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Continuing the continuous harvests of food production: from the perspective of the interrelationships among cultivated land quantity, quality, and grain yield

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The rapid population growth around the world has become one of the main challenges for countries to ensure adequate food supply. To address this difficulty and ensure adequate food production, sustainable land use, in particular sustainable cultivated land (CL) use, can make a great contribution. Sustainable utilization of CL encompasses several aspects such as quantity and quality, but previous studies have focused on increasing food production, while the interrelationships among cultivated land quantity, quality, and grain yield (CLQGGY) have still received less attention. Hence, based on the Globeland30 data during 2000–2020, this paper analyzed the changes of CLQGGY in 130 prefecture-level cities in the Yangtze River Economic Belt (YREB) in China and explored whether the current consecutive harvests is sustainable in the future to feed increasing population. The results revealed the areal loss and quality degradation of CL in most cities in the YREB, the total CL area decreased by $31.07 \times 10^4 \text{ hm}^2$ and $282.59 \times 10^4 \text{ hm}^2$ during 2000–2010 and 2010–2020, respectively, and the CL quality declining trend was presented in 68.46% and 69.23% cities in the YREB during 2000–2010 and 2010–2020, respectively. Even with such acreage and ecological losses, the total grain yield still increased by 3.77% and 9.53% during 2000–2010 and 2010–2020, respectively, continuing the miracle “continuous harvests” of grain yield in this region. This successive increase in food production in the context of decreasing acreage and ecological deterioration of CL depend mainly on the amount of chemical fertilizer usage, the total power of agricultural machinery and rural electricity consumption. However, due to the heavy reliance on a growth model driven by resource inputs, this type of harvest appeared to be unsustainable because of the significant negative effects brought out by overusing resources. With a view to achieving sustainable use of CL and food production, therefore, this paper proposed policies to promote the sustainable use of CL and food supply for supporting the survival of increasing population through the full implementation of administrative regulations and economic measures that focus on the balance among the quantity and quality and food production of CL in the process of agricultural production and CL management.

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Introduction

Past two decades have witnessed the increasing of world population from 6.31 billion in 2002 to 8.00 billion in 2022 (Cronan, 2023), and China, one of the world's most populous countries, has also seen its population growth from 1.28 billion in 2002 to 1.41 billion in 2022, with an increase rate of 10.16%. In the face of rapid global population growth, many countries have implemented strict farmland protection laws and planning tools to ensure domestic food supply security (Xue et al., 2013; Perrin et al., 2018; Qie et al., 2023). For example, the Farmland Protection Policy Act by the United States Congress in 1981 restricted the conversion of farmland to non-agricultural land (Ward, 1991), the new planning system in the United Kingdom since 2004 has emphasized the sustainable development of agriculture and placed greater emphasis on the protection of farmland (Baker et al., 2007; Rust et al., 2021), the Central Economic Work Conference of China held in 2013 set the tone for grain security goals and innovatively proposed "basic self-sufficiency of grains and absolute security of grain rations" (Niu et al., 2022). This was followed by the Chinese government's No. 1 Central Document issued in recent years, which repeatedly emphasized the importance of food security (Zhang and Lu, 2024), and in particular, No. 1 Central Document unveiled in February 2024 proposed a more specific and detailed implementation path to ensure China's national food security from seven dimensions. In addition, proposed as the part of Sustainable Development Goals announced by the United Nations, food security has received significant attention as an important factor in maintaining social stability and national security (Guo et al., 2023; Henry et al., 2022; Choithani et al., 2024). Food security is challenged by the growing food demand, and global food demand is projected to increase by 35–56% in 2050 compared to 2010, mainly due to population growth (Van Dijk et al., 2021). It also faces a series of severe social and economic challenges apart from this increase in food demand (Ristaino et al., 2021; Liu et al., 2023; Zhang et al., 2023a; Lee et al., 2024), especially following the outbreak of the COVID-19 around the world and the desert locust plague in the East African, which have severely impacted and even reduced global food supply (Okolie and Ogundeji, 2022; Devereux et al., 2020). These not only threaten global food security but also lead to volatility in international grain trade, further jeopardizing food safety (Savary et al., 2020).

In order to increase food supply, researchers have attempted to identify key influences on grain production. These factors include natural and economic aspects (Fujimori et al., 2022; Sun et al., 2024), with cultivated land (CL) resources being the most important of these dimensions (Chen et al., 2021a; Meyer et al., 2023). In this regard, sustainable CL use deserves further research to promote sustainable food supply for the survival of increasing population. Achieving sustainable use of CL includes the commitment to sufficient areas for food growth and high quality to support food harvesting. However, it is predicted that both the reduction in the quantity and the deterioration in the quality of CL owing to land deterioration and climate variation have the huge potential to reduce global food production by an average of 10% by 2050, forcing the migration of 500 million to 700 million population and even threatening the livelihoods of at least 3.20 billion people globally (Scholes et al., 2018). Rapid urbanization can also lead to a considerable loss of CL quantity, directly threatening grain security (Ge et al., 2018; Shen et al., 2024). Globally, loss of CL due to rapid urbanization is estimated at 1.8–2.4% from 2000 to 2030 (D'Amour et al., 2017). This is likely to be more severe, especially in the countries (regions) with higher urban population growth rates (Seto and Ramankutty, 2016; Koroso et al., 2021; Liu and Zhou, 2021; Zhang et al., 2023b). In a way, it is indicated that the quantity and quality of

CL can directly determine global grain production capacity and food safety (Wang et al., 2019b; Song et al., 2022).

Researches have been conducted within the CL quantitative and qualitative context to ensure sustainable food supply (Dong et al., 2015; Zhou et al., 2021; Chen et al., 2023; Liu et al., 2024). Up to now, a multifactorial and interconnected system of policy safeguards has been established to promise the sustainability and equity of grain security (Godfray et al., 2010; Wang et al., 2018; Cheng et al., 2023), specifically involving multiple policy elements concerning water, land, energy, and climate resources (Hasegawa et al., 2018; Wang et al., 2019c; Taghizadeh-Hesary et al., 2019; Pickson et al., 2022). The synergy of these resources has received increasing attentions and has been considered as an important support to guarantee food security under the circumstance of complex and changeable global scenario as well as climate variation (Howells et al., 2013; Hou et al., 2022; Viana et al., 2022). Among them, the main factor affecting increased production and food security is the availability of CL resources (Kumar et al., 2012; Sun et al., 2023). Food self-sufficiency rate is tightly related to the amount of CL resources, while the CL resources suitable for food production tend to be limited on the earth (Timsina et al., 2018; Liang et al., 2023). This has been a major concern in the world, and there are numerous studies focusing on the influence of the decline in CL quantity on global food security, attempting to figure out the main drivers from multiple perspectives (Zhou et al., 2021; Parven et al., 2022; Lu et al., 2024). The driving factors of CL decline can be categorized as natural and anthropogenic (Wang et al., 2021; Yuan et al., 2019), while rapid urbanization and abusive CL use are the primary reasons of the reductions in many countries (Jin et al., 2019; Su et al., 2019; Chen et al., 2023; Právalie et al., 2024). Specifically, natural factors mainly include soil wind erosion, rainstorm erosion, and accelerated decomposition of organic matter due to climate warming (Zhao et al., 2021a), and anthropogenic factors mainly include land use change, overconsumption of CL resources, and inputs of excessive agricultural materials such as agrochemicals, fertilizers, and agricultural films (Cordell et al., 2009; Livsey et al., 2021). However, the interrelationships among fluctuations in cultivated land quantity, quality, and grain yield (CLQGGY) has rarely been explored, and the interactions among these changes and agricultural production practices still remain unclear.

China has a rich endowment of land resources for food production, but food security remains extremely important and urgent as food demand remains relatively high at 1.41 billion people (Qiao et al., 2022a; Zhao et al., 2021b). Meanwhile, although China has no longer been the world's most populous country since 2022, it feeds about 20% of the global population with only 9% of the world's farmland (Qiu et al., 2022a; Qiao et al., 2022b), and is under enormous pressure to conserve CL resources and ensure food security (Hu et al., 2020; Chan et al., 2022; Han et al., 2024). Under this pressure, China has adopted various measures to guarantee national grain security, but the dynamic balance between grain supply and demand still remains precarious, and this precarious situation is primarily determined by CL quantity and unsatisfied production capacity of transferred CL compared to original occupied land (Pang et al., 2023; Qu et al., 2023). Despite a continuing downward trend in grain sown area during 2016–2020, China's grain yield achieved its 17th consecutive harvest in 2020 (Gao and Yu, 2021). However, this achievement was realized through the excessive inputs of chemical materials, degrading CL quality and contaminating the ecological environment (Chen et al., 2021a; German et al., 2017; Hadgu et al., 2009). Therefore, it is an urgent and realistic challenge to consider sustainable CL use during agricultural production to ensure future food security.

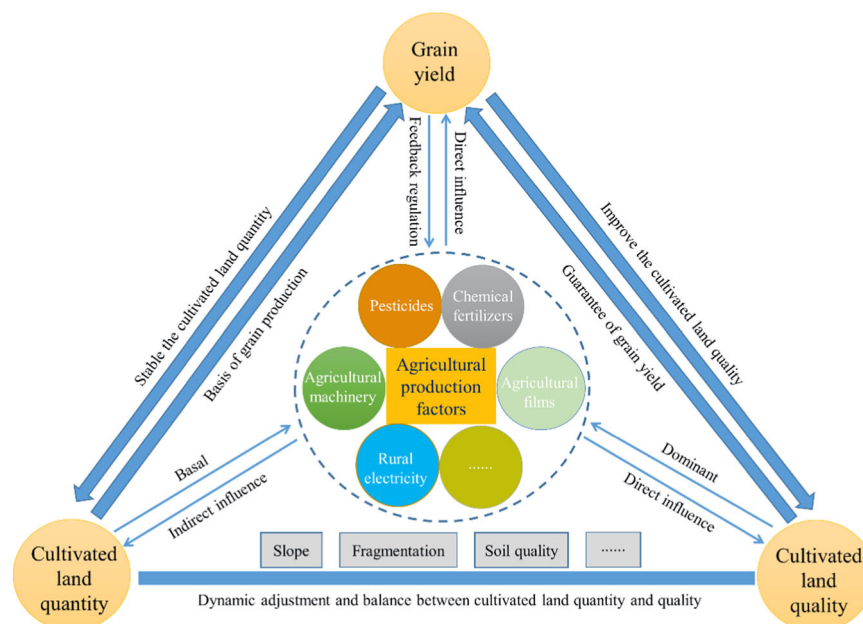


Fig. 1 Framework of interrelationships among CL quantity, CL quality, and grain yield.

Relying on the abundant local natural resources endowments, 11 provinces in the Yangtze River Economic Belt (YREB) in China have its natural advantages in agricultural production, and CL in this area plays a decisive role in guaranteeing national food safety. This article analyzed the variations in CLQGGY and the factors influencing food security in the YREB based on the GlobalLand30 data during 2000–2020 in 130 prefecture-level cities. We aimed to address the following issues: (1) variations in CLQGGY in the YREB from 2000 to 2020, (2) the interrelationships involved in CLQGGY changes, (3) factors affecting food production and the sustainability of successive food harvests to cope with national population growth, (4) policy implications of the sustainable use of CL and food production to support food demand of increasing population. This paper can provide important references for trade-offs among CL quantity, CL quality, and grain yield, contributing to ensuring sufficient food to feed population with a growing tendency.

A multilevel interrelationships among CL quantity, CL quality, and grain yield

Grain security is a multidimensional, multifactorial, and diversified issue that is mainly affected by grain production, grain transportation, and supply processes. Among these elements, grain production is the primary factor (Foley et al., 2011; Ray et al., 2022; Zhou et al., 2023; Lu et al., 2024). As the most essential element of food production, CL is characterized by integrity, scarcity, and irreversibility of pollution and destruction (Song and Liu, 2017; He et al., 2024). While investing in CL with a variety of agricultural production materials, including insecticides, fertilizers and agricultural films, has indeed increased food production, this over-investment undermined the quality of CL and threatened the sustainability of agriculture (Livsey et al., 2021; Su et al., 2019; Pang et al., 2023). Therefore, exploring the multilevel interrelationships between CL and grain yield would simultaneously contribute to improving the natural conditions of CL and agricultural production, further realizing sustainable CL use and sustainable food supply (Fig. 1).

Sufficient CL quantity is the basis of promising grain harvests (Timsina et al., 2018; Parven et al., 2022), and it is also the basic

vehicle for agricultural activities, carrying the entire production process and having a profound influence on grain yield (Zhuang et al., 2022; Qu et al., 2022). Under the backgrounds of the large population, limited per capita CL, and increasing grain demand in China, Chinese government has announced strict CL conservation policies (Liu et al., 2024) such as designating the red line of 1.8 billion mu of CL (Cao et al., 2020), CL requisition-compensation balance (Qie et al., 2023; Wang et al., 2024a), and permanent basic CL conservation policy (Chen et al., 2017; Wu et al., 2017), with the purpose of guaranteeing CL quantity and safeguarding grain security.

CL quality and grain yield are interconnected and interacted with each other. On the one hand, CL quality is one of the important determinants of food production. Land-use policies are in place that promise to protect CL quality and further contribute to grain yield growth and grain security, including land consolidation with the purpose of restoring soil quality by reducing fragmentation and increasing soil organic compounds (Jiang et al., 2017; Xie et al., 2020; Pang et al., 2023). CL quality can also dominate the amount of inputs used for agricultural production materials, and areas with poor CL quality (large slopes, large fragmentation or poor soil quality, etc.) tend to require greater inputs to stabilize or increase grain yield, while areas of good CL quality have relatively small inputs and are unable to produce an equivalent amount of crop yields (Wang et al., 2015). On the other hand, increasing grain yield can conversely contribute to improving CL quality. To meet the country's food requirements, Chinese government has implemented a series of policies and measurements to promise grain yield, including the designation of basic agricultural land reservation zones, and guidance and optimization of input ratios of agricultural production materials. These policies prioritize CL quality, increasing food production and ensuring the quality of CL at the same time (Chen et al., 2021a; Liu et al., 2022).

There are always trade-offs and dynamics between the quantity and quality of CL in order to ensure adequate food supply for food security. As a non-renewable resource, CL has the characteristics of scarcity and limitation in quantity, in other words, total CL area has little potential to increase with the acceleration of urbanization development, and may even decrease due to land

conversion and destruction (Su et al., 2019). Therefore, governments in China attempt to improve the CL quality through land consolidation and soil improvement with the aim of ensuring sustainable grain production (Wang et al., 2024b). In addition to improving CL quality through land consolidation projects, it is also feasible to apply optimal agricultural materials investments (Liu et al., 2020; Zhao et al., 2021a). While these adoptions have increased grain production, they have also compensated for the constant demand of improving CL quantity. It is worth noting that although continuous inputs of agricultural materials can significantly increase crop production in a short period of time, it disrupts the CL ecosystem to a certain extent, and when this disruption exceeds the ecological tolerance limits of the CL, it may lead to a decline in CL quality (Livsey et al., 2021). Furthermore, once started, there is a risk that the soil quality of CL will be completely destroyed without intervention, leading to a gradual loss of food production capacity and, ultimately, to a reduction in the number of CL, threatening the survival of a growing population (German et al., 2017; Tian et al., 2020). As a consequence, to meet the growing demand for food in a sustainable manner, measures should be taken to continuously and dynamically adjust agricultural production materials inputs in order to maintain high-quality CL and sustainable grain production, and further ensure human survival (Chan et al., 2022; Teeuwen et al., 2022).

Materials and methods

Study area. The YREB (Fig. 2) consists of 9 provinces and 2 municipalities directly under the central government (Chongqing and Shanghai) (Yang et al., 2023). The upper reaches of the YREB include Yunnan, Sichuan, Guizhou, and Chongqing, while Hunan, Hubei, and Jiangxi are located in the middle reaches. The lower reaches include Zhejiang, Anhui, Jiangsu, and Shanghai.

These provinces have jurisdiction over 130 prefecture-level city municipal administrations (including autonomous prefectures and province-governing counties, which are collectively referred to as cities in this paper), with a total area of $20,520 \times 10^4 \text{ km}^2$, making up around 21.4% of Chinese territorial area. According to statistical yearbook data in China, the gross domestic product (GDP) and population size in the YREB in 2020 reached 4.65×10^4 billion RMB and 6.10 billion, accounting for 45.74% of the national GDP and 43.20% of total population in China, respectively. These two proportions both exceeded 40.00%, indicating the YREB’s important strategic development status. The YREB is also regarded as an essential major grain-producing region, contributing substantially to the development of China’s national agricultural pattern. In 2020, the CL area and total grain yield of the YREB were $\sim 4362.68 \times 10^4 \text{ km}^2$ and $2.39 \times 10^8 \text{ t}$, accounting for 34.09% and 35.72% of those in China, respectively. In addition, the YREB has also made significant contributions to the supply of key agricultural products, modernization, improved agricultural competitiveness, ecological security, sustainable development, employment and income growth for farmers.

Data source and processing. Based on local natural resources and social development in the YREB as well as existing researches (Yang et al., 2021), this paper established an indicator system to analyze the factors influencing grain yield in four dimensions: CL quantity, CL quality, agricultural production conditions, and socioeconomic conditions. To comprehensively and reasonably measure the actual changes in CL and grain yield, as well as the specific impacts of various factors on food safety, this paper investigated the changes of these indicators over the periods of 2000–2010 and 2010–2020.

Relevant spatial and socio-economic statistical datasets were collected for this study (Table 1). Specifically, this study adopted

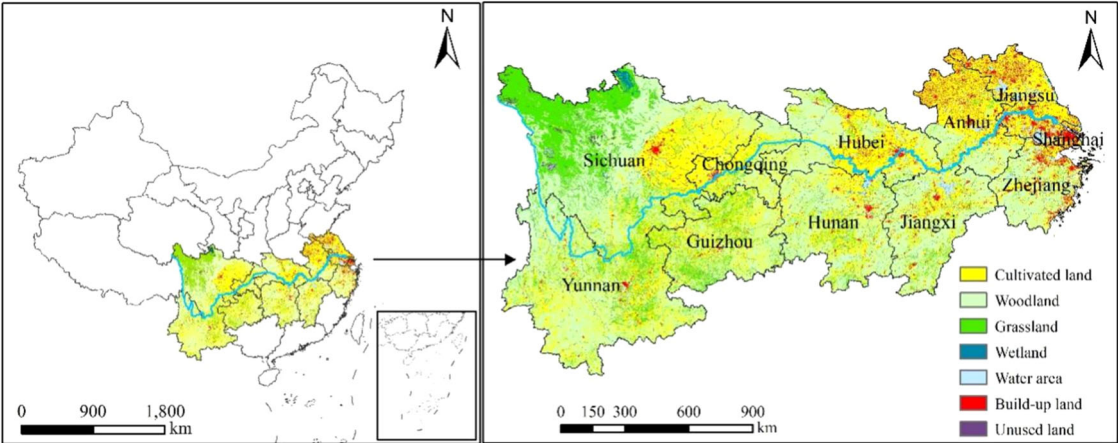


Fig. 2 Land use pattern of YREB in 2020.

Table 1 Basic information of relevant spatial and statistical datasets sources.			
Datasets	Data sources	Year	Resolution
Land use	National Basic Geographic Information Center Globeland30 (http://www.globallandcover.com/)	2000, 2010, 2020	30 m
DEM	Geospatial Data Cloud (https://www.gscloud.cn/)	2009	30 m
Soil	Worldwide Interpolated Soil Grid Data (https://soilgrids.org/)	2017	250 m
Administrative boundary	Resource and Environmental Science and Data Center of the Chinese Academy of Sciences (https://www.resdc.cn/)	2018	Provincial/ prefectural-level cities
Socio-economic	Statistical Yearbook (https://kns.cnki.net/kns/advsearch?dbcode=CYFD), Administrative Regions Bulletins of the National Economic and Social Development and Regional Economic Database	2000, 2010, 2020	/

land use data from the 30 m spatial resolution global land coverage data in 2000, 2010, and 2020, retrieved from the National Basic Geographic Information Center GlobeLand30. It is a global surface coverage dataset with the highest resolution in the world and includes 10 first-class land categories (Jun et al., 2014). We used ArcGIS 10.5 to reclassify the collected land-use data into 7 different land use types: CL, woodland, grassland, wetland, water area, built-up land, and unused land. CL slope was calculated through ArcGIS 10.5, using DEM data from the Geospatial Data Cloud with 30 m spatial resolution. CL fragmentation was calculated with the application of Fragstats 4.2 software (Zheng et al., 2022), and CL soil quality data were obtained from Worldwide Interpolated Soil Grid Data.

Agricultural production conditions included the total power of agriculture machinery, rural power consumption, and chemical fertilizer usage. The socioeconomic conditions included the multiple cropping index (annual ratio of total crop sowing area to CL area), GDP, and resident population. These related data were from the Statistical Yearbooks of Provincial and City levels in the YREB during 2000–2020. Missing data were supplemented by the corresponding years' data from the Administrative Regions Bulletins of the National Economic and Social Development and Regional Economic Database. The administrative boundary data of the YREB at the provincial and city levels were gotten from the Resource and Environmental Science and Data Center of the Chinese Academy of Sciences.

Research methods

CL use dynamic degrees. CL use dynamic degree can quantitatively report the variation rate in CL quantity in a region during the study period (Chen et al., 2021a). This study provided an in-depth analysis of variations in CL use in the YREB over the past two decades (2000–2010 and 2010–2020). The calculation is as follows:

$$D = \frac{A_{ib} - A_{ia}}{A_{ia}} \times \frac{1}{T} \times 100\% \quad (1)$$

$$T = b - a \quad (2)$$

where D represents the CL use dynamic degree; T is the duration of the study period; i means the target area, in specific, represents the i th province or city; a and b respectively represent the initiation and the cessation of the study; A_{ia} and A_{ib} represent the CL quantity at the initiation and the cessation of the study in the i th province or city, respectively. This paper regarded CL quantity as the area of CL.

Evaluation of CL quality. CL quality directly affects grain yield per unit area. On the basis of previous studies (Wang et al., 2019a; Song et al., 2022) and local situations in the YREB, CL quality could be measured by the comprehensive calculation of slope, fragmentation, and soil quality using the entropy method. It could be calculated as follows:

$$Q_i = \alpha \cdot \text{slope}_i + \beta \cdot \text{fragmentation}_i + \varepsilon \cdot \text{soil}_i \quad (3)$$

where Q_i represents the CL quality level in i th city; slope_i , fragmentation_i , and soil_i represent CL slope, fragmentation and soil quality in i th city, respectively; and α , β , and ε represent their weights, which are calculated through the entropy method (Wang et al., 2022). Prior to calculation, data was normalized with the consideration of possible positive or negative impacts of these indicators. Thus, the weight values of α , β , and ε obtained through calculation were 0.75, 0.06, and 0.19, respectively.

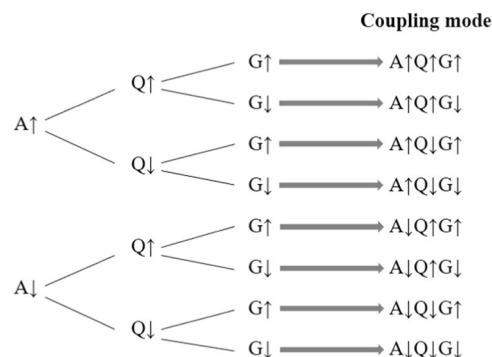


Fig. 3 The coupling mode types of the interrelationships among changes in CL quantity, CL quality, and grain yield.

Interrelationships measurement of CLQQGY change. Based on the change rates of CL quantity, CL quality, and grain yield during 2000–2010 and 2010–2020, this study applied the coupling model to show the interrelationship among these factors. Firstly, the formula for calculating the variation rates of these factors is as follows:

$$AR_{iT} = \frac{A_{ib} - A_{ia}}{A_{ia}} \quad (4)$$

$$QR_{iT} = \frac{Q_{ib} - Q_{ia}}{Q_{ia}} \quad (5)$$

$$GR_{iT} = \frac{G_{ib} - G_{ia}}{G_{ia}} \quad (6)$$

where AR_{iT} , QR_{iT} , and GR_{iT} represent the variation rates of CL area, CL quality, and grain yield in i th city, respectively; Q_{ia} and Q_{ib} represent the CL quality at the initiation and the cessation of the research period in i th city, respectively; G_{ia} and G_{ib} represent grain yield at the initial and final period in i th city, respectively.

Coupling mode types. Then, according to formulas (4), (5), and (6), eight types of coupling modes can be obtained for the interrelationships among changes in CLQQGY (Fig. 3). Among them, $A\uparrow$, $Q\uparrow$, and $G\uparrow$ represent $AR_{iT} > 0$, $QR_{iT} > 0$, and $GR_{iT} > 0$, respectively, indicating that the CL quantity, CL quality, and grain yield all increased during the study period. $A\downarrow$, $Q\downarrow$, and $G\downarrow$ represent $AR_{iT} < 0$, $QR_{iT} < 0$, and $GR_{iT} < 0$, respectively, indicating the decreases in CL quantity, CL quality, and grain yield during the study period.

Kernel density estimation. Kernel density estimation is a common nonparametric method for estimating probabilistic density functions (Dong et al., 2022). It integrates the position of point objects with other geographic data and considers diversities in aggregation intensity, spatiotemporal integrity, and geographic continuity at various locations. CL distribution is featured by spatial dispersion, multiple points, and a wide range. This estimation method can effectively identify the agglomeration of the distribution of CL transferred in or out of the plots in the study area, higher degree of kernel density indicates the stronger density of CL transformations in this location. The calculation formula is showed as:

$$f(x, y) = \frac{1}{nh} \sum_{i=1}^n k\left(\frac{d_i}{h}\right) \quad (7)$$

where $f(x, y)$ represents the kernel density function (x, y), n represents observations numbers, h represents distance attenuation threshold, k means spatial weight function, d_i is the range from location (x, y) to the i th target point.

Geodetector model. The Geodetector model, having been broadly applied in numerous research fields, is a statistical technique that illustrates the spatial differentiation of geographical features and their drivers (Wang and Xu, 2017; Feng et al., 2024). Using the factor detector module in the Geodetector model, this study identified main drivers influencing grain yield, which are also the main indicators reflecting food security. The calculation formula is presented below:

$$q_{X,Y} = 1 - \frac{\sum_{h=1}^L N_h \sigma_h^2}{N \sigma^2} \quad (8)$$

where $q_{X,Y}$ represents the influence intensity of factor X on grain yield Y with the value range of [0,1]. Value closer to 1 represents the greater effect of this factor on grain yield. L represents the stratification of the dependent or independent variables, $h = 1, 2, \dots, L$; while N and N_h respectively stand for the total

number of samples and the h -th layer sample; σ^2 and σ_h^2 represent the total sample variance and the h -th layer sample variance, respectively.

Results and analysis

Spatiotemporal change in CL quantity. *Distribution of CL transferred.* The total CL area in the YREB declined during 2000–2010 and 2010–2020, with the decreases of $31.07 \times 10^4 \text{ hm}^2$ and $282.59 \times 10^4 \text{ hm}^2$, respectively. The reduction rates in the two periods were as high as 0.40% and 3.90%, respectively, indicating an accelerated abatement of CL in the YREB. Figure 4a, b shows that CL transferred out was greater than the CL transferred in, and this phenomenon was more significant during 2010–2020. This indicated that the YREB had not reached a balance between occupancy and compensation for the amount of CL. In the light of the CL quantity transfer matrix in the YREB (Table 2),

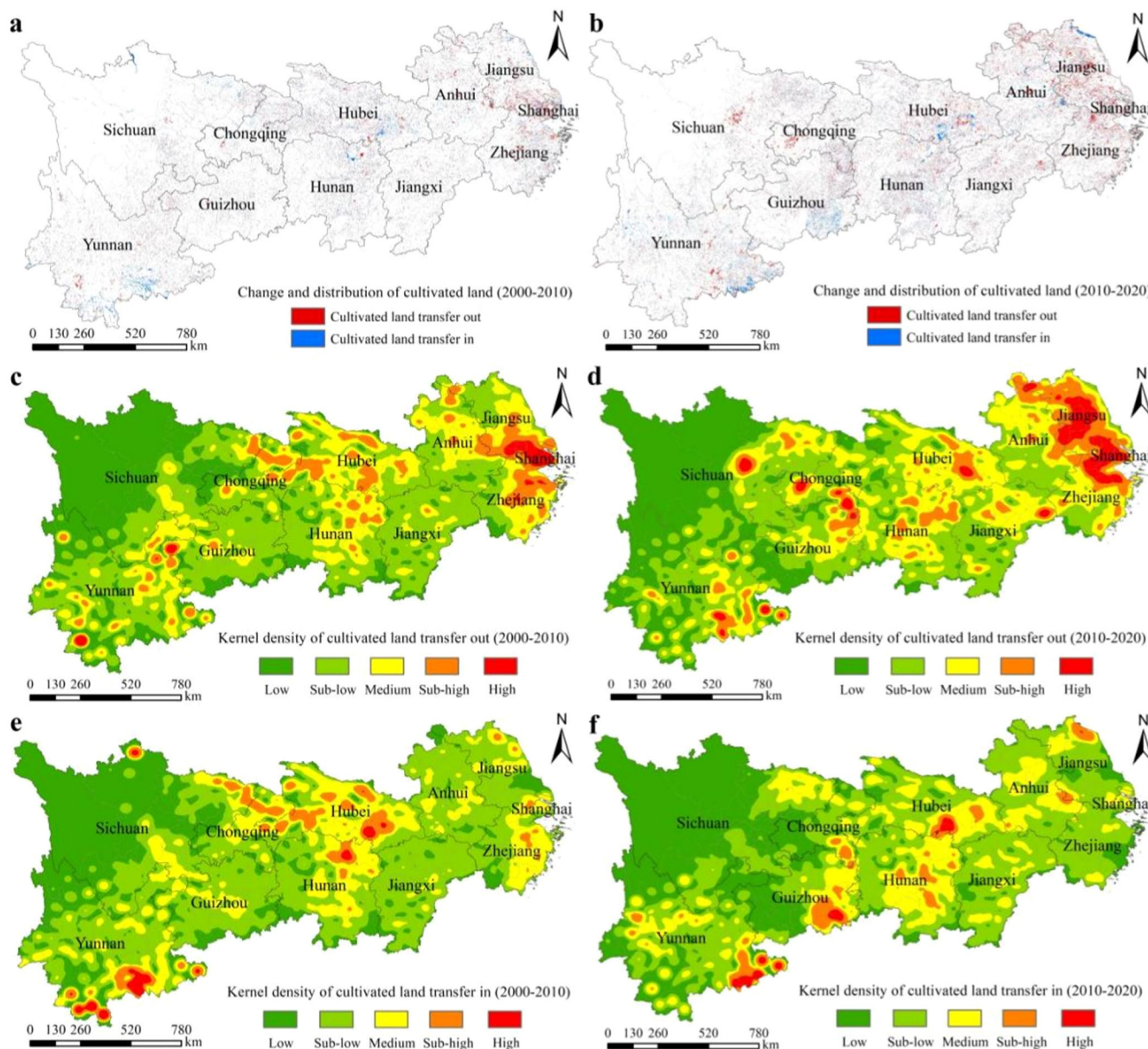


Fig. 4 Distribution of CL change and kernel density of the YREB during 2000–2020. **a** Denotes the change and distribution of CL during 2000–2010; **b** denotes the change and distribution of CL during 2010–2020; **c** denotes the kernel density of CL transfer out during 2000–2010; **d** denotes the kernel density of CL transfer out during 2010–2020; **e** denotes the kernel density of CL transfer in during 2000–2010; **f** denotes the kernel density of CL transfer in during 2010–2020.

Table 2 CL quantity transfer matrix in YREB during 2000–2020.

Change direction	Type	2000–2010		2010–2020	
		Area (10 ⁴ hm ²)	Change proportion (%)	Area (10 ⁴ hm ²)	Change proportion (%)
Cultivated land transferred out	Cultivated land→ Woodland	266.33	23.72	334.50	21.96
	Cultivated land→ Grassland	115.01	10.24	108.19	7.10
	Cultivated land→ Wetland	4.78	0.43	2.84	0.19
	Cultivated land→ Water area	60.30	5.37	96.10	6.31
	Cultivated land→ Built-up land	130.46	11.62	347.25	22.80
	Cultivated land→ Unused land	0.56	0.05	0.71	0.05
	Total	577.44	51.42	889.58	58.41
Cultivated land transferred in	Woodland→ Cultivated land	291.02	25.92	378.19	24.83
	Grassland→ Cultivated land	127.20	11.33	116.72	7.66
	Wetland→ Cultivated land	10.40	0.93	5.95	0.39
	Water area→ Cultivated land	75.97	6.77	73.18	4.80
	Built-up land→ Cultivated land	40.48	3.61	58.97	3.87
	Unused land→ Cultivated land	0.37	0.03	0.44	0.03
	Total	545.44	48.58	633.45	41.59

substantial CL was replaced by construction land. The net areas of CL transferred to built-up land during 2000–2010 and 2010–2020 were $89.98 \times 10^4 \text{ hm}^2$ and $288.28 \times 10^4 \text{ hm}^2$, respectively, and the value in the second decade was 3.20 times higher than that in the first decade. This suggested that the converted CL was mainly used for construction land and this transformation tendency has a gradually intensifying trend.

Kernel density of CL transferred. Significant regional differences were observed in the changes of CL quantity among diverse administrative regions in the YREB. The high-density regions of CL transferred out were primarily witnessed in the downstream regions of the YREB in 2000–2010 and 2010–2020, particularly during 2010–2020 (Fig. 4c, d). In general, downstream areas are more economically developed compared to upstream and mid-stream areas, and this result therefore revealed that the loss of CL quantity was more severe in economically developed districts. While the overall CL area was showing a downward trend, it is noticeable that the areas of CL in Sichuan, Chongqing, Hunan, and Hubei increased during 2000–2010 but decreased during 2010–2020. Upstream Yunnan and Guizhou also witnessed significant changes in CL. CL use dynamic degrees in Yunnan and Guizhou were 0.17% and -0.07% during 2000–2010, respectively, whereas they were 0.03% and 0.06% during 2010–2020, indicating the decreasing trend of CL quantity in Yunnan. In comparison, CL quantity in Guizhou first decreased and then increased. Figure 4a, b also shows a large shift and concentration of CL in the upper reaches of the southern part of Yunnan and Guizhou, which is also confirmed by the results of the kernel density distribution (Fig. 4e, f). In addition, these results indicated that the growth of CL areas in Yunnan and Guizhou not only achieved the requisition-compensation balance of CL quantity but also made a significant contribution to the whole YREB during the study period.

CL quantity change. To elucidate the changes in the amount of CL in 130 cities of the YREB, this study utilized the distribution interval of natural breaks in ArcGIS 10.5 and defined $5.00 \times 10^4 \text{ hm}^2$ as the interval dividing the degree of variation in CL area (Fig. 5a, b). Figure 5a shows that CL areas of 81 cities in the YREB declined during 2000–2010, with a total net reduction of $103.31 \times 10^4 \text{ hm}^2$, of which Shanghai had the largest reduction ($7.91 \times 10^4 \text{ hm}^2$). However, only 49 cities witnessed

increases in CL area, with an overall net increase of $72.24 \times 10^4 \text{ hm}^2$, of which Honghe in Yunnan had the largest increase ($22.88 \times 10^4 \text{ hm}^2$). It is worth noting that Shanghai, Wuxi, Honghe, Xishuangbanna and Ngawa had a range of change in CL area higher than $5 \times 10^4 \text{ hm}^2$, while change ranges in other 125 cities were lower than $5 \times 10^4 \text{ hm}^2$.

The CL area in 112 cities in the YREB (Fig. 5b) decreased during 2010–2020, and the total net reduction ($317.11 \times 10^4 \text{ hm}^2$) was 3.07 times greater than that during 2000–2010. Among them, Chongqing city had the largest reduction ($20.91 \times 10^4 \text{ hm}^2$) during 2010–2020, but CL area increased by 7588 hm^2 during 2000–2010 in the same city. The primary reason for this trend was the conversion of CL to built-up land ($18.80 \times 10^4 \text{ hm}^2$) as a result of Chongqing's urban sprawl. However, only 18 cities saw increases in the CL area during 2010–2020, with a net increase of $61.29 \times 10^4 \text{ hm}^2$. This resulted in a distinct decline in the overall CL area in the YREB during 2010–2020. Among those regions, 4 cities with the largest increases were Wenshan ($16.03 \times 10^4 \text{ hm}^2$) and Dali ($7.35 \times 10^4 \text{ hm}^2$) in Yunnan, as well as Qiandongnan ($10.73 \times 10^4 \text{ hm}^2$) and Qiannan ($7.81 \times 10^4 \text{ hm}^2$) in Guizhou. These cities have increased their CL area mainly by clearing ecological land such as forest and grassland. Although Yunnan and Guizhou provinces achieved the overall CL quantity requisition-compensation balance, the newly transferred CL was of poor quality, with poor agricultural production conditions and deterioration of the pristine ecological environment.

Dynamic degrees of CL quantity change. The dynamic degree model was applied to calculate CL area changes at the city scale in the YREB during 2000–2010 and 2010–2020. Combined with the distribution interval of natural breaks in ArcGIS 10.5, 0.1% was defined as the interval to delineate the degree of change (Fig. 5c, d). Figure 5c shows that the interval of change in the CL area dynamic degrees in the 120 cities were $[-0.1\%, 0.1\%]$ during 2000–2010. Cities with a value lower than -0.1% included Suzhou (-0.114%), Changzhou (-0.115%), and Wuxi (-0.182%) in Jiangsu, Jinhua (-0.117%) in Zhejiang, Diqing (-0.195%) in Yunnan, and Shanghai (-0.177%); while cities with the dynamic degrees higher than 0.1% only included the Shennongjia Forestry District (0.163%) in Hubei, Xishuangbanna (0.202%) and Honghe (0.231%) in Yunnan, and Ngawa (0.449%) in Sichuan. Figure 5d reveals that the dynamic degrees of CL area changes during

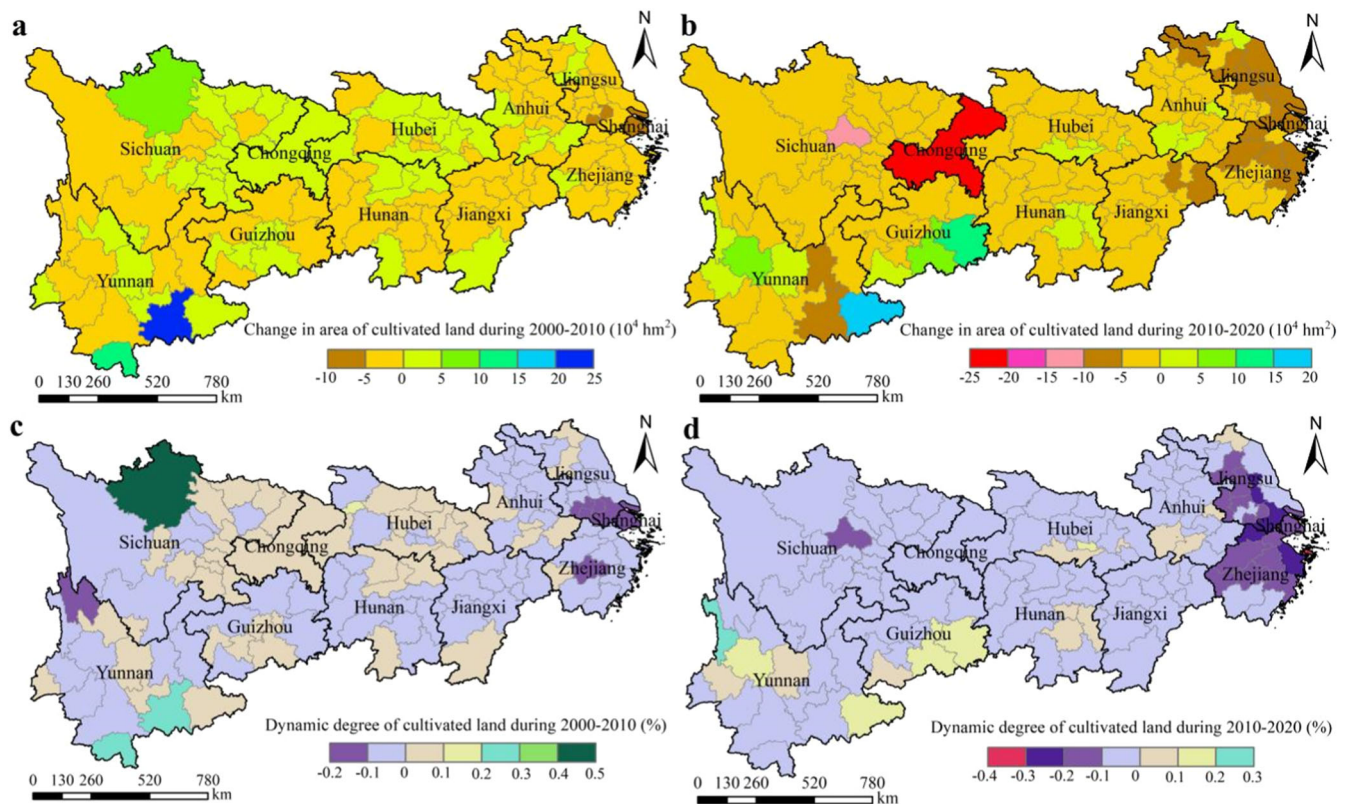


Fig. 5 Distribution change in the area and dynamic degree of CL at the city scale in the YREB during 2000–2020. **a** Denotes the change in area of CL during 2000–2010; **b** denotes the change in area of CL during 2010–2020; **c** denotes the dynamic degree of CL during 2000–2010; **d** denotes the dynamic degree of CL during 2010–2020.

2010–2020 were mainly distributed between $[-0.4\%, 0\%]$, and values of 112 cities were in this distribution. This suggested that CL in the YREB was mainly shifted out during the period of 2010–2020. In particular, the dynamic degree distributions during 2000–2010 and 2010–2020 revealed that the loss in CL area in Jiangsu, Zhejiang, and Shanghai in the downstream regions of the YREB during 2010–2020 was more severe than that during 2000–2010. This was mainly caused by the rapid socio-economic growth in coastal cities, during which a large amount of CL was occupied and converted into built-up area to satisfy the requirements of urban construction. The results of these large-scale occupations of CL demonstrated the importance and urgency of stricter and more effective protection of the use of CL.

Spatiotemporal change in CL quality. *CL slope change.* Among the 130 cities in the YREB during 2000–2010 and 2010–2020, the proportions of cities with degraded CL quality were high at 68.46% and 69.23%, respectively (Fig. 6g, h). These overall results indicated that CL quality experienced extremely serious degradation during the study period and this damage situation even showed an intensified trend. To address this problem, it was recommended that governments should attach great importance and release corresponding policies to enhance CL quality in the YREB through improved protection measurements and CL quality monitoring. CL quality could be determined by multi-dimensional factors, and Fig. 6a, b showed the changes in CL slope factor in 130 cities of the YREB with the significant increasing trend. The number of cities with increased CL slope during 2000–2010 and 2010–2020 accounted for 56.15% and 82.31%, respectively. This also indicated that the slope of supplemental CL tended to be greater than that of occupied CL in the

policy environment with CL requisition-compensation balance. This further deteriorated CL quality on the whole, while slope itself did have an obvious influence on agricultural efficiency and productivity. Therefore, while implementing CL requisition-compensation balance policy, local governments should avoid utilizing upslope land areas as the compensate for CL occupation, because obtaining equivalent grain yields on sloping land was often the result of investing excessive agricultural production materials, leading to a decline in CL quality.

CL fragmentation change. The CL fragmentation in 130 cities of the YREB primarily decreased from 2000 to 2020 (Fig. 6c, d), with a high percentage of cities with decreasing CL fragmentation (75.38% and 87.69% during 2000–2010 and 2010–2020, respectively), indicating a significant improvement in CL connectivity. This was primarily due to the large-scale land consolidation projects implemented by the Chinese government since 1998, which have helped to improve CL quality, achieve large-scale agricultural mechanization, and increase agricultural production efficiency. However, the improvement in CL quality has had a limited effect and has not been sufficient to offset the downward trend caused by other factors.

CL soil quality change. The soil quality of CL in the 130 cities in the YREB also showed a predominantly decreasing trend (Fig. 6e, f), with the number of cities with decreased CL soil quality accounting for 87.69% and 86.15% during 2000–2010 and 2010–2020, respectively. This might be caused by the poorer soil quality of supplementary CL compared to occupied CL and the potential deterioration of CL soil quality due to insufficient protection of soil layers during land consolidation and cultivation (Jiang et al., 2022). Notably, the cities with increased CL soil quality during 2000–2010 were primarily distributed in some economically underdeveloped cities in Sichuan, Yunnan, and

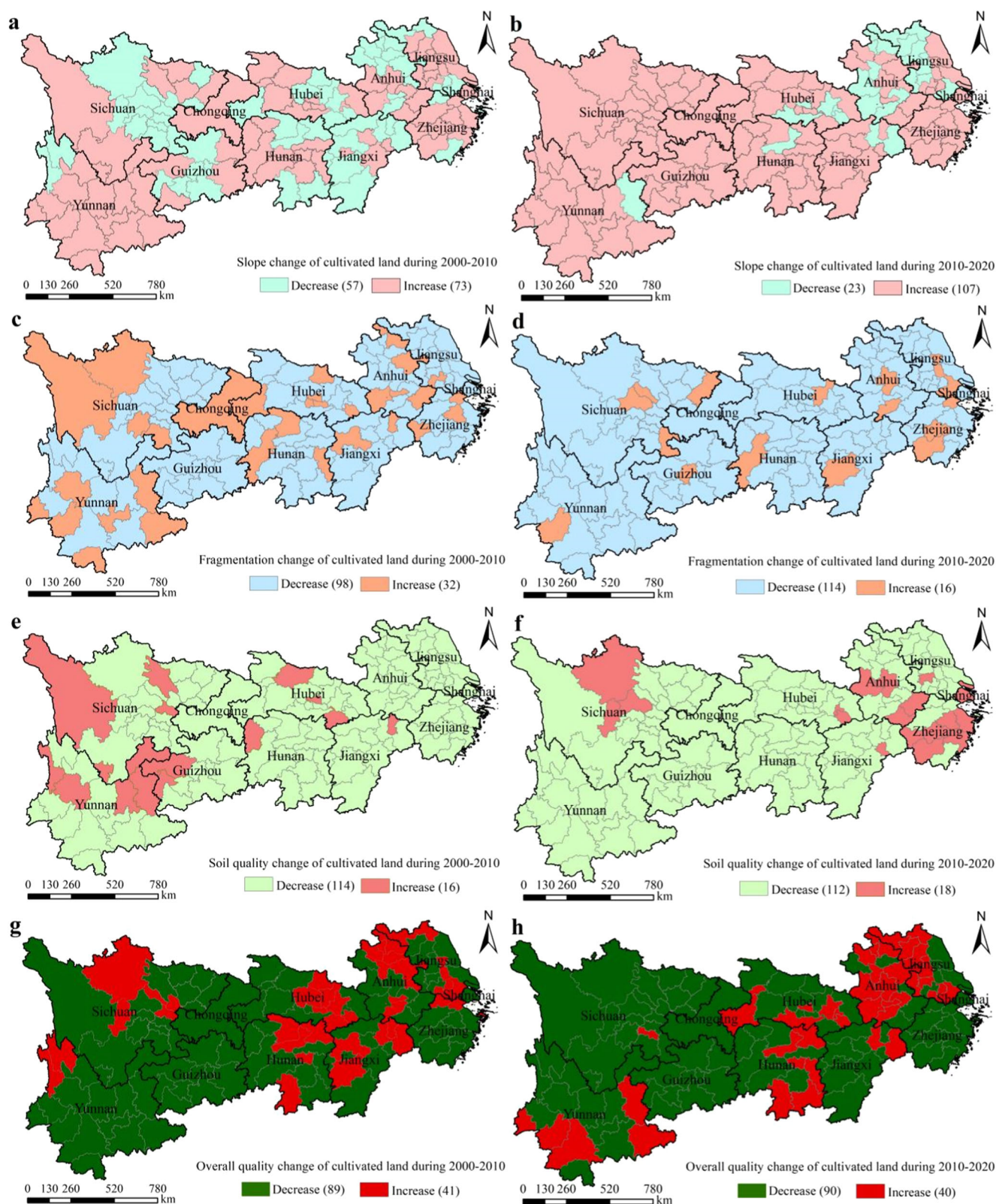


Fig. 6 Changes in slope, fragmentation, soil quality, and overall quality of CL at the city level in the YREB during 2000–2020. **a** Denotes the slope change of CL during 2000–2010; **b** denotes the slope change of CL during 2010–2020; **c** denotes the fragmentation change of CL during 2000–2010; **d** denotes the fragmentation change of CL during 2010–2020; **e** denotes the soil quality change of CL during 2000–2010; **f** denotes the soil quality change of CL during 2010–2020; **g** denotes the overall quality change of CL during 2000–2010; **h** denotes the overall quality change of CL during 2010–2020.

Zhejiang province declined by more than 20% from 2010 to 2020.

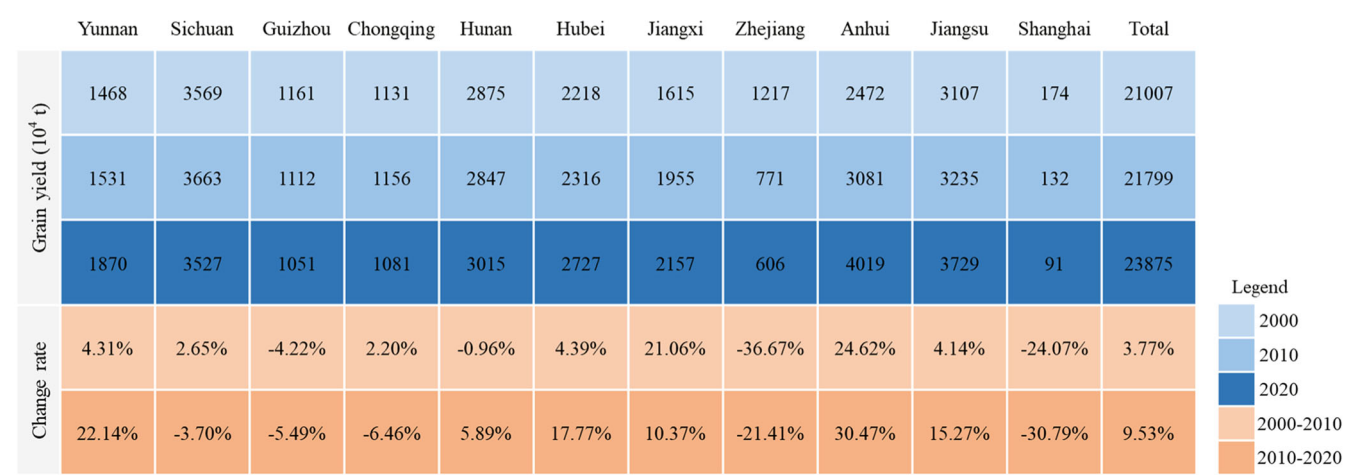


Fig. 7 Grain yield and its change rate at the level of province in the YREB from 2000 to 2020.

Guizhou. In contrast, the cities with increased CL soil quality during 2010–2020 were mainly located in some economically developed cities in Zhejiang and Shanghai. This was because the farmers in these economically developed cities primarily focused on non-agricultural incomes and adopted rotation cultivation with low intensity of CL utilization, which effectively restored the fertility of CL in these cities during 2010–2020, which can also be confirmed by the multiple cropping index of these cities. This relationship between economic development and changes in CL quality may stem from the fact that farmers in less economically developed cities were geographically constrained to access only uphill areas of poorer CL quality, and thus local farmers tended to make intensive use of CL resources by investing large quantities of pesticides and fertilizers in order to increase agricultural yields. In addition, since relatively flat and fertile land was replenished as CL in the previous period, only uphill areas can be supplemented as CL to achieve the CL requisition-compensation balance in the near future. These reasons together exacerbated the decline in soil quality in those economically underdeveloped cities during 2010–2020 compared with that during 2000–2010.

Spatiotemporal change in grain yield. The gross grain yield in the YREB increased from $21,006.52 \times 10^4$ t in 2000 to $23,875.48 \times 10^4$ t in 2020 (Fig. 7), with a total increase rate of 13.66% from 2000 to 2020. The increase rates in the YREB during 2000–2010 and 2010–2020 were 3.77% and 9.53%, respectively, indicating the higher increase rate of food production during the latter decade. Among the 11 provinces of the YREB, Anhui (24.62%) and Jiangxi (21.06%) had the largest growth in the change rate of grain yield during 2000–2010, while the largest growth in grain yield during 2010–2020 was recorded in Anhui (30.47%) and Yunnan (22.14%), indicating the largest increase in grain yield during 2000–2020 in Anhui. In addition, the grain yield in Yunnan, Hubei, and Jiangsu also increased from 4.31%, 4.39%, and 4.14% during 2000–2010 to 22.14%, 17.77%, and 15.27% during 2010–2020, respectively. Figure 8a, b shows that the cities with increasing grain output during 2000–2010 were primarily distributed in the upstream and midstream sections of the YREB, as well as the lower reaches of Anhui and Northern Jiangsu. The increases in grain yield during 2010–2020 were mainly located in Yunnan and Southwest Sichuan in upstream regions of the YREB. However, the greatest reduction in grain yields could be seen in economically developed Zhejiang (–50.23%) and Shanghai (–47.45%) during 2000–2020, and 11

cities in the economically developed province of Zhejiang also showed the same declining trend in the grain yield during 2000–2010, including 7 cities experiencing a decline of more than 20%. It is worth noting that food production in all cities in Zhejiang province declined by more than 20% from 2010 to 2020.

Interrelationships among CL quantity, CL quality, and grain yield. *Coupling modes of CLQGGY change.* Figure 8c, d indicates that the most numerous coupling pattern in the change of CLQGGY in 130 cities in the YREB during 2000–2010 was the mode in which the CL area increased with the degradation in CL quality and the decrease in grain yield ($A \uparrow Q \downarrow G \downarrow$, 37 cities, accounting for 28.46%). During 2000–2010, 5 cities (Wuxi and Suzhou in Jiangsu, Jiaxing, Huzhou and Zhoushan in Zhejiang) exhibited a pattern of areal loss and declining CL quality but increasing grain yield ($A \downarrow Q \downarrow G \uparrow$), which was an unsustainable resource-input-driven grain production pattern. However, 31 cities in the YREB (primarily located in the western and southern Sichuan and southern Hunan) exhibited the $A \downarrow Q \downarrow G \uparrow$ mode during 2010–2020, which illustrated that this unsustainable resource-input-driven food production pattern was widely distributed during this period and required urgent attention. Notably, during 2010–2020, the number of cities with the mode of increased CL area, quality, and grain yield ($A \uparrow Q \uparrow G \uparrow$) was the least with only 3 cities. These all indicated that the overall changes in CL quantity and quality during 2010–2020 were not satisfied and related authorities should urgently strengthen the supervision of CL quantity and quality in the agricultural production process.

Sources of the CLQGGY change modes. Figure 9 indicates that among the 130 cities of the YREB, 12 cities shifted from the $A \uparrow Q \downarrow G \downarrow$ mode during 2000–2010 to the $A \downarrow Q \downarrow G \uparrow$ mode in 2010–2020. In addition, 11 cities changed from the pattern of increased CL area and quality but decreased grain yield ($A \uparrow Q \uparrow G \downarrow$) during 2000–2010 to the $A \downarrow Q \downarrow G \uparrow$ mode during 2010–2020. These alterations revealed that many cities have adopted unsustainable resource-input-driven grain production patterns during 2010–2020. This mode was often achieved through unsustainable but potentially high-yielding production methods (such as increased utilization of chemical inputs).

Discussion
Influences of current land use policies on grain yield and CL. As the primary material for crop production, CL is the fundamental prerequisite for ensuring food supply. Nevertheless, fast

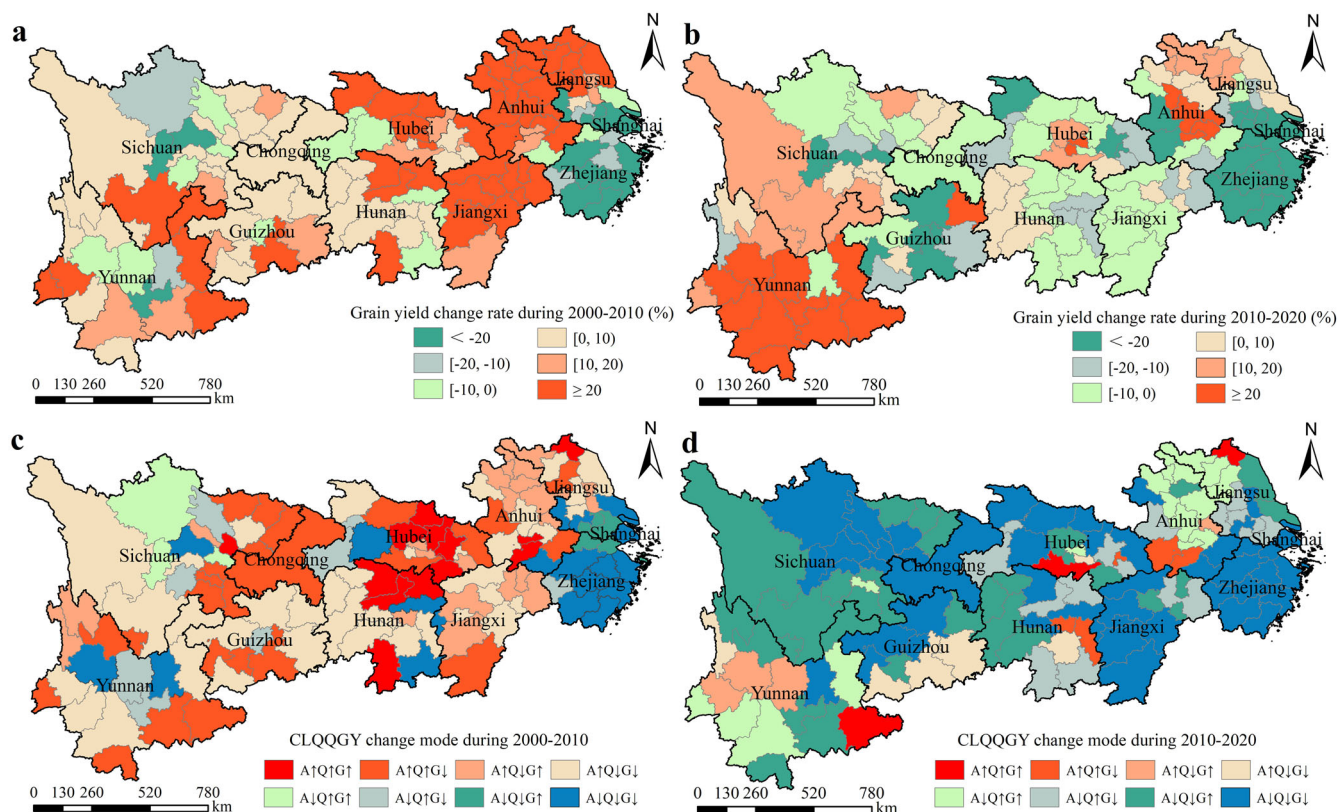


Fig. 8 Grain yield change rate and the coupling modes of CLQQGY change in the YREB during 2000–2020. **a** Denotes the grain yield change rate during 2000–2010; **b** denotes the grain yield change rate during 2010–2020; **c** denotes the CLQQGY change mode during 2000–2010; **d** denotes the CLQQGY change mode during 2010–2020.

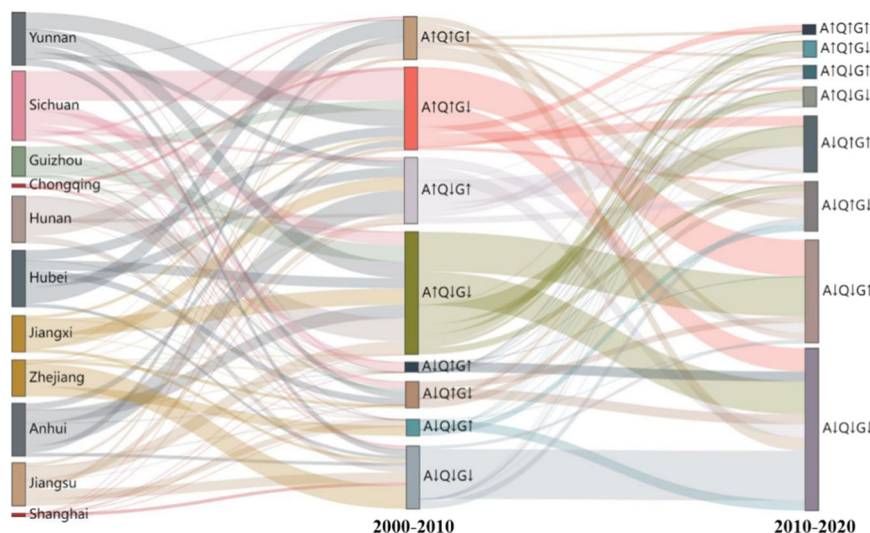


Fig. 9 Sources of the CLQQGY change modes in the YREB during 2000–2020. Note: the height of the column represents cities included in the province or the mode; higher column indicates large number of included cities.

urbanization process and the implementation of “grain for green programs” have led to a significant loss of CL, directly endangering grain security (Xie et al., 2020). Our findings show that areas of CL in the YREB declined by $313.66 \times 10^4 \text{ hm}^2$ during 2000–2020 (a decrease of 4.34% in 2020 compared to that in 2000), which increases the pressure on ensuring food production. Although the policy of CL requisition-compensation balance implemented by the Chinese government has ensured the overall quantity of CL to a certain extent, the quality of the supplemented

CL is relatively poor compared to the occupied land. This directly leads to the degradation of total CL quality, causing the yield reduction per unit area and further posing great threat to guarantee food supply in the face of population growth. In order to achieve a dynamic balance of total CL, China has adopted strict CL protection and active land resource development policies (Chen et al., 2021b). Since 1998, China has conducted national large-scale land consolidation projects to promote CL conservation and to improve the continuity of CL (Chen et al., 2022; Zhao

et al., 2024). The contiguity of CL improves agricultural production conditions, modernizing and mechanizing large-scale agriculture production. These improvements, combining with the overuse of pesticides and chemical fertilizers, did increase total grain yield in the past decades. However, the overall quality of CL in this region still faces a severe decline trend: the slope of the supplementary CL is usually larger than the original land occupied by construction areas, and the soil quality of CL decreases due to the utilization of upslope regions as supplementary CL in the YREB.

Consecutive grain harvests to support survivals of more people.

We find an overall decline trend in CL quantity and quality in the YREB, while the overall grain yield shows a continuous harvest trend. With the application of the Geodetector model, this study analyzes the factors influencing grain yield during 2000–2020 (Fig. 10), and find that the primary reason for this pattern (double declines in CL quantity and quality but the consecutive harvests in grain yield) is the widespread utilization of fertilizers, agriculture machinery, and rural electricity, which coincides with previous research results (German et al., 2017; Qiu et al., 2022b). However, this is a typical unsustainable resource-input-driven grain production pattern, where increased food production through excessive agricultural mechanization leads to increased soil compaction and degradation, affecting the future sustainable production capacity of CL. This unsustainable influence also exists in the consumption of fossil energy and electricity for mechanized agricultural production. The main source of rural electric energy is the combustion of fossil fuels, which is a non-renewable resource. The consumption of large amounts of non-renewable energy not only leads to an energy crisis, but also seriously pollutes the environment.

Additionally, the overuse of fertilizers leads to the deterioration of soil properties and acidification, which also reduces land productivity and threatens the safety of agricultural products (Van Wesenbeeck et al., 2021; Liu et al., 2013). Although the utilization of chemical fertilizers can indeed improve crop yield per unit area in the early stage, the yield of crops will not continue to increase once the amount reaches the certain upper limit. This continuous input of chemical fertilizer activities may not necessarily bring out stable yields, but may lead to the degradation of CL quality and irreversible damage to CL in the long term. Various chemicals present in these fertilizers can lead to environmental pollution problems, such as the eutrophication of water resources once they flow into rivers. Therefore, the current consecutive harvests driven by the extensive production

modes are unsustainable. If this situation continues, human society will have to withstand great costs (environmental degradation, grain quality decline, etc.) to maintain food harvests in order to feed more people in the future. When the increased grain yield encounters a bottleneck period, it is necessary to implement an intensive eco-agriculture development mode that integrates future social, economic, and ecological benefits. Therefore, it is significant for government authorities to simultaneously announce related policies to conserve CL quantity and quality. These policies should play an important role in CL quantity supervision as well as regulation of plant types to avoid “non-grain” and even “non-agriculturalization” of CL use through integrating administrative (such as CL protection zoning) and economic measures (such as agricultural subsidies). Moreover, it is recommended to innovate and apply contemporary and advanced technologies to improve CL quantity and quality, to promote a steady increase in crop production, and to guarantee an increasing trend of grain yield to support survivals of more people.

Policy implications for sustainable CL use and increasing grain yields.

CL quantity conservation is prerequisite to guarantee grain production, while ecological conservation of CL is an inevitable way to realize sustainable food production (Jiang et al., 2020; Zhou et al., 2021). Consequently, it is suggested to establish a comprehensive CL protection system that integrates quantity, quality, and ecological environment of CL to promise grain security (Wang et al., 2024b). For example, the red line policy of 1.8 billion mu of CL in China strictly restricts the CL use, having been delegated as a permanent basic policy to protect CL. CL requisition–compensation balance policy in China has also been put into place for decades in many regions, contributing greatly to CL conservation. However, to achieve the goal of cropland protection, these policies could be further strengthened by integrating all aspects of CL quantity, quality, and ecological protection. For instance, CL requisition–compensation balance policy in China requires the quality of new CL and has not yet required the supplementary CL the same quality of original CL, which could potentially lead to the appropriation of high-quality CL but replenishment of low-quality CL (Chen et al., 2021a). Moreover, there is an urgent need to give high priority to ecological conservation of CL, including input requirements for fertilizers, pesticides, and other agricultural materials while ensuring food supply, reforming agronomic measures to improve soil organic matter content and microbial activity, carrying out the high-quality ecological CL construction, and improving CL

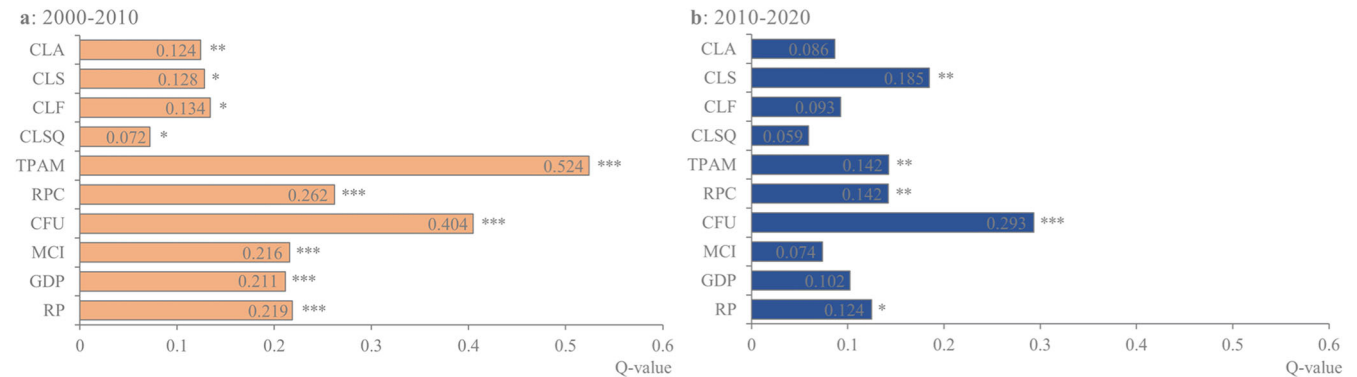


Fig. 10 Analysis of factors influencing grain yield during 2000–2020. Notes: (1) *, **, and *** imply statistical significance levels of 10%, 5%, and 1%, respectively. (2) The abbreviations are defined as follows: cultivated land area (CLA), cultivated land slope (CLS), cultivated land fragmentation (CLF), cultivated land soil quality (CLSQ), total power of agriculture machinery (TPAM), rural power consumption (RPC), chemical fertilizer usage (CFU), multiple cropping index (MCI), gross domestic product (GDP), and resident population (RP).

productivity by a combination of land cultivation and land conservation.

In the reality of excessive input of agricultural production materials in exchange for higher grain yields, it is urgent to innovate grain production mode as well as increase sustainable investment to achieve a stably high grain yield. Although the results of this paper indicate a trend towards continuous harvests in China, this pattern of grain production is highly dependent on large amounts of pesticides and chemical fertilizers, which is unsustainable and can indirectly threaten people's survivals (Zhuang et al., 2022). Therefore, the new grain production mode should comprehensively consider the quality and quantity of grain production, environmental protection and stability, and production efficiency, ensuring the consistency of food production with economic development and environment conservation. In addition, based on the results of this study, large-scale intensive food production is a feasible way to support sustainable grain production with the consideration of cost reduction, quality and yield improvement, and differentiated production methods for different CL qualities. It is also significant to encourage and support agricultural technology investment, encourage advances in agricultural technology such as food production, water-saving, and pesticide-saving technology. These policies and measurements can comprehensively improve economic, social, and ecological benefits of grain production.

Under the influence of the market economy and driven by competitive interests, farmers tend to abandon grain cultivation and choose cash crops with higher incomes (Hu et al., 2018). This not only reduces CL quantity and quality but also destabilizes China's food production, and even jeopardizes global grain safety. As a result, the trend of "non-grain" in CL should be curbed (Huang et al., 2024). Specifically, to contain "non-grain" of CL, differentiated governance measures should be adopted in regions with varying CL resource endowments. This can be combined with economic instruments such as grain subsidy systems to guarantee the income of grain-crop farmers. To standardize and balance the areas and proportions of cash and food crops, a unified "non-grain index" trading market can be established on the standardization of "non-grain indicators".

Conclusions

This study demonstrated the characteristics and patterns of CLQGY, identified factors influencing food security, and tested the sustainability of the current "continuous harvests" production mode for improving grain yield in response to growing food demand based on GlobeLand30 data from 2000 to 2020 in 130 prefecture-level cities in YREB in China. Areal loss and quality decline of CL were observed in most cities in the YREB. The total CL areas declined by $31.07 \times 10^4 \text{ hm}^2$ and $282.59 \times 10^4 \text{ hm}^2$ during 2000–2010 and 2010–2020, respectively, affecting a large proportion of cities (68.46% and 69.23%, respectively). However, the total grain yields increased by 3.77% and 9.53% during 2000–2010 and 2010–2020, respectively, which were attributed to continuous harvests of grain yield during these periods. A noteworthy concern is that this type of harvest was excessively dependent on the use of chemical fertilizers and other resources, which contribute to environmental damage and associated negative impacts. Consequently, current grain production was unsustainable in the mode of "areal loss and quality degradation of CL but increased grain yield" in the YREB. It was a typical resource-input-driven growth mode with huge negative ecological effects, the use of chemical fertilizers, the total power of agricultural machinery and the consumption of rural electricity were found to be the main factors threatening the sustainability of grain supply. In the future, we should implement an intensive

agroecological production mode that brings social, economic, and ecological benefits to ensure a healthy and sustainable "continuous grain harvests". This research can serve as the basis for policy-making on the development of CL conservation and consolidation policies that balance CL quantity and quality for the growth of more people. This study can also provide a different and important perspective for developing grain production capacity in countries around the world by optimizing grain growth conditions and farming practices, and contribute to addressing food shortage caused by population growth through sustainable CL use and grain supply.

Data availability

All data in this study were obtained from official reports and databases, and the specific sources have been described in detail in the "Materials and methods" section. If necessary, the datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

Conceptualization: PC, YZ, KL, and PJ; Methodology: PC, KL, and SW; Formal analysis: PC, KL, SW, and HY; Supervision: YZ, KL, XK, and PJ; Writing—original draft: PC, and KL; Writing—review & editing: PC, YZ, KL, XK, and PJ; Project administration: PC, YZ, SW, and PJ; funding acquisition: PC, YZ, SW, and PJ. All authors have read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Ethical approval

Ethical approval was not required for this study, as it did not involve human participants. No primary surveys were conducted; all data were obtained from official reports and databases.

Informed consent

Informed consent was not required as the study did not involve human participants.

Additional information

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