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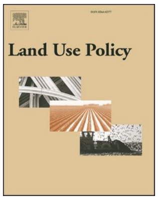

Estimate provincial-level effectiveness of the arable land requisition-compensation balance policy in mainland China in the last 20 years

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ABSTRACT

The “requisition-compensation balance policy” is a basic arable land protection policy promulgated by the Chinese government to maintain the dynamic balance of the total arable land. Since the implementation of the “requisition-compensation balance policy”, its important role in the conservation of arable land has been widely noted. Multiple studies indicate the effectiveness of the policy by estimating the quantity and quality change of arable land. In addition, the defects and negative externalities of the policy are disputed. The overall goal of this study is to estimate the provincial-level effectiveness of the “requisition-compensation balance policy” in mainland China in two periods (i.e., 2000—2010; 2010—2020) from four perspectives: arable land quantity dynamic balance; arable land productivity balance; farming distance; and sustainability of arable land use. The results showed that, first, the arable land quantity balance was achieved during 2000–2020 from a national perspective. There are still 19–23% of provinces have failed to reach the quantity balance. Second, the decrease in China’s total arable land productivity was exacerbated from 9612.1 thousand tons. to 31254.6 thousand ton. The average potential yield balance index was less than 1 for nearly all provinces during 2000–2010 and became even worse in the next decade because of occupying superior arable land while compensating for inferior arable land. The conservation of arable land productivity has become more important than the conservation of quantity. Third, due to the lack of constraints on the farming distance changes in the “requisition-compensation balance policy”, most provinces convert arable land around urban and rural areas to built-up land while replenishing land far from residential areas without providing adequate agricultural infrastructure, which leads to an increase in the cost of farming and consequently to an increase in the marginalization of arable land. During 2010–2020, the average farming distance of compensated arable land at the provincial level reached 2–7 times that of occupied arable land. However, the average farming distance of the whole arable land at the provincial level decreased by 3.82–63.88% during the same period. This contradiction is mainly due to increasing marginalization and opportunity costs resulting in arable land with high farming distance (including arable land that was compensated in the past) to be used with low intensity or even abandoned and thus identified as other land use types by remote sensing classification models. This factor outweighed that of “occupy nearby arable land while compensating farther one”, resulting in a reduction in the provincial average farming distance. Fourth, the percentage of sustainable compensated arable land in most provinces was lower than 70%. This indicated that the utilization and protection of arable land in these provinces was insufficiently implemented and monitored. Challenges along optimization of the “requisition-compensation balance policy” were discussed from two respects: data, theory and methodology and policy design and implementation. The authors argue that a more comprehensive “requisition-compensation balance policy” should be designed considering not only the quantity and productivity of arable land but also the farming distance, sustainability and ecological protection. A differentiated regulation mechanism of arable land requisition compensation in trans-provincial areas should be formulated. This study can provide guidance for optimizing the implementation of regional arable land protection and can also provide a reference for other countries to protect arable land.

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1. Introduction

Food security is a fundamental requirement for human survival and development, as well as a worldwide challenge, and has always been a concern for countries around the world (Rosegrant and Cline, 2003). From 2000 to 2050, global food demand is expected to grow by 100–110% with the increase of population and consumption level (Tilman et al., 2011). This poses a formidable challenge for worldwide policy-makers and scientists, namely, how to maintain the stability of arable land ecosystems with achieving the increasing food demand (Coyle et al., 2016; Ye et al., 2019; Huang et al., 2020; Feng et al., 2021; Gao et al., 2023a; Gao et al., 2023b). As a country with a large population, China's per capita arable land is only 40% of the world average, and the superior arable land area is less than 3% of the total arable land in the country. Despite scarce per capita arable land resources, China has carried 20% of the world's population with less than 9% of the global farmland (Ye, 2020a), which has made distinguished contributions to the United Nations Millennium Development Goals (Deng et al., 2015; Fang et al., 2022; Liu, 2019). In recent decades, the contradictions among economic development, urban expansion, natural resources and ecological protection lead to a dramatic reduction in arable land (especially high-quality farmlands in the plains) and ecological degradation (Liu et al., 2010; Bai et al., 2014; Ye et al., 2014, 2022a, 2022b; Ren et al., 2022). Against this background, strengthening arable land protection in China is of important meaning for national stability and sustainable human development (Liu et al., 2013; Liu, 2018a).

The government of China "attach great significance to the protection of arable land" and regards "treasuring and employing every inch of land, protecting arable land" as the national basic policy (Li et al., 2018b; Lu et al., 2016b; Bai et al., 2014). The "requisition-compensation balance policy" is a basic arable land protection policy to "maintain the dynamic balance of the total arable land", as one of the core clauses in the "Land Management Law" in 1998 (Liu and Li, 2017). This policy is a scheme to remedy the massive occupation of arable land for urbanization and industrialization (Song and Pijanowski, 2014; Gao et al., 2018; Su et al., 2019). In the initial version, the basic principle of the "requisition-compensation balance policy" is that arable land approved for built-up land should be compensated by an equal quantity one through land reclamation (Bai, 2014; Liu et al., 2018c). The revision of the "requisition-compensation balance policy" supplemented the requirement of quality balance to restrain the phenomenon of "occupying high-quality arable land while compensating for inferior land". In the subsequent implementation process, the requirements for "paddy field area balance" and ecological protection were added to the policy. The "requisition-compensation balance policy" marks the basic formation of laws and regulations and institutional systems related to arable land protection in China (Liu et al., 2015b; Li et al., 2014; Liu and Zhou, 2021a).

After the "requisition-compensation balance policy" carried out, its important role in the conservation of arable land in China has been widely noted. Additionally, multiple studies indicate the effectiveness of the "requisition-compensation balance policy" by estimating the quantity and quality change of arable land in mainland China. According to Tan et al. (2005), the downward rate and trend in the total area of arable land at the national level have been effectively controlled since 1997, parts of the arable land is occupied by built-up land, and these has basically been replenished by development and reclamation to achieve a quantity balance. Deng et al. (2005) found that from 1986 to 2000, the net increase in arable land area in China (+1.9%) almost offset the decline in potential productivity. In Yan's (2009) study, from 1990 to 2000, the area of cropland in China had a net increase of 2.79 Mha, resulting a slight increase in net primary production (6.96 Mt C). Song and Pijanowski (2014) present that the arable land quantity balance was achieved in mainland China during 1999—2008. Xu et al. (2015) show that China's arable land area decreased from 2000 to 2010, and the goal of the "requisition-compensation balance" on arable land quantity was basically maintained in the whole country, but the quantity balance varied among provinces. In contrast, there is a growing decline in arable land quality (or potential output) in mainland China due to the loss of high-productively arable land from urban expansion and economic development and a flawed approach to compensate for arable land, especially in the period of 2010—2020. Liu et al. (2015a) proposed that China's potential output of arable land decreased from 1990 to 2010: during 1990–2000, the Huang-Huai-Hai Plain and the middle-lower Yangtze Plain were the critical areas of lost potential output; during 2000–2010, South China emerged as the new critical area of lost potential output. Kuang et al. (2021) showed that during 2000–2015, in regions with high-quality croplands or with excellent farming conditions, the total loss of cropland was 79.1%. By contrast, 73.6% of newly reclaimed land was moderate or poor cropland. According to Ye et al. (2022a), due to land-use change, the arable land productive capacity of 2733 counties in China (nearly 73.5% of the total counties' count) decreased from 1990 to 2010. The declining counties are mostly located in central and southern China while the arable land productive capacity in most countries in northeastern and northwestern China was increased due to land-use change.

However, the defects and externalities of the "requisition-compensation balance policy" are discussed in some studies. Li (1996) analysed the changing trend and spatial distribution of arable land area in China in the 1990 s, and the idea of "dynamic balance of the total arable land" should be gradually transformed into the effective protection of basic farmland. In Li's subsequent studies, the process of "land occupation in plain areas and land compensation in mountainous areas" has been revealed and explained as an important cause of land abandonment in mountainous areas (Li and Li, 2018a; Li and Li, 2016). Some public opinion has even described the process as a "Numbers Game" (Zhao, 2014). Lin and Cheng (2001) proposed that the methods and standards for the productivity per unit area of arable land should be developed as soon as possible in accordance with the characteristics of China and then provide a basis for the conversion between arable land quantity balance and quality balance. Yue and Liu (2013) point out that the current system of arable land "requisition-compensation balance" lacks the mechanism of supervision and encouragement, relies too much on the development of reserve land resources, and pays insufficient attention to the ecological environment. Sun et al. (2014) argues that in the early stage of the implementation of the arable land "requisition-compensation balance" system, more emphasis was placed on the "arable land quantity balance", but in the practical application, the responsibility subject for arable land compensation was not clear, and there was a lack of implementable balance measures. According to Kong (2014), although the trend of declining arable land quantity has been alleviated, there is still the phenomenon of "occupy high-quality arable land while compensating for inferior land", resulting in a decline in arable land quality and productive capacity. Liu et al. (2015a) propose that in economically developed areas, there is still an obvious expansion of urbanization and industrialization, and the arable land occupied by built-up land has not decreased. The occupied high-quality arable land is usually located around towns and roads, while most of the compensated arable land is located in remote areas such as undeveloped mountainous regions. Ye et al. (2022b) calculated the driving power of arable land-area change to arable land productive-capacity balance in mainland China. The result shows that the main driving factor of the increase of arable land productive-capacity at county-level is the change of arable land-area. The determinant power of arable land-area change was calculated as 74.154%. On the contrary, its determinant power to county-level arable land productive capacity decrease was only 38.542%, indicating that occupying high-capacity arable land and supplementing low-capacity arable land had a greater impact on the decline of arable land productive capacity at county level.

The above studies have explored the effectiveness of the "requisition-compensation balance policy" from multiple perspectives, including arable land use changes, policy shortcomings, and externalities, and

Table 1
Accuracy evaluation of GlobeLand30 from published articles.

Region	Classes	Accuracy	References
China	10 classes	82.4%	Yang et al. (2017)
China	Cropland	79.6%	Lu et al. (2016a)
China	Forest	80.7%	Wang et al. (2015)
Iran	10 classes	77.9%	Arsanjani et al. (2016a)
Italy	10 classes	80.0%	Brovelli et al. (2015)
Nepal	10 classes	80.1%	Cao et al. (2016)
Portugal	10 classes	77.0%	Mozak (2016)
Henan Province, China	10 classes	81.5%	Ma et al. (2016)
Shanxi Province, China	Cropland	80.6%	Chen et al. (2017c)

have provided important guidance for this study. However, first, these studies focus on the quantity and quality balance of arable land, and it is difficult to answer the question: "What are the characteristics of the externalities (i.e., marginalization) and sustainability of requisition-compensation of arable land process in China?" (Note: externalities refer to policy externalities, i.e., policies may have effects on society and groups not targeted by them, and such effects may be external or incidental. The externalities in the requisition-compensation of arable land process are caused by the land use mechanism ignoring the ecological and social benefits of arable land) Second, most studies show the effectiveness of the "requisition-compensation balance policy" before 2010, and few studies reveal the question: "How has the effectiveness of the requisition-compensation balance policy in China changed in the following decade?" A clear explanation of this issue is essential for China to develop appropriate arable land control policies that can weigh against food security, economic growth and ecological stability in the coming decades (Liu et al., 2014b; Liu and Zhou, 2021b; Wen, 2020; Zhou et al., 2023).

The overall goal of this study was to estimate the provincial-level effectiveness of the "requisition-compensation balance policy" in mainland China in two periods (i.e., 2000—2010; 2010—2020) from four perspectives: arable land quantity dynamic balance; arable land productivity and yield dynamic balance; farming distance and arable land use sustainability. The arable land quantity dynamic balance was calculated as the ratio of compensated arable land quantity to the land occupied by built-up land. The arable land productivity dynamic balance was calculated as the ratio of provincial total compensated arable land productivity to that reduced due to the conversion of arable land to built-up land. The yield balance was estimated as the ratio of the average potential yield of compensated arable land to that of arable land occupied by built-up land. Provincial average farming distance change has been used to indicate the influence of the "requisition-compensation balance policy" on arable land marginalization. The sustainability of arable land use was estimated in accordance with the rule that arable land being compensated during 2000—2010 would be deemed sustainable if it was still being used as arable land in 2020. Finally, comprehensive effects and deficiencies, comparative studies and challenges of the "requisition-compensation balance policy" are discussed. This study can provide guidance for optimizing the implementation of regional arable land protection and can also provide a reference for other countries to protect arable land.

2. Materials and methods

2.1. Data

2.1.1. Land use change data

In this study, the GlobeLand30 dataset was used to calculate the provincial land use change quantity during 2000—2010 and 2010—2020 and to analyze the spatial distribution characteristics of arable land. GlobeLand30 is a peer-reviewed 30-meter resolution global land cover dataset developed by Chen et al. (2010). In the GlobeLand30 dataset, the land cover has been divided into ten classes (i.e., farmland; forest; grassland; shrubland; wetland; water bodies; tundra; built-up land; bare land; permanent snow and ice) covering three specific years: 2000, 2010 and 2020. The dataset is mainly from Landsat Thematic Mapper (TM) and Enhanced TM plus (ETM+) satellites, and more than 10000 scenes are required to be collected and classified (Chen et al., 2017a).

Researchers from China, Greece, Italy, Mexico, and Sweden made preliminary evaluations of GlobeLand30 to assess its quality (Brovelli et al., 2015). A large number of samples have been collected from all over the world, and these results have achieved an overall accuracy of over 80%, as shown in Table 1. The results showed that GlobeLand30 is a reliable product for LUCC studies. China's overall accuracy was estimated to be satisfactory at 82.4% at the country/region level, (Yang et al., 2017).

To date, the GlobeLand30 dataset has been widely used in many fields by more than 7000 scientists and users from nearly 120 countries. For instance, GlobeLand30 is mainly used by government departments to analyze and study disaster resilience, energy and mineral resource management, and urban sustainable development (Arsanjani et al., 2016a). Most applications in nongovernmental organizations and the United Nations are related to "food security and sustainable agriculture, biodiversity and ecosystem sustainability, and public health surveillance" (Arsanjani et al., 2016b; Brovelli et al., 2015; Cao et al., 2016; Chen et al., 2017b).

2.1.2. Arable land potential yield data

Arable land potential yield dataset (unit: kg/ha.) proposed by Xu et al. (2017) and Liu et al. (2015a) is used to estimate the effectiveness of arable land "requisition-compensation balance" on maintaining arable land productivity. The simulation of the arable land potential yield dataset was performed at a 1 km spatial resolution by using the Global Agro-Ecological Zones Model (GAEZ) (Fischer, 2001).

The potential yield over four years (i.e., 1980; 1990; 2000; 2010) was calculated by inputting corresponding farmland distribution data, soil data, terrain elevation data, and meteorological data. Five staple crops (i.e., wheat, corn, rice, soybean, potato) and suitable multiple cropping systems were considered. Previous studies have shown that the arable land potential yield dataset is practical for evaluating the impact of arable land conversion on agricultural productivity (Yan et al., 2009; Liu et al., 2015a; Zhong et al., 2012).

2.1.3. Road data

The road data were used to specify the artificial lands to calculate the farming distance between arable land and rural settlements. The overall road data contain highways, roads, and unpaved tracks of China. The data were derived from the Data Basin (https://databasin.org).

2.2. Methods

2.2.1. Calculate arable land occupation and compensation quantity

The effectiveness of the "requisition-compensation balance policy" on maintaining arable land quantity during 2000—2010 and 2010—2020 has been estimated at the provincial level from four perspectives. First, the arable land quantity balance index $\boldsymbol{Q_B}$ was calculated as the ratio of compensated arable land quantity to the land occupied by built-up land, as shown in Eq. (1). $\boldsymbol{C_{BA}}$, $\boldsymbol{C_{GA}}$, $\boldsymbol{C_{FA}}$, $\boldsymbol{C_{WA}}$, and $\boldsymbol{C_{OA}}$ represent compensation of arable land area from built-up land, grassland, forest, water, and other types (e.g., bare land; permanent snow and ice), respectively. $\boldsymbol{O_{AB}}$ represents the quantity of arable land that was occupied by built-up land.

$$\boldsymbol{Q_B} = \frac{\boldsymbol{C_{BA}} + \boldsymbol{C_{GA}} + \boldsymbol{C_{FA}} + \boldsymbol{C_{WA}} + \boldsymbol{C_{OA}}}{\boldsymbol{O_{AB}}} \tag{1}$$

Second, the "requisition-compensation balance policy" only ensures that the arable land occupied by built-up land is compensated but ignores the arable land area decrease caused by ecological construction or natural destruction. Eq. (2) has been proposed to estimate the importance degree of the policy on controlling arable land area decrease. OP_{AB}, OP_{AG}, OP_{AF}, and OP_{AWO} represent the proportion of arable land area occupied by built-up land, grassland, forest, water and other types to the total occupied land area, respectively. O_{AG}, O_{AF}, O_{AW}, and O_{AO} represent occupation of arable land area of grassland, forest, water, and other types, respectively. O_{A*} represents the sum of occupation of arable land area.

$$OP_{AB} = \frac{O_{AB}}{O_{A*}};\ OP_{AG} = \frac{O_{AG}}{O_{A*}};\ OP_{AF} = \frac{O_{AF}}{O_{A*}};\ OP_{AWO} = \frac{O_{AW}+O_{AO}}{O_{A*}};$$

$$O_{A*} = O_{AB} + O_{AG} + O_{AF} + O_{AW} + O_{AO} \tag{2}$$

Third, the source of arable land compensation has been quantified, as shown in Eq. (3). CP_{BA}, CP_{GA}, CP_{FA}, and CP_{WOA} represent the proportion of arable land area compensated from built-up land, grassland, forest, water and other types to the total compensated land area, respectively. C_{*A} represents the sum of compensation of arable land area.

$$CP_{BA} = \frac{C_{BA}}{C_{*A}};\ CP_{GA} = \frac{C_{GA}}{C_{*A}};\ CP_{FA} = \frac{C_{FA}}{C_{*A}};\ CP_{WOA} = \frac{C_{WA}+C_{OA}}{C_{*A}};$$

$$C_{*A} = C_{BA} + C_{GA} + C_{FA} + C_{WA} + C_{OA} \tag{3}$$

2.2.2. Assessment of provincial total arable land productivity

The crop potential yield (unit: kg/ha.) has been affected by both climate change and human activities. Since our study is focused on the influence of LUCC on total arable land productivity, the average crop potential yield AP_i was calculated for each grid i to reduce the impact of climate change, as shown in Eq. (4). $P_{j,i}$ (j=1980, 1990, 2000, 2010) represents the crop potential yield of grid i in 1980, 1990, 2000 and 2010.

$$AP_i = \frac{P_{1980,i} + P_{1990,i} + P_{2000,i} + P_{2010,i}}{4} \tag{4}$$

For each arable land grid i' in the GlobeLand30 data in a specific year (i.e., 2000; 2010; 2020), its corresponding crop potential yield $AP_{i'}$ has been set as AP_i of the nearest neighbour grid i by the spatial overlay method. For province y, its total arable land productivity $P_{y,w}$ (unit: kg) in specific year w has been calculated by summing the productivity of each grid that belongs to it, as shown in Eq. (5). Then, the provincial total arable land productivity change rate PR_{e-s} from year s to year e (e.g., 2000–2010; 2010–2020) driven by LUCC was calculated. $AP_{i'}$ and $M_{i'}$ are the crop potential yield and area (unit: ha.) of arable land grid i'. m presents the quantity of arable land grids within province y.

$$PR_{e-s} = \frac{P_{y,e} - P_{y,s}}{P_{y,s}};\quad P_{y,w} = \sum\nolimits_{i'=1}^{m} AP_{i'} * M_{i'}\,(w = 2000, 2010, 2020) \tag{5}$$

The ratio of provincial total compensated arable land productivity to that reduced due to the conversion of arable land to built-up land has been estimated as $R_{y,w}$ in Eq. (6). The ratio of the average potential yield of compensated arable land to that of arable land occupied by built-up land was estimated as $RU_{y,w}$. $R_{y,w}$ and $RU_{y,w}$ can be used to indicate arable land productivity balance and yield balance in a specific period. For province y in year w, $PA_{y,w}$ and $UA_{y,w}$ respectively represent total productivity and average potential yield of the compensated arable land; $PB_{y,w}$ and $UB_{y,w}$ respectively represent total productivity and average potential yield of the arable land occupied by built-up land.

$$R_{y,w} = \frac{PA_{y,w}}{PB_{y,w}};\quad RU_{y,w} = \frac{UA_{y,w}}{UB_{y,w}} \tag{6}$$

It should be noted that although 4 periods of data were used to calculate the average arable land potential yield, some grids of GlobeLand30 data lack productivity data. Considering that differences in climatic conditions in small areas can be ignored, the focal statistics method was used to complement the missing values. In practice, we used the focal statistics tool in ArcGIS 10.6 to perform neighbourhood statistics by taking each no data grid as the centre point and 150 m as the radius. The statistical average was assigned as the grid value.

2.3. Determination of farming distance by eliminating road influence

In this study, the farming distance of each arable land grid was calculated as its distance to the margin of the nearest rural (or urban) residential region. Firstly, because the line vector in the road data is relatively subtle, it may not be recognized. Therefore, we used a buffer zone of 100 m for each vector line feature in the road data to improve the accuracy of identification. Secondly, we changed the new road polygon to a 30-meter resolution raster. Then we erase the roads from built-up land data to obtain the new built-up land layers. Thirdly, calculate the minimum Euclidean distance from the arable land grid to the built-up land grid with a resolution of 30 m, and the average farming distance is calculated by zonal statistics on a basis of province level. Through these steps, we can better ensure the reliability of the calculated results in the farming distance calculation process. In addition, some changes of farming distance are consistent with our understanding of the changes of arable land in reality, which also verifies the rationality of the calculated results.

2.4. Estimate sustainability of arable land use

The arable land use sustainability was estimated from two perspectives. First, although the land use type of compensated arable land is strictly restrained by the land use control policy of China, its actual land cover can be changed due to arable land marginalization, agricultural facilities construction or other reasons. The arable land that was compensated during 2000–2010 would be deemed sustainable if it was still being used as arable land in 2020; otherwise, it was considered unsustainable. A_S was calculated as the ratio of sustainable arable land to total compensated arable land area during 2000—2010 for each province of China, as shown in Eq. (7). C_{BA}, C_{GA}, C_{FA}, C_{WA}, and C_{OA} represent compensation of arable land area from built-up land, grassland, forest, water, and other types (e.g., bare land; permanent snow and ice), respectively, during 2000—2010. U_{BA}, U_{GA}, U_{FA}, U_{WA}, and U_{OA} represent unsustainable arable land areas that were converted to built-up land, grassland, forest, water, and other types during 2010–2020, respectively. U_S was calculated as the percentage of unsustainable arable land area that returns to its initial land cover type to the total unsustainable arable land area, as shown in Eq. (8). U_B represents the percentage of unsustainable arable land area that returns to its initial land cover type. U_{*A} represents the total unsustainable arable land area.

$$A_S = \frac{C_{*A} - U_{*A}}{C_{*A}} \tag{7}$$

$$C_{*A} = C_{BA,2010} + C_{GA,2010} + C_{FA,2010} + C_{WA,2010} + C_{OA,2010}$$

$$U_{*A} = U_{BA} + U_{GA} + U_{FA} + U_{WA} + U_{OA}$$

$$U_S = \frac{U_B}{U_{*A}} \tag{8}$$

Second, if one farmland plot had been adjusted to ecological land (i.e., forest; grassland; water) during 2000—2010 and then been converted to built-up land during the next ten years, it would circumvent the constraints of the “requisition-compensation balance policy”. The percentage of this phenomenon has been calculated in Eq. (9). B_{AE} is the total area of arable land that was converted to forest, grassland, and water during 2000—2010 and then converted to built-up land during 2010—2020; B_{AB} is the quantity of built-up land that was converted from arable land during 2010—2020; and B_{OB} is the quantity of other land occupied by built-up land in the same period. R_{AE}, R_{AB}, **and** R_{OB} represent the percentages of the three sources of built-up land increase from 2010 to 2020.

Table 2
Provincial arable land quantity balance index and total arable land area change in China during 2000–2020.

		Arable land quantity balance index			Total arable land area change (unit: 10e4 ha.)		
Zoning	**Provinces**	**2000-2010**	**2010-2020**	**Changes**	**2000-2010**	**2010-2020**	**Changes**
Northeast Plain	**Heilongjiang**	4.88	4.49	-7.99%	-15.13	8.71	157.55%
	Jilin	5.16	1.92	-62.79%	6.34	-20.37	-421.13%
	Liaoning	3.44	1.77	-48.55%	1.24	-42.34	-3503.53%
	Inner Mongolia	12.18	8.98	-26.27%	-27.64	137.89	598.82%
North China Plain	Beijing	2.64	**0.13**	-95.08%	4.84	-13.66	-382.03%
	Tianjin	**0.69**	**0.97**	40.58%	-5.43	-1.97	63.74%
	Hebei	2.48	**0.61**	-75.40%	-0.74	-63.10	-8473.04%
	Shandong	**0.90**	**0.35**	-61.11%	-42.37	-98.75	-133.07%
	Henan	**0.83**	**0.65**	-21.69%	-27.75	-49.45	-78.23%
The Middle-lower Yangtze Plain	**Anhui**	1.80	1.03	-42.78%	-10.80	-24.50	-126.88%
	Jiangsu	**0.90**	**0.48**	-46.67%	-26.62	-76.73	-188.26%
	Jiangxi	7.96	3.79	-52.39%	-2.89	-24.48	-745.81%
	Hubei	6.20	1.94	-68.71%	9.40	-16.15	-271.75%
	Hunan	17.75	5.67	-68.06%	1.67	-14.26	-956.17%
	Shanghai	**0.29**	**0.57**	96.55%	-7.80	-5.67	27.31%
The southern hill region of China	Zhejiang	**0.71**	1.40	97.18%	-45.39	-24.29	46.48%
	Fujian	4.11	3.36	-18.25%	-7.79	-5.95	23.57%
	Guangdong	5.36	1.28	-76.12%	-10.70	-52.67	-392.24%
	Guangxi	19.16	3.87	-79.80%	19.11	-18.17	-195.11%
	Hainan	9.33	4.51	-51.66%	-16.34	7.10	143.44%
	Chongqing	58.01	1.74	-97.00%	13.82	-13.32	-196.34%
	Sichuan	12.37	3.19	-74.21%	-11.86	-14.62	-23.28%
	Guizhou	44.14	10.05	-77.23%	-35.41	32.31	191.25%
	Yunnan	22.98	7.14	-68.93%	6.48	12.47	92.56%
Irrigated agricultural region in the west	Shanxi	2.60	1.14	-56.15%	-12.67	-28.92	-128.18%
	Shaanxi	3.39	3.38	-0.29%	-12.62	-2.36	81.28%
	Ningxia	2.74	2.88	5.11%	-9.01	10.26	213.86%
	Gansu	13.19	3.76	-71.49%	-31.01	16.81	154.22%
	Qinghai	12.72	4.53	-64.39%	-1.22	15.10	1337.70%
	Xizang	8.82	21.28	141.27%	-6.61	27.54	516.64%
	Xinjiang	11.04	6.48	-41.30%	56.62	132.72	134.41%

Note: The arable land quantity balance index is the ratio of compensated arable land quantity to the land occupied by built-up land. If arable land quantity balance index is equal to or greater than 1, quantity balance has been achieved. Otherwise, quantity balance of arable land has not been met. Major grain-producing provinces and the arable land quantity balance index that greater than 1 are rendered in bold font. Positive changes are rendered in gray shading.

$$R_{AE} = \frac{B_{AE}}{B_{AE} + B_{AB} + B_{OB}}, R_{AB} = \frac{B_{AB}}{B_{AE} + B_{AB} + B_{OB}}, R_{OB} = \frac{B_{OB}}{B_{AE} + B_{AB} + B_{OB}} \tag{9}$$

3. Results

3.1. *Effectiveness of the requisition-compensation balance policy on maintaining arable land quantity*

From a national perspective, the arable land quantity balance in China was achieved during 2000–2020. In the past two decades, the total area of arable land occupied by built-up land was 14781.05 thousand ha, while the total area of compensated arable land was 40277.02 thousand ha. However, there was a large variation in the arable land quantity balance index among provinces (Table 2). The arable land quantity balance index was significantly greater than 1 for almost all provinces in the Northeast Plain, the southern hill region, and the irrigated agricultural region in the west. The arable land quantity balance index in Guizhou was even greater than 10. The provinces of the North China Plain were not doing enough to ensure the arable land

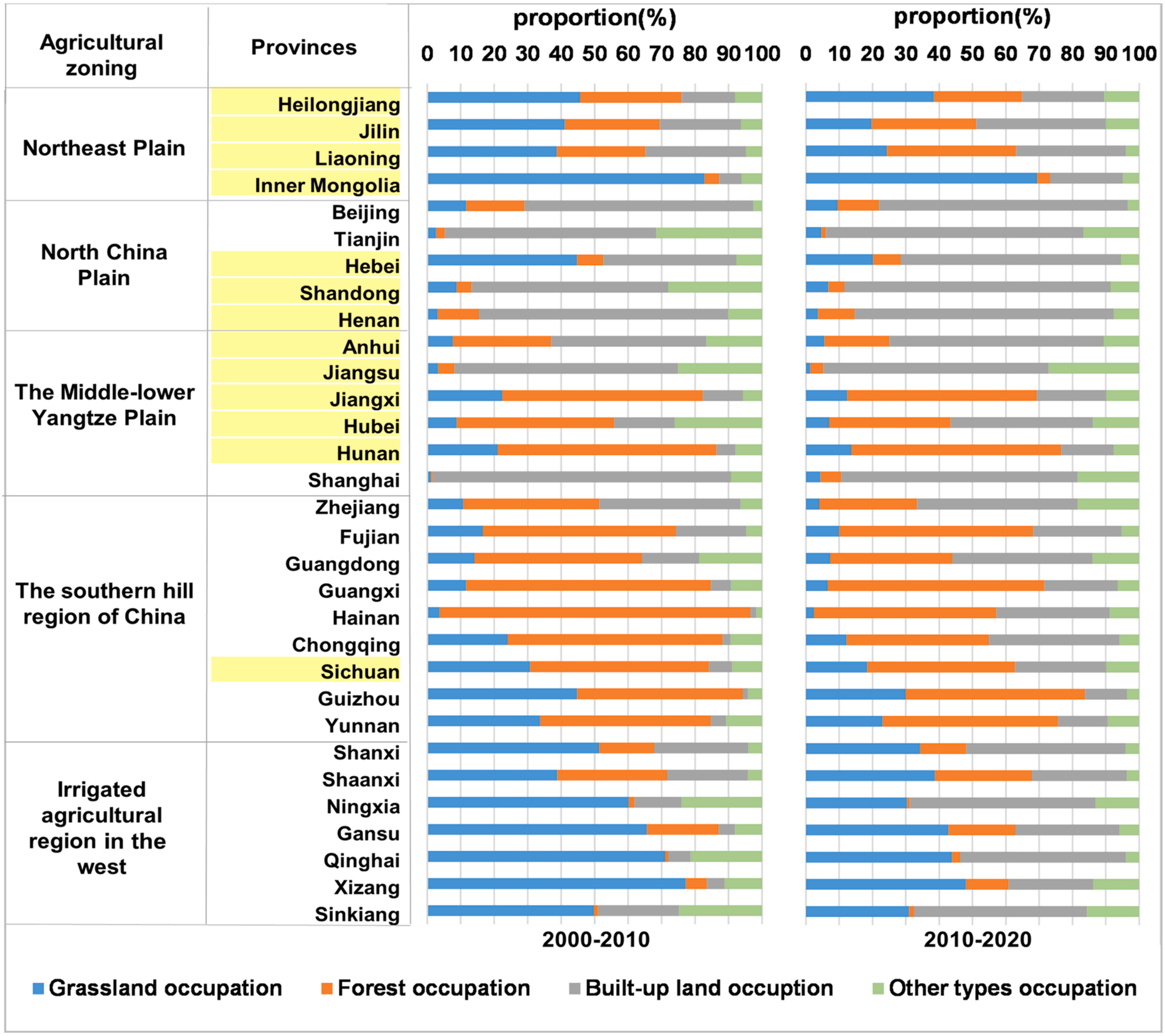


Fig. 1. The ratio of arable land quantity converted into grassland, forest, built-up land or other land-use types to the total quantity of arable land that was occupied at the province level. Major grain-producing provinces are rendered in yellow.

quantity balance. Only Beijing and Hebei reached the arable land quantity balance from 2000 to 2010, while all provinces failed to reach the arable land quantity balance from 2010 to 2020. In the middle-lower Yangtze Plain, most provinces reached the arable land quantity balance, except for Jiangsu and Shanghai. As major grain-producing provinces, Shandong, Henan, Hebei and Jiangsu had an imbalance in the arable land quantity that needs to be remedied.

At the provincial level, there were differences in the arable land quantity balance index among provinces. From 2000–2010, 6 of the 31 provinces failed to reach the quantity balance, accounting for 19%, and 3 of them were major grain-producing provinces. Other provinces had reached the arable land quantity balance. From 2010–2020, 7 of the 31 provinces failed to reach the quantity balance, accounting for 23%, with imbalances occurring mostly in the densely populated plains. The arable land quantity balance index decreased in 26 provinces, with Beijing, Hebei, Guangdong, Guangxi, Sichuan, Chongqing, Guizhou and Gansu decreasing by more than 70%. Provinces with arable land quantity balance indices less than 1 were mainly distributed in the eastern and central parts of China. It is difficult for these provinces to achieve arable land quantity balance because of high urbanization demand and limited arable land reserves. The pressure of arable land quantity balance is much less in the northwest and northeast regions because they have more arable land reserves and lower population density.

For a province, achieving the arable land quantity balance does not mean no reduction in the area of arable land. This is because the “requisition-compensation balance policy” stipulates that arable land converted to built-up land is compensated, but there is no requirement for compensation of arable land for ecological use or natural destruction. As shown in Table 2, the arable land area decreased in most provinces of China from 2000 to 2010. The total decreased arable land area was 2482.8 thousand ha. The provinces with the lowest total arable land area change were Zhejiang (-45.39×10^4 ha), Shandong (-42.37×10^4 ha) and Guizhou (-35.41×10^4 ha). Provinces located in the North China Plain and the Middle-lower Yangtze Plain suffered the most significant decrease. The decrease in arable land was mainly related to the transformation of arable land into built-up land. The arable land of most provinces in the southern hill region and the western irrigated agricultural region decreased heavily, despite their relatively high arable land

Table 3
Arable land productivity balance index and potential yield balance index during 2000–2020.

Zoning	Provinces	Arable land productivity balance index		Potential yield balance index		Total arable land productivity change (unit: 10e4 ton.)	
		2000–2010	2010–2020	2000–2010	2010–2020	2000–2010	2010–2020
Northeast Plain	**Heilongjiang**	3.26	2.75	0.67	0.61	-51.49	-15.30
	Jilin	3.25	1.24	0.63	0.65	9.33	-87.88
	Liaoning	2.44	1.30	0.71	0.73	-11.46	-126.15
	Inner Mongolia	10.28	5.05	0.84	0.56	-41.50	140.88
North China Plain	Beijing	2.76	0.10	1.04	0.75	21.01	-56.42
	Tianjin	0.68	0.85	0.99	0.87	-18.66	-10.40
	Hebei	1.58	0.32	0.64	0.53	-10.27	-386.54
	Shandong	0.91	0.31	1.01	0.89	-147.46	-598.06
	Henan	0.77	0.59	0.93	0.90	-185.14	-354.61
The Middle-lower Yangtze Plain	**Anhui**	1.50	0.93	0.84	0.90	-73.48	-145.81
	Jiangsu	0.95	0.45	1.05	0.94	-135.74	-492.34
	Jiangxi	5.44	2.46	0.68	0.65	-14.95	-124.60
	Hubei	3.50	1.14	0.56	0.59	27.05	-141.43
	Hunan	15.04	4.04	0.85	0.71	23.49	-53.49
	Shanghai	0.39	0.60	1.32	1.05	-34.22	-34.52
The southern hill region of China	Zhejiang	0.57	0.72	0.80	0.51	-131.44	-169.31
	Fujian	3.34	2.29	0.81	0.68	-10.41	-23.54
	Guangdong	4.78	0.92	0.89	0.72	-17.99	-156.08
	Guangxi	9.52	1.89	0.50	0.49	29.61	-76.50
	Hainan	8.45	3.98	0.91	0.88	-59.74	29.85
	Chongqing	47.42	0.77	0.82	0.44	73.55	-76.55
	Sichuan	6.88	1.59	0.56	0.50	-53.39	-118.46
	Guizhou	23.88	4.85	0.54	0.48	-59.61	23.30
	Yunnan	7.91	2.73	0.34	0.38	-39.67	-61.99
Irrigated agricultural region in the west	Shanxi	1.61	0.73	0.62	0.64	-46.06	-91.40
	Shaanxi	1.33	1.27	0.39	0.38	-64.47	-56.51
	Ningxia	1.49	1.35	0.54	0.47	-18.19	-4.06
	Gansu	7.09	1.94	0.54	0.52	-50.88	-16.57
	Qinghai	7.11	1.14	0.56	0.25	-6.37	8.80
	Xizang	3.51	7.05	0.40	0.33	-0.97	-3.50
	Xinjiang	6.98	2.61	0.63	0.40	138.31	153.73

Note: The arable land productivity balance index is the ratio of the provincial total compensated arable land productivity to that reduced due to the conversion of arable land to built-up land; the potential yield balance index is the ratio of the average potential yield of compensated arable land to that of arable land occupied by built-up land. If the arable land productivity balance index is equal to or greater than 1, productivity balance has been achieved. Otherwise, the productivity balance of arable land has not been met. If the potential yield balance index is equal to or greater than 1, yield balance has been achieved. Otherwise, the yield balance of arable land was not met. Details can be found in Eq. (7). Major grain-producing provinces are rendered in bold font.

quantity balance index. The reduction in arable land in these provinces was mainly related to China's ecological conservation projects, such as returning arable land to forest and grassland.

From 2010–2020, the reduction in the total arable land area in China was 2108.4 thousand ha, compared to 2482.8 thousand ha from 2000 to 2010. The decrease in arable land quantity intensified in the North China Plain and the middle-lower Yangtze Plain. The decreasing trend of arable land quantity in the southern hill region and the western irrigated agricultural region diminished. The arable land quantity shifted from decreasing to increasing obviously in irrigated agricultural region in the west, Heilongjiang, Inner Mongolia, Guizhou and Hainan. In addition, 11/13 of the major grain-producing provinces experienced a decrease in arable land quantity. In summary, the decline in the area of arable land in China has been effectively controlled in the last decade. From a spatial perspective, arable land shifted from the eastern plains and southeastern coastal provinces with high agroclimatic resources and good farming conditions to the northwestern regions with lower water and heat conditions and farming conditions.

Over the past 20 years, the role of the "requisition-compensation balance policy" in maintaining regional arable land quantity has been increasing because the ratio of arable land quantity converted to built-up land to the total quantity of arable land occupied increases pervasively in multiple provinces, as shown in Fig. 1. In the period of 2000—2010, provinces with a high proportion of arable land converted to built-up land were mainly located in the North China Plain and the Middle-lower Yangtze Plain. Fifty-two percent of provinces had a built-up land occupation proportion of less than 20%, especially in Guizhou, Hainan and Chongqing. From 2010—2020, there was an increase in the proportion of arable land occupied by built-up land in all provinces except Shanghai, with the most notable province being Qinghai. Ninety percent of provinces had a built-up land occupation proportion higher than 20%. The proportion of built-up land occupation in Shanghai, Beijing, Tianjin, Henan and Shandong even exceeded 70%.

As is presented in Figure A.1 (*see detailed results in Appendix A*), it can be seen that the proportion of arable land converted to built-up land and the arable land quantity balance index are highly correlated. First, the provincial arable land quantity balance index was higher in the southern hill region and the irrigated agricultural region in the west than in the North China Plain and the middle-lower Yangtze Plain, which does not mean that the "requisition-compensation balance policy" is more strongly implemented in the former areas. In fact, in the former regions, the conversion of arable land to built-up land had less impact on the change in arable land area, and it was easier to achieve arable land quantity balance. In the latter regions, the occupation of arable land for built-up land was the main factor of the arable land area decrease, which makes it more difficult to achieve the dynamic arable land quantity balance. The implementation of the "requisition-compensation balance policy" is highly effective for maintaining the arable land quantity in these regions. Second, compared to 2000—2010, the percentage of arable land converted to built-up land in most provinces increased in 2010—2020, which led to a decrease in the arable land quantity balance index in the relevant provinces. The importance of "requisition-compensation balance policy" implementation in the southern hill region and the irrigated agricultural region in the west increased. Third, returning arable land to forest and grass is a key factor in the reduction of arable land area in the southern hill region and the irrigated

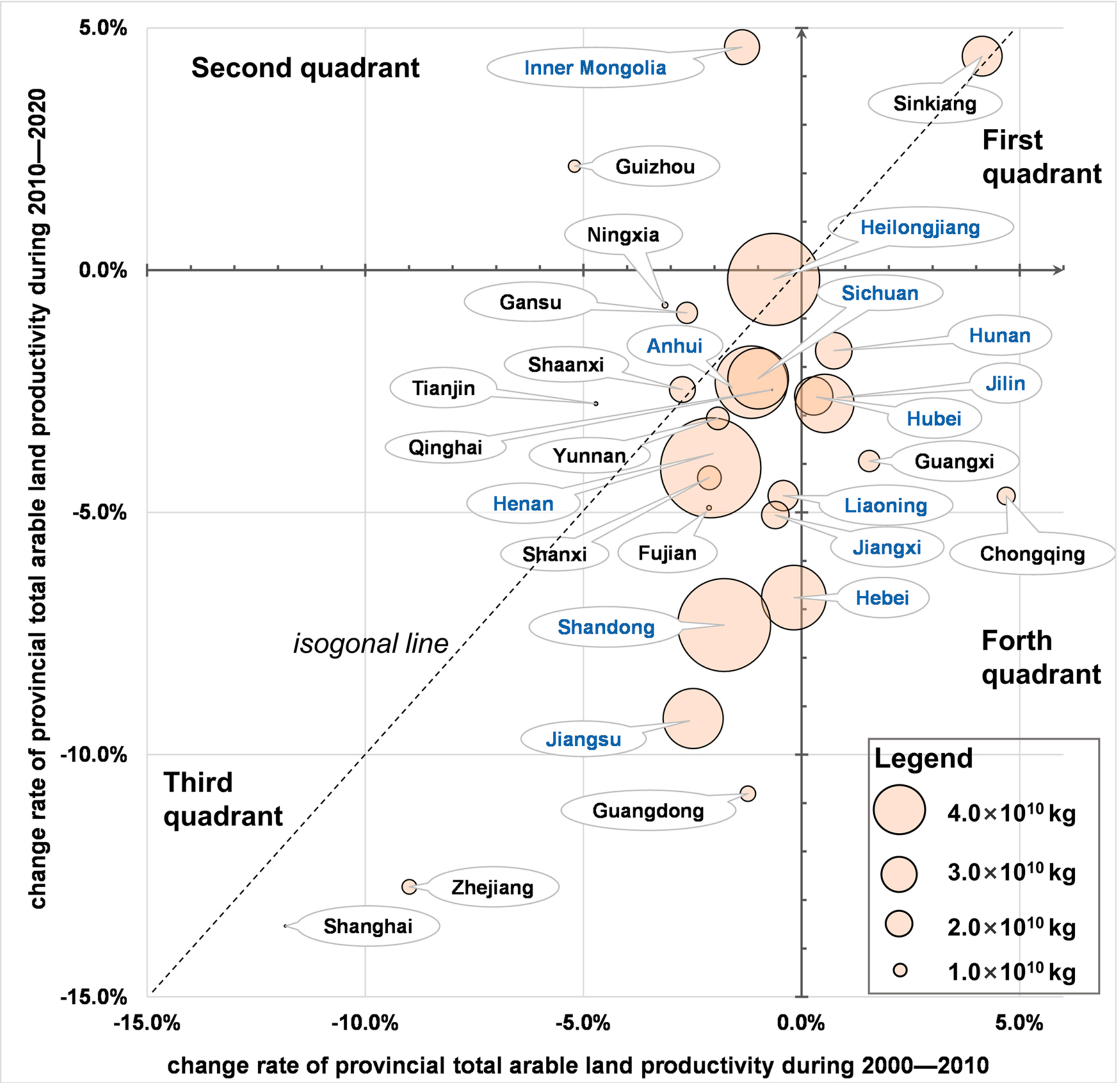


Fig. 2. Provincial total arable land productivity change rate during 2000–2020. The time horizon has been divided into two periods: 2000—2010 and 2010—2020. Annual arable land productivity changes in these periods are presented as the X axis and Y axis (unit: %). Then, each province can be located in the coordinate system as a circle. Circle size depends on the average arable land productivity of the province over multiple periods. On that basis, the map can be divided into four quadrants. Provinces located in the first quadrant show a continuous arable land productivity increase in both periods. However, provinces located in the third quadrant show a continuous arable land productivity decrease. Major grain-producing provinces are rendered in blue. Beijing, Xizang and Hainan are not shown in the figure.

agricultural region in the west, respectively. However, the dynamic arable land quantity balance does not propose a compensation strategy for the conversion of arable land caused by these factors. This makes the "requisition-compensation balance policy" less effective in maintaining the quantity of arable land in these areas and leads to loopholes in the policy, i.e., arable land occupied for ecological construction reasons may bypass the constraints of the policy if it is converted to built-up land in the future.

3.2. *Effectiveness of the requisition-compensation balance policy on maintaining arable land productivity dynamic balance*

In the period of 2000—2010, the total productivity of the compensated arable land was greater than that of the arable land occupied by built-up land for nearly all provinces (Table 3). The realization of arable land productivity balance is mainly due to excess compensation of arable land quantity (i.e., arable land quantity balance index greater than 1). This is because the potential yield balance index was less than 1 for all provinces except Beijing, Shandong, Jiangsu and Shanghai. The average potential yield balance index revealed a widespread phenomenon of occupying superior arable land while compensating for inferior arable land, especially in Yunnan, Shaanxi, Guangxi and Xizang. This explains why the provincial arable land productivity balance index was lower than the corresponding quantity balance index. The arable land productivity balance index was less than 1 for Tianjin, Shandong, Henan, Jiangsu, Shanghai and Zhejiang, which is consistent with their imbalance in requisition-compensation of arable land quantity.

From 2010—2020, the provincial arable land productivity balance index decreased dramatically, driven by the decline in the arable land quantity balance index and the phenomenon of occupying superior arable land while compensating for inferior arable land. Provinces with a decline rate higher than 80% were Beijing, Guangdong, Guangxi, Chongqing, Guizhou and Qinghai. The arable land productivity imbalance was most serious in the North China Plain. The increase in the arable land productivity balance index in Xizang was driven by arable land quantity expansion because its potential yield balance index had fallen to 0.33. The phenomenon of occupying superior arable land while compensating for inferior arable land worsened since the potential yield

Table 4
Changes in the provincial farming distance in China during 2000–2020. Major grain-producing provinces are rendered in bold font.

Zoning	Provinces	average farming distance (unit: km)			Changes	
		2000	2010	2020	2000–2010	2010–2020
Northeast Plain	**Heilongjiang**	1.60	1.43	1.38	-10.62%	-3.82%
	Jilin	1.16	1.01	0.83	-13.42%	-17.89%
	Liaoning	0.81	0.83	0.65	2.26%	-21.85%
	Inner Mongolia	2.28	2.53	1.86	10.77%	-26.48%
North China Plain	Beijing	0.45	0.55	0.32	23.38%	-42.18%
	Tianjin	0.83	0.60	0.53	-27.83%	-11.25%
	Hebei	0.70	0.77	0.53	10.01%	-32.17%
	Shandong	0.76	0.60	0.45	-20.75%	-25.18%
	Henan	0.90	0.68	0.50	-24.30%	-27.43%
The Middle-lower Yangtze Plain	**Anhui**	1.05	1.01	0.75	-3.57%	-26.22%
	Jiangsu	0.95	0.79	0.64	-17.02%	-19.34%
	Jiangxi	1.42	1.40	0.98	-1.50%	-29.75%
	Hubei	2.84	2.79	1.85	-1.87%	-33.81%
	Hunan	3.56	3.01	1.64	-15.58%	-45.47%
	Shanghai	0.69	0.63	0.40	-9.17%	-35.77%
The southern hill region of China	Zhejiang	1.91	1.68	0.95	-12.05%	-43.73%
	Fujian	1.33	1.32	1.09	-0.48%	-17.70%
	Guangdong	1.45	1.33	0.85	-8.07%	-36.50%
	Guangxi	3.23	3.01	1.83	-6.68%	-39.21%
	Hainan	1.28	1.25	0.90	-1.74%	-28.51%
	Chongqing	3.41	4.68	2.35	37.32%	-49.74%
	Sichuan	4.93	5.16	3.22	4.60%	-37.51%
	Guizhou	5.94	5.54	3.11	-6.67%	-43.93%
	Yunnan	6.31	5.73	3.19	-9.25%	-44.34%
Irrigated agricultural region in the west	Shanxi	2.30	2.07	1.08	-9.93%	-47.62%
	Shaanxi	5.44	5.23	2.89	-3.81%	-44.78%
	Ningxia	4.75	4.67	1.69	-1.64%	-63.88%
	Gansu	5.58	5.67	2.39	1.69%	-57.86%
	Qinghai	3.29	3.41	2.44	3.55%	-28.47%
	Xizang	16.63	14.59	5.97	-12.24%	-59.09%
	Xinjiang	3.07	3.07	2.15	0.09%	-29.95%

balance index decreased. The potential yield imbalance was most serious in the irrigated agricultural region in the west and southern hill regions of China. The quantity balance index of Shanxi, Chongqing, Guangdong, Zhejiang and Anhui was higher than 1, but the excess compensation of arable land quantity cannot fill the lost arable land productivity, which causes them to have a productivity balance index less than 1.

The decrease in China's total arable land productivity has accelerated in the past 20 years. From 2000—2010, the total reduction in arable land productivity was 9612.1 thousand tons. To 2010—2020, the total reduction increased to 31254.6 thousand tons. The largest productivity decline occurred in Hebei, Jiangsu, Shandong and Henan.

The provincial total arable land productivity change rate during 2000—2020 is presented in Fig. 2. Sinkiang was the only province distributed in the first quadrant, whose total arable land productivity continued to increase in the two periods. The total arable land productivity of Inner Mongolia, Hainan, Qinghai and Guizhou decreased in the first period (i.e., 2000—2010) and increased in the second period (i.e., 2010—2020). For Beijing, Jilin, Hubei, Hunan, Guangxi, and Chongqing, the situation was reversed. The total arable land productivity of twenty provinces decreased in both periods. For 75% of these provinces, including all major grain-producing provinces in the third quadrant, the productivity decrease accelerated. Provinces with a high decrease rate of total arable land productivity were distributed mainly in coastal regions in eastern China. From 2010—2020, 12/13 major grain-producing provinces experienced a decrease in total arable land productivity. The authors argue that conservation of arable land productivity has become more important than conservation of arable land quantity in mainland China.

3.3. Influence of the requisition-compensation balance policy on farming distance

Spatially, the average farming distance showed an overall characteristic of low in the north and high in the south (Table 4). The farming distance in the plains was significantly smaller than that in the mountainous hilly areas and plateau areas, with an overall average of less than 1.5 km. Among them, the average farming distance in the provinces within the North China Plain was the smallest, generally less than 1 km. Hunan and Hubei had higher average farming distances than their neighbouring provinces in the plains due to the extensive mountainous areas within them. In the southern hill region of China, Hainan, Guangdong, and Fujian had relatively small average farming distances. Average farming distances were generally high in the provinces of the western irrigated agricultural region, especially in the sparsely populated highland areas. The average farming distance in Tibet may be overestimated in 2000 and 2010 because most of the local arable land was distributed in semiarid river valleys, and the nearby sparse rural residential regions were scattered and difficult to identify in the 30-metre resolution remote sensing images.

From the perspective of temporal change, the average farming distance decreased by 0.48%– 27.83% in 22/31 provinces during 2000—2010. The average farming distance increased in Liaoning, Inner Mongolia, Beijing, Hebei, Chongqing, Sichuan, Gansu, Qinghai, and Xinjiang. The reduction in the average farming distance expanded to all provinces during 2010–2020, and the magnitude of the reduction was further intensified. The reduction in average farming distance was higher in mountainous areas than in plain areas. The main reason for this phenomenon is the increased marginalization of compensated

Table 5
Provincial farming distance changes in compensated arable land and occupied arable land during 2000–2020.

	Average occupied farming distance (km)			Average compensated farming distance (km)		
Provinces	2000–2010	2010–2020	Ratio of change	2000–2010	2010–2020	Ratio of change
Heilongjiang	0.37	0.37	1.35%	2.16	2.62	21.17%
Jilin	0.12	0.44	263.02%	1.90	1.28	-32.61%
Liaoning	0.20	0.42	106.88%	0.99	1.24	24.75%
Inner Mongolia	0.65	1.08	66.18%	2.87	4.33	50.92%
Beijing	0.29	0.34	16.74%	0.18	0.74	312.47%
Tianjin	0.56	0.29	-48.79%	0.80	0.60	-25.10%
Hebei	0.24	0.40	69.35%	0.73	1.13	55.40%
Shandong	0.29	0.34	14.70%	0.47	1.05	123.35%
Henan	0.37	0.33	-10.22%	1.15	0.81	-29.22%
Anhui	0.21	0.48	132.90%	1.57	1.37	-12.78%
Jiangsu	0.37	0.40	7.71%	0.78	1.27	63.22%
Jiangxi	0.31	0.71	129.58%	1.76	1.78	1.18%
Hubei	0.75	1.06	41.42%	3.27	3.67	12.08%
Hunan	1.31	1.44	9.64%	3.84	3.31	-13.62%
Shanghai	0.34	0.32	-3.21%	1.52	0.69	-54.42%
Zhejiang	0.56	0.75	34.15%	2.24	3.17	41.41%
Fujian	0.21	0.43	104.77%	1.53	1.56	1.93%
Guangdong	0.32	0.62	90.51%	1.81	1.87	3.36%
Guangxi	0.56	1.17	110.77%	4.33	5.92	36.79%
Hainan	0.10	0.53	427.34%	1.33	1.46	9.41%
Chongqing	1.26	1.82	44.40%	2.99	5.88	96.85%
Sichuan	0.59	1.66	183.40%	6.90	6.44	-6.70%
Guizhou	1.54	2.34	51.88%	6.35	5.88	-7.35%
Yunnan	1.08	1.79	66.71%	7.54	6.66	-11.67%
Shanxi	0.71	1.00	40.45%	2.81	2.89	2.84%
Shaanxi	0.78	1.21	55.15%	7.20	7.12	-1.22%
Ningxia	0.35	1.94	458.33%	5.37	5.65	5.08%
Gansu	0.49	2.57	421.25%	6.68	6.94	3.87%
Qinghai	0.94	1.71	81.33%	4.07	6.24	53.30%
Xizang	4.49	6.81	51.75%	22.10	14.55	-34.17%
Xinjiang	0.74	1.69	129.43%	5.77	6.99	21.17%

Note: Major grain-producing provinces are rendered in bold font. Average occupied farming distance is the average farming distance of arable land be converted to built-up land (unit: km). Average compensated farming distance is the average farming distance of compensated arable land (unit: km).

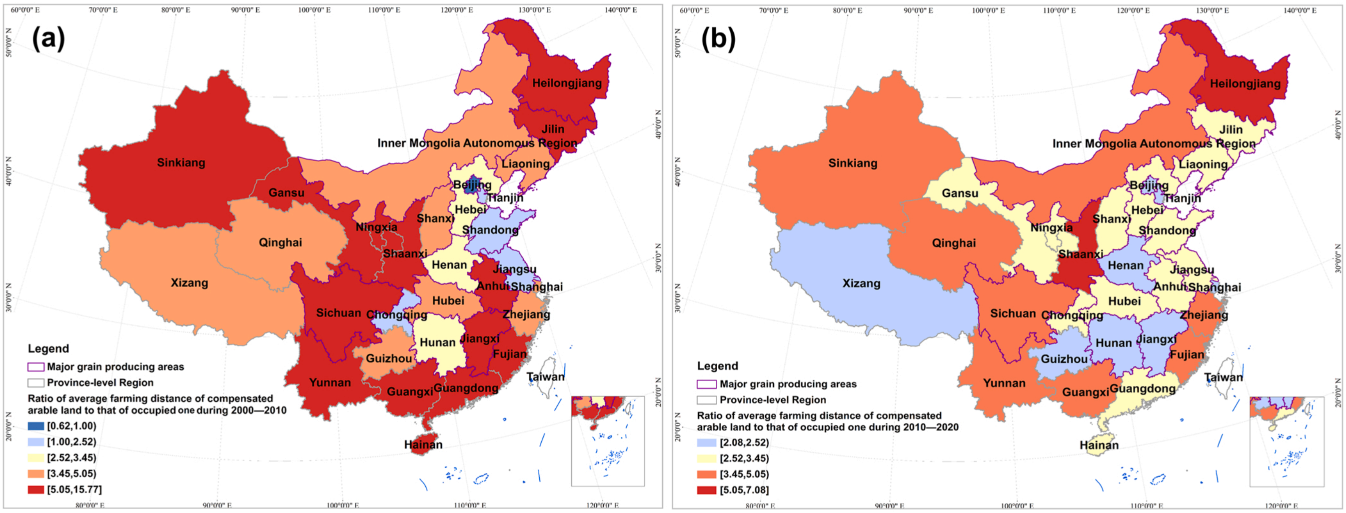


Fig. 3. (a) Ratio of the average farming distance of compensated arable land to that of occupied land during 2000—2010. (b) Ratio of the average farming distance of compensated arable land to that of occupied land during 2010—2020. The index is calculated as the ratio of compensated arable land to occupied arable land.

arable land with high farming distance due to lower grain yield and the increase in abandoned areas. The marginalization is higher in mountainous areas than in plain areas because of the difficulty in promoting large-scale operation, low labour productivity, and high farming costs. In addition, the expansion of built-up land and the construction of infrastructure in rural areas is another reason for the reduction in average farming distance.

Table 5 indicates that the provincial average farming distance changes of compensated arable land and occupied arable land during 2000–2020. The average occupied farming distance is the average farming distance of arable land converted to built-up land. First, the average farming distance of all arable land occupied by built-up land was significantly smaller than that of all arable land at the provincial level, which is consistent with the reality that the expansion of built-up land usually occurs at the edge of residential areas. Provinces in mountainous areas and plateau areas (including Chongqing, Sichuan, Guizhou, Yunnan, Ningxia, Gansu, Qinghai, Tibet, etc.) were affected by factors such as topography and altitude, and the average farming

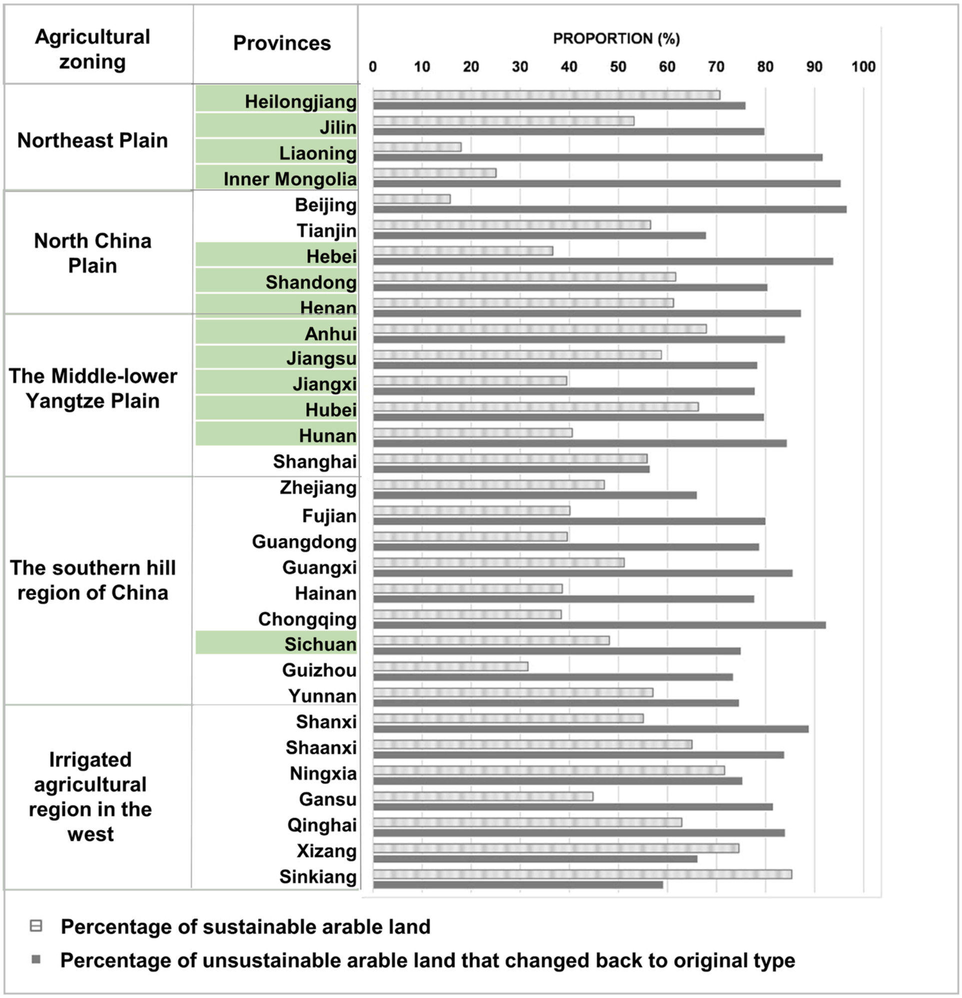


Fig. 4. Percentage of provincial sustainable arable land. Major grain-producing provinces are rendered in green.

distance of arable land occupied by built-up land was higher than that of provinces in plains areas. This difference became more pronounced as the proportion of arable land occupied by built-up land in these provinces intensified from 2010 to 2020. During 2010—2020, the average farming distance of compensated arable land increased further in more than 60% of the provinces, with the most significant changes occurring in Beijing, Shandong and Chongqing. For most provinces, the average farming distance of arable land occupied by built-up land increased further during 2010–2020 compared to the previous decade, which was caused by the accelerated expansion of built-up land. Second, the average farming distance of compensated arable land at the provincial level reached 2–7 times that of occupied arable land. However, the average farming distance of the whole arable land at the provincial level decreased by 3.82–63.88% during the same period. This contradiction is mainly due to increasing marginalization and opportunity costs resulting in arable land with high farming distance (including arable land that was compensated in the past) to be used with low intensity or even abandoned and thus identified as other land use types by remote sensing classification models. This factor outweighed that of "occupy nearby arable land while compensating farther one", resulting in a reduction in the provincial average farming distance.

Fig. 3 shows that during the period 2000—2010, the average farming distance of compensated arable land was much greater than that of occupied arable land in most provinces in China, especially more significantly in the northeast, northwest, southwest, and southeast coastal regions. This indicated that the compensated arable land was farther away from the urban residential area compared to the occupied arable land. Most of the compensated arable land is poor-quality arable land in the outer suburbs, while most of the occupied arable land is high-quality arable land in the suburbs of cities. Only in Beijing was the average farming distance of compensated arable land smaller than that of occupied arable land, indicating that compensated arable land was closer to urban residential areas than occupied arable land. Compared with the period 2010—2020, the difference in the ratio of the average farming distance of compensated arable land to that of occupied arable land decreased significantly, indicating that the distance between the compensated arable land and the occupied arable land from urban residential areas was shrinking. Among them, the reduction in the North China Plain and the central region was more obvious. From a national perspective, the average farming distance of compensated arable land was greater than that of the occupied land. Among them, Heilongjiang in the northeast, Xinjiang, Qinghai, Shanxi, and Inner Mongolia in the northwest, Sichuan and Yunnan in the southwest, and Zhejiang, Fujian, and Guangxi in the southeast coast were particularly noticeable.

3.4. *Sustainability of arable land use under the requisition-compensation balance policy*

The percentage of sustainable compensated arable land in most provinces was low, as shown in Fig. 4. From 2000–2020, only 4 of 31 provinces in China had a percentage of sustainable arable land exceeding 70%. The percentage of sustainable arable land was generally low in the southern hill region and Liaoning, Beijing and Inner Mongolia. This indicated that the utilization and protection of arable

Table 6
Provincial sustainability of arable land use from 2000 to 2020.

Zoning	Provinces	Q_{AE}	RQ_{AB}	R_{AE}	R_{AB}	R_{OB}
Northeast Plain	**Heilongjiang**	56.47	1.36%	2.68%	69.47%	27.85%
	Jilin	18.91	1.37%	0.74%	89.58%	9.68%
	Liaoning	29.01	3.34%	2.35%	81.24%	16.41%
	Inner Mongolia	130.22	0.75%	1.37%	43.45%	55.18%
North China Plain	Beijing	1.89	12.17%	1.75%	86.50%	11.75%
	Tianjin	3.25	8.00%	3.14%	83.21%	13.65%
	Hebei	32.34	1.27%	0.54%	91.81%	7.65%
	Shandong	31.78	4.37%	1.20%	94.50%	4.31%
	Henan	17.20	2.56%	0.55%	96.37%	3.08%
The Middle -lower Yangtze Plain	**Anhui**	33.57	3.07%	2.02%	90.04%	7.95%
	Jiangsu	21.89	7.45%	1.89%	89.19%	8.92%
	Jiangxi	52.79	2.82%	3.64%	60.08%	36.27%
	Hubei	64.76	1.28%	1.74%	82.68%	15.58%
	Hunan	109.07	2.66%	7.04%	53.34%	39.63%
	Shanghai	1.10	10.00%	1.42%	86.87%	11.71%
The southern hill region of China	Zhejiang	36.98	4.71%	3.46%	72.06%	24.48%
	Fujian	30.76	2.99%	3.18%	65.43%	31.38%
	Guangdong	66.01	7.60%	5.43%	55.53%	39.04%
	Guangxi	104.92	2.12%	5.25%	66.04%	28.71%
	Hainan	18.88	5.24%	6.95%	30.53%	62.53%
	Chongqing	28.98	0.38%	0.58%	86.82%	12.59%
	Sichuan	76.66	1.19%	2.39%	82.96%	14.65%
	Guizhou	99.48	1.64%	6.49%	60.63%	32.88%
	Yunnan	120.41	3.35%	9.02%	61.04%	29.94%
Irrigated agricultural region in the west	Shanxi	33.41	3.41%	3.05%	80.61%	16.34%
	Shaanxi	51.30	1.23%	2.35%	71.26%	26.39%
	Ningxia	11.38	1.58%	1.14%	60.47%	38.39%
	Gansu	76.95	1.17%	2.25%	73.47%	24.28%
	Qinghai	6.89	3.34%	1.70%	44.25%	54.06%
	Xizang	10.52	7.13%	11.81%	24.72%	63.46%
	Xinjiang	18.64	3.11%	1.13%	56.68%	42.19%

Note: Q_{AE} is the quantity of arable land that converted to ecological land (i.e., forest; grassland; water) during 2000—2010 (unit: 10^4 ha); RQ_{AB} is the percentage of Q_{AE} that was converted to built-up land during 2010—2020; R_{AE} is the total area of arable land that was converted to forest, grassland, and water during 2000—2010 and then occupied by built-up land during 2010—2020, as a percentage of the increase in built-up land; R_{AB} is the quantity of arable land occupied by built-up land during 2010—2020, as a percentage of the increase in built-up land; and R_{OB} is the quantity of other land occupied by built-up land during 2010—2020, as a percentage of the increase in built-up land. Details can be found in Eq. (9). Major grain-producing provinces are rendered in bold font.

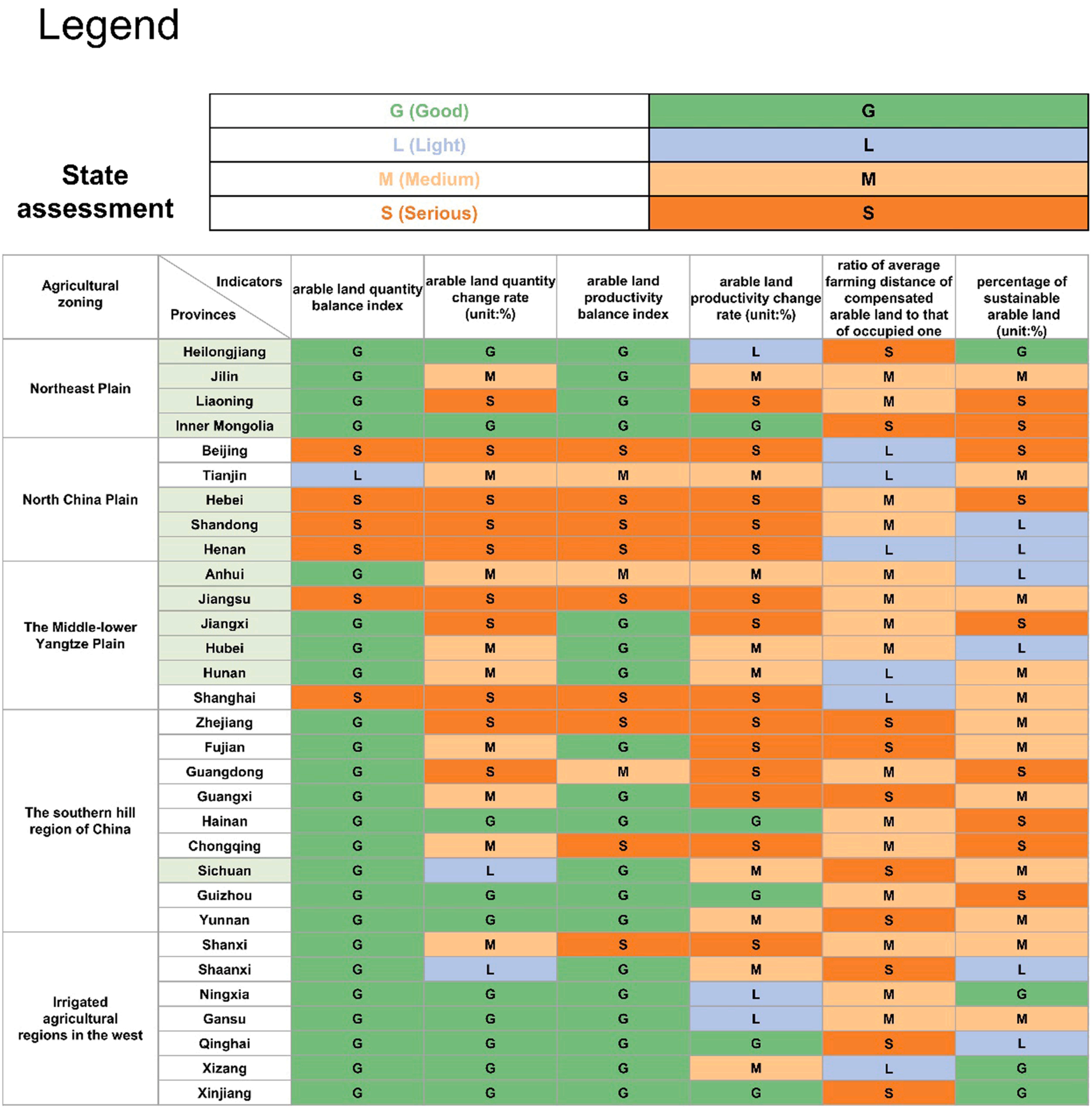
land in these provinces was insufficiently implemented and monitored. Much of the compensated arable land was located in unsuitable areas, which made them difficult to use for long-term crop cultivation in the next decade. In contrast, Heilongjiang in the Northeast Plain, Shandong and Henan in the North China Plain, Anhui and Hubei in the middle-lower Yangtze Plain, and Shaanxi, Ningxia, Xizang and Xinjiang in the western provinces had relatively higher percentages of sustainable arable land. Land-use policies and measures such as land consolidation and remediation, arable land transfer, and land reclamation have achieved remarkable results for the sustainable use of compensated arable land in these provinces. It is worth noting that the regions with low arable land sustainability had a high percentage of unsustainable arable land whose land use type changed back to the original type in the last decade, especially in Liaoning, Inner Mongolia, Beijing, Hebei, and Chongqing. Moreover, the percentage of unsustainable arable land that changed back to the original type was higher in major grain-producing provinces, reaching more than 70%.

As shown in Table 6, encroachment on arable land is the main source of expansion for built-up land in Henan (96.37%), Shandong (94.50%), Hebei (91.81%), Anhui (90.04%), Jilin (89.58%) and Jiangsu (89.19%). The index RQ_{AB} (i.e., the ecological land converted from arable land in the first decade was occupied by built-up land in the second decade) was high in Beijing (12.17%), Tianjin (8.00%), Shanghai (10.00%), Jiangsu (7.45%), Guangdong (7.60%) and Tibet (7.13%). Its percentage of the increase in built-up land exceeds 6%. In addition, the conversion of arable land to built-up land in these provinces contributes significantly less to the expansion of built-up land than in other provinces, probably because their arable land was already heavily encroached by built-up land in the previous decade. Therefore, those provinces with low R_{AE} (i.e., the percentage of the total area of arable land that was converted to forest, grassland, and water during 2000—2010 and then converted to built-up land during 2010—2020) also need to pay attention to the continuity of arable land in the implementation of the "requisition-compensation balance policy".

4. Discussion

4.1. Summarized analysis of the effect and deficiency of the requisition-compensation balance policy in China

To analyse the implementation of the "requisition-compensation balance policy", the results of 6 indicators during 2010–2020 have been summarized. As shown in Fig. 5, the overall situation in the Northeast Plain was good. The arable land quantity balance and arable land productivity balance reached a good level. The arable land productivity decrease in Jilin and Liaoning Provinces is mainly caused by a reduction in arable land area. The problems of arable land marginalization and arable land sustainability are prominent in the Northeast Plain and need more attention. Protection of arable land quantity and productivity is commonly serious for provinces in the North China Plain. This problem was explicit because the balance index and change rate of arable land quantity and productivity were both at a serious or medium level. The problem of "occupy nearby arable land while compensating farther one" was relatively mild, and the sustainability of arable land in Shandong and Henan was better. The provinces in the middle-lower Yangtze Plain showed an implicitly serious situation, whose arable land quantity and productivity appeared to be generally in good status, but the change rate was all in medium or serious status. Provinces in the southern hill region of China have also presented an implicitly serious situation in maintaining arable land quantity and productivity. Thereinto, the decline of



Legend

State assessment	
G (Good)	G
L (Light)	L
M (Medium)	M
S (Serious)	S

Agricultural zoning	Indicators / Provinces	arable land quantity balance index	arable land quantity change rate (unit:%)	arable land productivity balance index	arable land productivity change rate (unit:%)	ratio of average farming distance of compensated arable land to that of occupied one	percentage of sustainable arable land (unit:%)
Northeast Plain	Heilongjiang	G	G	G	L	S	G
	Jilin	G	M	G	M	M	M
	Liaoning	G	S	G	S	M	S
	Inner Mongolia	G	G	G	G	S	S
North China Plain	Beijing	S	S	S	S	L	S
	Tianjin	L	M	M	M	L	M
	Hebei	S	S	S	S	M	S
	Shandong	S	S	S	S	M	L
	Henan	S	S	S	S	L	L
The Middle-lower Yangtze Plain	Anhui	G	M	M	M	M	L
	Jiangsu	S	S	S	S	M	M
	Jiangxi	G	S	G	S	M	S
	Hubei	G	M	G	M	M	L
	Hunan	G	M	G	M	L	M
	Shanghai	S	S	S	S	L	M
The southern hill region of China	Zhejiang	G	S	S	S	S	M
	Fujian	G	M	G	S	S	M
	Guangdong	G	S	M	S	M	S
	Guangxi	G	M	G	S	S	M
	Hainan	G	G	G	G	M	S
	Chongqing	G	M	S	S	M	S
	Sichuan	G	L	G	M	S	M
	Guizhou	G	G	G	G	M	S
	Yunnan	G	G	G	M	S	M
Irrigated agricultural regions in the west	Shanxi	G	M	S	S	M	M
	Shaanxi	G	L	G	M	S	L
	Ningxia	G	G	G	L	M	G
	Gansu	G	G	G	L	M	M
	Qinghai	G	G	G	G	S	L
	Xizang	G	G	G	M	L	G
	Xinjiang	G	G	G	G	S	G

Fig. 5. State assessment of China's arable land based on multiple indicators during 2010–2020. The 6 indicators are divided into 4 levels: Good, Light, Medium and Serious. G (Good) represents that the value of the indicator meets the balance, and then the value of the indicator that does not meet the balance is subdivided into L (Light), M (Medium), and S (Serious). The partition standards of the arable land quantity balance index Q_B are good ($Q_B \geq 1$); light ($1 > Q_B \geq 0.9$); medium ($0.9 > Q_B \geq 0.7$); and serious ($Q_B < 0.7$). The partition standards of arable land quantity change rate Q_R are good ($Q_R \geq 0$); light ($0 > Q_R \geq -0.02$); medium ($-0.02 > Q_R \geq -0.05$); and serious ($Q_R < -0.05$). The partition standards of the arable land productivity balance index $R_{y,w}$ are good ($R_{y,w} \geq 1$); light ($1 > R_{y,w} \geq 0.95$); medium ($0.95 > R_{y,w} \geq 0.8$); and serious ($R_{y,w} < 0.8$). The partition standards of arable land productivity change rate P_R are good ($P_R \geq 0$); light ($0 > P_R \geq -0.01$); medium ($-0.01 > P_R \geq -0.04$); and serious ($P_R < -0.04$). The partition standards of R_D (i.e., the ratio of the average farming distance of compensated arable land to that of occupied land) are good ($R_D < 1$); light ($2.5 > R_D \geq 1$); medium ($3.5 > R_D \geq 2.5$); and serious ($R_D \geq 3.5$). The partition standards of the percentage of sustainable arable land P_S are good ($P_S \geq 70$); light ($70 > P_S \geq 60$); medium ($60 > P_S \geq 40$); and serious ($P_S < 40$). Major grain-producing provinces are rendered in green.

arable land productivity in this region is more serious than that of arable land quantity because of "occupying high quality arable land while compensating inferior one". Other urgent challenges in this region were relief of the phenomenon of "occupying nearby arable land while compensating for farther arable land" and relatively low sustainability for compensated arable land. The irrigated agricultural regions in the west both reached the arable land quantity balance and productivity balance with a mild decline in arable land quantity. The main problem was that the average farming distance of compensated arable land was greater than that of occupied arable land, which aggravated arable land marginalization.

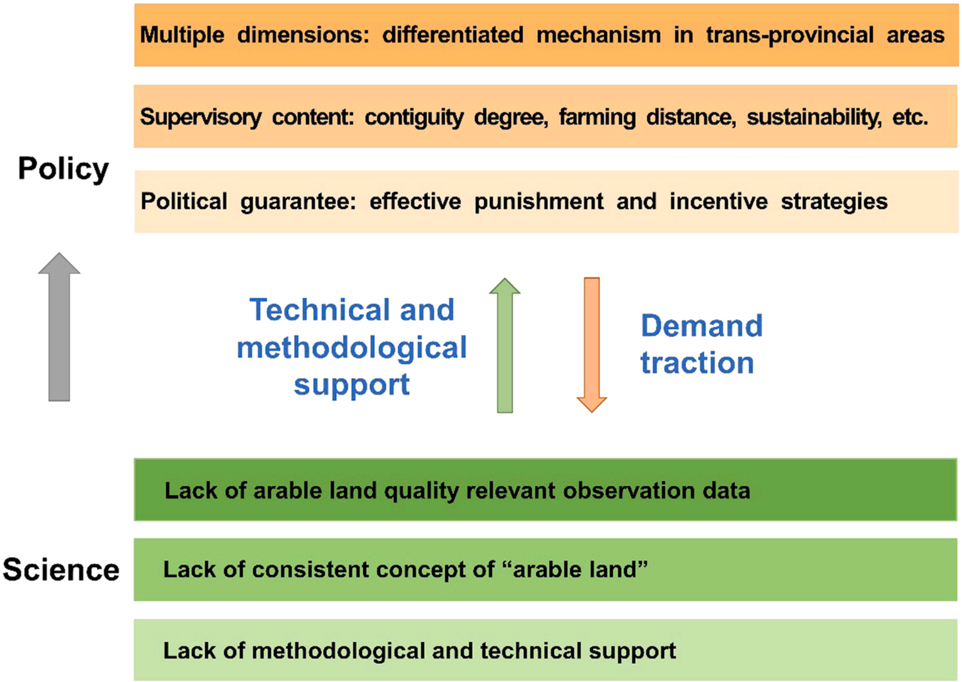


Fig. 6. Challenges along optimization of the requisition-compensation balance policy in two respects: data, theory and methodology; policy design and implement.

4.2. Comparative studies on the requisition-compensation balance in China

The results of this study were verified by comparison with the existing research results (*see detailed results in Appendix A*). Although different from the research data and research methods adopted by different researchers, this study was basically consistent with the research conclusions of many researchers, which also confirmed the credibility of the research conclusions of this study (Deng et al., 2006; Xu et al., 2015; Kuang et al., 2021; Yan et al., 2017; Liu et al., 2014a). Additionally, based on previous studies, the research had more advantages in various aspects. For example, for arable land quantity, Xu et al. (2015) believed that China's arable land area decreased from 2000 to 2010, most provinces failed to achieve the basic target of the arable land quantity balance, and it was difficult to effectively implement the arable land balance in the eastern region. Zhou et al. (2023) argued that China's arable land increased first and then decreased during 1996—2019. The characteristics of regional land-use change are obvious. Arable land in Northeast, Inner Mongolia and Xinjiang had been increasing, while in the east coast and southwest continued to decrease. Liu, Zhou (2021a) argued that the reduction rate of arable land in China gradually slowed down during 1978—2018. The quantity of arable land remains dynamic balance, but the arable land quality had not achieved. Our study extended the time period from 2000 to 2020 and focused on the arable land quantity balance as well as total area changes. The results showed that China basically reached the arable land quantity balance at the national level. The imbalance of arable land quantity was mainly distributed in the eastern and central regions of China, and the pressure on the arable land quantity balance in southwest China increased during the study period. For arable land quality, according to Kuang et al. (2021), the croplands in northeast China were characterized by comparatively low quality and low productivity during 1990—2015, and the redistribution of cropland to marginal lands impaired ecosystem services and led to environmental deterioration. Zhou et al. (2020) pointed out that the occupation of arable land, forest and grassland mainly comes from built-up land during 1995–2015. Liu (2019) believed that arable land quality declined in the process of "requisition-compensation balance", and the distance between occupied and compensated land was large. The situation of the ecologically fragile area was also worrying. For land policy making, Liu et al. (2014a) analysed the key problems of land use in China, and innovatively propose an innovative three-layer (i.e., strategic layer; policy layer; protection layer) coupling strategic land-use policy system which possesses Chinese characteristics. Liu's (2014a) strategic land-use policy system is widely recognized and provides great guidance for optimizing the design and implementation of the "requisition-compensation balance policy". In this study, we came to the same conclusion that most of the provinces in the Northeast Plain showed a continuous arable land productivity decrease from 2000 to 2020. In the Northeast Plain, the built-up land occupied a large quantity of high-grade arable land, and the compensated arable land was mainly low yielding. In this study, we also studied the farming distance and sustainability of arable land, which have less considered in previous studies. During 2010–2020, the average farming distance of compensated arable land at the provincial level reached 2–7 times that of occupied arable land. According to Liu's (2014a) viewpoint, this "occupy nearby arable land while compensating farther one" phenomenon is because "some local governments tended to explore the unused land of low cost rather than land consolidation". However, the average farming distance of the whole arable land at the provincial level decreased by 3.82–63.88% during the same period. This contradiction is mainly due to increasing marginalization and opportunity costs resulting in arable land with high farming distance (including arable land that was compensated in the past) to be used with low intensity or even abandoned and thus identified as other land use types by remote sensing classification models. Furthermore, the authors of this paper believed that the percentage of sustainable arable land in each province was generally low, and 17 of 31 provinces in China had less than 50% sustainable arable land. In addition, as the research period of this paper is the last 20 years, some conclusions vary with different research periods.

4.3. Challenges along optimization of the requisition-compensation balance policy

To improve the effectiveness of the "requisition-compensation balance policy", the contradiction between humans and land should be mitigated upon cognizing the overall information of arable land systems (e.g., land cover, land quality, potential yield, ecosystem service, and soil pollution) and exploring trade-off strategies for agricultural intensification and spatial optimum allocation. Challenges of that goal mainly focus on two respects: (a) data, theory and methodology and (b) policy design and implementation, as shown in Fig. 6.

Optimization and supervision of the "requisition-compensation balance policy" put forward high requirements for data, theory (mainly related to the mechanism of arable land use change affected by human activities and the mutual feedback mechanism of arable land use-quality- ecosystem services) and methodology of arable land computing (Yao et al., 2017; Ye et al., 2018, 2020a; Zhang and Li, 2022). First, the availability of high-resolution remote sensing data promoted land-cover change research and brought a gradually clear understanding to spatial and temporal changes in arable land distribution around the world (Liu et al., 2014a, Liu, 2018a; Liu et al., 2018b). Despite this, there is still a long way to go to meet the research requirements because arable land supplements mostly occur in the form of fragmentation in very small areas, which requires high spatial resolution of remote sensing data for detection (Ye et al., 2016, 2018; Wang et al., 2022). The other challenge is the deficiency in long-term point-scale observational data on arable land properties, particularly indicators for the evaluation of ecosystem services. Second, another obstacle comes from the inconsistent concept of "arable land" among scientists and government officials, which makes the spatial distribution of arable land in multiple open-access datasets different. These datasets were also different from official data from the Ministry of Natural Resources, China. Third, to provide methods and technical support for the construction of arable land quality observation networks (including the development of professional field data collection equipment), especially for soil microorganism investigations (Wan et al., 2021; Ye et al., 2020b). Fourth, theory and innovative methods from a holistic perspective should be promoted for estimating arable land quality and trading off arable land use and ecological protection.

Formulating and implementing an effective arable land "requisition-compensation balance policy" is the other major challenge. Additionally, it is important to have a comprehensive consideration of multiple dimensions of the arable land "requisition-compensation balance", establish a systematic planning and design method, and formulate a differentiated regulation mechanism of arable land requisition compensation in trans-provincial areas. This is because the effect of the arable land "requisition-compensation balance policy" is the regional natural-social-economic-technology result of many factors. If regional differences are not considered, the adoption of uniform standards of implementation may exacerbate land fragmentation, marginalization and ecological destruction in some areas. In some provinces, it will be difficult to stimulate the potential yield of arable land, resulting in a waste of resources. Additionally, excessive interprovincial occupation may also increase the ecological risk of arid and semiarid areas in northwest China, resulting in an insufficient water supply or increased pesticide use. However, the contiguity degree, farming distance and sustainability of compensated arable land should be designed as supervisory content in arable land "requisition-compensation balance policy". Third, in the absence of effective punishment and incentive strategies, the arable land "requisition-compensation policy" is difficult to guarantee and implement. Liu et al. (2018b) pointed out that government at all levels need to pay more attention on land systems reforming and focus more on the economic measures of land use change process. According to some studies (Liu et al., 2010; Su et al., 2020), the most important cause for the inefficiency of the system is the relationship between the central government and the local government. Local governments are the direct administrators of arable land. Influenced by the current objective GDP-oriented evaluation, their understanding and motivation for arable land protection are very different from those of the central government. In the arable land balance system, insufficient attention is given to the interest difference between the central government and local government, leading to deviations in the implementation of the policy. Fourth, the cost of violating land-management regulations is low. Therefore, the competent authority for the protection of arable land must clarify who is mainly responsible for the damage to arable land. The impact of arable land requisition and compensation on potential crop outputs, water loss and soil erosion, agricultural carbon emissions and agro-product quality safety should be estimated and used as standards of performance.

5. Conclusions

In this study, the provincial effectiveness of the "requisition-compensation balance policy" in mainland China in two periods (i.e., 2000—2010; 2010—2020) was estimated from four perspectives: arable land quantity dynamic balance; arable land productivity dynamic balance; farming distance balance and sustainability of arable land use. According to the results, first, the arable land quantity balance was achieved during 2000–2020 from a national perspective. There were still 19–23% of provinces have failed to reach the quantity balance. The reduction in the total arable land area was effectively controlled from 2482.8 (during 2000—2010) to 2108.4 (during 2010—2020) (unit: thousand ha.). The role of the "requisition-compensation balance policy" in maintaining regional arable land quantity increased because the ratio of arable land quantity converted to built-up land to the total quantity of arable land occupied increased pervasively in multiple provinces. Second, the decrease in China's total arable land productivity was. The average potential yield balance index was less than 1 for nearly all provinces during 2000–2010 and became even worse in the next decade, which revealed a widespread and anabatic phenomenon of occupying superior arable land while compensating for inferior arable land. The conservation of arable land productivity has become more important than the conservation of quantity. Third, the average farming distance showed an overall characteristic of being low in the north and high in the south. The average farming distance of compensated arable land at the provincial level is obviously higher than that of occupied arable land during 2000—2020. However, the average farming distance decreased by 0.48–27.83% in 22/31 provinces during 2000—2010. Then, the reduction in the average farming distance was further intensified and expanded to all provinces during 2010—2020. This contradiction is mainly due to increasing marginalization and opportunity costs resulting in arable land with high farming distance (including arable land that was compensated in the past) to be used with low intensity or even abandoned and thus identified as other land use types by remote sensing classification models. Fourth, the percentage of sustainable compensated arable land in most provinces was lower than 70% during 2000—2020. This indicates that the utilization and protection of arable land in these provinces were insufficiently implemented and monitored. Much of the compensated arable land was located in unsuitable areas, which made them difficult to use for long-term crop cultivation in the next decade. Challenges along optimization of the "requisition-compensation balance policy" were discussed from two respects: data, theory and methodology and policy design and implementation. The authors argue that a more comprehensive "requisition-compensation balance policy" should be designed considering not only the quantity and productivity of arable land but also the farming distance, sustainability and ecological protection. A differentiated regulation mechanism of arable land requisition compensation in trans-provincial areas should be formulated. Effective punishment and incentive strategies should be designed. This study can provide guidance for optimizing the implementation of regional arable land protection and can also provide a reference for other countries to protect arable land.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

The data used in this article is all public sharing datasets. We annotated the data acquisition address in the manuscript.

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Appendix A

Fig. A.1,Table A.1.

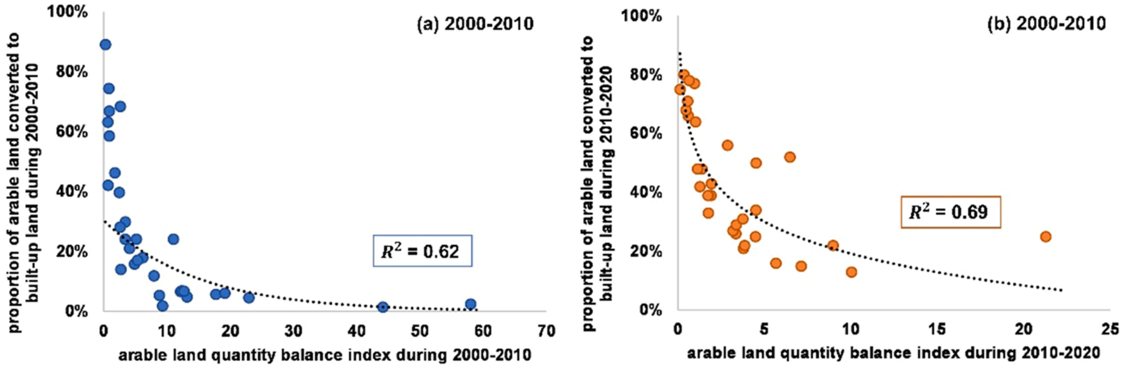

Fig. A.1. (a) 2000–2010 and (b) 2010–2020 The correlation between arable land quantity balance index and proportion of arable land converted to built-up land by province in China.

Table A.1
Comparison with the results of previous studies.

	Results of previous studies	Results of this paper
1	Xu et al. (2015) believed that China's arable land area decreased from 2000 to 2010, most provinces failed to achieve the basic target of the arable land quantity balance, and it was difficult to effectively implement the arable land balance in the eastern region.	From 2000–2020, China basically reached the arable land quantity balance at the national level. The imbalance of arable land quantity was mainly distributed in the eastern and central regions of China, and the pressure on the arable land quantity balance in southwest China will increase in the future.
2	Chen et al. (2010) believed that China achieved the arable land quantity balance during 1999–2007, but it did not fundamentally reverse the situation of continuous decrease of arable land.	During 2000–2020, arable land had declined in most provinces. The North China Plain and the Middle-lower Yangtze Plain showed the greatest decline.
3	According toTan et al. (2005), the total arable land in China was in dynamic balance from 1991 to 2003, but the quality of arable land deteriorated year by year and the productivity of arable land declined.	In the recent two decades, arable land productivity gradually tends to balance by imbalance. The productivity of arable land declined in China.
4	According toDeng et al. (2006), in the 1990 s, there was a national increase of 5% in total agricultural productivity.	During 2000–2020, the decrease of productivity was greater than the increase of area. The productivity balance index of 28 provinces out of 31 administrative regions decreased, and the yield balance index of 25 provinces decreased.
5	Liu et al. (2015a) believed that lost potential yield was primarily in the Middle-lower Yangtze Plain and the Huang-Huai-Hai Plain during 1990–2010. South China became a new key area of lost potential yield during 2000–2010.	During 2000–2020, the occupied arable land was mostly located in the southeast, while the compensated arable land was mostly located in the north and northwest.
6	According toKuang et al. (2021), the crop lands in northeast China were characterized with relatively low quality and low productivity during 1990–2015, the cropland redistribution to marginal lands had diminished ecosystem services and caused environmental deterioration.	Most of the provinces in the Northeast Plain, showed a continuous arable land productivity decrease from 2000 to 2020, the built-up land occupied a large number of high-grade arable land and the compensated arable land was mainly low-yielding.
7	Yan et al. (2017) believed that land use in southeastern China was more intensive than that in the northwestern part in 2000. Huang-Huai-Hai Region had the largest area of artificial land but was inferior to Middle and Lower Reaches of the Yangtze River Region in its land use intensity.	During 2000–2020, the development and construction activities in Henan, Shandong and the Middle-lower Yangtze Plain were very intense. The natural ecological environment background in northwest China is relatively fragile, and the ecological security situation is worth paying attention to.
8	Yan et al. (2016) believed that low-yield cropland was distributed in regions with poor natural geographic and climatic conditions, such as the Loess Plateau, the Yunnan-Guizhou Plateau, and the farming-pastoral ecotone of Inner Mongolia during 2001–2010.	During 2000–2020, the productivity of the Loess Plateau region and southwest region decreased obviously, the soil and water loss in these two regions was serious, and most of the arable land was located in hilly mountains.
9	According toSong et al. (2014), the arable land quantity balance had been realized nationwide from 1999 to 2008, but it had some negative effects on the ecological environment.	During the study period, the requisition-compensation balance policy still focuses on the balance of quantity, while the quality and ecology of arable land deteriorate.
10	According toZhao et al. (2014), during 1999–2009, the overall sustainability of land use in all regions was low. Among the 31 provinces, about 71% showed an upward trend of land use sustainability, but the growth rate was uneven.	From 2000–2020, the percentage of sustainable arable land in each province was generally low, and 4 of 31 provinces in China had more than 70% sustainable arable land.

References

Arsanjani, J.J., See, L., Tayyebi, A., 2016a. Assessing the suitability of GlobeLand30 for mapping land cover in Germany. Int. J. Digit. Earth 9 (9), 873–891.

Arsanjani, J.J., Tayyebi, A., Vaz, E., 2016b. GlobeLand30 as an alternative fine-scale global land cover map: Challenges, possibilities, and implications for developing countries. Habitat Int. 55, 25–31.

Bai, X., Shi, P., Liu, Y., 2014. Realizing China's urban dream. Nature 509 (7499), 158–160.

Brovelli, M.A., Molinari, M.E., Hussein, E., Chen, J., Li, R., 2015. The first comprehensive accuracy assessment of GlobeLand30 at a national level: methodology and results. Remote Sens. 7, 4191–4212.

Cao, X., Li, A., Lei, G., Lei, G., Tan, J., Zhang, Z., Yan, D., Xie, H., Zhang, S., Yang, Y., et al., 2016. Land cover mapping and spatial pattern analysis with remote sensing in Nepal. J. Geo-Inf. Sci. 18, 1384–1398.

Chen, J., Wu, H., Li, S., 2017a. Research progress of global land domain service computing: take globeland 30 as an example. Acta Geod. Et Cartogr. Sin. 46 (10), 1526–1533.

Chen, J., Cao, X., Peng, S., Ren, H., 2017b. Analysis and applications of globeLand30: a review. ISPRS Int. J. Geo-Inf. 6 (8), 230.

Chen, X., Lin, Y., Zhang, M., Yu, L., Li, H., Bai, Y., 2017c. Assessment of the cropland classifications in four global land cover datasets: a case study of Shaanxi Province, China. J. Integr. Agric. 16, 298–311.

Chen, Y., Xiao, B., Chen, J., 2010. Suggestion and analysis on effects of balance between cultivated land occupation and compensation and land development and consolidation. Chin. J. Agric. Resour. Reg. Plan. 31 (1), 1–6.

Coyle, C., Creamer, R.E., Schulte, R., et al., 2016. A functional land management conceptual framework under soil drainage and land use scenarios. Environ. Sci. Policy 56, 39–48.

Deng, X., Huang, J., Rozelle, S., et al., 2006. Cultivated land conversion and potential agricultural productivity in China. Land Use Policy 23 (4), 372–384.

Deng, X.Z., Huang, J.K., Rozelle, S., Zhang, J.P., Li, Z.H., 2015. Impact of urbanization on cultivated land changes in China. Land Use Policy 45, 1–7.

Fang, D., Cai, Q., Wu, F., Chen, B., Zhang, L., 2022. Modified linkage analysis for water-land nexus driven by interregional trade. J. Clean. Prod. 253, 131547.

Feng, Z., Jin, X., Chen, T., et al., 2021. Understanding trade-offs and synergies of ecosystem services to support the decision-making in the Beijing–Tianjin–Hebei region. Land Use Policy 106, 105446.

Fischer, G., Sun, L., 2001. Model based analysis of future land use development in China. Agric. Ecosyst. Environ. 85, 163–176.

Gao, J., Chen, W., Liu, Y., 2018. Spatial restructuring and the logic of industrial land redevelopment in urban China: II. A case study of the redevelopment of a local state-owned enterprise in Nanjing. Land Use Policy 72, 372–380.

Gao, P., Gao, Y., Ou, Y., McJeon, H., Zhang, X., Ye, S., Wang, Y., Song, C., 2023a. Fulfilling global climate pledges can lead to major increase in forest land on Tibetan Plateau. iScience. https://doi.org/10.1016/j.isci.2023.106364.

Gao, P., Xie, Y., Song, C.*, Cheng, C., Ye, S., 2023b. Exploring detailed urban-rural development under intersecting population growth and food production scenarios: Trajectories for China's most populous agricultural province to 2030. J. Geogr. Sci. https://doi.org/10.1007/s11442-023-2080-3.

Huang, Q., Liu, Z., He, C., Gou, S., Bai, Y., Wang, Y., Shen, M., 2020. The occupation of cropland by global urban expansion from 1992 to 2016 and its implications. Environ. Res. Lett. 15 (8), 084037.

Kong, X., 2014. China must protect high-quality arable land. Nature 506, 7.

Kuang, W., Liu, J., Tian, H., et al., 2021. Cropland redistribution to marginal lands undermines environmental sustainability. Natl. Sci. Rev. 1, 1.

Li, S., Li, X., 2016. Progress and prospect on farmland abandonment. Acta Geogr. Sin. 71 (3), 370–389.

Li, S., Li, X., 2018a. Economic characteristics and the mechanism of farmland marginalization in mountainous areas of China. Acta Geogr. Sin. 73 (5), 803–817.

Li, X., 1996. A review of the international researches on land use/land cover change. Acta Geogr. Sin. 51 (6), 553–558.

Li, Y., Liu, Y., Long, H., 2014. Community-based rural residential land consolidation and allocation can help to revitalize hollowed villages in traditional agricultural areas of China. Land Use Policy 39, 188–198.

Li, Y., Wu, W., Liu, Y., 2018b. Land consolidation for rural sustainability in China: practical reflections and policy implications. Land Use Policy 74 (5), 137–141.

Lin, P., Cheng, Y., 2001. Annotation and implement approaches to dynamic overall cultivated land balance policy on cultivated land conservation. China Land Sci. 15 (3), 12–14.

Liu, L., 2019. Quantifying the amount, heterogeneity, and pattern of farmland: implications for China's requisition-compensation balance of farmland policy. Land Use Policy 81.

Liu, L., Xu, X., Chen, X., 2015a. Assessing the impact of urban expansion on potential crop yield in China during 1990–2010. Food Secur. 7 (1), 33–43.

Liu, T., Liu, H., Qi, Y., 2015b. Construction land expansion and cultivated land protection in urbanizing China: insights from national land surveys, 1996-2006. Habitat Int. 46, 13–22.

Liu, Y., 2018a. Introduction to land use and rural sustainability in China. Land Use Policy 74, 1–4.

Liu, Y., Li, Y., 2017. Revitalize the world's countryside. Nature 548 (7667), 275–277.

Liu, Y., Zhou, Y., 2021a. Territory spatial planning and national governance system in China. Land Use Policy 102.

Liu, Y., Zhou, Y., 2021b. Reflections on China's food security and land use policy under rapid urbanization. Land Use Policy 109, 109.

Liu, Y., Wang, J., Long, H., 2010. Analysis of arable land loss and its impact on rural sustainability in Southern Jiangsu Province of China. J. Environ. Manag. 91 (3), 646–653.

Liu, Y., Wang, G., Zhang, F., 2013. Spatio-temporal dynamic patterns of rural area development in eastern coastal China. Chin. Geogr. Sci. 23 (2), 173–181.

Liu, Y., Fang, F., Li, Y., 2014a. Key issues of land use in China and implications for policy making. Land Use Policy 40, 6–12.

Liu, Y., Yang, Ren, Long, H., et al., 2014b. Implications of land-use change in rural China: a case study of Yucheng, Shandong province. Land Use Policy 40, 111–118.

Liu, Y., Li, J., Yang, Y., 2018b. Strategic adjustment of land use policy under the economic transformation. Land Use Policy 74, 5–14.

Liu, Y., Zhang, Z., Zhou, Y., 2018c. Efficiency of construction land allocation in China: An econometric analysis of panel data. Land Use Policy 74, 261–272.

Lu, M., Wu, W., Zhang, L., et al., 2016a. A comparative analysis of five global cropland datasets in China. Sci. China Earth Sci. 59 (12), 2307–2317.

Lu, X., Jiang, H., Zhang, X., Jin, J., 2016b. Relationship between nitrogen deposition and LUCC and its impact on terrestrial ecosystem carbon budgets in China. Sci. China Earth Sci. 59, 2285–2294.

Ma, J., Sun, Q., Xiao, Q., Wen, B., 2016. Accuracy assessment and comparative analysis of GlobeLand30 dataset in Henan province. J. Geo-Inf. Sci. 18, 1563–1572.

Mozak, S., 2016. Comparing Global Land Cover Datasets through the Eagle Matrix Land Cover Components for Continental Portugal. Master's Thesis, Nova Information Management School, Lisbon, Portugal.

Ren, S., Song, C., Ye, S., Cheng, C., Gao, P., 2022. The spatiotemporal variation in heavy metals in china's farmland soil over the past 20years: a meta-analysis. Sci. Total Environ. 806, 150322.

Rosegrant, M.W., Cline, S.A., 2003. Global food security: challenges and policies. Science 302, 1917–1919.

Song, W., Pijanowski, B.C., 2014. The effects of China's cultivated land balance program on potential land productivity at a national scale. Appl. Geogr. 46, 158–170.

Su, M., Guo, R., Hong, W., 2019. Institutional transition and implementation path for cultivated land protection in highly urbanized regions: A case study of Shenzhen, China. Land Use Policy 81, 493–501.

Su, Y., Qian, K., Lin, L., et al., 2020. Identifying the driving forces of non-grain production expansion in rural China and its implications for policies on cultivated land protection. Land Use Policy 92, 104435.

Sun, R., Sun, P., Wu, J., Zhang, J., 2014. Effectiveness and limitations of cultivated land requisition-compensation balance policy in China. China Popul. Resour. Environ. 24 (3), 41–46.

Tan, Y., Wu, C., Wang, Q., Zhou, L., Yan, D., 2005. The change of cultivated land and ecological environment effects driven by the policy of dynamic equilibrium of the total cultivated land. J. Nat. Resour. 20 (5), 727–734.

Tilman, D., Balzer, C., Hill, J., et al., 2011. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences of the United States of America 50, 108.

Wan, C., Kuzyakov, Y., Cheng, C., Ye, S., Gao, B., Gao, P., et al., 2021. Soil sampling design for arable land quality observation by using spcosa-clhs hybrid approach. Land Degrad. Dev. 32 (17), 4889–4906.

Wang, H., Lv, Z., Gu, L., Wen, C., 2015. Observations of China's forest change (2000–2013) based on Global Forest Watch dataset. Biodivers. Sci. 23 (5), 575–582.

Wang, K., Ye, S., Gao, P., et al., 2022. Optimization of numerical methods for transforming UTM plane coordinates to lambert plane coordinates. Remote Sens. 14 (9), 2056.

Wen, D., 2020. Rural residential land transition in the Beijing-Tianjin-Hebei region: spatial-temporal patterns and policy implications. Land Use Policy 96, 1.

Xu, L., Li, B., Yuan, Y., et al., 2015. Changes in China's cultivated land and the evaluation of land requisition-compensation balance policy from 2000 to 2010. Resour. Sci. 37 (8), 1543–1551.

Xu, X., Liu, L., Cai, H., 2017. China farmland production potential dataset. Data Registration and Publication System of the Resource and Environmental Science and Data Center. Chinese Academy of Sciences.

Yan, H., Liu, J., Huang, H., Tao, B., Cao, M., 2009. Assessing the consequence of land use change on agricultural productivity in China. Glob. Planet. Change 67 (1), 13–19.

Yan, H., Ji, Y., Liu, J., et al., 2016. Potential promoted productivity and spatial patterns of medium and low-yield cropland land in China. J. Geogr. Sci. 26, 259–271.

Yan, H., Liu, F., Liu, J., et al., 2017. Status of land use intensity in China and its impacts on land carrying capacity. J. Geogr. Sci. 27 (4), 387–402.

Yang, Y., Xiao, P., Feng, X., Li, H., 2017. Accuracy assessment of seven global land cover datasets over China. ISPRS J. Photogramm. Remote Sens. 125, 156–173.

Yao, X.C., Mokbel, M.F., Alarabi, L., Eldawy, A., Yang, J.Y., Yun, W.J., Li, L., Ye, S.J., Zhu, D.H., 2017. Spatial coding-based approach for partitioning big spatial data in Hadoop. Comput. Geosci. 106, 60–67.

Ye, S., Song, C., Gao, P., Liu, C., Cheng, C., 2022a. Visualizing clustering characteristics of multidimensional arable land quality indexes at the county level in mainland China. Environ. Plan. A: Econ. Space 54 (2), 222–225.

Ye, S., Ren, S., Song, C., Cheng, C., Shen, S., Yang, J., Zhu, D., 2022b. Spatial patterns of county-level arable land productive-capacity and its coordination with land-use intensity in mainland China. Agric. Ecosyst. Environ. 326, 107757.

Ye, S.J., Zhu, D.H., Yao, X.C., Zhang, N., Fang, S., Li, L., 2014. Development of a highly flexible mobile GIS-based system for collecting arable land quality data. IEEE J. -Stars 7, 4432–4441.

Ye, S.J., Yan, T.L., Yue, Y.L., Lin, W.Y., Li, L., Yao, X.C., Mu, Q.Y., Li, Y.Q., Zhu, D.H., 2016. Developing a reversible rapid coordinate transformation model for the cylindrical projection. Comput. Geosci. 89, 44–56.

Ye, S.J., Liu, D.Y., Yao, X.C., Tang, H.Z., Xiong, Q., Zhuo, W., Du, Z.B., Huang, J.X., Su, W., Shen, S., Zhao, Z.L., Cui, S.L., Ning, L.X., Zhu, D.H., Cheng, C.X., Song, C.Q.,

2018. RDCRMg: a raster dataset clean & reconstitution multi-grid architecture for remote sensing monitoring of vegetation dryness. Remote Sens 10 (9), 1376.

Ye, S.J., Song, C.Q., Cheng, F., et al., 2019. Cultivated land health-productivity comprehensive evaluation and its pilot evaluation in China. Trans. Chin. Soc. Agric. Eng. 35 (22), 66–78.

Ye, S.J., Song, C.Q., Shen, S., Gao, P.C., Cheng, C.X., Cheng, F., Wan, C.J., Zhu, D.H., 2020a. Spatial pattern of arable land-use intensity in China. Land Use Policy 99.

Ye, S.J., Song, C.Q., Cheng, C.X., Shen, S., Gao, P.C., Zhang, T., Chen, X.Q., Wang, Y.H., Wan, C.J., 2020b. Digital Trade Feature Map: A New Method for Visualization and Analysis of Spatial Patterns in Bilateral Trade. ISPRS Int. J. Geo-Inf. 9 (6), 363.

Yue, Y., Liu, X., 2013. Some problems in the balance of arable land system and sound recommendations. Nat. Resour. Econ. China 6, 13–16.

Zhang, Z., Li, J., 2022. Spatial suitability and multi-scenarios for land use: simulation and policy insights from the production-living-ecological perspective. Land Use Policy 119, 106219.

Zhao, X., Pan, X., Ding, S., et al., 2014. Evaluation of regional land use sustainability and its spatial-temporal pattern among provinces in China. Trans. Chin. Soc. Agric. Eng. 30 (3), 196–204.

Zhao, Y., 2014. Why basic farmland goes uphill. People's Dly. 07–13 (009).

Zhong, X., Liu, L., Xu, X., et al., 2012. Characteristics of spatial-temporal variation of maize climate productivity during last 30 years in China. Trans. Chin. Soc. Agric. Eng. 28 (15), 94–101.

Zhou, Y., Li, X., Liu, Y., 2020. Land use change and driving factors in rural China during the period 1995-2015. Land Use Policy 99, 105048.

Zhou, Y., Zhong, Z., Cheng, G., 2023. Cultivated land loss and construction land expansion in China: Evidence from national land surveys in 1996, 2009 and 2019. Land Use Policy 125, 106496.