also considered. Therefore, this study selected
126 four ES that were representative of the study area, including two provisioning services (food
127 supply [FS], water yield [WY]), one regulating service (soil conservation [SC]), and one

128 supporting service (net primary productivity [NPP]). The mapping and quantification of ES was
129 implemented for 2000, 2007, and 2014, and results are presented on a grid map with 30-m
130 resolution.

131   **Food supply:** food supply is an important provision services of ecosystems, especially
132 agricultural ecosystems. Based on the land use classification, this study uses the yield per unit
133 area of different land use types as an indicator to measure the FS capacity of each land use type.
134 There is a significant linear relationship between the yield of crops and livestock products and
135 NDVI (Li et al., 2012; Zhao et al., 2012). Therefore, NDVI (range 0–1) was used to spatialize
136 the statistical data of food yield. Specifically, the grain yield and husbandry yield were allocated
137 to cropland and grassland grids, respectively, according to the NDVI. The calculation formula
138 used was as follows:

$$P_i = \frac{NDVI_i}{NDVI_{sum}} \times P_{sum} \tag{1}$$

139 Where P_i refers to the grain yield and animal husbandry at grid i. P_{sum} represents the gross grain
140 yield and animal husbandry. $NDVI_i$ is the NDVI at grid i; $NDVI_{sum}$ is the sum of NDVI of
141 cropland or grassland in the study area. In addition, the yield of freshwater aquaculture and
142 marine aquaculture was assigned to inland waters and marine aquaculture areas, respectively.

143   **Net primary productivity:** NPP is an important index for evaluating vegetation
144 productivity and coverage and is an important component of the terrestrial carbon cycle (Field et
145 al., 1998). It was used to express the organic matter energy accumulated per unit area of
146 vegetation in a unit time; i.e., the residual amount of organic matter created by deducting oxygen
147 respiration from vegetation during photosynthesis (Ruimy et al., 1994). In our study, NPP was
148 modelled using the process-based Carnegie–Ames–Stanford approach (CASA) (Potter et al.,
149 1993). Two important variables were used to account for NPP in the CASA model: the absorbed
150 photosynthetically active radiation (APAR) and the actual solar energy utilization efficiency of
151 plants (ε).

$$NPP(x,t) = APAR(,t) \times \varepsilon(x,t) \tag{2}$$

152 Where $APAR(x,t)$ the photosynthetically active radiation (MJ/m^2·a^{-1}) absorbed by the pixel x in
153 the month t. $\varepsilon(x,t)$ refers to the actual utilization rate of light energy at the x pixel in the month t.

154   **Water yield:** WY was calculated using the water production module of the InVEST model
155 v.3.3.3. Considering the influence of topography on runoff and the spatial differences in soil
156 permeability under different land use types, the InVEST model is based on the principle of water
157 balance to estimate the water supply of different landscape types quantitatively (Hoyer & Chang,
158 2014). The basic principles are as follows:

$$Y(x) = \left(1 - \frac{AET(x)}{P(x)}\right) \times P(x) \tag{5}$$

159   Where $Y(x)$ is the annual WY of grid x (mm); $AET(x)$ is the actual annual evaporation of grid x
160   (mm); $P(x)$ is the annual precipitation of grid x (mm).

161   **Soil conservation:** Soil conservation was simulated using the revised universal soil loss
162   equation (RUSLE) model (Renard et al., 1997). Based on the replacement hypothesis of surface
163   cover, SC amount can be expressed as the difference between potential soil erosion and actual
164   soil erosion; i.e., the difference between the amount of soil erosion without any vegetation cover
165   management and soil and water conservation measures and the amount of soil erosion under
166   current vegetation cover management and soil and water conservation measures (Wu et al.,
167   2017). The calculation formula used was as follows:

$$A_c = A_p - A_r \tag{9}$$

168   Where A_c represents SC (t/hm^2·a), A_p is the amount of the potential soil erosion (t/hm^2·a), and A_r
169   is the amount of the actual soil erosion (t/hm^2·a). The potential soil erosion and actual soil
170   erosion were quantified as follows:

$$A_p = R \times K \times LS \tag{10}$$

$$A_r = R \times K \times LS \times C \times P \tag{11}$$

171   Where R is the rainfall erosion factor; K is the soil erosion index; LS represents the combined
172   slope length (L) and factor of slope length (S); C is the vegetation cover index; and P is the SC
173   measure index.

Correlation analysis among ecosystem services

175   To quantify the relationships among the four ES (FS, NPP, WY, and SC) we calculated the
176   correlation coefficient matrix among ES (Raudsepp-Hearne et al., 2010; Turner et al., 2014).
177   Each indicator was standardized by the maximum value ranging from 0–1 to remove the effect of
178   ES unit differences. We used ArcGIS 10.2 to extract standardized ES into tables using Create
179   Fishnet tools, and then calculated the Spearman's rank correlation for all pairs of ES using the
180   scatterplot matrix function of the "car" package in R 3.4.3 (Fox & Weisberg, 2011; R
181   Development Core Team, 2017). Moreover, correlation coefficients were tested in SPSS 20.0
182   (SPSS Inc., Chicago, IL, USA).

183   Based on the correlation analysis, the trade-offs relationships among ES were clarified.
184   When a correlation coefficient among ES passed the significance test at 0.01 level and the
185   coefficient was negative, then there was deemed to be a significant trade-offs relationship. On
186   the contrary, if the correlation coefficient was positive, then there was a significant synergies
187   relationship (Jopke et al., 2015). In our study, all the significant correlation coefficients were
188   classified into strong correlations ($|r| \geq 0.5$), moderate correlations ($0.3 \leq |r| < 0.5$), and weak

189   correlations ($0.1 \leq |r| < 0.3$) according to the classification of the intensity of significant
190   correlation coefficients of Cohen (1992).

Scenario analysis based on OWA-GIS

192   Ordered weighted averaging is a method for controlling factor weight combination. By
193   reordering the data of each index according to their attribute value and giving different order
194   weights and weighting aggregation values according to the order of each index, OWA reflects
195   the decision-making results when the decision maker ranks the importance of each index
196   differently (Yager, 1996; Zhang et al., 2017). Its model principle is as follows:

$$OWA(x_{ij}) = \sum_{i=1}^{n} w_i s_{ij}, \left(w_i \in [0,1] \text{ and } \sum_{i}^{n} w_i = 1, \text{ for } i \text{ and } j = 1,2,3 \cdots n \right) \tag{12}$$

197   Where x_{ij} refers to four standardized raster maps of ES (NPP, SC, FS, and WY) in 2.4.1; s_{ij} is the
198   new sequence obtained by reordering the attribute values of x_{ij} in descending order. In our study,
199   we ranked the new sequence according to the average value of each ES; w_i was the ordered
200   weights of the s_{ij}; n refers to the number of ES.

201   We introduced the OWA operator into the trade-offs analysis of ES and simulated decision-
202   making scenarios under different preferences by setting different risk coefficients. At the same
203   time, combined with the calculation of trade-offs degree (Zhang et al., 2015), the best trade-offs
204   of ES in Wafangdian under feasible decision-making conditions was determined. The specific
205   steps were as follows:

206   (1) Four evaluation indicators (four ES) were ranked in descending order according to their
207   mean value.

208   (2) The order weights w and trade-offs degree with different risk-degree coefficients were
209   calculated (Yager, 1993; Zhang et al., 2015) as follows (Table 1):

$$w_i = Q_{RIM}\left(\frac{i}{n}\right) - Q_{RIM}\left(\frac{i-1}{n}\right), i = 1,2,3 \cdots n \tag{13}$$

$$Q_{RIM}(r) = r^{\alpha}, \alpha \in (0, +\infty) \tag{14}$$

$$\text{trade} - \text{off} = 1 - \sqrt{\frac{n\sum_{i}^{n}\left(w_i - \frac{1}{n}\right)^2}{n-1}}, 0 \leq \text{tradeoff} \leq 1 \tag{15}$$

210   Where w_i is the order weight; Q_{RIM} is a monotone increasing function; i is the ordinal number,
211   and n represents the number of ES; r is the independent variable; and α is the risk coefficient
212   (scenario), also known as the optimistic degree coefficient, which based on the risk perception of

213   decision-making caused by the difference in the numerical value of indicators and the difference
214   in subjective weights.

215   (3) Combining the OWA operator with the GIS platform, the OWA-based ES raster was
216   obtained.

217   (4) Using the Getis-Ord Gi* module in ArcGIS 10.2 to analysis the cold and hot spots of the
218   OWA-based ES raster under different scenarios. In our study, 99% of the hot spots were defined
219   as the highest ES area, 95% as a high ES area, and 0 as a medium ES area. On the contrary, 99%
220   of the cold spots were named as the lowest ES area, and 95% were low ES area. Finally, the
221   trade-off coefficient and the area of the highest and high ES areas of each scenario were
222   combined to determine the optimal trade-offs of ES in Wafangdian.

Results

Overall change in ecosystem services

225   The maps in Figure 2 show the distribution of ES in 2000, 2007, and 2014. FS was highly
226   distributed in the central and western areas but had a smaller distribution in the east. The high
227   value areas were mainly in the vast central cropland and southwestern coastal waters, and the
228   overall trend decreased from west to east. The average FS yield in 2000 was 173.33 t/km^2. In
229   comparison, the mean FS yield in 2007 was 250.57 t/km^2, with a 44.56% increase compared with
230   2000. The mean FS production was 228.17 t/km^2 in 2014 and decreased by 8.94% compared
231   with 2007. In terms of temporal scale, FS yield showed a trend of rapid growth in the early stage
232   followed by a slow decline in the later stage. Among them, the FS capacity increased
233   significantly in the southwest coastal waters and the cropland along the lower reaches of the
234   Fuzhou River.

235   The total NPP of Wafangdian in 2000, 2007, and 2014 was 1.62 trillion g C, 1.85 trillion g
236   C, and 1.65 trillion g C, respectively (Table 2), showing a similar trend to that of FS in temporal
237   scale. However, the spatial distribution was different from that of FS. The high value areas were
238   mostly concentrated in the mountains with high vegetation coverage, such as Laomao Mountain
239   and Longtan Mountain in the east and Dabei Mountain in the middle and south. Low value areas
240   were mostly distributed in the southwest coastal areas, and in Fuzhou Town and the downtown
241   of Wafangdian.

242   The spatial pattern of WY was mainly influenced by precipitation and evapotranspiration. It
243   was higher in the west compared with the east, in the aquatic habitats compared with the
244   terrestrial ones, and in the flat lands compared with the mountains. The spatial distribution of
245   WY was similar in 2000, 2007, and 2014; however, the average annual WY varied considerably
246   among the 3 years. In the early stage, it increased from 230.20 mm in 2000 to 390.02 mm in
247   2007, and then decreased sharply to 197.35 mm in 2014.

248   The average SC in 2000, 2007, and 2014 was 61.46 t/hm^2, 66.28 t/km^2, and 48.03 t/hm^2,
249   respectively (Table 2), showing a moderate increase and then a sharp decrease through time. The

250 spatial distribution of SC was similar to that of NPP. Forest dominated the mountainous area in
251 the northeast, with high vegetation coverage; therefore, the SC had a high capacity. The terrain in
252 the southwest was flat, where towns and villages were concentrated. Owing to the high intensity
253 of land development and utilization, the SC capacity was low. On the whole, except for the
254 sustained growth of SC, the ES of the study area increased initially and then decreased from
255 2000 to 2014.

Spatiotemporal changes in ecosystem services with different land use
257 **types**

258 Our study focused on the changes in ES and their relationships among forest, grassland, and
259 cropland (three vegetation-covered land use types). The mean values of the four ES according to
260 each land use type were determined. To ensure a more intuitive comparison among the different
261 ES, min–max normalization was used to remove dimension and then Nightingale's rose diagram
262 was made. As shown in Figure 3, compared with cropland and grassland, forest had the largest
263 NPP and SC, while grassland had the largest FS. The WY of cropland was the highest, while SC
264 and NPP were the lowest, and FS was slightly lower than that of grassland. In terms of temporal
265 dynamics, the WY and NPP of the forest increased and then decreased from 2000 to 2014 (NPP:
266 0.68 in 2000, 0.77 in 2007, and 0.62 in 2014; WY: 0.23 in 2000, 0.29 in 2007, and 0.12 in 2014),
267 while SC increased. However, the change was not significant (SC increased by 0.01 in 3 years).
268 The WY of the grassland also presented an inverted U-shaped curve from 2000 to 2014 (0.32 in
269 2000, 0.35 in 2007, and 0.23 in 2014), while FS and NPP decreased significantly (FS: 0.79 in
270 2000, 0.71 in 2007, and 0.67 in 2014; NPP: 0.56 in 2000, 0.43 in 2007, and 0.50 in 2014).
271 Except for SC, the other three ES in cropland showed a significant inverted U-shaped trend
272 representing an initial increase that then decreased over the 14 years investigated (Fig. 3).
273 Overall, our results showed that NPP, FS, and WY decreased in forest, farmland, and grassland
274 from 2000 to 2014. SC in the three land use types increased slightly; however, this was not
275 significant (Fig.3).

Trade-offs and synergies

277 Figure 4 shows the Spearman's correlation coefficients and significance levels among ES in
278 2000, 2007, and 2014. These values were used to describe trade-offs and synergistic
279 relationships. During the 3 years, all 18 pairs of ES passed the significance test at 0.01, with
280 seven pairs strongly correlated ($|r| \geq 0.5$), three moderately correlated ($0.3 \leq |r| < 0.5$), and eight
281 weakly correlated ($0.1 \leq |r| < 0.3$). From 2000 to 2014, except for NPP and SC, FS and WY were
282 synergistic, and the other pairs of services were trade-offs. In the synergistic relationship, NPP
283 and SC had the highest synergistic relationship, with a significant positive correlation (2000: r =
284 0.52; 2007: r = 0.62; 2014: r = 0.53), while FS and WY had a moderately positive correlation in
285 2000 (r = 0.30) and weakly positive correlation in 2007 and 2014 (2007: r = 0.10; 2014: r =
286 0.12). Among the 12 pairs of trade-offs, that between NPP and WY was the highest, with a
287 significantly negative correlation (2000: r = −0.63; 2007: r = −0.67; 2014: r = −0.64). The trade-

288   off between NPP and FS in 2014 was the weakest, with a weak negative correlation (r = −0.08).
289   Overall, during the study period, trade-offs dominated the relationships among ES in
290   Wafangdian.

291   To clarify the trends in trade-offs and synergies among ES in 2000, 2007, and 2014, we
292   drew a histogram of the correlation coefficient of each pair of ES (Fig. 5). The two pairs of
293   synergistic ES changed significantly from 2000 to 2014. The synergy between NPP and SC
294   increased and then decreased in 14 years, while the synergy between WY and FS decreased
295   sharply over the same period, with a drop of 46.15%. For the four pairs of trade-offs, NPP-WY
296   and SC-WY both presented inverted U-shaped curves over 14 years, while SC-FS decreased
297   from 2000 to 2007, and then increased from 2007 to 2014. However, the trade-off of NPP-FS
298   decreased consistently over 14 years without fluctuation. The results showed that the trade-offs
299   and synergies between ES without human intervention were more highly significant and their
300   changes were more stable (synergy: NPP-SC; trade-offs: NPP-WY and SC-WY). Conversely, ES
301   directly affected by human intervention, such as FS, tended to change considerably and
302   irregularly (trade-offs: NPP-FS and SC-FS; synergy: FS-WY). In addition, the trade-off between
303   regulating services and provisioning services was intense and stable, especially the relationship
304   between regulating services and WY, which remained stable without fluctuating (SC-WY: NPP-
305   WY)

Optimal allocation scenario of ecosystem services and land use

307   Through setting seven different levels of risk coefficients, and according to the three
308   formulas (Eqs 13–15), the trade-offs and weights under each scenario were determined. Figure 6
309   shows the OWA-based raster layer of ES under the seven scenarios based on the weights in
310   Table 1. The OWA-based ES spatial distribution was different under each scenario. Compared
311   with the other six scenarios, the ES of scenario 1 presented low values. The spatial distribution of
312   the high and low values of scenarios 2–4 were more uniform than those of scenario 1. However,
313   the high values were more concentrated in the coastal mariculture areas, while the ES of
314   terrestrial areas were distributed evenly but were still dominated by low values. The trend in high
315   value clustering of ES under scenarios 5–7 became increasingly evident. In particular, there were
316   large sea–land differences under scenarios 6 and 7. The high values were mostly concentrated in
317   the eastern mountainous areas covered by forest, while the coastal waters were completely
318   covered by low values. Overall, from scenario 1–7, the spatial distribution of OWA-based ES
319   tended to be low-value clustering to uniform distribution to high-value clustering.

320   Scenarios 1 and 7 were two extreme scenarios (extremely optimistic and pessimistic,
321   respectively) in decision making, which were dominated by a single type of ES. These two
322   scenarios do not exist in reality and also do not meet the needs of diversification of ES.
323   Therefore, we excluded scenarios 1 and 7, and then the cold hot spot analysis module in ArcGIS
324   10.2 was used to determine the high (hot spot) and low (cold spot) value aggregation under the
325   other five scenarios (Fig. 7). For the spatial distribution of ES regionalization, scenario 2–6

326   changed from low value agglomeration dominant (scenario 2) to coexisting high-value and low
327   value agglomeration (scenario 6). Under scenario 5, the high ES areas radiated to the western
328   plains and to the coastal areas, including the highest ES observed. The smallest sea–land
329   differences in ES were observed under all scenarios.

330   The results of ES regionalization (Table 3) showed that the sum of the high ES areas under
331   scenario 5 covered an area of 2086.50 km^2, accounting for 53.91% of the total area of
332   Wafangdian, far exceeding that of the other scenarios. Combining the trade-off coefficients of
333   each scenario in Table 1, scenario 5 had a trade-off coefficient of 0.68, which was the highest
334   under all feasible decision-making scenarios. Although the trade-off coefficient of scenario 4
335   was 1, the weights of services were equal under this scenario, which is an ideal decision-making
336   scenario for the complete equalization of ES. By comparing with the spatial distribution and area
337   of the high ES areas of each scenario and combining with the trade-off coefficients of each
338   scenario, it was found that scenario 5 had the largest high ES area (53.91% of the whole region)
339   and the highest ES trade-off coefficient (0.68). Consequently, the optimal trade-off scenario in
340   Wafangdian was the area defined under scenario 5.

341   Figure 8 shows that, in the optimal trade-off scenario, the high and highest ES areas of
342   Wafangdian covered all kinds of land use types and were distributed throughout the study area.
343   Cropland encompassed an area of 730.28 km^2 and constituted 35% of all of the high ES areas.
344   Forest and mariculture area were ranked second and third, respectively. Forest encompassed an
345   area of 542.49 km^2 and constitutes 26% of all of the high ES areas.

Discussion
Ecosystem services mapping and drivers of variation

348   In the present study, for the purpose of making better decisions on the optimization of
349   environmental and social services, methods based on remote sensing data were used for spatially
350   visualizing ES to enable stakeholders and policy-makers to compare with the actual land use
351   (Mina et al., 2017). Therefore, three ES use an evaluation model based on remote sensing or GIS
352   (SC based on RUSLE, WY based on InVEST, and NPP based on CASA). Maps were
353   comparable after standardization, which also facilitated the subsequent implementation of map
354   algebraic overlay and GIS spatial analysis. The maps produced by the models were the products
355   of a linear combination of multiple variables, such as evapotranspiration, soil composition,
356   vegetation cover index, and even statistical data of grain yield, which serve to supplement and
357   enrich land use data. The information provided by combinatory ability of the model was more
358   accurate and reliable than that obtained from the direct interpretation of land use (e.g., Eigenbrod
359   et al., 2010; Kandziora et al., 2013).

360   The map in Fig. 2 shows the spatial distribution of the four ES analyzed. The two
361   provisioning services (FS and WY) maintained the same spatial distribution pattern. This was
362   different from the results of Sun et al. (2016), whose results suggested that, where FS is high, the
363   water consumption of crops is also high, and thus, the higher the FS the lower the WY. These

364 results are reasonable for inland areas or research areas excluding offshore waters. However, the
365 large area used for aquaculture, and the highly important position of fisheries in the local
366 economy, introduce difficulties when attempting to classify coastal aquaculture areas into land
367 use types. The high production value and yield of mariculture areas result in a broader
368 distribution of FS in aquatic areas compared with that of terrestrial areas.

369 From 2000 to 2014, all ES presented a fluctuating inverted U-shaped curve, and 2007 was
370 the node for all ES fluctuations when each ES reached its highest level in 14 years.
371 Meteorological conditions, such as precipitation, temperature, and radiation, were the drivers of
372 the observed fluctuations. The monthly average precipitation, average temperature, and total
373 solar radiation in 2007 were higher than those in 2000 and 2014 of the same period. Precipitation
374 in 2007 was particularly high with monthly average precipitation increasing by 74.31%
375 compared with that of 2000 and twice as much as was observed in 2014 (Figs S1 and S2 and
376 Table S1). These meteorological factors played a decisive role in the CASA, water yield module
377 of InVEST, and RUSLE models (Huston & Michael, 2012), which directly contributed to
378 increases in ES, such as NPP, WY, and SC, in 2007. In addition, our results clearly demonstrate
379 that the particular hydrothermal conditions in 2007 resulted in a higher crop yield in that year
380 compared with those of the same period over 14 years. Especially for Wafangdian, which is
381 located in the temperate monsoon climate zone, timely and sufficient precipitation and heat in
382 spring and summer (April–September) ensure the growth of crops and other plants.

Interaction among ecosystem services

384 The specific interactions between different ES were complex. The results of correlation
385 analysis among ES in different research areas are not consistent, especially regarding the
386 relationships among multiple ES in some areas where the interface between humans and land is
387 more prominent, which have not been clarified (Wu et al., 2017). In addition, the trade-offs
388 relationship has spatiotemporal heterogeneity, and the synergies relationship determined in one
389 region is often expressed as a trade-off in another region. For example, the study by Enfors et al.
390 (2008) at catchment scale showed that FS and SC are synergistic, while a study by Maes et al.
391 (2012) across the European continent showed a trade-off between these two ES. Therefore, the
392 trade-offs and synergies among ES derived from our study are not globally uniform, or even
393 nationally, and are also different from the results of previous studies.

394 Our study identified the synergies within provisioning services, the trade-offs between
395 provisioning services and regulating services, and the synergies between supporting services and
396 regulating services in Wafangdian. Previous studies have reported the synergies between WY
397 and regulating services, but trade-offs between WY and FS (Qiu & Turner, 2013; Sun et al.,
398 2016). Conversely, our results revealed a more differentiated picture. One of the reasons for the
399 difference is as mentioned in the analysis of WY spatial distribution pattern in section 4.1; i.e.,
400 differences in study site location. Another reason is the different models of WY estimation. Sun
401 et al. (2016) used a method considering comprehensive water-holding capacity to calculate WY.

402   This method estimates WY by calculating canopy interception, water retention in litter layers,
403   and loose soil interception (Wang et al., 2007). The mechanism of this estimation is more
404   focused on reflecting the capacity of water regulation, which is essentially a regulating service.
405   Similar to most previous studies, our results indicate trade-offs among provisioning services and
406   other services (Schirpke et al., 2019; Jopke et al., 2015). This was especially evident for the two
407   pairs of trade-offs involving WY (WY-NPP and WY-SC), which were the most significant
408   among all trade-offs in this study. Synergistic effects were often found in the same type of ES
409   (Raudsepp-Hearne et al., 2010; Zhao et al., 2018), which is further demonstrated by the moderate
410   synergies observed between FS and WY in our study. In addition, similar to the results of
411   Schirpke et al. (2019), our results showed that the synergies between supporting services (NPP)
412   and regulating services (SC) are all determined by the presence of forest owing to its high
413   capacity for ES provision.

414   As shown in Figure 5, the changes in ES trade-offs in Wafangdian in the 14 years
415   investigated were complex, and there were either increasing or decreasing trade-offs and
416   synergies among ES. Therefore, it is difficult to judge whether the change in overall ES
417   allocation was positive. In addition, although trade-offs and synergies have changed to some
418   extent during the study period, there was no mutual transformation between trade-offs and
419   synergies observed in our study. Thus, it can be concluded that there were no reversible trade-
420   offs in Wafangdian in the 14 years investigated. Evidently, a pair of trade-offs (NPP-FS) and a
421   pair of synergies (WY-FS) involving FS were both weakened in the 3 years, which contrasts with
422   the observed decreasing trend in cropland. Whether the advancement of farming technology
423   promotes the growth of grain production or whether the continuous expansion of offshore
424   mariculture compensates for the decline in land FS capacity remains to be further investigated.

Ecosystem service optimization and land use management strategies

426   The basic concept of the OWA-based trade-off coefficient of ES is different from the trade-
427   off relationship among ES. Optimal trade-offs refer to the allocation of ES that maximize the
428   service capacity of an ecosystem (Zhang et al., 2015). The optimal trade-off coefficient based on
429   OWA considers the risks of decision-making and the value of each service to the combined
430   provision of services to redistribute the existing service allocation. In summary, the optimal
431   trade-off coefficient is essentially an optimization objective for the status quo of regional trade-
432   offs and synergies.

433   In the optimal scenario (scenario 5), NPP and WY were found to be highly capable ES that
434   exhibited stable changes over the 14 years, and thus were highly weighted, while highly
435   fluctuating FS and SC with low ES capability were designated as lower weight. Therefore, to
436   optimize the interactions among ES and improve the overall ES level, it is entirely reasonable to
437   increase the weight of services with stable ecological functions and decrease that of services with
438   large fluctuations (Liao et al., 2017). In the future, land use management strategies should
439   consider the eastern mountainous areas and western coastal areas as important areas to focus on

440   and implement ecosystem protection and restoration projects. On the one hand, from the
441   perspective of strengthening existing protected areas, the eastern area should strengthen the
442   management of forest resources, and achieve the goal of returning farmland to forests at the edge
443   of forested lands, steep-sloped areas, water-source areas, and highly-polluted cultivated lands in
444   the eastern area contain Lao Mao Mountain, Longtan Mountain, and Camel Mountain. On the
445   other hand, the western coastal area is more seriously affected by ES degradation. Relevant
446   departments should strengthen the protection of typical ecosystems such as coastal wetlands,
447   estuaries, and bays, and also important fishery waters such as spawning grounds, bait grounds,
448   wintering grounds, and migration channels. They should establish wetland nature reserves in the
449   estuary area of Fuzhou Bay, and restore wetland ecosystems in the Fuzhou and Fudu estuaries.
450   Such management strategies that coordinate land–sea habitats can help to maintain a balanced
451   and efficient operation of ES in Wafangdian.

452   Human intervention in ecosystems should fully consider the resistance and recovery of
453   different ecosystems to external disturbance (Bertness et al.,2015). Therefore, the resilience of
454   different ecosystems should be coupled in formulating Ecosystem Optimization objectives. The
455   four ecosystem services provided by Wafangdian forestland have changed steadily in 14 years,
456   while coastal wetland and cropland have changed dramatically. Most previous studies showed
457   that forest ecosystem had great natural recovery and ecology resilience, while wetland and
458   farmland ecosystem were more fragile and less resilient (Liu et al., 2018; Seidl et al., 2014).
459   Evidently, there was a linear correlation between ecosystem services and ecosystem resilience
460   (Li et al., 2017). The study of ecosystem resilience is of great significance to the ecological risk
461   warning and sustainable management of ecosystems (Bertness et al.,2015). Detecting and
462   analyzing the fluctuation of ecosystems regime shift, correcting and constraining the objectives
463   of Ecosystem Optimization with different ecosystem resilience values are more conducive to
464   achieving sustainable management of regional ecosystems, which also require continuous
465   monitoring and regulation in follow-up research.

466

Conclusions

467

468   Coordinated land–sea management of ES in coastal cities has always been a challenge for
469   scientific and effective land use management. Our study revealed that the GIS-based OWA
470   multi-criterion evaluation method can be used to determine the optimal allocation of ES trade-
471   offs by adjusting land use artificially. The results showed that ES in Wafangdian fluctuated over
472   the 14 years tested, which is reflected in the increase from 2000–2007 and the decrease from
473   2007–2014. Under the influence of ES changes, the trade-offs and synergies also fluctuated.
474   Based on the trade-offs and synergies in 2014, an optimized service allocation is proposed; i.e.,
475   the ES allocation under scenario 5. In future, ES research should systematically determine the
476   trade-off and synergy mechanisms and promote the application of the results in the land field. At
477   present, China is actively seeking solutions to balance economic development and ecological

478 protection, such as land use planning and ecological red line delimitation. Research into trade-
479 offs and synergies can effectively identify the ecological space that is essential for maintaining
480 regional ES and requires protection.

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Figure 1

Location of Wafangdian County in China.

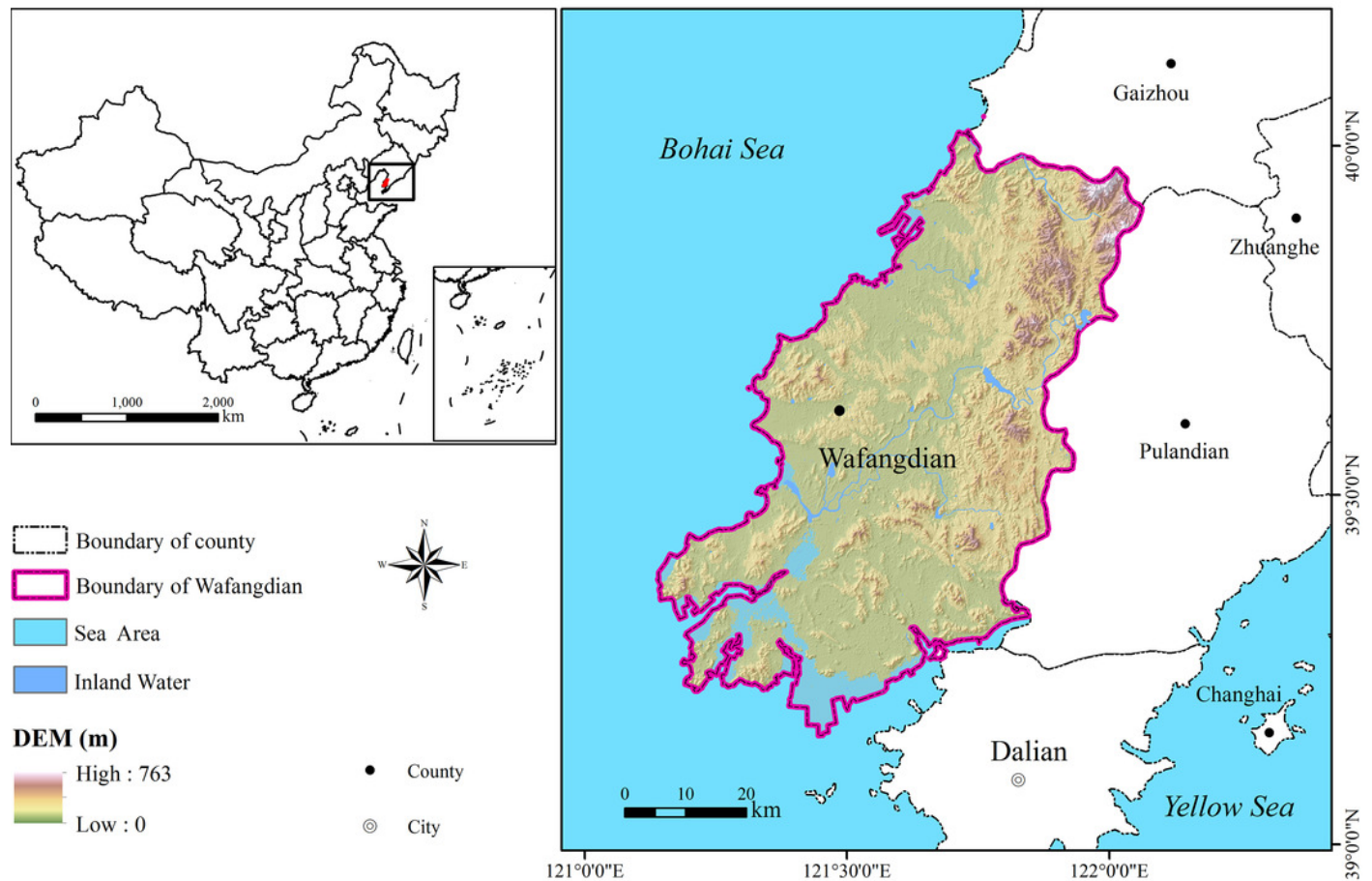



Figure 2

Mapping of ecosystem services in 2000, 2007, and 2014.

NPP: net primary productivity; FS: food supply; WY: water yield; SC: soil conservation; (A) FS in 2000; (B) FS in 2007; (C) FS in 2014; (D) NPP in 2000; (E) NPP in 2007; (F) NPP in 2014; (G) WY in 2000; (H) WY in 2007; (I) WY in 2014; (J) SC in 2000; (K) SC in 2007; (L) SC in 2014.

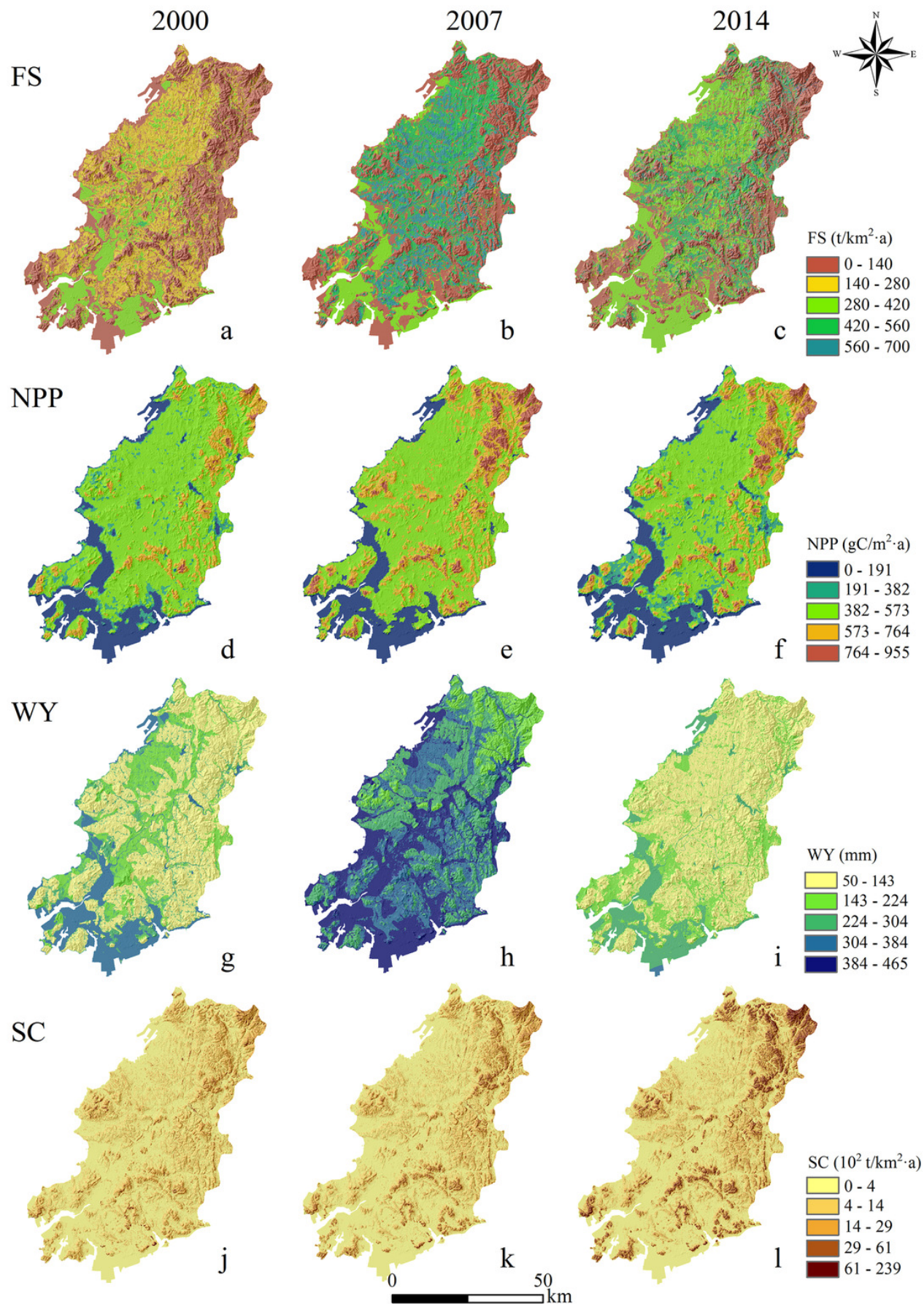



Figure 3

Rose map of ecosystem services in 2000, 2007, and 2014.

NPP: net primary productivity; FS: food supply; WY: water yield; SC: soil conservation; (A) ES rose map of forestland in 2000; (B) ES rose map of grassland in 2000; (C) ES rose map of cropland in 2000; (D) ES rose map of forestland in 2007; (E) ES rose map of grassland in 2007; (F) ES rose map of cropland in 2007; (G) ES rose map of forestland in 2014; (H) ES rose map of grassland in 2014; (I) ES rose map of cropland in 2014.

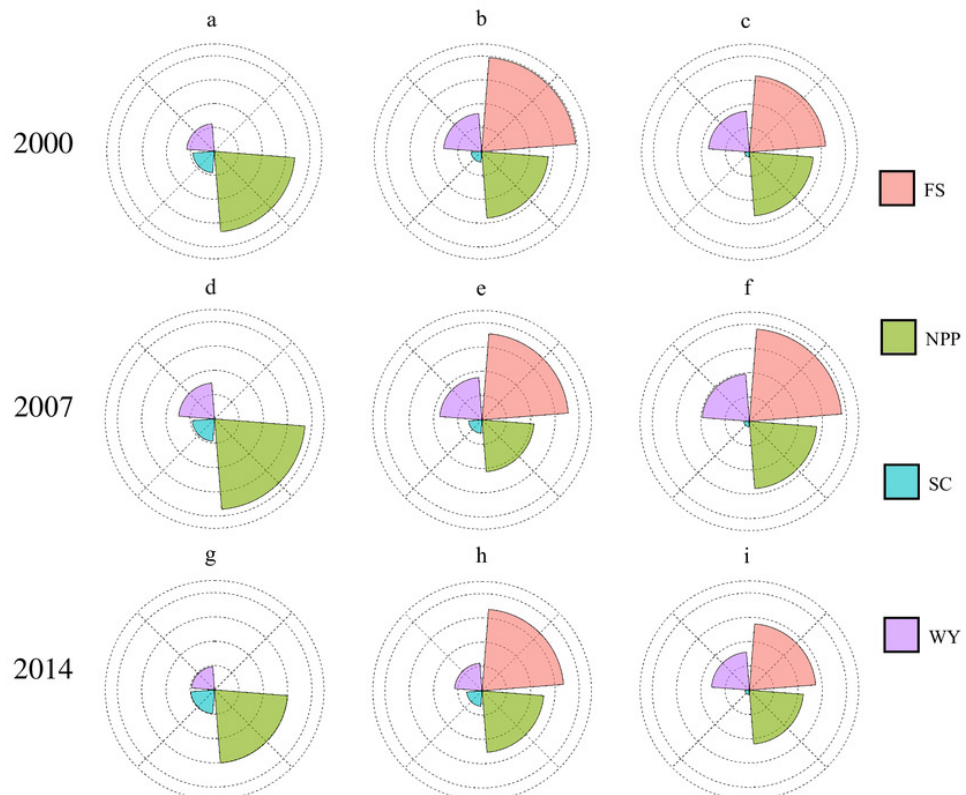
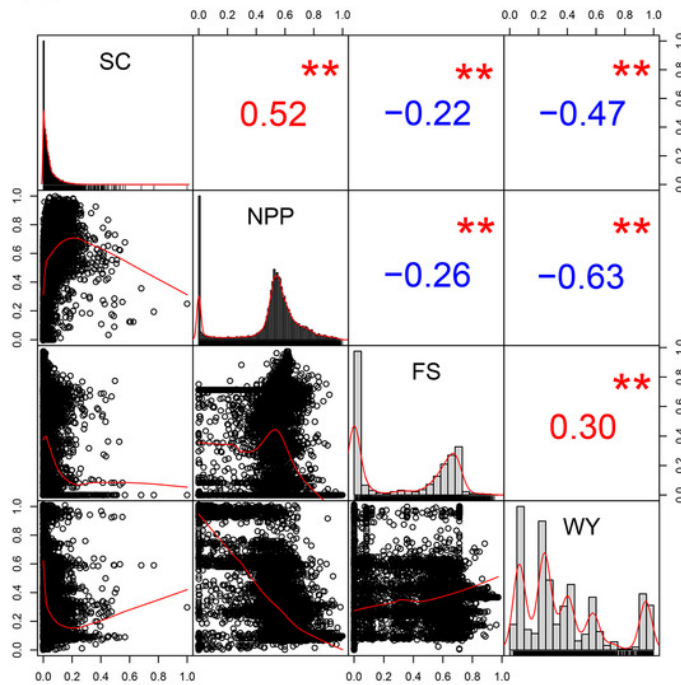
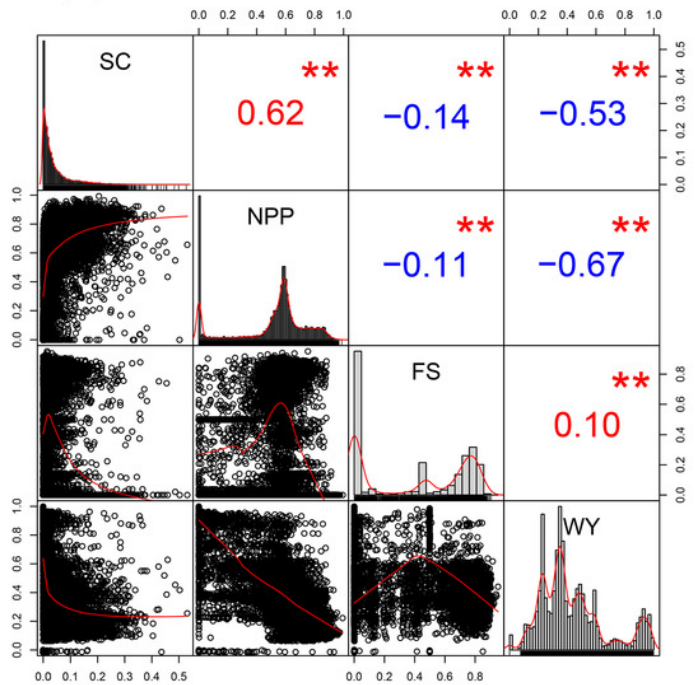



Figure 4

Spearman's correlation coefficient matrix between ES in 2000 (A), 2007 (B), and 2014 (C).

Red numbers indicate positive correlation and blue numbers indicate negative correlation; ** correlation is significant at the 0.01 level.

(a)2000

(b)2007

(c)2014

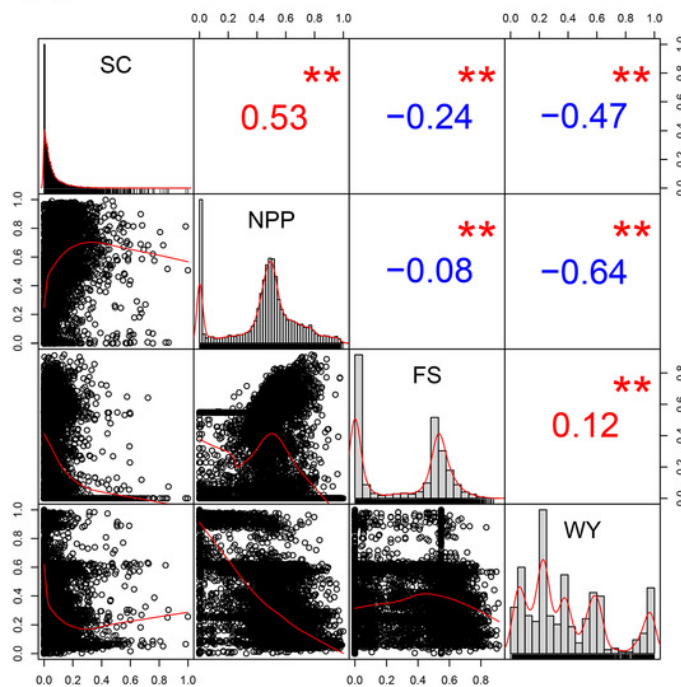



Figure 5

Comparison of correlation coefficient among ecosystem services in 2000, 2007, and 2014.

NPP: net primary productivity; FS: food supply; WY: water yield; SC: soil conservation.

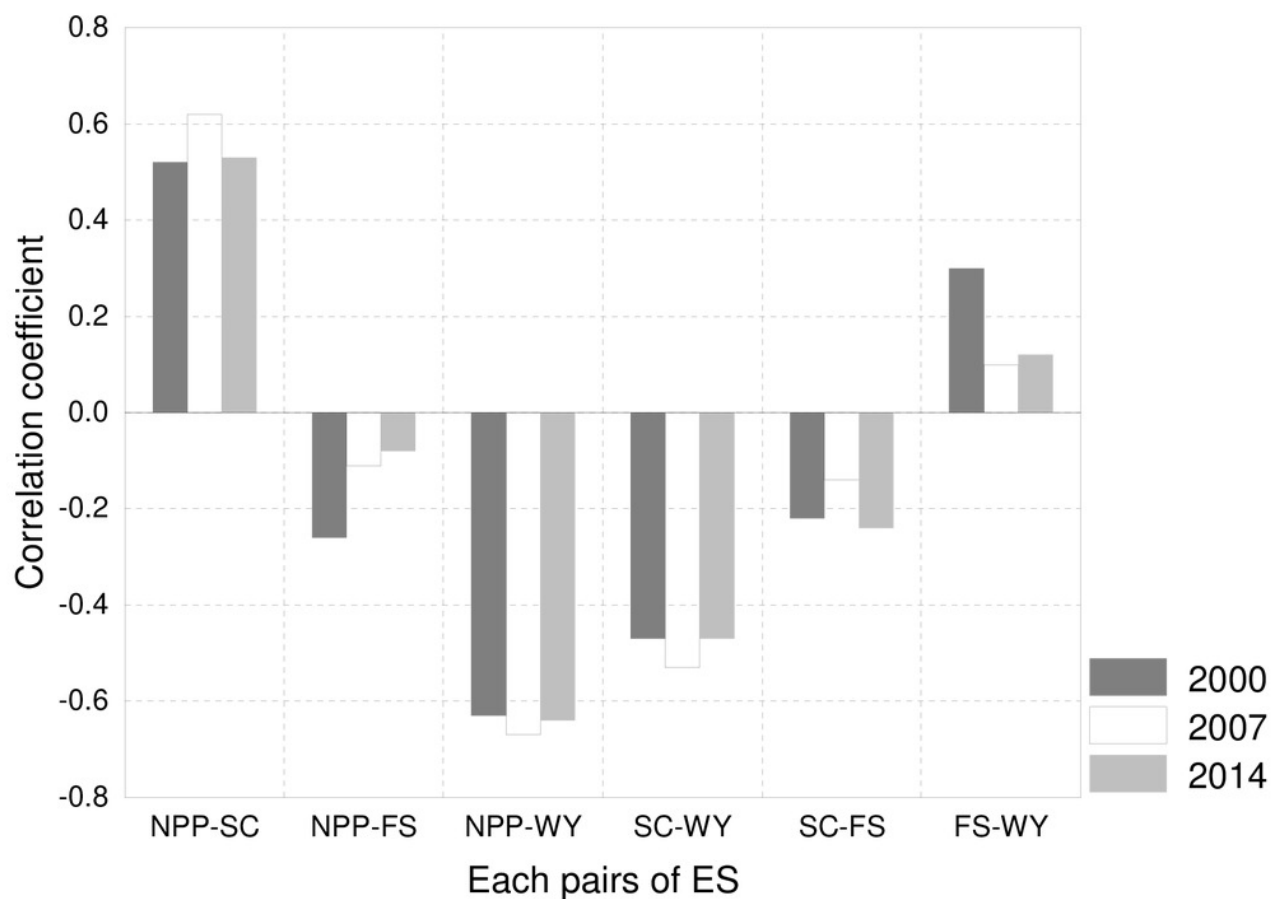



Figure 6

The spatial distribution of ecosystem services based on ordered weighted averaging-graphical information system (OWA-GIS) model under different scenarios.

(A): Scenario 1 (α=0.0001); (B): Scenario 2 (α=0.1); (C): Scenario 3 (α=0.5); (D): Scenario 4 (α=1); (E): Scenario 5 (α=2); (F): Scenario 6 (α=10); (G): Scenario 7 (α=10000).

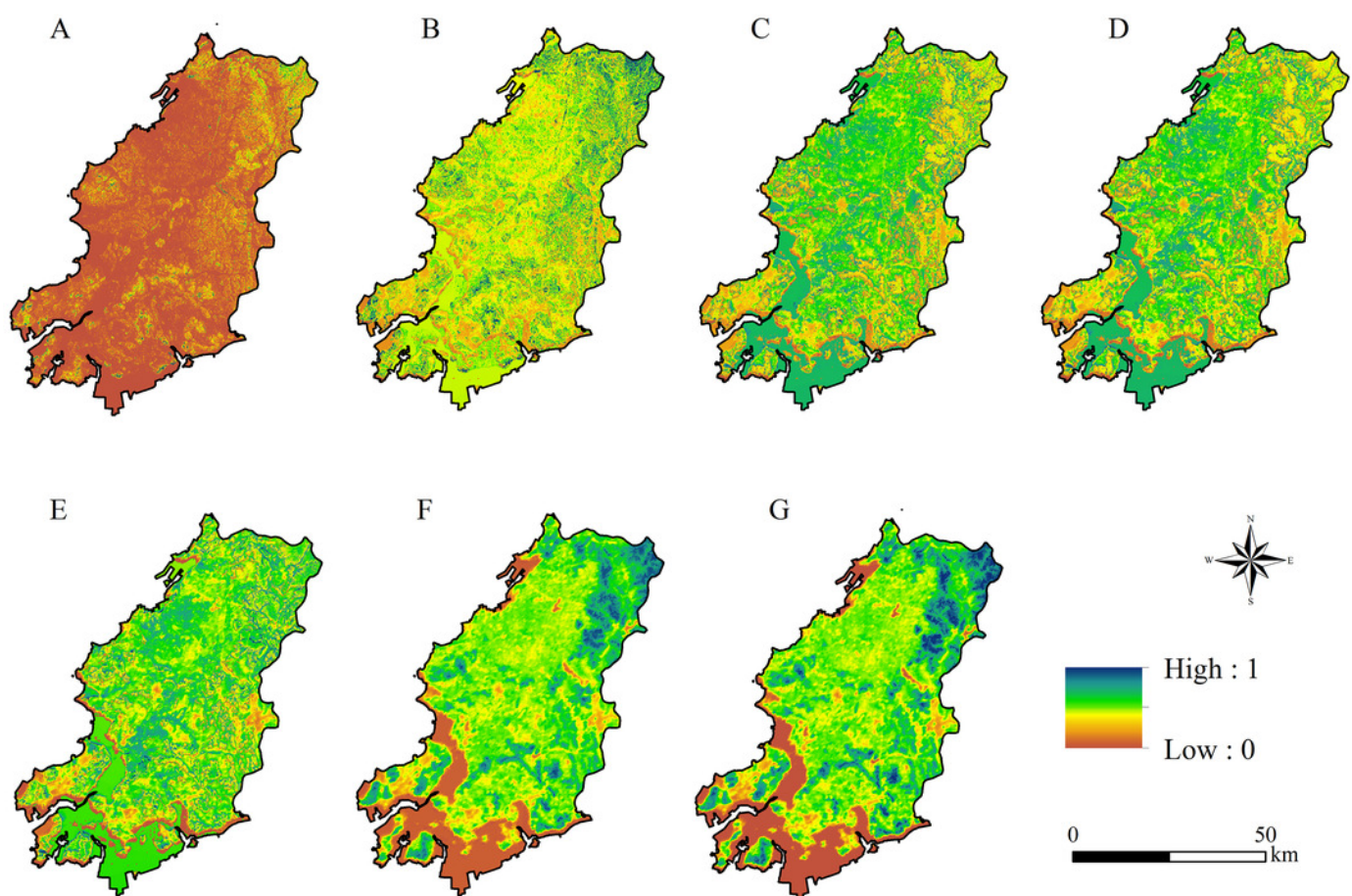



Figure 7

Ecosystem services (ES) regionalization under different risk scenarios.

(A):Scenario 2 (α=0.1); (B): Scenario 3 (α=0.5); (C): Scenario 4 (α=1); (D): Scenario 5 (α=2);
(E): Scenario 6 (α=10).

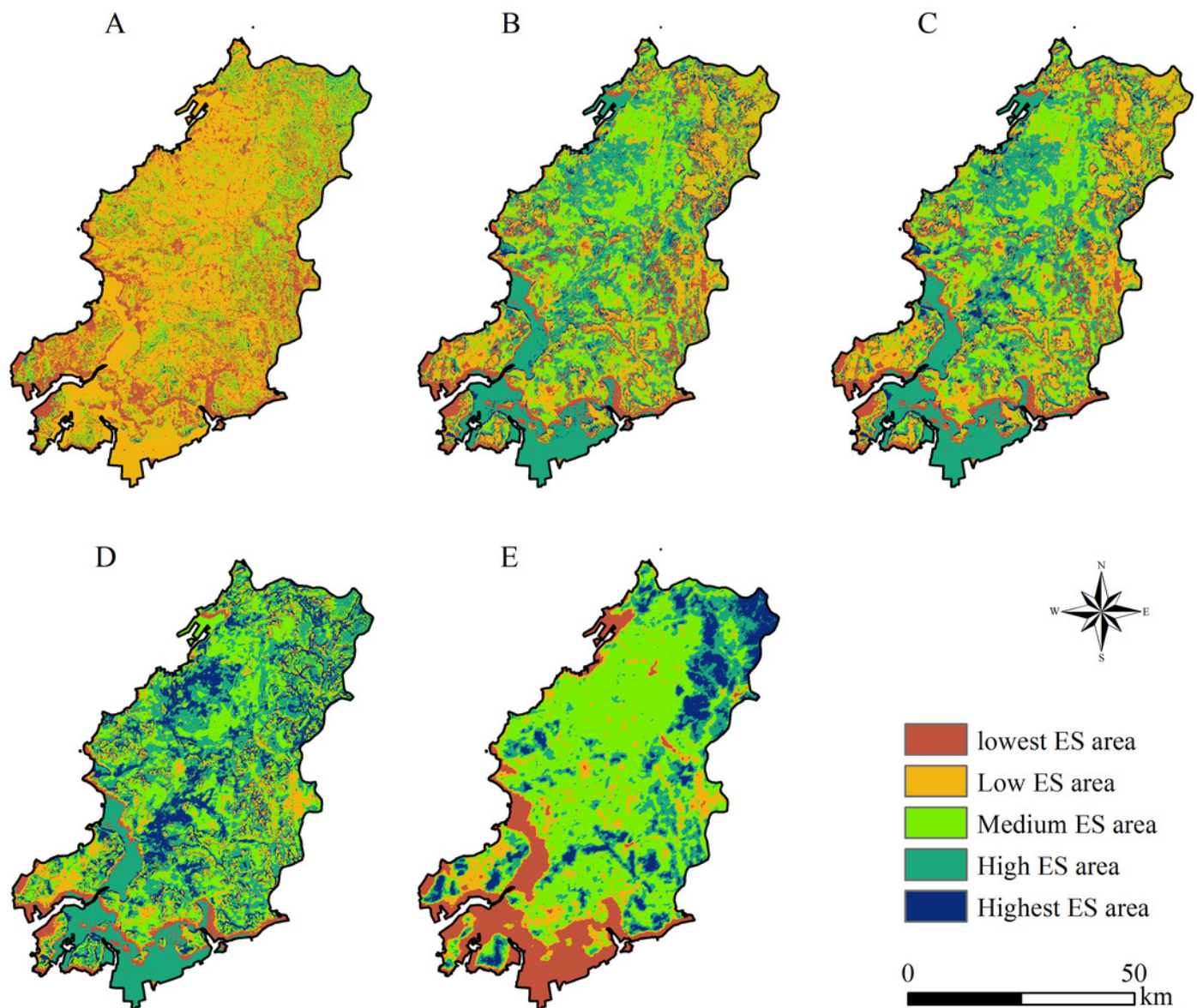
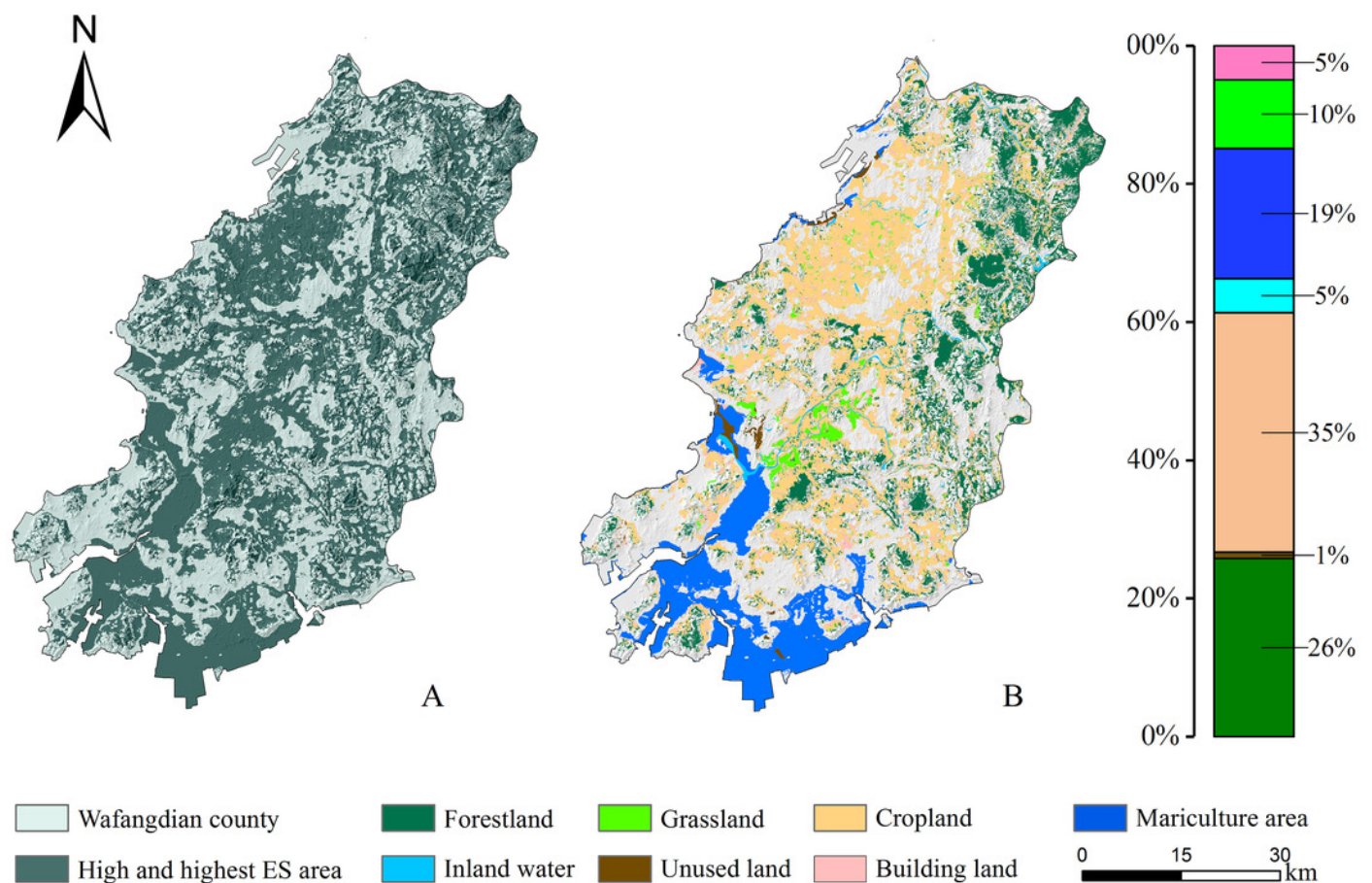



Figure 8

Land use structure under the optimal scenario.

(A) Spatial distribution of high and highest ES area; (B) Land use structure under the optimal scenario.

A   B

☐ Wafangdian county	■ Forestland	■ Grassland	■ Cropland	■ Mariculture area
■ High and highest ES area	■ Inland water	■ Unused land	■ Building land	0 15 30 km

Weight and trade-offs under different scenarios.

ω1: soil conservation (SC); ω2: food supply (FS); ω3: water yield (WY); ω4: net primary productivity (NPP).

Scenario	Risk coefficients (α)	$\omega 1$	$\omega 2$	$\omega 3$	$\omega 4$	Trade-off
1	0.0001($\alpha\rightarrow 0$)	1.000	0.000	0.000	0.000	0.000
2	0.1	0.871	0.062	0.039	0.028	0.170
3	0.5	0.500	0.207	0.159	0.134	0.630
4	1	0.250	0.250	0.250	0.250	1.000
5	2	0.063	0.187	0.313	0.437	0.680
6	10	0.000	0.001	0.055	0.944	0.070
7	10000 ($\alpha\rightarrow\infty$)	0.000	0.000	0.000	1.000	0.000

Average values of ecosystem services (ES) in 2000, 2007, and 2014.

NPP: net primary productivity (g C/m^2·a); FS: food supply (t/km^2·a); WY: water yield (mm); SC:

soil conservation (t/km^2·a).

ES	2000	2007	2014	Change rate(%)	
				2000–2007	2007–2014
FS (t/km^2 a)	173.33	250.57	228.17	44.56	−8.94
NPP (g C/m^2 a)	412.42	478.83	423.05	16.10	−11.65
WY (mm)	230.20	390.02	197.35	69.43	−49.40
SC (t/km^2 a)	61.46	66.28	48.03	7.84	27.53

Characteristics of ecosystem services (ES) regionalization for scenarios 2–6.

(A): Highest ES area; (B): High ES area; (C): Medium ES area; (D): Low ES area; (E): Lowest ES area.

Scenario	Area of each ES Regionalization (km^2)					Proportion of A and B (%)
	A	B	C	D	E	
2(α=0.1)	22.57	121.73	656.68	2229.73	839.26	0.04
3(α=0.5)	226.80	1190.46	950.71	945.73	556.27	0.37
4(α=1)	257.06	1195.97	943.30	940.28	533.36	0.38
5(α=2)	686.20	1400.30	1113.45	465.50	204.51	0.54
6(α=10)	362.20	702.44	1765.16	410.27	630.37	0.28