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RESEARCH ARTICLE

The sustainable arable land use pattern under the tradeoff of agricultural production, economic development, and ecological protection—an analysis of Dongting Lake basin, China

Guanyi Yin[1] · Liming Liu[2] · Xilong Jiang[2]

Abstract To find a solution regarding sustainable arable land use pattern in the important grain-producing area during the rapid urbanization process, this study combined agricultural production, locational condition, and ecological protection to determine optimal arable land use. Dongting Lake basin, one of the major grain producing areas in China, was chosen as the study area. The analysis of land use transition, the calculation of arable land barycenter, the landscape indices of arable land patches, and the comprehensive evaluation of arable land quality(productivity, economic location, and ecological condition) were adopted in this study. The results showed that (1) in 1990–2000, the arable land increased by 11.77%, and the transformation between arable land and other land use types actively occurred; in 2000–2010, the arable land decreased by 0.71%, and more ecological area (forestland, grassland, and water area) were disturbed and transferred into arable land; (2) urban expansion of the Changsha-Zhuzhou-Xiangtan city cluster (the major economy center of this area) induced the northward movement of the arable land barycenter; (3) the landscape fragmentation and decentralization degree of arable land patches increased during 1990–2010; (4) potential high-quality arable land is located in the zonal area around Dongting Lake, which contains the Li County, Linli County, Jinshi County, Taoyuan County, Taojiang County, Ningxiang County, Xiangxiang County, Shaoshan County, Miluo County, and Zhuzhou County. The inferior low-quality arable land is located in the northwestern Wuling mountainous area, the southeastern hilly area, and the densely populated big cities and their surrounding area. In the optimized arable land use pattern, the high-quality land should be intensively used, and the low-quality arable land should be reduced used or prohibitively used. What is more, it is necessary to quit the arable land away from the surrounding area of cities appropriately, in order to allow more space for urban expansion. This study could provide guidance for sustainable arable land use by both satisfying the future agricultural production and the local economic development, which can be used for the other major grain-producing areas in this rapid developing country.

Keywords Arable land resources · Agricultural production · Economic development · Ecological protection · Optimized arable land use pattern

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Introduction

As the most populous country in the world, China has seen a rapid economic growth and urbanization process. In 2013, the per-capita arable land area in China was only 0.0779 ha, less than 40% of the global average per-capita arable land area (Wang and Scott 2008), which is ranked 184th in the world (The World Bank 2014). Affected by urban expansion and rural construction, the land use pattern changed quickly and dynamically. Land use for construction has encroached on the high-quality arable land, which has brought huge challenge for the agricultural productivity in China (Wei 2014). The area of arable land in China has reduced since 1980, during the process of the national "sixth 5-year plan", the "seventh 5-year plan", and the "eighth 5-year plan"; the total arable land

area in China has decreased by 2.35 million, 1.23 million, and 0.702 million hm^2, respectively (National Bureau of Statistics of China 2008). In 2006, the arable land area in China was 121.8 million hm^2 (equal to 1.827 billion mu), which was approaching the compulsory data of arable land area—1.8 billion mu ("mu" is an area unit widely used in China. 1 hm^2 equals to 15 mu) (Chen et al. 2014) (Long et al. 2012). Although in recent years, China has implemented some measures to increase the arable land area, the total arable land resource is facing future challenges (Xiangbin et al. 2004). Untill 2050, the per-capita arable land area would approach the international warning line of 0.05 hm^2 (Zhiming 2007). As a result, the sustainable use of precious arable land has become an urgent issue in China.

Researches have paid much attention to the promotion of large-scale management of arable land (Zheng et al. 2016); the restriction of non-agricultural use of arable land (Li et al. 2015); the choice of different land use patterns for different stakeholders, e.g., farmers, governments or merchants. (Qiu et al. 2014); and the improvement of the arable land productivity (Wei and Pijanowski 2014). In addition, national policy choices have chronically focused on the protection, the reclamation of arable land, and the reformation of land use pattern. In the Northern Wei Dynasty (in AD 368–534), Jia Siyi wrote "*Qi Min Yao Shu*", the earliest agricultural monograph in the world, which recorded the land use categories and their differences (Jinrong 2014). Since 1999, China has implemented the compensation system for the non-agricultural use of arable land. In 2003, the government carried out the "The plan of national land reclamation," providing a detailed guide on the protection target on the quality and quantity of arable land. In 2005–2010, the government proposed the solution of balancing rural residential land and farmland (the decentralized rural residential lands was advised to be reclaimed as arable land, and the rural residential lands was then resettled into newly constructed central villages) (Tang et al. 2015). In recent years, the policy of top soil protection (transferring the top soil of high-quality arable land if it is used as construction land) was highly recommended (Chen et al. 2016a, b). After several decades of development, China has improved its sustainable use of arable land (Huang et al. 2011) (Jing et al. 2011).

Up to now, several questions are still in need to be answered. During the rapid urbanization process, especially in the major grain-producing areas, are we losing the most productive arable land? How do we maintain the production ability of the major grain production area in this country? How do we satisfy the demand of arable land to feed the future population? Can we balance the economic development and the agricultural production? Answers to the above questions are critical for the government to find a solution for both food security and economic growth in the coming decades for the major grain-producing areas in China.

Overall, current studies about sustainable arable land use patterns have contributed to the optimization of arable land management skills, such as conservation tillage (Carr and Mäder 2012), integrated pest protection (Gay 2013), precision farming (Gerhards et al. 2012), and organic farming skills (Carr and Mäder 2012). Moreover, the innovative practice of land fallow, green for food policy, the plan for zero increase of the use of chemical fertilizer and chemical by 2020, and the spatial hooking between population and land, the technology of integrative drip irrigation and fertilizer, fish cultivation in paddy field have made great help to the optimized arable land use pattern. However, few studies have focused on the land itself. Differences in the productivity of arable land resources are vital factors for the optimized arable land use patterns. Even within the same arable land plot, different places have different grain production capacity (Zhong et al. 2010) (Sojneková and Chytrý 2015). Conversely, there are spatial differences in the economic and social development in different administrative area, which has stimulated the differences of the transformation between arable land and construction land (Nyanga et al. 2016) (Wang et al. 2014). Moreover, there are spatial differences in the ecological condition in different arable land plots (Zhu et al. 2010).

In contrast to previous studies, this paper focused on the land itself and was innovative in exploring an integrated arable land use pattern (integrated the vital attributes of arable land: the natural resource productivity, the social-economic condition, and the ecological state). Based on this idea, this study had three purposes: (i) determine the land use characteristics and the change of arable land use in Dongting Lake basin; (ii) evaluate the quality of the arable land and the unused land and explore the spatial distribution of the high-quality arable land; and (iii) provide reasonable guidance of sustainable arable land use patterns in the future and provide reference for the other major grain-producing zones in China.

Material and methods

Study area

The Dongting Lake area (110°29′ ~ 114°15′E and 26°03′ ~ 30°08′N) is located in the northern area of Hunan Province, located in south-central China. As one of the major grain-producing areas in China, Dongting Lake basin plays an important role in guaranteeing national food security (Yin et al. 2015). In 2006, its total arable area covered 1.68 million hectares, accounting for 44% of the total arable area of Hunan Province, and its total grain output was 1.48 × 103 million tons, accounting for 51% of the total grain output in Hunan province. The land with a gradient higher than 6° occupied 9.56% of the total land

area, which is mostly located in the Wuling Mountain ecoregion in the northwest and Chaling County and Yanling County in the southeast of the study area. Distinctive advantages in the landform, climate condition, and soil productivity made Dongting Lake basin became a significant long-standing agricultural production zone (Fig. 1).

Data resource

This study obtained extensive spatial data, including (1) land use maps in 1990, 1995, 2000, 2005, and 2010 by visual interpretation of remote sensing image; (2) raster data of DEM, GDP, and population; (3) raster data of photosynthetic potential productivity, light, and temperature potential productivity; climate potential productivity; and the soil potential productivity of the arable land resources in Dongting Lake basin; and (4) vector data of the distribution of the ecological preservation area and the grades of soil erosion. All raster data are on a 1 km × 1 km grid. The dataset is provided by Data Center for and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn).

Methods

Land use transformation

To analyze the land use transformation, we created a land use change map, which was obtained from the land use maps in 1990, 1995, 2000, 2005, and 2010. Based on the transferring data of different land use type, we could calculate the area of each kind of land transferring.

For example, the detailed calculating method of land use transformation during 1990 to 1995 was as follows:

1. Reclassify the arable land, forest land, grassland, construction land, water area, and unused land in 1990 as land use types 1, 2, 3, 4, 5, and 6, respectively. Then, reclassify the corresponding land in 2010 as land use type 10, 20, 30, 40, 50, and 60, respectively (Table 1);

2. Use the raster calculator in Arcgis to calculate the sum of the grid data in land use map of 1990 and 2010: $G_{sum} = G_{1990} + G_{2010}$,; G_{sum} was the grid data of summing maps 1990 and 2010 and G_{1990} and G_{2010} were the grid data of 1990 and 2010, respectively. Thirty-six kinds of grid data,
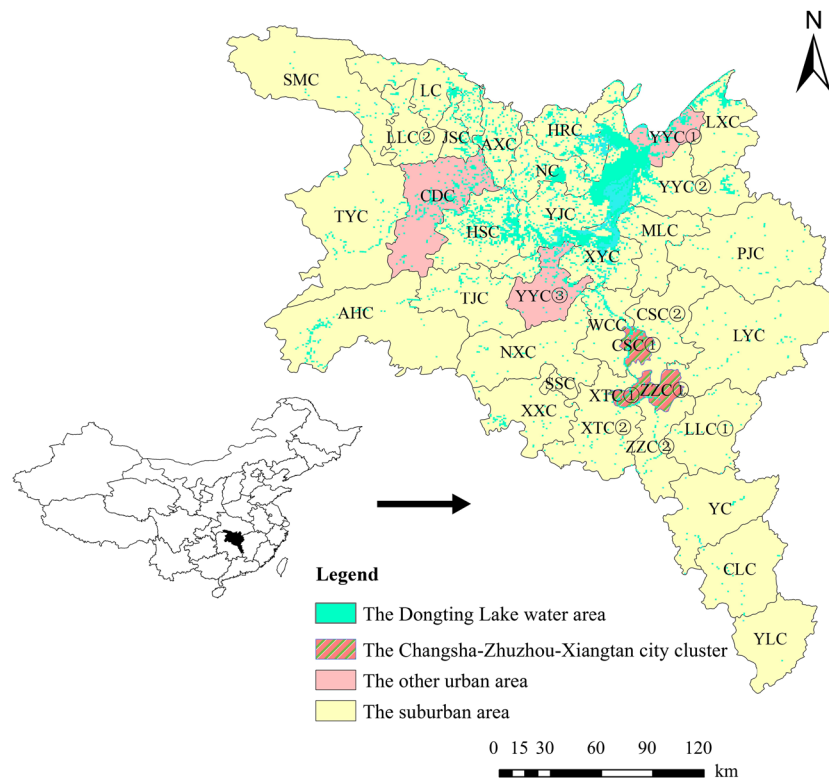

Fig. 1 The location of Dongting Lake basin. Note: CSC①: Changsha City; CSC②:Changsha County; WCC: Wangcheng county; NXC: Ningxiang County; LYC: Liuyang County; ZZC①: Zhuzhou City; ZZC②: Zhuzhou County; YC: You County; CLC: Chaling County; YLC: Yanling County; LLC: Liling County; XTC①: Xiangtan City; XTC②: Xiangtan County; XXC: Xiangxiang County; SSC: Shaoshan County; YYC①: Yueyang City; YYC②: Yueyang County; HRC: Huarong County; XYC: Xiangyin County; PJC: Pingjiang County; MLC: Miluo County; LXC: Linxiang County; CDC: Changde City; AXC: Anxiang County; HSC: Hanshou County; LC: Li County; LLC: Linli County; TYC: Taoyuan County; SMC: Shimen County; JSC: Jinshi County; YYC③: Yiyang City; NC: Nan County; TJC: Taojiang County; AHC: Anhua County; YJC: Yuanjiang County

Table 1 The reclassified grid value of 1990 and 2010

Year	Grid value					
1990	1	2	3	4	5	6
2010	10	20	30	40	50	60
Implication	Arable land	Forest land	Grassland	Construction land	Water area	Unused land

11, 12, 13, 14, 15, 16, 21, 22, 23, 24, 25, 26, 31, 32, 33, 34, 35, 36, 41, 42, 43, 44, 45, 46, 51, 52, 53, 54, 55, 56, 61, 62, 63, 64, 65, and 66, could be obtained by the calculation.

3. The grid value of the new map shows the new implication, i.e., 11 represents the unchanged arable land, 12 is the land transferred from forestland to arable land, etc. (Table 2). The corresponding area is the area where each land transformation type occurred. This method has been used extensively in land use transition analysis (Xu et al. 2016) (Liu et al. 2015).

Barycenter of the arable land

The barycenter modeling, which has been extensively utilized in the fields of urban planning, economic geography, and land use science, is a preferred modeling approach that traces spatial movement direction of the barycenter for targeted objects. Moreover, movement direction and distance to the center of gravity can reflect changes in quantity and changing trends of the targeted object over time. The barycenter tool was firstly used in the change of population and the economy (Hui et al. 2011), and then it is extensively used in the study of the spatial change of land use (He et al. 2011) (Sen and Smith 1995). Differing from the qualitative description of the spatial change of arable land, this method is more convenient and faster to evaluate the spatial change of arable land in macro view.

To determine the total spatial change of the location of the arable land, the arable land barycenter was applied to obtain an estimate of the change in total arable land of Dongting Lake for 1990–2010. Exploration of the land barycenter could summarize the dynamic change in land use and analyze the concentrated distribution of a certain land use type in spatial

perspectives. The calculation method of the barycenter of arable land was as follows:

$$
\begin{cases}
X_j = \sum_{i=1}^{n} (C_i \times X_i) \Big/ \sum_{i=1}^{n} C_i \\
Y_j = \sum_{i=1}^{n} (C_i \times Y_i) \Big/ \sum_{i=1}^{n} C_i
\end{cases}
\tag{1}
$$

in which X_j and Y_j refer to the coordinates of the whole arable land barycenter in the jth year. C_i is the area of an arable land plot, X_i and Y_i is the geometric center of the ith district, and n is the number of the arable land plots.

The barycenter can be calculated using Arcgis software. We converted the raster data of arable land into vector data, then used the "dissolve" function to make it a multiple geometric figure, and used the "calculate geography" function to calculate the coordinate of the arable land barycenter of Dongting Lake basin in different years (Chun 2014) (Huiyi et al. 2007).

Landscape characteristics

Landscape pattern refers to the spatial arrangement state of landscape mosaics (arable land patches, grassland patches, etc.) with different sizes, different shapes, and different distributions. The landscape characteristics can express the heterogeneity of landscape and imply the results of different ecological process interactions on the landscapes. After the concept of landscape pattern emerged in Europe more than half a century ago (Naveh and Lieberman 1990), the past two decades have seen unprecedented developments in theory and practice of landscape studies (Wu and Hobbs 2002). The landscape indexes, developed from the landscape theories, have become a rapidly developing tool worldwide to explore the internal change of the spatial pattern land patches (Li and Wu 2004). In this study, landscape indexes were chosen to analyze the change of arable land patches from a more detail view.

Table 2 The implication of the new grid value of the land transition map

Grid value	implication	Grid value	Implication	Grid value	Implication
11	Unchanged arable land	21	Arable land → forest land	31	Arable land → grassland
12	Forestland → arable land	22	Unchanged forest land	32	–
13	grass land → arable land	23	Grass land → forest land	–	–
14	Water area → arable land	24	Water area → forest land	–	–
15	Construction land → arable land	25	Construction land → forest land	–	–
16	Unused land → arable land	26	unused land → forest land	–	–

Table 3 The landscape indices and their implication

Categories	Indices	Introduction	Formulas
Intensity indices	NP	Number of patches (#)	Number of land patches
	PD	Patch density (#/100 ha)	$PD = {}^{NP}/_{S}$,. NP was the number of arable land patches and S was the total arable land area
	LPI	Largest patch index(%)	$LPI = {}^{a_{max}}/_{A}$, where a_{max} was the area of the largest arable land patch and A was the total arable land area
Shape indices	LSI	Landscape shape index	$LSI = \frac{0.25E}{\sqrt{A}}$,E was the total perimeter of all land patches, A was the total arable land area
	AWMSI	Area-weighted mean shape index	$AWMSI = \sum_{i=1}^{n} w_i \frac{L_i}{a_i}$, where L_i and a_i was the perimeter and area of each arable land patches, w_i was the calculation coefficients of each land patches
Contagion indices	CONTIG_AM	Contagion (%)	$Contag = 2\ln n + \sum_{i=1}^{n}\sum_{j=1}^{n} P_{ij} \ln P_{ij}$, where n was the number of patch types, P_{ij} was the probability of the adjacent between patch i and patch j
	DIVISION	Landscape isolation	$DIVISION = 1 - \sum_{i=1}^{n}\left(\frac{a_i}{A}\right)^2$, where a_i was the area of the ith arable land patch and A was the total arable land area.

Note: LPI could indicate the dominance of large arable land patch in all arable patches. LSI could indicate the regularity of land shape. AWMSI could imply the complexity of the shape condition of the arable land patches. The Contig_AM index refers to the reunion degree and ductility of arable land patches; higher Contig_AM index represents for better connectivity among arable land patches. DIVISION index refers to the degree of separation of arable land patches

We extracted the arable land patches of Dongting Lake basin in 1990 and 2010 from the land use maps (raster format) and input them into Fragstats software. The landscape indexes calculated in Fragstat, and the calculation results were systematically exported, which could indicate the intensity, fragmentation, and shape complexity of arable land (Table 3). The analysis of the landscape indices has been widely discussed in previous studies (Zhou et al. 2011) (Chen et al. 2016a, b).

Evaluation of the comprehensive quality of arable land

Even within the same arable land plot, different places have different grain production capacities, economic development levels, and ecological conditions. Based on this fact, we constructed an integrated arable land use pattern (integrate the vital attributes of arable land: the natural resources productivity, the locational condition, and the ecological state). The evaluation of the land quality is classified into three procedures:

1. Establishment of the evaluation indicators

To find potential arable land with high quality in comprehensive aspects, we classified the quality of arable land into

three classes: productivity potential, locational condition, and ecological security condition. The three classes were classified into ten sub-classes (X1-X10), which is shown in Table 1. Taking the exploitation of unused land into account, we extracted the unused land and arable land to determine the distribution of the potential high-quality arable land (Table 4).

1. $Y_Q = KEQ$, where Y_Q was the photosynthetic potential productivity (kg/hm^2), K the conversion factor from energy to crop production(5.952×10^{-5} g/J), E the utilization efficiency of light energy(6.6%), and Q the gross radiation intensity (J/cm^2)
2. $Y_T = f(T) Y_Q$, where Y_T was the light and temperature potential productivity (kg/hm^2), $f(T)$ the correction coefficient for temperature, $f(T) = n/365$, and n the number of no frost days
3. $Y_w = f(W) Y_T$, where Y_w was the climatic potential productivity (kg/hm^2), $f(W)$ the the correction coefficient for weather, $f(W) = R/E$, R the average annual rainfall, and E the annual evaporation (if $R > E, f(W) = 1$)
4. $Y_S = f(S) Y_W$, where Y_S was the soil potential productivity(kg/hm^2), $f(S)$ the soil modification coefficient, $f(S) = \sqrt[5]{El \cdot S \cdot pH \cdot F \cdot Te}$, El the elevation, S the slope, F the soil fertility, and Te the soil texture, respectively (the data of El, S, Ph, F, and Te were graded into [0,1] scope).

Table 4 The evaluation indicators of arable land quality

Indicator	Sub-indicator	The implication of indicators	Weights
Productivity potential	Photosynthetic potential productivity (X1)	Reflecting the local photosynthetic efficiency	0.15
	Light and temperature potential productivity (X2)	Reflecting the local light and heat resources	0.15
	Climatic potential productivity (X3)	Reflecting the local light-heat and water condition	0.15
	Soil potential productivity (X4)	Reflecting the physical, chemical characteristics, and the productivity of the soil	0.35
	Slope (X5)	Reflecting the topographic condition	0.2
Locational condition	Population (X6)	Avoiding arable land use in the densely populated area	0.25
	GDP (X7)	Avoiding arable land use in the economic developed regions	0.35
	The city buffer area (X8)	Reflecting the effect of urban expansion on the arable land distribution	0.4
Ecological security condition	Ecological preservation area (X9)	Avoiding arable land use on the ecologically vulnerable area	0.45
	Soil erosion grades (X10)	Avoiding arable land use in the area with serious soil erosion	0.55

Note: the photosynthetic potential productivity, light and temperature potential productivity, climatic potential productivity, and soil potential productivity were calculated step by step by rgw following formulas (Wei et al. 2014):

2. Standardization of the indicators

To avoid the difference of data dimension, a standardization treatment of the indicators was performed. The method was as follows:

$$Y = \begin{cases} \dfrac{X - X_{min}}{X_{max} - X_{min}}, if\ X\ is\ a\ positive\ index \\ \dfrac{X_{max} - X}{X_{max} - X_{min}}, if\ X\ is\ a\ negative\ index \end{cases} \qquad (2)$$

in which Y refers to the standardized data of X, $0 \leq Y \leq 1$. X_{max} and X_{min} refer to the maximum value and minimum value of X, respectively.

The X indexes could be classified as positive indexes and negative indexes. If the arable land quality increases as the X increases, X could be considered as a positive index. In contrast, if the arable land quality decreases as the X increases, X could be considered as a negative index.

Obviously, the higher the land production capacity potential is, the better the land quality is, and as a result, X1, X2, X3, and X4 were considered as positive indexes. In addition, the population and economic activities that could result in a high GDP were concentrated in the urban areas; thus, the use of arable land is not appropriate in these areas. Therefore, X5, X6, and X7 were considered as negative indexes. Moreover, the higher the soil erosion grade is, the lower the productivity of the arable land would be, so X10 was considered as a negative index.

The standardization method of X8 is as follows: the land in the city buffer was assigned 0, whereas the land outside the city buffer was assigned 1 directly. The standardization method of X9 is as follows: land in the ecological preservation area assigned 0, whereas the land outside the ecological preservation area was assigned 1 directly.

3. Calculation of the arable land quality score

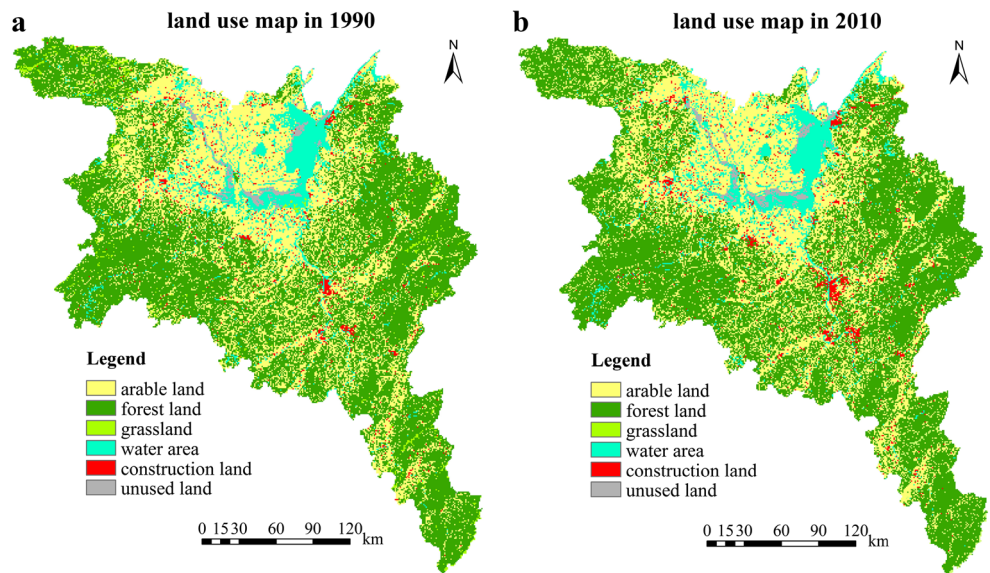$$S = \sum_{i=1}^{10} w_i Y_i \qquad (3)$$

in which S refers to the score of arable land quality, Y_i refers to the standardized data of X1-X10, and w_i refers to the weight of Y_i (given according to their importance in the evaluation of arable land quality). After obtaining the arable land quality score in the spatial view, we could identify the distribution of high-quality land and the potential fertile unused land, which is helpful for the sustainable use of arable land and the reasonable exploitation of unused land in the future.

Results

The change of land use types in Dongting Lake basin

The total area of the Dongting Lake basin is 73,439.8 km^2; the main change in this area is the increase in arable land and constructed land and the decrease in ecological land (forest land, grassland, and water land). From 1990 to 2010, the percentage of arable land area in total land area increased from 20.9 to 23.2%, the percentage of the forest land decreased from 55.8 to 55.0%, the percentage of the grassland decreased from 4.5 of to 3.9%, the percentage of

Fig. 2 The land use map of
Dongting Lake basin in 1990 and
2010

a land use map in 1990   **b** land use map in 2010

Legend
arable land
forest land
grassland
water area
construction land
unused land

0 15 30   60   90   120 km

the water area decreased from 10.2 to 9.8%, the percentage of the construction land increased from 4.7 to 4.8%, and the percentage of the unused land decreased from 3.9 to 3.3% (Fig. 2).

The transformation between arable land and other land types

The amount of transformation between arable land and other land types

The land use transformation was active from 1990 to 2010 in Dongting Lake basin. Among the active land use change process, the transformation of arable land with other land plays a critical role in the land use change (Table 5). The newly increased arable land is mainly transferred from forest land (2789 km^2 of forestland was transferred into arable land in 1990–2010) and unused land (2098 km^2 of forestland was transferred into arable land in 1990–2010). The decreased arable land is mainly transferred into construction land (2616 km^2 of arable land was transferred into construction

land in 1990–2010) and forest land (1473 km^2 of arable land was transferred into forestland in 1990–2010).

In general, the transformation between arable land and other land types has disturbed a large amount of ecologically sensitive land (forest land, grassland, and water area etc.). The arable land changed largely in both amount and spatial distribution: 8029 km^2 of arable land has been used for non-agricultural purposes, whereas 6343 km^2 of non-arable land has transformed into arable land. In addition, the causes of arable land decrease are affected by recent social and economic factors: (i) the growth of construction land induced by the urban expansion; (ii) the abandonment behavior of arable land induced by the farmers' choice of non-agricultural livelihood; (iii) the policy of changing cultivated land for ecological protection (changing arable land into forestland, grassland, and water area).

The spatial change of transformation between arable land with other land types

Figure 3 shows the spatial distribution of transformation between arable land and other land types, which could be

Table 5 The land use transfer matrix of Dongting Lake basin in from 1990 to 2010 (km^2)

	Arable land	Forest land	Grass land	Water area	Construction land	Unused land
Arable land	9685	1473	136	1061	2616	1057
Forest land	2789	33,366	661	374	401	7
Grassland	1077	558	2085	30	3	2
Water area	1063	401	109	5502	246	193
Construction land	1001	166	163	73	2277	528
Unused land	2098	151	214	141	5	1858

Fig. 3 The transformation of arable land with other land in 1990–2000 and 2000–2010. Note: AL-AL is the unchanged arable land, AL-Others is the land transferred from arable land to other land (forestland, grassland, water area, construction land, and unused land), Others-AL is the land transferred from other land to arable land, and Others-Others is the land transferring without arable land
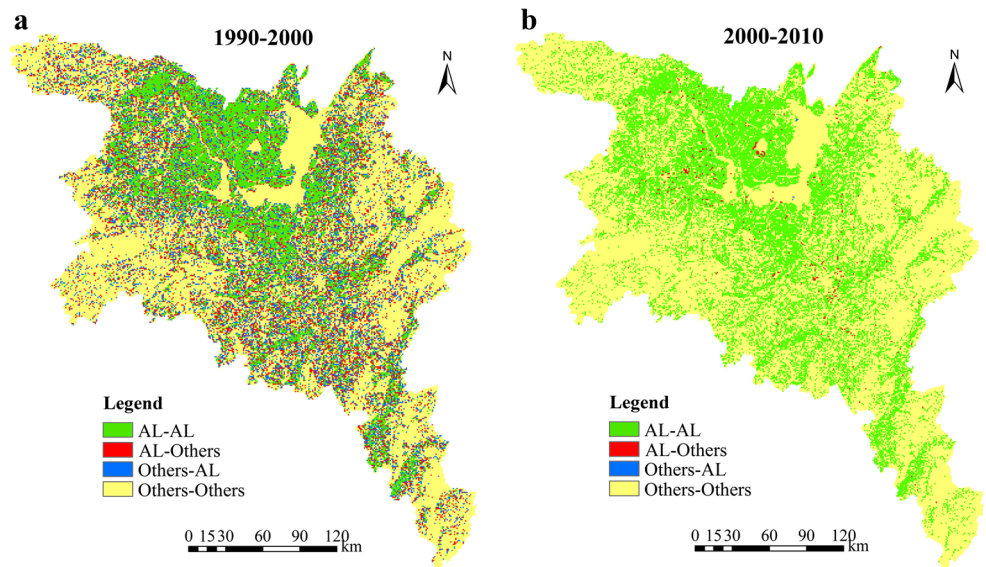
divided into two stages: actively changing stage (1990–2000) and relevantly stable stage (2000–2010).

In 1990–2000, the increase in the arable land showed a spatially dispersed characteristic, whereas the decrease of the arable land is more concentrated. The increase in arable land mainly occurred in the rural area of Dongting Lake basin, which contained Shimen County, Taoyuan County, Anhua County, Ningxiang County, Xiangxiang County, Xiangtan County, Zhuzhou County, You County, Chaling County, Yanling County, Liling County, Liuyang County, Pingjiang County, Linxiang County, and Huarong County, showing a scattered layout. The decrease in the arable land area mainly occurred in the south and north shores of Dongting Lake and in the Changsha-Zhuzhou-Xiangtan city cluster. The Changsha-

Zhuzhou-Xiangtan city cluster is a major agglomeration of economies, which has shown a significant leading role in the economic growth in the entire Hunan Province. In this stage, the cities' expansion has occupied a large amount of arable land and made the arable land plots more fractal. The increase in arable land fragmentation would increase the difficulty of scale management for the arable land. Moreover, higher fragmentation largely increases labor waste and the diseconomies of scale.

In 2000–2010, the arable land transformation became more stable. A small quantity of change occurred between arable land with construction land, forest land, and grassland in the northwest (containing Changde City, Hanshou County, Jinshi County, Linli County, Anxiang County) and the area around

Fig. 4 The distribution of arable land barycenter in 1990–2010 in Dongting Lake basin. Note: NC, YJC, YYC③, XYC, NXC, and WWC refer to Nan County, Yuanjiang County, Yiyang City, Xiangyin County, and Wangcheng County, respectively
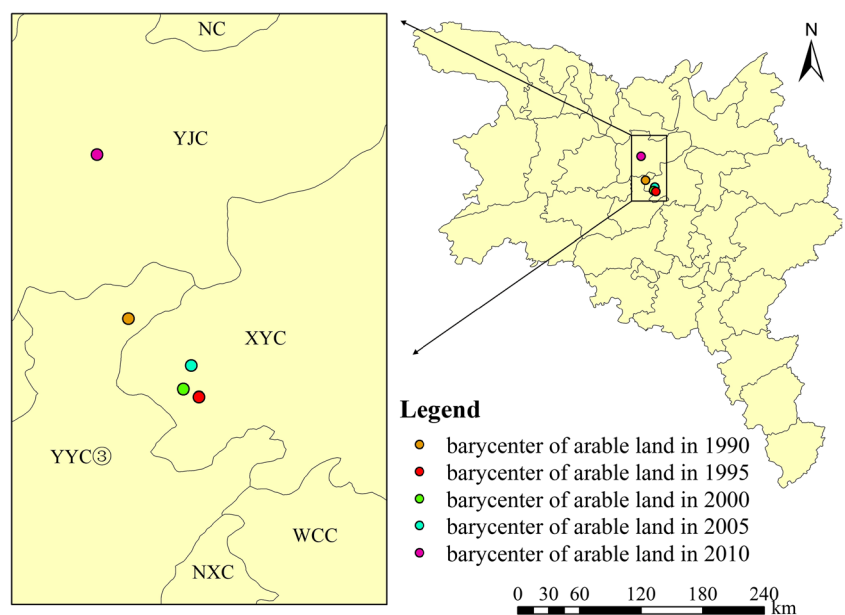
Table 6 The landscape indices of arable land patches in Dongting Lake basin in 1990–2010

Categories	Indices	Introduction	1990	1995	2000	2005	2010
Intensity indices	NP	Number of patches (#)	1773	1751	1809	1875	1835
	PD	Patch density (#/100 ha)	0.07	0.07	0.07	0.03	0.03
	LPI	The largest patch indices (%)	55.43	61.25	68.74	14.33	19.35
Shape indices	LSI	Landscape shape indices	68.34	67.43	68.30	70.40	68.97
	AWMSI	Average area weighted shape indices	23.52	25.70	30.92	19.62	24.22
Contagion indices	CONTIG_AM	Contagion(%)	0.57	0.57	0.57	0.55	0.56
	DIVISION	Landscape isolation	0.68	0.62	0.53	0.98	0.96

the Changsha-Zhuzhou-Xiangtan city cluster. The majority of arable land remained unchanged. In this stage, the arable land protection and arable land stability played an important role in the social economy development. Excavating more high-quality arable land under the stress of decreasing land resources became urgent for agricultural development.

The changes of the arable land barycenter and landscape features

The barycenter of the arable land in Dongting Lake basin

The barycenter of arable land concentrated around Dongting Lake because of the rich irrigation condition. In 1990–1995, the barycenter of arable land moved southward, and in 1995–2010, the barycenter of arable land moved northward (Fig. 4). In general, the barycenter of arable land moved northward, farther away from the Changsha-Zhuzhou-Xiangtan city cluster. The whole northward movement in the later period indicated that the expansion of big city clusters has had a significant impact on the spatial distribution of arable land. The future agricultural production will rely more on the northern region of Dongting Lake basin.

The landscape features of arable land patches

The landscape indices of arable land patches contained intensity indices, shape indices, and contagion indices (Table 6). During 1990–2010, the increase of NP and PD indices indicated that the number of arable land patches increased, and the landscape of arable land became more fractured. The reduction of LPI implied that as a result of human disturbances, the size of small arable land patches became more equal, and the large arable land patches became smaller. LSI and SHAPE_AM increased by 0.92 and 2.98%, respectively, indicating that the shapes of arable land patches became more irregular and complex, which would make mechanized farming more difficult. In addition, the decrease in Contag and the increase in DIVISION implied that the distance among adjacent arable land patches increased and the patches became more dispersive.

In general, the change of landscape indices of arable land patches showed an overall trend: in 1990–2005, the amount, the fragmentation degree, and the shape complexity of arable land patches increased, whereas the aggregation degree of arable land patches decreased; in 2005–2010, the shape of arable land patches became regular, the connectivity became better, which indicated that there is potential for improving the spatial distribution of arable land through effective land consolidation and reclamation.

Evaluation of the arable land quality and the suggested arable land use pattern

The evaluation of comprehensive arable land quality

According to the evaluation method of comprehensive arable land quality in the "Evaluation of the comprehensive quality of arable land" section, we established the indicator database (Fig. 5) to evaluate the land productivity, social economy condition, and ecological security condition of land in different areas. All the grid sizes are 1 km × 1 km.

Productivity potential score Because the photosynthetic potential productivity, light and temperature potential productivity, climatic potential productivity, and soil potential productivity were calculated step by step according to the estimation formulas, so we assigned 0.15, 0.15, 0.15, and 0.35 as their weights, respectively. The gradient data was assigned 0.2 as its weight. The productivity capacity potential was the weighted sum of the five sub-indicators. The results showed that the arable land with higher productivity potential was concentrated in the northern and southern shores of Dongting Lake, whereas the land with lower production potential was located in the eastern, western, and the southeastern hilly areas (Fig. 6).

The locational condition score The locational condition score contained three sub-indicators: population, local GDP, and the city buffers (Fig. 5f–h). Because areas with dense population and higher economic condition mainly concentrate on the cities and some rich counties, the
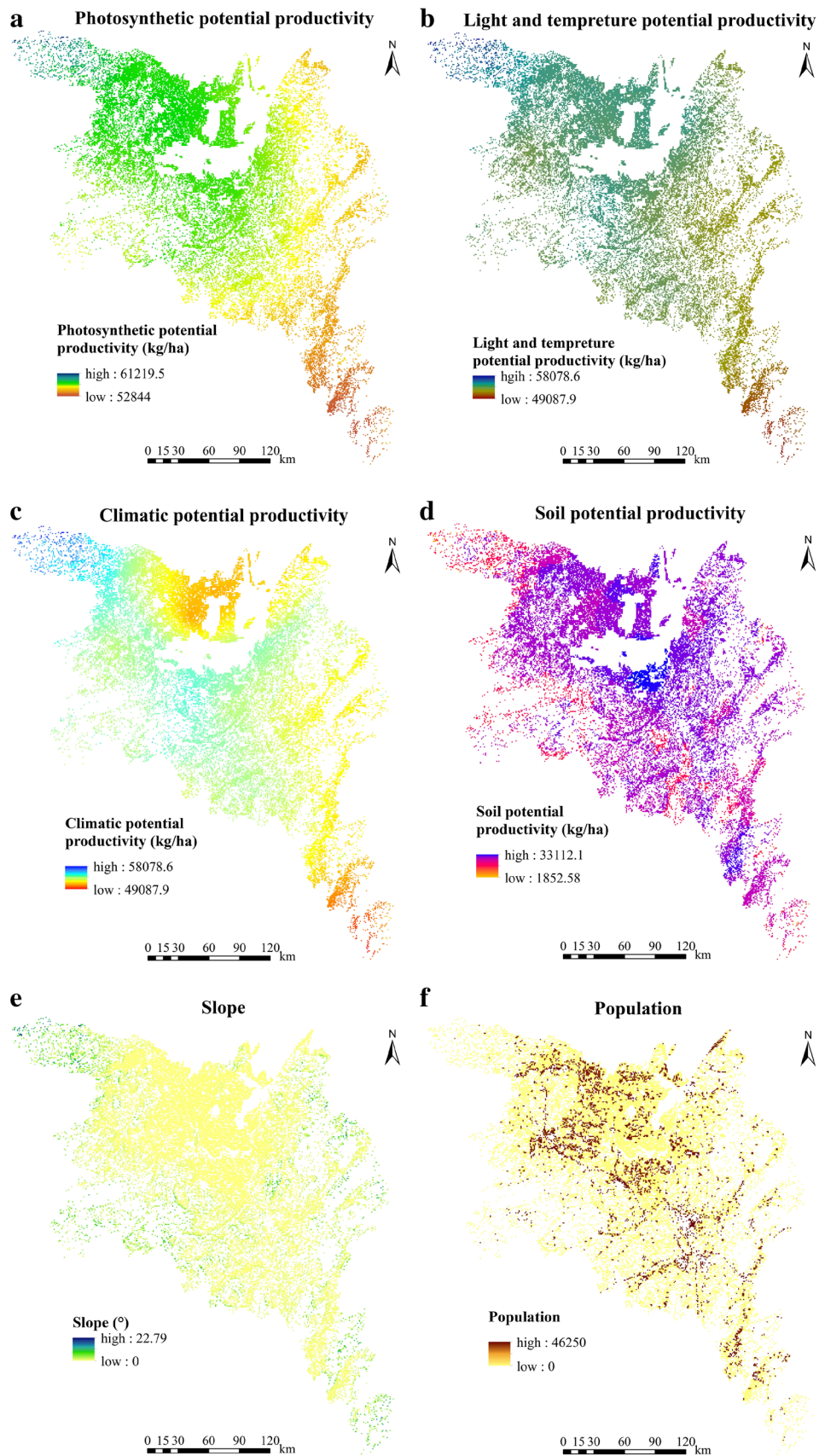
Fig. 5 The spatial distribution of evaluation indicators of arable land quality in Dongting Lake basin
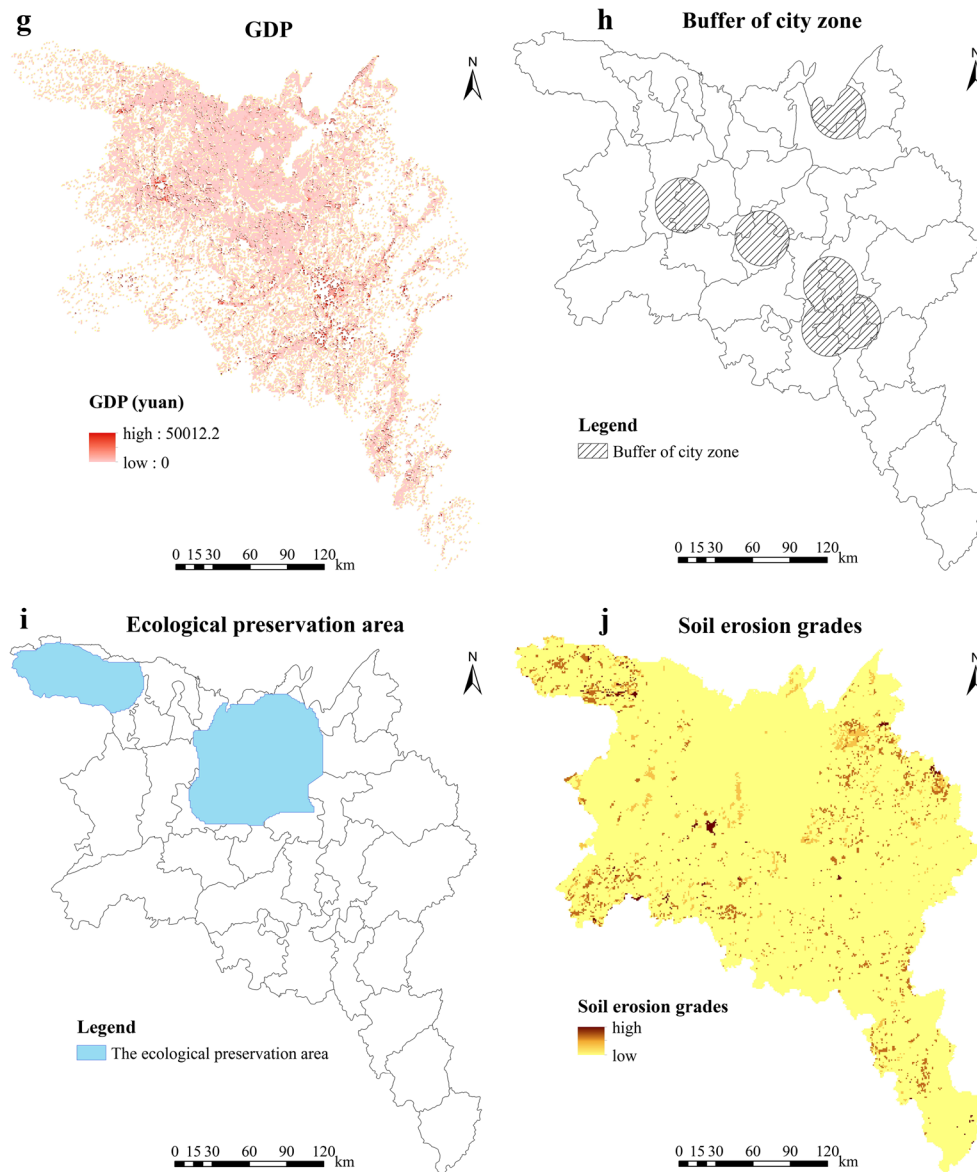
Fig. 5 (continued)

potential of developing arable land in this area is less suitable for the local development. In contrast, the places with lower GDP and population are often located in the rural area and have better arable resource endowment for developing agriculture. As a result, the areas outside the city expansion area and the densely populated area showed a higher locational condition score (Fig. 7).

Ecological security score The ecological security score contained two sub-indicators: the ecological protection area and the soil erosion grades (Fig. 5i, j). The soil erosion in the Dongting Lake area is mainly dominated by water erosion. There are two large national ecological protection zones: (1) the ecological protection area of Wuling Mountain and (2) the ecological protection area of Dongting Lake, which was one

of the vital Chinese ecological function reserve areas (Fig. 8). The distribution of ecological security score could provide guidance for the site selection of arable land by avoiding the ecologically vulnerable region.

The optimized arable land use pattern

We designed different optimization patterns of arable land use based on different focuses:

1. High productivity pattern, which emphasized on the soil productivity. In this pattern, the land with higher productivity potential score was given a higher weight, whereas the social economy potential score and the ecological security score were given lower weights.

Fig. 6 The productivity potential
score of the land in Dongting
Lake basin
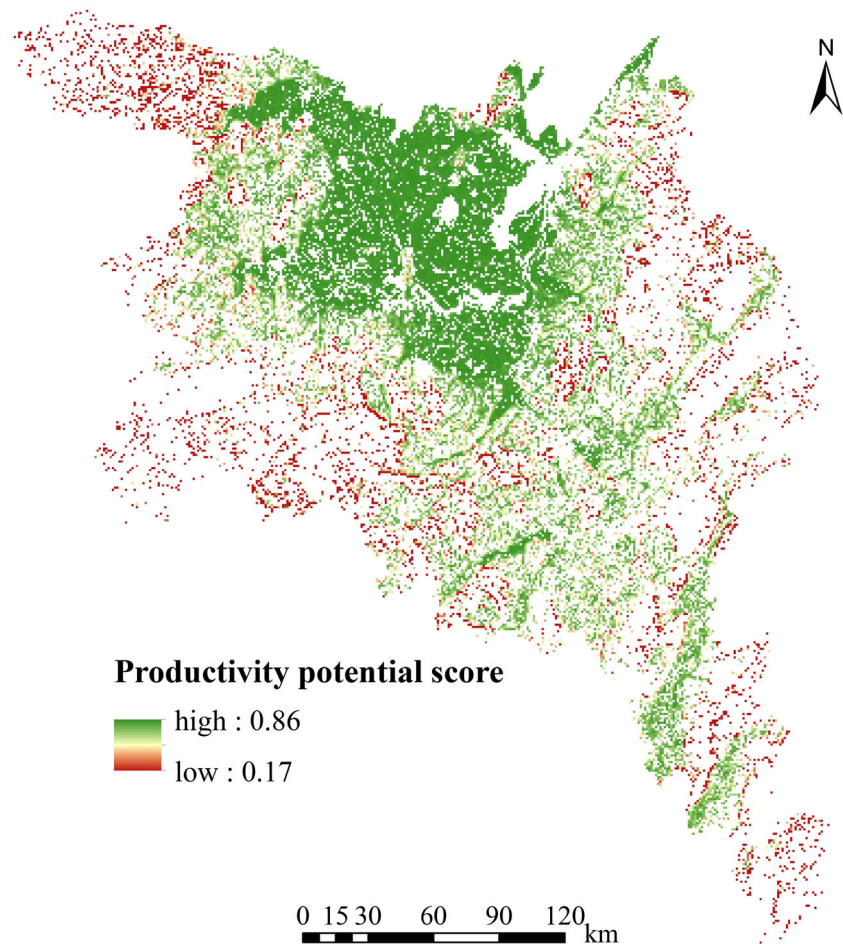
2. Spatial adjustment pattern, which emphasized on the optimization of the locational condition of the arable land. In this pattern, the land with higher social economy potential score was given a higher weight, whereas the other two scores were given lower weights.
3. Ecological conservation pattern, which emphasized the long-term ecological conservation. In this pattern, the land with higher ecological security score was assigned a higher weight. The weights are shown in Table 7.

According to the methods in the "Evaluation of the comprehensive quality of arable land" section, the scores of comprehensive arable land quality were calculated. The land was classified into five grades: the high intensive utilization (the scores of arable land quality 0.8–1), the intensive utilization (the scores of arable land quality 0.6–0.8), the traditional utilization (the scores of arable land quality: 0.4–0.6), the reduced utilization (the scores of arable land quality 0.2–0.4), and the prohibitive utilization (the scores of arable land quality 0–0.2). The high intensive

utilization land has the best productivity, location, and ecological condition and could be considered the most suitable land for intensified cultivation, followed by the intensive utilization land and the traditional utilization land, whereas the reduced utilization land and the prohibitive utilization land are considered the most unsuitable land for cultivation.

The optimized arable land use patterns are shown in Fig. 9. Three patterns showed differences in the distribution of arable land quality: in the high productivity pattern, the high intensive utilization arable land is located in the northwest and southeast of Dongting Lake (away from the near lakeshore), whereas prohibitive utilization, reduced utilization arable lands, are located in the hilly area in the southeast; in the spatial adjustment pattern, the high-intensive utilization arable land is situated in the traditional agricultural area, whereas the prohibitive utilization arable land is situated in the cities with higher economy levels and population densities and their surrounding counties; in ecological conservation pattern, the arable land suited for high-intensive utilization are scattered around the Dongting Lake and the important water conservation area and the mountainous ecological preservation area.

Fig. 7 The locational condition score of the arable land in Dongting Lake basin
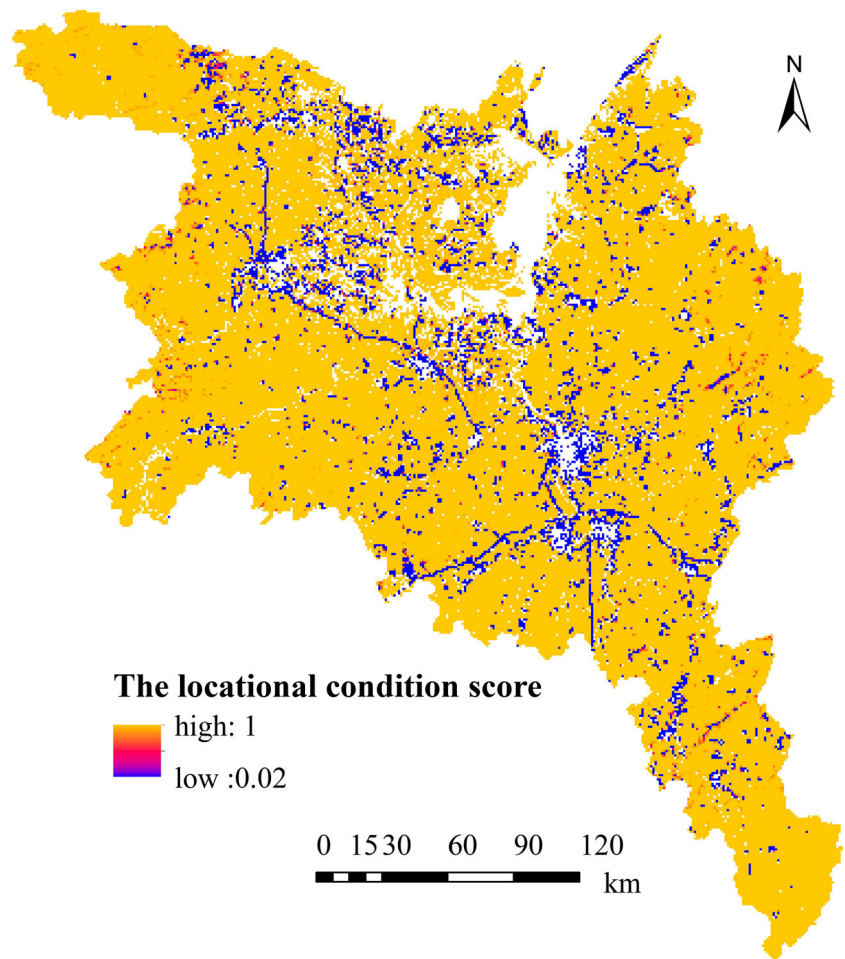
From a more detailed view, guidance of optimized arable land use for different areas in Dongting Lake basin could be given:

For the Changsha and Yueyang City area, due to the higher economic development level, the main challenge of arable land is the occupation by construction land. As a result, protecting the quality and quantity of the existing arable land is of major importance in this area. Arable land in Ningxiang County, Changsha County, Miluo County, Yueyang County around Changsha, and Yueyang City have higher-quality arable land; hence, the intensive use of arable land in these counties could help increase local crop yield. In addition, Changsha and Yueyang serves as a high urbanization zone of Hunan Province, and the active economic activities and job opportunities attract numerous human movements from rural areas into city areas. As a result, the "hooking people with land" policy should be preferentially carried out in this area, i.e., where people moved to is where the newly increased construction land would be, and where the people moved away from is where the newly increased arable land should be.

For Changde and Xiangtan area, the arable land in this area showed advantages in production efficiency and location (the productivity score, the social economic score, and the ecological security score is relatively high in this area). Hence, in addition to taking full advantage of the existing arable land, the utilization of the reserve arable land resource is important (large number of high-quality reserve arable land resources are located in the surrounding Taoyuan County, Linli County, Jinshi County, Li County). In addition, the mountainous arable land in Shimen County should be reasonably changed for reforestation in order to prevent more serious water and soil loss.

For the Yiyang City area, the main challenge of the arable land use is the flood disaster induced by the Dongting Lake area. As a result, construction on the reservoir and flood control facilities should be put into place. Moreover, the fertilizer input should be exactly controlled according to "testing soil for formulated fertilization" policy (use fertilizer according to the tested soil fertility and the crop demand) in order to prevent the excessive use of fertilizer in this area from stimulating the eutrophication of Dongting Lake water.

For Zhuzhou City, the complex terrain of Luoxiao Mountain and the low arable land quality in this area showed a disadvantage for planting. The arable land in the southeast

Fig. 8 The ecological security score of the arable land in Dongting Lake basin

The ecological security score

high : 1
low : 0.22

0 15 30   60   90   120
                        km
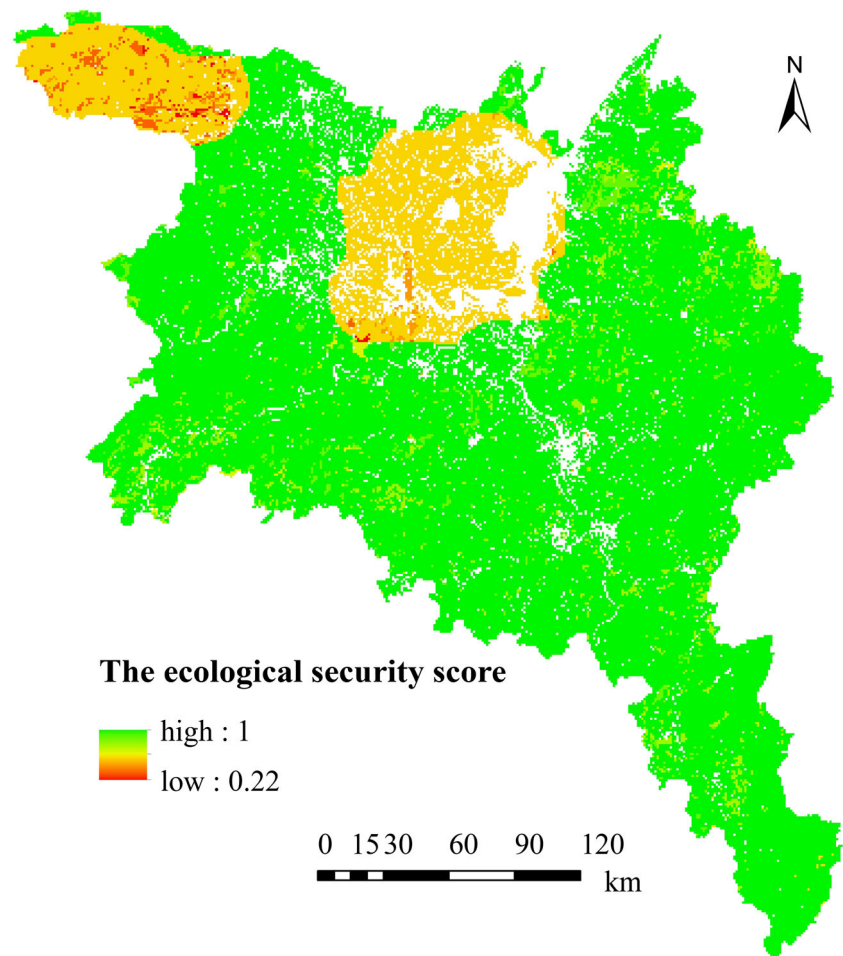
mountainous area should be transferred for reforestation, and the preferential exploitation arable land in the flat counties (Lili County, Zhuzhou County) could be centralized managed.

Discussion

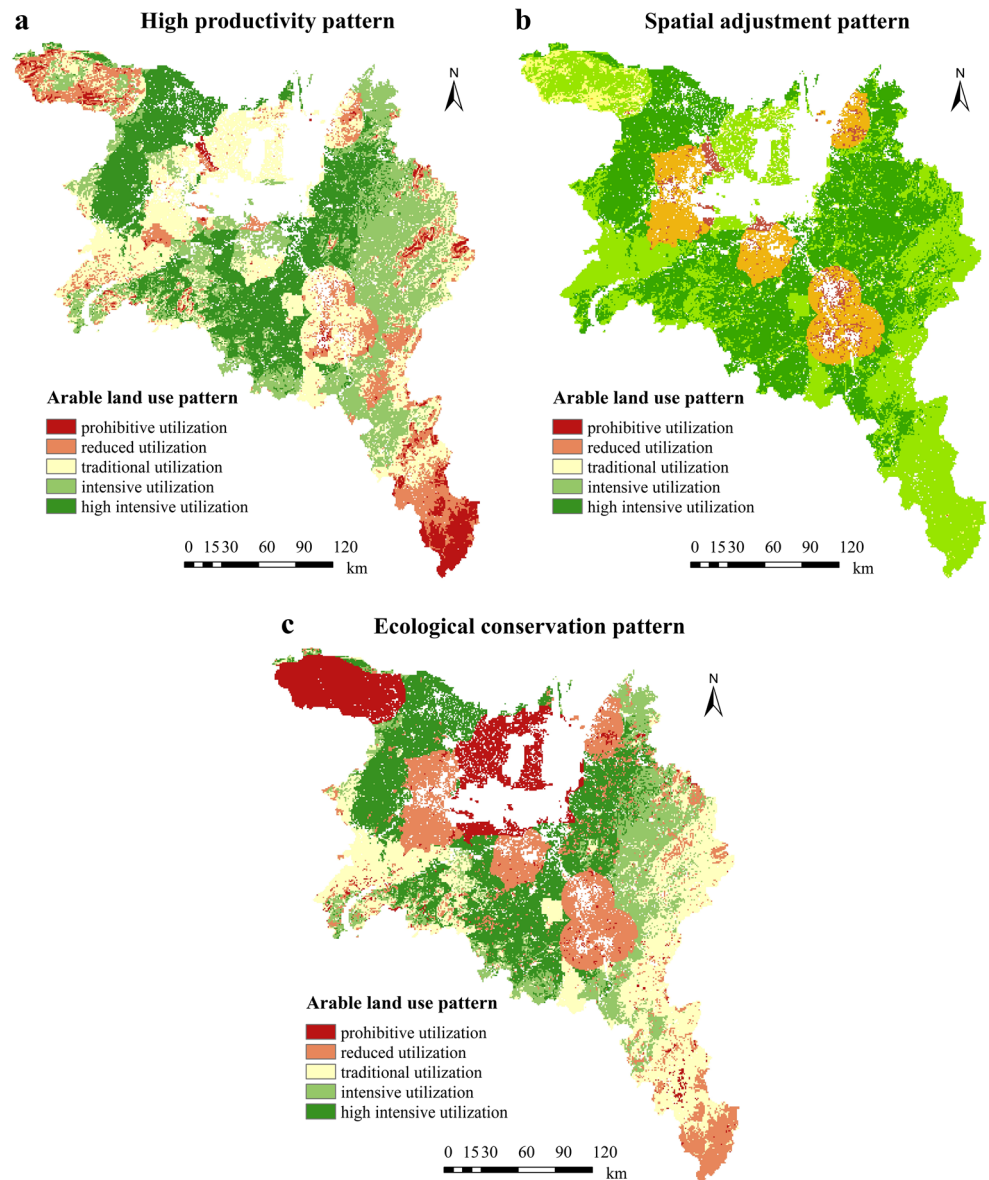### Thoughts on the optimized land use pattern

The spatial distribution of the suggested arable land use pattern is more reasonable than the current condition: First, since slope planting would increase the risk of flood disaster and the water and soil loss and induce non-point source pollution (Xu et al. 2015) (Hu et al. 2010); thus, reforestation and protection of the existing forestland in the hilly region could safeguard the tender ecological security in the hilly zone (Cho et al. 2013). Second, arable land in the southern and northern adjacent shores of Dongting Lake showed a lower land quality, and removing the arable land away from this area is a sustainable choice. Additionally, it is helpful for resisting the surplus nutrient elements coming from the arable land and protecting the water quality of Dongting Lake. Third, though some arable land is suggested to be retreated from the surrounding of cities and some hilly area, newly increased arable land with higher quality would be exploited from the

Table 7 Weights of the indicators under different optimization pattern

	Productivity potential score	Locational condition score	ecological security score
High productivity pattern	0.6	0.2	0.3
Spatial adjustment pattern	0.2	0.6	0.2
Ecological conservation pattern	0.2	0.2	0.6

Fig. 9 The optimized arable land use pattern

a   High productivity pattern

Arable land use pattern
- prohibitive utilization
- reduced utilization
- traditional utilization
- intensive utilization
- high intensive utilization

0 15 30   60   90   120
km

b   Spatial adjustment pattern

Arable land use pattern
- prohibitive utilization
- reduced utilization
- traditional utilization
- intensive utilization
- high intensive utilization

0 15 30   60   90   120
km

c   Ecological conservation pattern

Arable land use pattern
- prohibitive utilization
- reduced utilization
- traditional utilization
- intensive utilization
- high intensive utilization

0 15 30   60   90   120
km

unused land (total amount of arable land resources would not decrease), which would improve the total land productivity and release more space for urban expansion.

What is next: using the results for policy making of agricultural land use

The distribution of the optimization of the arable land use pattern is different from the current arable land use pattern; as a result, it is beneficial to make some adjustments to the layout of the arable land. The current arable land distribution is scattered around Dongting Lake, and some is still situated on the hilly area. Moreover, some arable land is located in the ecological protection area of Dongting Lake, which would create the potential threat of agricultural pollution for the water ecosystem. Future land demand should be guaranteed by increasing the comprehensive efficiency of land use, taking the productivity, the locational conditions, and ecological standards into account (White 2016). To spare land space for urban expansion, arable land surrounding the urban area could be transferred appropriately to the construction land; correspondingly, the construction land in the surrounding rural area could be reclaimed for planting to make the land structure in urban and rural area more rational. Moreover, because today's rural area faces the challenge of both guaranteeing agricultural production and improving the ecological environment, conducting an environmental impact assessment (EIA) is necessary before a policy of arable land use is implemented (Lindhjem et al. 2007). Beyond this, effective public participation (Hartley and Wood 2005) in the creation of government agencies (Sánchez and Morrison-Saunders 2011) can also lead to a strengthening of land use adjustment.

Table 8　The area of arable land under different adjustment pattern

Arable land use pattern	High productivity pattern		Spatial adjustment pattern		Ecological conservation pattern	
	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)	Area (km^2)	Ratio (%)
Prohibitive utilization	12.01	0.06	16.01	0.08	32.03	0.16
Reduced utilization	498.48	2.49	252.25	1.26	334.32	1.67
Traditional utilization	3044.91	15.21	3509.36	17.53	4198.02	20.97
Intensive utilization	9651.24	48.21	10,608.16	52.99	10,171.74	50.81
High intensive utilization	6812.52	34.03	5633.39	28.14	5283.05	26.39

Do the optimized arable land use patterns satisfy the agricultural requirements?

The arable land area of each grade in this study is shown in Table 8. In the high productivity pattern, the total area of high intensive utilization, intensive utilization, and traditional utilization land is 6812.52 km^2. In the spatial adjustment pattern and the ecological conservation pattern, the corresponding land area is 19,751 and 19,653 km^2, respectively. These data could satisfy the predicted arable land demand (land demand to satisfy the food self-sufficient, the grain export, and the grain storage) of Dongting Lake basin in 2030 according to our previous study (Yin et al. 2016). That is, in order to feed the local people and maintain agricultural production in the national grain-producing area, we should emphasize the reclaiming of the high-quality unused land and the reclamation of the superior arable land.

Conclusion

Taking the land's own comprehensive attributes into account, this study evaluated the land use change, the barycenter transformation of arable land, and the landscape indices of arable land patches of Dongting Lake basin in 1990–2010. By integrating the land productivity, social economy, and ecological security of arable land, an optimized arable land use pattern was proposed in this study.

Despite the fact that arable land tended to be more fragmented and decentralized during recent decades, and the transformation between arable land and other land is becoming less frequent and more stable, the arable land use has shown a potential to be more sustainable through some adjustment on the land use pattern. According to the evaluation of arable land quality and the optimized arable land use pattern, the high-quality arable land and the suitable unused land were advised to be preferentially exploited in the northwest and southeast of Dongting Lake (away from the near lakeshore) and the traditional agricultural counties. The low-quality arable land located in the west-northern Wuling mountainous area, the east-southern hilly area, and the densely populated big cities and their surrounding area was advised to be prohibitively exploited. In the future agricultural planning and land-use planning process, more focus should be placed on the adjustment of arable land distribution. The arable land should be more spatially concentrated and moved from the city development area appropriately in order to release more space for urban expansion. Focusing on the characteristics of local land productivity, economy development, and ecological level, this study can provide a reference for future arable land use and sustainable management for the major grain producing zone.

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