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Per Capita Cropland Estimations for Traditional Agricultural Areas of China over Past Millennium

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Abstract: Studying changes in land use per capita is critical for understanding the interactions between humans and ecosystems, and for modeling the impacts of land use changes on climate systems. However, many uncertainties in historical estimates significantly hinder climate modeling. This study estimated the per capita cropland area in traditional agricultural regions of China over the past millennium using historical-document-based and modern statistical cropland and population data. The findings showed that changes in the per capita cropland area in the provinces of the middle and lower reaches of the Yellow River could be characterized into three stages: slow decrease, rapid increase, and fluctuating decrease, whereas, in the provinces of the middle and lower reaches of the Yangtze River, there was a continuous decrease. Spatially, the per capita cropland area was higher in the middle and lower reaches of the Yellow River and lower in the middle and lower reaches of the Yangtze River during the study period. The per capita cropland areas showed clear differences in the HYDE dataset and our study; the corresponding values of our study were 2.1–8.0, 1.7–8.2, and 1.6–8.8 times higher than those from the HYDE dataset for the early Song, Yuan, and Ming dynasties, respectively.

Keywords: land use; per capita cropland; historical document; China; the past millennium

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1. Introduction

The history of human land use is characterized by continuous reorganization of the land to adapt its use and spatial structure to changing human needs [1,2]. These changes in land use have resulted in the transformation of Earth's surface landscapes from natural ecosystems such as forests and grasslands to anthropogenic landscapes like residential areas, agricultural zones, and roads, and this transformation has reached approximately 50% since the advent of agriculture [3–6]. Consequently, the significant changes in land cover have biogeochemically and biogeophysically influenced global climate systems by affecting radiative forcing by changing surface roughness, surface albedo, and latent heat fluxes and exchanging greenhouse gases (GHGs) and other gases in the atmosphere [7–9]. Previous studies have estimated that the atmospheric CO_2 net emissions from land cover changes were more than 50% of the total emissions before 1940 [10,11]. To enhance our comprehension of the interactive dynamics between humans and ecosystems and to precisely quantify the impacts of human activities on long-term global climate change, substantial efforts have been dedicated to acquiring historical information on global land use and land cover changes (LUCCs) [12–19].

Over the past decades, using satellite data, multisource historical statistics, and inventory data, substantial progress has been made in global and regional historical LUCC reconstruction. These reconstructions are dominated by two different approaches. The regional- and local-level approach consists of comparing a set of land uses and land covers for different time steps to determine their changes. The second approach focuses on global historic LUCC reconstructions, which are often developed specifically for the climate change modeling community [20]. For global-scale studies, the most representative achievements are shown in the four global LUCC datasets [12–15]. The Center for Sustainability and the Global Environment (SAGE) and Pongratz Julia (PJ) produced a historical database of global cropland and pasture for AD 1700–1992 and AD 800–1700, respectively [13,14]. The Historical Database of the Global Environment (HYDE) was established by the Netherlands Environmental Assessment Agency, and the latest version reconstructed global cropland, pasture, and built-up land cover for 10,000 BC–AD 2015 [16]. KK10 was developed by Kaplan and Krumhardt in AD 2010, including anthropogenic land cover changes for 8000 BP–AD 2015 [15]. These datasets have been widely utilized to simulate LUCC impacts on global and regional climate and ecological environments, as well as in studies of carbon emissions, owing to their high spatial resolution and long-term coverage [21–24].

These datasets reconstructed the amount of land use at the national or provincial level for the pre-1960 period, mainly relying on hindcasting techniques based on historical population estimates and assumptions regarding the relationship between population and land use, since most countries lacked reliable land use surveys prior to the middle of the twentieth century [25]. Uncertainties arise due to large temporal and spatial variations in historical population data and the assumptions made regarding the relationship between population and land use [26,27]. Therefore, a better understanding of the relationship between population and land use and how it has changed over time is essential. Primary studies, including earlier versions of the HYDE and PJ datasets, have established the relationship between population and land use using the quantitative link between modern populations and land use data for the post-1960 era, assuming that per capita land use was nearly constant for the pre-1960 era [14,28]. However, the assumption that land use per capita has remained constant over time is unsupported by evidence or the accepted land use theory. Evidence has been synthesized from field studies to confirm that per capita land use decreases over time as populations increase, land availability per capita declines, technologies improve, and land use intensifies [29]. Moreover, regional historical observations from Europe and China support the theory that land cover change per capita has sharply declined over the last 2000 years [26,30]. In short, the assumption of constant land use per capita during pre-industrial times is unjustified. However, establishing the exact shape of the land use per capita curve and the timing of such a process remains challenging. Subsequently, based on the land use theory of previous studies, KK10 and HYDE 3.2 attempted to define a per capita land use curve for different countries or main regions based on the limited historical sources and reconstructed global ALCC by combining it with historical population estimates.

Despite constant adjustments to the per capita land use curve to enhance the accuracy of land use data by providing more empirical evidence, national- and regional-level uncertainties persist, because these studies do not utilize rich indigenous empirical data. For instance, both global datasets and regional research have indicated a slight decrease in per capita cropland area in China over historical periods, but there are significant variations in the per capita values of cropland between the global and regional datasets [31]. As this variable is the primary parameter in the reconstruction of historical cropland areas, any variation in the per capita cropland area will result in a significant difference in the results of the total cropland reconstruction [31–34]. Therefore, it is essential to conduct further research to establish a more reliable per capita cropland curve for different study areas by identifying regional historical sources and incorporating local research [26,27].

China has a rich history of agriculture and ancient civilization, making it one of the few countries with extensive historical records of cropland farming. These historical ma-

terials provide a strong foundation for studying the quantitative relationships between historical populations and croplands in China. However, current local research has primarily focused on reconstructing historical cropland areas at the national, provincial, and county levels. The changes in per capita cropland area over time and space have not been clearly defined. This study aims to estimate the per capita cropland area in traditional agricultural areas of China over the past millennium using historical records of cropland and population from the Song, Yuan, and Ming dynasties, along with modern statistical data for the past 300 years. Subsequently, the temporal–spatial changes in the per capita cropland area within the study area over the past millennium were analyzed based on these estimations. The results of this study will present more detailed information on the temporal–spatial patterns of per capita cropland changes in the traditional agricultural areas of China over the past millennium. It can also provide more regional empirical data on historical per capita land use, which can contribute to improving global land use datasets and reconstructing regional land use.

2. Study Area

Our study focused on the middle and lower reaches of the Yellow and Yangtze Rivers, encompassing 13 provinces and three cities (Figure 1). This area extends between latitudes 23°31′ N and 42°40′ N and longitudes 105°29′ E and 122°43′ E, covering approximately 2.46×10^8 ha, equivalent to about one-fourth of the territory area of China. Renowned for their superior climatic and topographical conditions, the middle and lower reaches of the Yellow and Yangtze Rivers are the foremost traditional agricultural regions in China. Archaeological evidence has revealed that agriculture in China originated in the Yellow and Yangtze River Basins during the Neolithic Period [32,33]. However, significant natural geographical disparities between the middle and lower reaches of the Yellow and Yangtze Rivers led to distinct cultivated crops and farming practices in these two regions. Specifically, from the mid and late Tang Dynasty to the Northern Song Dynasty, a millet–wheat–legume cropping system with two years of planting and three harvests and a rice–wheat cropping system with one year of planting and two harvests began to appear and were established in the middle and lower reaches of the Yellow and Yangtze Rivers, respectively. From the Southern Song Dynasty, Vietnamese rice (Zhancheng Rice) was introduced into China, and a double-season rice or a wheat–rice–rice cropping system with two or three harvests per year gradually appeared in the middle and lower reaches of the Yangtze River, finally maturing during the Ming and Qing dynasties [35,36].

Over the past millennium, this region has been governed by successive dynasties, including the Song (AD 960–1279), Jin (AD 1115–1234), Yuan (AD 1271–1368), Ming (AD 1368–1644), and Qing (AD 1644–1912). Since the Song Dynasty, provinces situated along the middle and lower reaches of the Yellow and Yangtze Rivers have been crucial contributors to national fiscal revenue. Governments across various dynasties have attached great importance to the registration of population and cropland quantities in these provinces to ensure food supply and taxation security. These historical records provide abundant regional empirical data on historical per capita cropland information and play an essential role in understanding the historical population and land use. With dynastic changes, the administrative divisions within the study area have undergone frequent alterations. The primary administrative divisions also transitioned from the Lu of the Song and Jin dynasties to the province of the Yuan Dynasty. Consequently, comparing historical data with modern statistics or investigative data across different historical periods is challenging using uniform administrative units. Some current provincial units were amalgamated into historical units to mitigate uncertainties in the estimation results. For example, Beijing, Tianjin, and Hebei were merged to form Jing–Jin–Ji and Shanghai and Jiangsu were merged to form Hu–Ning. These provincial units align with historical records from the Qing Dynasty. Subsequently, we employed the adjusted 13 provinces as foundational administrative units to estimate and analyze the per capita cropland over the past millennium.

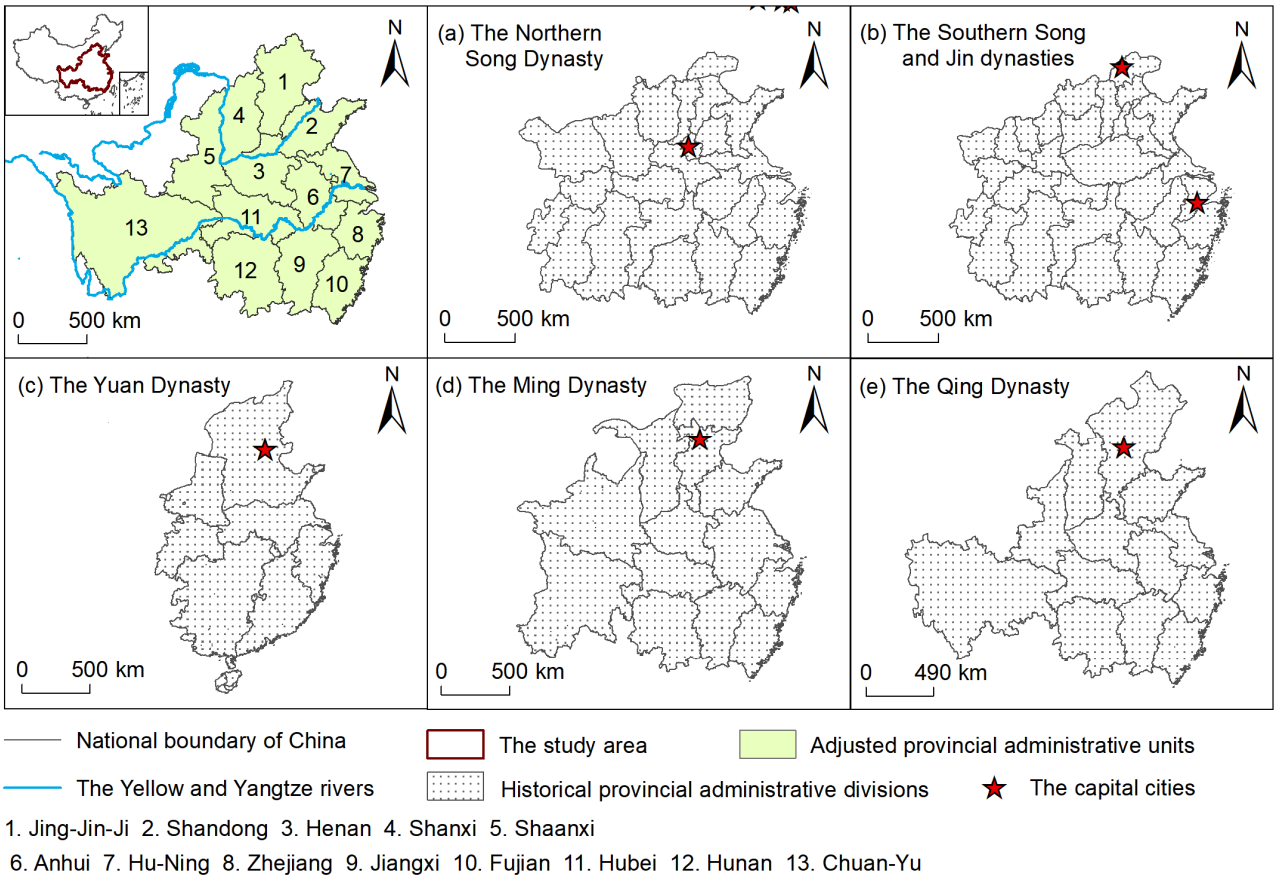


Figure 1. Adjusted 13 provincial administrative units in this study and changes in the provincial boundaries in the traditional agricultural areas of China over the past millennium (**a**–**e**).

3. Materials and Methods

The primary data sources used in this study were historical records of cropland areas, household numbers, and modern statistical data on croplands and populations. In ancient China, national taxes were levied on households, with a particular emphasis placed on the registration of household income and property by local governments. The cropland area owned by each household was the primary basis for taxation [37]. Consequently, historical records of the cropland areas and household numbers during this period are plentiful. However, these data do not equate to modern statistical data in their implications and were recorded by the government of feudal China for tax collection; thus, these historical data typically only represent tax units and do not adequately reflect the actual cropland and population data at that time [38]. Moreover, the meaning of these historical cropland data is subject to change owing to variations in land management and taxation systems across different historical dynasties. Consequently, we delineated the data sources and corresponding processing methodologies in accordance with distinct historical dynasties.

3.1. The Song Dynasty (AD960–1279)

The Song Dynasty comprised the Northern Song (AD 960–1127) and Southern Song (AD 1127–1279) dynasties. The Northern Song Dynasty was established in AD 960, and its territory covered the entire study area. In AD 1115, the Jin Dynasty (AD 1115–1234), founded by the Jurchen in northeast China, successively occupied the northern territory of the Northern Song Dynasty and expanded its territory to the Huaihe River to the north in AD 1127. Subsequently, the Jin and Southern Song dynasties ruled the middle and lower reaches of the Yellow and Yangtze Rivers, respectively [39]. Thus, historical data

on cropland area and household numbers for this period were obtained from historical documents originating from the Song and Jin dynasties.

The historical documents of this period indicated that the historical cropland data comprised two categories: taxed cropland area data and cropland area inventory data. While the former serve primarily as an indicator of agricultural taxes, their close correlation with the actual cropland areas render them pivotal in our estimations. Conversely, the latter can represent actual cropland areas, as they were meticulously measured and recorded by government-appointed officials tasked with investigating the quantity of cropland and safeguarding national tax revenue. Nevertheless, due to obstruction from feudal aristocrats and the landlord class, these measurements were only carried out in certain regions, resulting in a sporadic availability of data.

3.1.1. Data Sources

(1) Taxed cropland area data. National- and provincial-level taxed cropland area data for the Northern Song Dynasty were obtained mainly from the *Collections of Historical Governmental Archives* (《文献通考》). This volume contains provincial taxed cropland area data for AD 1078 and national taxed cropland area data for AD 976, AD 997, AD 1066, and AD 1078 (Table 1). These data cover the study area. County-level taxed cropland area data were derived mainly from *Collections of Local Chronicles of the Song and Yuan Dynasties* (《宋元方志集刊》), as well as the *Collected Texts of the Administrative Statues of the Song Dynasty* (《宋会要辑稿》). We derived taxed cropland area data for 27 counties from AD 1164 to AD 1234 in the middle and lower reaches of the Yangtze River from nine local chronicles of the Southern Song Dynasty.

Table 1. Spatial and temporal coverage of taxed cropland, cropland inventory, and household numbers data during the Northern Song, Southern Song, and Jin dynasties.

Data Types	Historical Periods	Temporal Coverage	Spatial Coverage
Taxed cropland area data	Northern Song	AD 996, 997, 1066, and 1078	National
		AD 1078	Provinces (*Lu*)
	Southern Song	AD 1164–1234	Counties
Cropland area inventory data	Northern Song	AD 1072–1085	Provinces (*Lu*)
	Southern Song	AD 1174–1189	Counties
	The Jin Dynasty	AD 1189	Provinces (*Lu*)
Household numbers data	Northern Song	AD 980 and 1078	Provinces (*Lu*)
	Southern Song	AD 1162 and 1223	Provinces (*Lu*)
		AD 1164–1234	Counties
	The Jin Dynasty	AD 1207	Provinces (*Lu*)

(2) Cropland area inventory data. Cropland area inventory data for five provinces (*Lu*) in the middle and lower reaches of the Yellow River during the Northern Song Dynasty, including Kaifeng, Jingdong, Hebei, Hedong, and Shaanxi, were derived from the *Monograph on Food and Property from the History of the Song Dynasty* (《宋史·食货志》). In comparison, cropland area inventory data for six counties within the Jiangnandong province (*Lu*) of the middle and lower reaches of the Yangtze River during the Southern Song Dynasty, including Xi, Xiuning, Qimen, Wuyuan, Jixi, and Yi, were extracted from the Xinan Chronicles (《新安志》) (Table 1). These cropland area data were obtained during the implementation of the *Land Measurement and Tax Equalization Law* (方田均税法) and the *Land Boundary Survey Law* (经界法), which were completed in the Yuanfeng (between AD 1072 and 1085) and Chunxi Terms (between AD 1174 and 1189), respectively. Similar to the Song Dynasty, the Jin Dynasty also collected agricultural taxes based on the cropland area occupied by the farmers, and the cropland inventory was also performed in the middle and lower reaches

of the Yellow River during this period, with the results beinf recorded in AD 1189 in the *Monograph on Food and Property from the History of the Jin Dynasty* (《金史·食货志》).

(3) Household numbers data. The household data estimates used in this period were obtained from Wu and Ge [40]. The authors calibrated and estimated provincial household numbers for several periods during the Northern Song, Southern Song, and Jin dynasties (i.e., for AD 980 and AD 1078 during the Northern Song Dynasty, for AD 1162 and AD 1223 during the Southern Song Dynasty, and for AD 1207 during the Jin Dynasty, respectively) using various historical documents, including the *National Gazette* (《太平寰宇记》), *General Condition of Society and Natural Environment in Yuanfeng Term* (《元丰九域志》), *Monograph on Geography from the History of the Song Dynasty* (《宋史·地理志》), and *Monograph on Geography from the History of the Jin Dynasty* (《金史·地理志》). County-level household numbers data in the middle and lower reaches of the Yangtze River during the Southern Song Dynasty were supplemented by local chronicles from the Song Dynasty, as well as the *Collected Texts of the Administrative Statues of the Song Dynasty* (《宋会要辑稿》).

3.1.2. Estimation of Per Capita Cropland Area

(1) The Northern Song period. During this period, when the study area was under the unified governance of the Song Dynasty, we employed the same method to estimate the per capita cropland area in both the middle and lower reaches of the Yellow and Yangtze Rivers. Based on historical data from this period, we first calculated the ratios between the taxed cropland area (C_t) and real cropland area (C_r) of the middle and lower reaches of the Yellow and Yangtze Rivers using the aforementioned taxed cropland and cropland area inventory data from five provinces in the north and six counties in the south of the Northern Song Dynasty. These ratios were used as calibration coefficients to convert the provincial (*Lu*) taxed cropland areas for AD 1078 into real cropland areas. Finally, provincial household numbers for AD 1078 were converted to population data using population numbers per household of 5.4 and 5.2 for the middle and lower reaches of the Yellow and Yangtze rivers during the Song Dynasty, respectively. These values were calculated using the following equations:

$$PCA_k = \frac{\alpha \cdot (C_r / C_t) \cdot C_{kt}}{H_k \cdot HP_k} \quad (1)$$

where PCA_k is the per capita cropland area of the province (*Lu*) k for AD 1078 and α is the ratio between unit areas of mu (a Chinese unit of area, where 1 mu = 666.7 m^2) and Song-mu (an area unit used by the Northern Song Dynasty, where 1 Song-mu = 584.0 m^2): 0.876 [41]. C_{kt} is the taxed cropland area of the province (*Lu*) k for AD 1078. The ratio between C_r and C_t was 2.03 in the north and 1.93 in the south, H_k is the household number of the province (*Lu*) k for AD 1078, and HP_k is the population numbers per household during the Song Dynasty.

Subsequently, we analyzed the distribution time points of the obtained cropland area and household numbers data and selected the national taxed cropland area data from AD 976 and provincial household numbers data from AD 980 to estimate the provincial per capita cropland area for the early Northern Song period in the study area. For this estimation, the national cropland area for AD 976 was calibrated based on the cropland calibration ratio for AD 1078. Selecting the impact factors of the provincial cropland distribution (including altitude, slope, and population distribution) and analyzing the relationship between provincial cropland distribution and these factors facilitated the development of the provincial cropland area allocation model, and the provincial cropland areas for AD 976 were estimated [42]. Combined with the provincial household numbers for AD 980 and the population numbers per household during the Song Dynasty, the provincial per capita cropland areas for AD 976 were calculated using the following equation:

$$PCA_k = \frac{PCA(k,\ 1078)/\max(PCA(k,\ 1078)) \cdot 0.904 \cdot e^{0.273 \cdot H_k \cdot HP_k}}{\sum_i PCA(k,\ 1078)/\max(PCA(k,\ 1078)) \cdot 0.904 \cdot e^{0.273 \cdot H_k \cdot HP_k}} \cdot C / (H_k \cdot HP_k) \quad (2)$$

where PCA_k is the per capita cropland area of province $(Lu)k$forAD976, $PCA(k,\ 1078)$ is thepercapitacroplandareaofprovince$(Lu)k$for AD 1078, and max$(PCA(k,1078))$ is the maximum value of $PCA(k,1078)$, H_k is the number of households in province (*Lu*) *k* for AD 980, and HP_k is the population per household during the Song Dynasty.

(2) Southern Song and Jin Dynasties. Subsequent to AD 1127, variations in the population composition, land management systems, and taxation systems of the Jin and Southern Song dynasties provided distinct historical data characteristics between the middle and lower reaches of the Yellow and Yangtze Rivers. Consequently, different methods were employed to estimate the per capita cropland areas in the two regions. For the middle and lower reaches of the Yangtze River, provincial household numbers for AD 1162 and 1223, as well as sporadic county-level taxed cropland area data and household numbers from AD 1164 to 1234, were recorded in the local chronicles of the Southern Song Dynasty. Thus, we calibrated these sporadic county-level taxed cropland area data utilizing the ratios derived from the taxed cropland area and cropland area inventory data of the six counties situated in the middle and lower reaches of the Yangtze River. The per capita cropland area for each province was then estimated using the calibrated county-level cropland area and household numbers within these provinces, along with the population numbers per household for the middle and lower reaches of the Yangtze River during the Southern Song Dynasty. Due to the inconsistent timelines recorded in these county-level data, we ultimately standardized the estimation time point to AD 1200. The calculation equation is as follows:

$$PCA_k = \frac{\sum_{i=1}^{n} \alpha \cdot (C_r / C_t) \cdot C_{kit}}{\sum_{i=1}^{n} H_{ki} \cdot HP_{ki}} \quad (3)$$

where PCA_k is the per capita cropland area of province (*Lu*) *k* for AD 1200, α is the ratio between the unit areas of mu and Song-mu: 0.876 [41], C_{kit} is the taxed cropland area of county *i* within the province (*Lu*) *k* from AD 1164 to AD 1234, the ratio between C_r and C_t was 1.93, H_{ki} is the number of households in county *I* within the province (*Lu*) *k* from AD 1164 to AD 1234, and HP_{ki} is the population per household of county *i* within the province (*Lu*) *k* during the Song Dynasty.

In contrast to the middle and lower reaches of the Yangtze River, the middle and lower reaches of the Yellow River were ruled by the Jin dynasty from 1127 to AD 1234. During this period, there were limited preserved historical cropland data, with provincial (*Lu*) household numbers only available for AD 1207, making it challenging to estimate the per capita cropland area. However, records related to historical land management and taxation systems provided valuable insights into the relationship between croplands and population. From historical records, during the Jin Dynasty, the population of the middle and lower reaches of the Yellow River was consistently composed of the Jurchens and Han populations, and the government created two local administrative organizations to manage the two groups: ordinary prefectural households and the Mengan Mouke [40]. Two different taxation systems and land policies were also implemented to collect revenue and manage land; thus, we separately estimated the per capita cropland area for the Jurchens of the Mengan Mouke and Han populations of ordinary prefectural households at the provincial level.

For the Jurchens of the Mengan Mouke, cropland was allocated by the government, while the so-called Cattle and Tool Tax stipulated that this should be allocated according to the population level [43]. According to the *Monograph on Food and Property from the History of the Jin Dynasty* (《金史·食货志》), each group of 25 Jurchen people was eligible for approximately 404 Song-mu under the Mengan Mouke system. We utilized these historical records to calculate the per capita cropland area of the Jurchens of the Mengan Mouke at 16.2 Song-mu, equivalent to approximately 14.2 mu. For the Han population of the ordinary prefectural household, with the cropland area inventory data encompassing present day Jing-jin and surrounding areas only available for AD 1189, along with household number data and population numbers per household for the middle and lower reaches of the Yellow River during this period, the per capita cropland area was obtained.

Subsequently, we estimated the per capita cropland area for each province in the middle and lower reaches of the Yellow River using the proportions of the Jurchen and Han populations (Figure 2) as weights by combining the previously calculated per capita cropland areas for the Jurchen and Han populations.

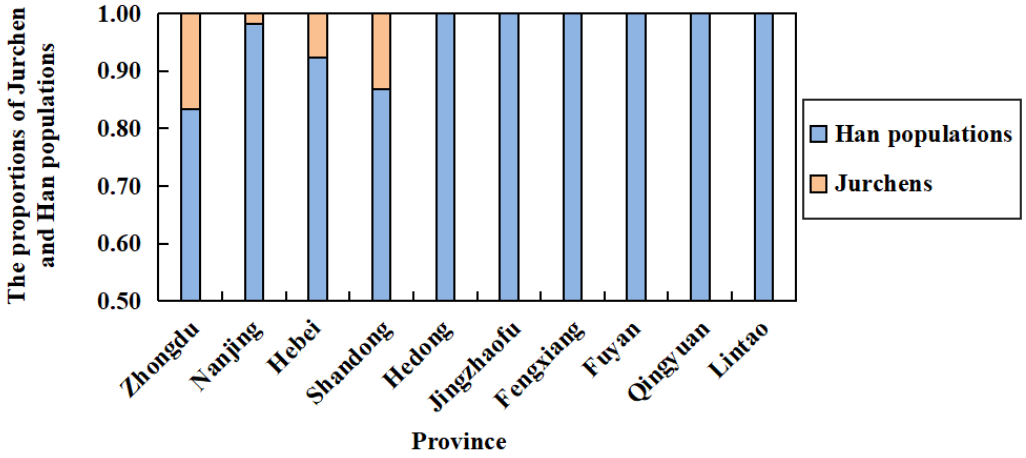


Figure 2. Proportions of Jurchen and Han populations in the provinces of the middle and lower reaches of the Yellow River for AD 1207, the corresponding values obtained from Li et al. [44].

Considering the time difference between the provincial household number data and the estimated per capita cropland area based on the available data, we standardized the research time point for the provincial per capita cropland area in the middle and lower reaches of the Yellow River to AD 1200. The calculation equation is as follows:

$$PCA_k = \alpha \cdot \frac{H_m \times HP_m}{(H_k - H_m) \times HP_p + H_m \times HP_m} \cdot PCA_m + \alpha \cdot \frac{(H_k - H_m) \times HP_p}{(H_k - H_m) \times HP_p + H_m \times HP_m} \cdot PCA_p \quad (4)$$

where PCA_k is the per capita cropland area of province (*Lu*) k for AD 1200, α is the ratio between the unit areas of mu and Song-mu: 0.876 [41], H_k and H_m are the total number of households and numbers of Mengan Mouke households in province (*Lu*) k for AD 1207, respectively, and *HP* is the population per household. Values of 5.4 and 10 were applied for *HP* in the ordinary prefectural (HP_p) and Mengan Mouke (HP_m) households, respectively [40]. PCA$_m$ and PCA_p are the per capita cropland areas of Mengan Mouke households and ordinary prefectural households, respectively.

3.2. The Yuan Dynasty (AD 1279–1368)

After AD 1234, the Mongolians gradually unified the present-day territory of China from north to south by conquering the Jin and Southern Song dynasties, as well as local western regimes, establishing the Yuan Dynasty in AD 1271. Until the establishment of the Ming Dynasty, the middle and lower reaches of the Yellow and Yangtze Rivers were under Mongolian control. After the establishment of the Yuan Dynasty, the government implemented two entirely different cropland management systems throughout the country: military-oriented croplands and ordinary croplands. Military-oriented croplands were uniformly allocated to each military or ordinary household by the government, and the grain produced was delivered to the government according to quotas or shares, primarily used for military supplies [45]. Ordinary croplands were owned by local landlords and farmers, and the government collected taxes according to cropland area based on household units. To ensure a steady supply of military provisions and national tax revenue, the government worked diligently to register the number of households and the amount of cropland, focusing especially on households with military affiliations during this period. These data are crucial for comprehending the connection between croplands and crop populations.

3.2.1. Data Sources

(1) Military-oriented cropland areas and household data. Provincial military-oriented cropland area and household numbers data were obtained from the *Monograph on Military from the History of the Yuan Dynasty* (《元史·兵志》). According to records, most military-oriented cropland areas were reclaimed in succession from AD 1264 to 1294. Moreover, these croplands were cultivated during this period and represent military-oriented cropland areas in AD 1294. We derived data on military-oriented cropland areas and household numbers for seven provinces covering the middle and lower reaches of the Yellow and Yangtze Rivers.

(2) Total cropland area and household numbers data. These data include military-oriented and ordinary cropland areas and household numbers. Provincial data for the Henan, Jiangzhe, and Jiangxi provinces were obtained from the *Monograph on Food and Property from the History of the Yuan Dynasty* (《元史·食货志》). The *Lu* (a secondary administrative region of the Yuan Dynasty) and county-level data in the Jiangzhe and Jiangxi provinces were derived from the *New Jinling Chronicles* (《金陵新志》), *Zhenjiang Chronicles* (《镇江志》), *Siming Chronicles* (《四明志》), and *Nanhai Chronicles* (《南海志》), respectively. According to historical records, these data originated from a massive measurement project during the Renzong period (AD 1311–1320). This project was first implemented in the Henan, Jiangzhe, and Jiangxi provinces. However, owing to obstruction attributed to the large landowning class, this project was not implemented in other regions and was completed in AD 1328 [46]. Therefore, reliable cropland areas were available for only three provinces.

3.2.2. Estimation of Per Capita Cropland Area

We used data on cropland area, household numbers, and population numbers per household to calculate the military-oriented cropland area per capita at the provincial level, as well as the per capita cropland area at the provincial and county levels. The results revealed that military-oriented cropland areas and cropland areas per capita exhibited similar spatial patterns, with higher values in the middle and lower reaches of the Yellow River and lower values in the middle and lower reaches of the Yangtze River (refer to Figure 3). Specifically, the military-oriented cropland areas per capita for three provinces in the middle and lower reaches of the Yellow River varied between 11.8 and 26.3 Yuan-mu (1 Yuan-mu = 600.0 m^2), while the cropland area per capita in Henan Province was approximately 16.3 Yuan-mu. On the other hand, in four provinces in the middle and lower reaches of the Yangtze River, military-oriented cropland areas per capita ranged mainly between 3.1 and 3.5 Yuan-mu, while cropland area per capita varied between 1.8 and 7.6 Yuan-mu. The values for the Jiangzhe and Jiangxi provinces were 3.8 and 4.0 Yuan-mu, respectively (Figure 3). Historical documents from the Yuan Dynasty also support this disparity. We hypothesized that the significant differences are attributable to variations in the natural environment and planting practices between the middle and lower reaches of the Yellow and Yangtze Rivers.

After comparing the military-oriented cropland areas and cropland areas per capita at the provincial level, we found a strong correlation in the Henan, Jiangzhe, and Jiangxi provinces. The ratios of cropland area per capita to military-oriented cropland area per capita were 0.65, 1.22, and 1.24 for the Henan, Jiangzhe, and Jiangxi provinces, respectively. This suggests that the government allocated military-oriented croplands to each household based on the local cropland area per household. The data on military-oriented cropland area and household numbers were comprehensive, covering 10 provinces during the Yuan Dynasty, while the data on cropland area and household numbers were more fragmented, with records only available for three provinces and some regions and counties within these provinces. To estimate the provincial per capita cropland area, this study primarily used military-oriented cropland areas, household numbers, and population numbers per household. The ratios between military-oriented cropland areas per capita and cropland areas

per capita for the three provinces were used as conversion coefficients for the provinces in the middle and lower reaches of the Yellow and Yangtze Rivers:

$$PCA_k = \alpha \cdot \left(\frac{C_{km}}{H_{km}} \right) \cdot \frac{\sum_{i=1}^{n} (C_i / H_i)}{\sum_{i=1}^{n} (C_{im} / H_{im})} \; / \; HP_k \tag{5}$$

where PCA_k is the per capita cropland area of province k for AD 1294 and α is the conversion coefficient from Yuan-mu to mu, and its value is 0.92 [41]. C_{km} and H_{km} are the military-oriented cropland area and number of households for province k, respectively, C_i and C_{im} are the provincial and military-oriented cropland areas in the middle and lower reaches of the Yellow River, including Henan Province, and the middle and lower reaches of the Yangtze River, including the Jiangzhe and Jiangxi provinces, respectively, H_i and H_{im} are the provincial and military-oriented household numbers in the two regions, respectively, and HP_k is the population per household for province k, with a value of 5 [40].

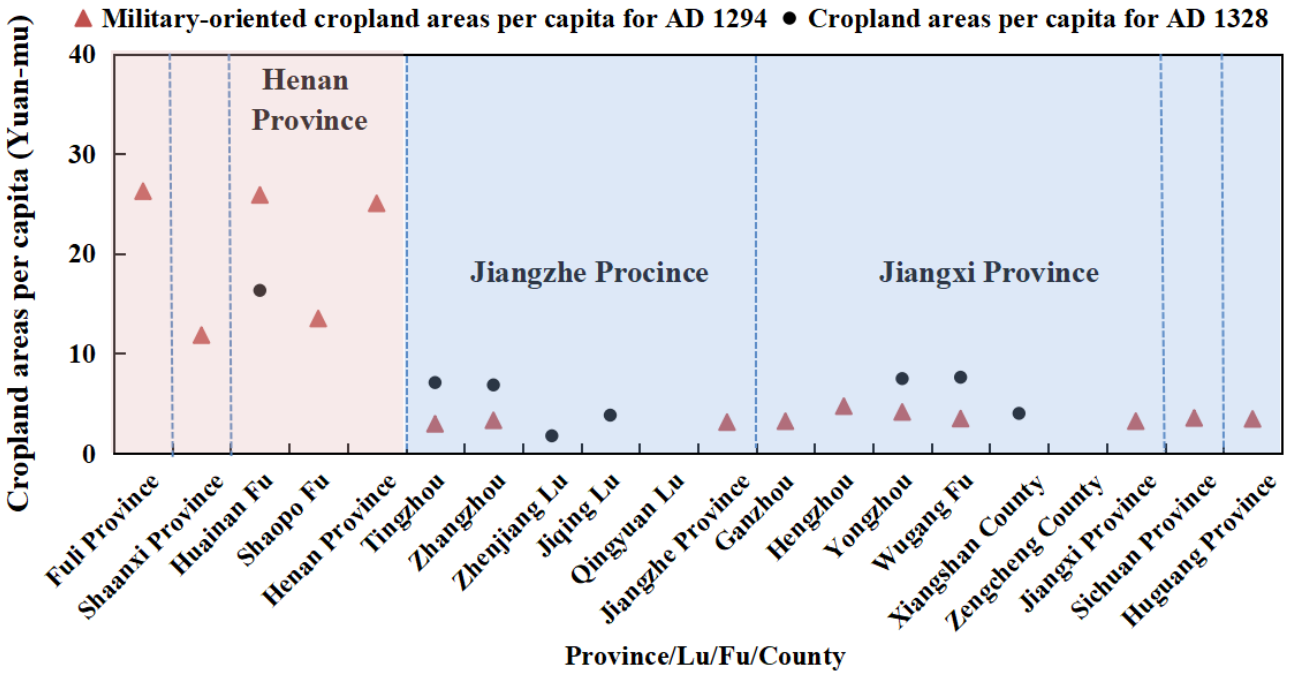


Figure 3. Cropland and military-oriented cropland areas per capita in seven provinces and their sub-level administrative regions during the Yuan Dynasty. The red and blue areas represent the data for the middle and lower reaches of the Yellow River and the Yangtze River, respectively.

3.3. The Ming Dynasty (AD 1368–1644)

In the late Yuan Dynasty, Zhu Yuanzhang, the founding emperor of the Ming Dynasty, gradually overthrew the Yuan regime and established the Ming Dynasty in AD 1368. This dynasty covered the entire region of present-day China. During this period, the study area was completely controlled by the Ming Dynasty. Historical records show that, similar to the Yuan Dynasty, croplands during the Ming Dynasty consisted of two types: military-oriented croplands and ordinary croplands. The military-oriented croplands were owned by the national military and managed by provincial military command posts, while ordinary croplands, being the main source of national revenue, were managed by administrative commissioners [47]. Historical documents from this period recorded multiple sets of ordinary provincial cropland data, enabling the possibility of conducting per capita cropland area estimations.

3.3.1. Data Sources

(1) Provincial ordinary cropland data. Provincial ordinary cropland data for AD 1393 were obtained from the *Zhusi Zhizhang* (《诸司职掌》), data for AD 1502 and 1542 were obtained from the *Houhu Zhi* (《后湖志》), data for AD 1578 were obtained from the *Laws and Systems Records in the Ming Dynasty* (《明会典》), and data for AD 1583 were obtained from the *Royal Records in the Ming Dynasty* (《明实录》). Among the five sets of data, previous studies suggest that the data for AD 1393 and 1583 were considered reliable, since these data were obtained through land surveys conducted by Zhu Yuanzhang and Zhang Juzheng during the Hongwu (AD 1387–1393) and Wanli (AD 1581–1585) periods. In contrast, data from other periods were constrained by the "original quota" concept, resulting in their values basically being equivalent to the data in AD 1393 and primarily serving as the basis for tax collection [48].

(2) Provincial population data. The provincial population data for AD 1393 were obtained from Cao and Ge [49]. They calibrated and estimated the provincial population for AD 1393 using a range of historical documents, including the *Royal Records in the Ming Dynasty* (《明实录》), the *Great Ming Unified Records* (《大明一统志》), the *History of the Ming Dynasty: Military Records* (《明史·兵志》), the *History of the Ming Dynasty: Geographical Records* (《明史·地理志》), and local chronicles within each province. In their studies, the average annual growth rates of the population at the provincial level from AD 1393 to AD 1502 and from AD 1502 to AD 1630 were estimated using local records.

3.3.2. Estimation of Per Capita Cropland Area

Based on the historical records of the Ming Dynasty and previous studies, land surveys and registration during the Ming Dynasty were mainly conducted for tax collection purposes. As a result, the statistics included not just taxable croplands, but also non-cropland types like mountains, ponds, lakes, and marshes, which were partially subject to taxes. The registration of non-croplands varied depending on the natural conditions and socioeconomic development levels of different regions. Generally, the northern provinces in the middle and lower reaches of the Yellow River had fewer non-croplands recorded, while the southern provinces in the middle and lower reaches of the Yangtze River recorded croplands, mountains, ponds, lakes, and marshes as tax records [50]. Therefore, when estimating the provincial per capita cropland areas for the Ming Dynasty, it is important to exclude non-cropland data, like mountains, ponds, lakes, and marshes, from the total cropland area for these provinces.

We obtained historical data on cropland, mountains, ponds, lakes, and marshes for 29 counties in the middle and lower reaches of the Yangtze River during the Hongwu period and provincial-level data for five provinces during the Wanli period from the *Collection of Local Chronicles in the Ming Dynasty in Tianyi Pavilion* (《天一阁藏明代方志选刊》) and the *Complete Collection of Books of the Past and the Present* (《古今图书集成·职方典》). Based on these data, we calculated the proportion of non-cropland areas in the ordinary cropland areas recorded by province (Figure 4). The results showed that, during the Hongwu and Wanli periods, the proportions of non-cropland areas in the recorded ordinary cropland areas in the Zhejiang, Southern Zhili, Jiangxi, Fujian, and Huguang provinces were approximately 24.7%, 23.3%, 4.4%, 3.0%, and 3.7%, respectively, and 28.9%, 19.2%, 16.2%, 2.5%, and 11.6%, respectively.

During the Yuan Dynasty, the government allocated military-oriented croplands to each household based on the local ordinary cropland area per household. In cases where military-oriented cropland data from the Ming Dynasty were incomplete, we assumed that the per capita cropland areas derived from ordinary cropland and population data represented the per capita cropland areas at the provincial level. Based on this assumption, we estimated the provincial per capita cropland area for AD 1393 and 1583 by using calibrated ordinary cropland area and population data. The population data for AD 1583 were estimated based on data for AD 1393 and the average annual growth rate of the population for two historical periods. The calculation equation is as follows:

$$PCA_k = \alpha \cdot \frac{C_k(1-\gamma)}{P_k} \quad (6)$$

where PCA_k is the per capita cropland area of province k for AD 1393 and AD 1583, α is the conversion coefficient from Ming-mu to mu, and its value is 0.92 [41], C_k and P_k are the ordinary cropland area and population data for province k, respectively, and γ is the proportion of non-cropland area in the recorded ordinary cropland area for the Zhejiang, Southern Zhili, Jiangxi, Huguang, and Fujian provinces in the middle and lower reaches of the Yangtze River.

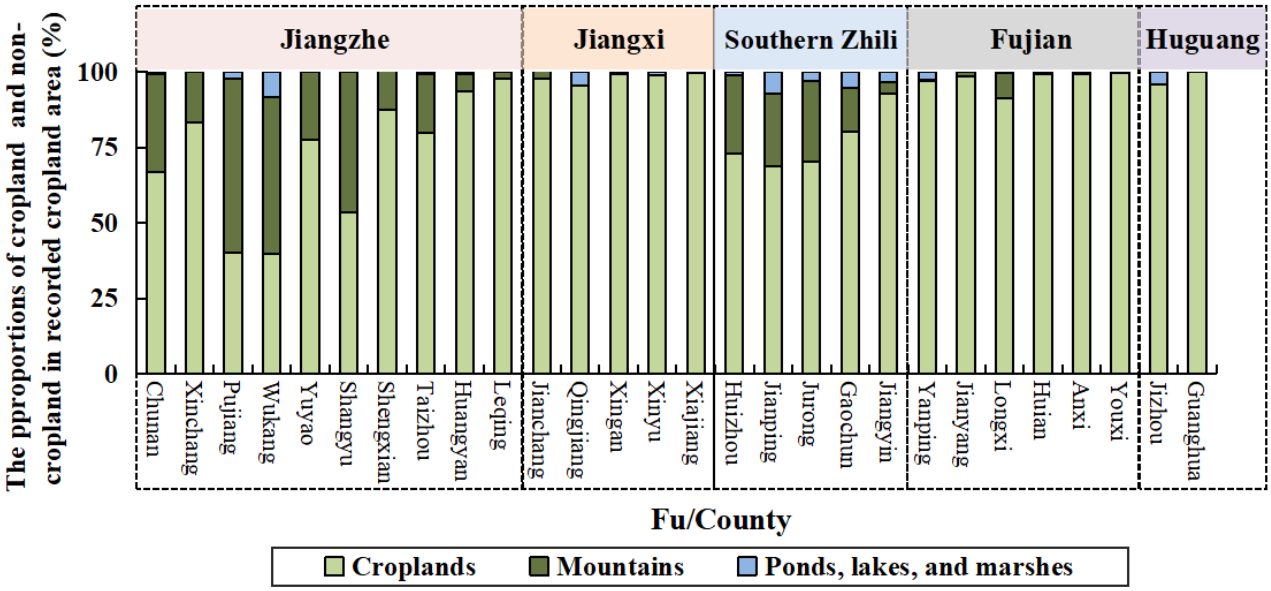


Figure 4. Proportions of cropland and non-cropland areas in the recorded ordinary cropland areas for Zhejiang, Southern Zhili, Jiangxi, Fujian, and Huguang provinces in the middle and lower reaches of the Yangtze River during the Hongwu period.

3.4. Since the Qing Dynasty (AD 1644-Present)

After the Ming Dynasty, the study area underwent successive periods of rule by the Qing Dynasty, the Republic of China (AD 1912–1949), and the People's Republic of China (AD 1949–present). Compared with the pre-Ming era, historical records and statistical data on croplands and population have been abundant since the Qing Dynasty. Chinese scholars have used these records to correct and reconstruct cropland areas and population data at the provincial and county levels. The reconstructed results provide important basic data for estimating the per capita cropland area from the Qing Dynasty onwards

3.4.1. Data Sources

(1) Provincial cropland area data. Li et al. [51] compiled the provincial cropland area data from AD 1661 to 1999 based on the provincial cropland areas from AD 1661 to 1933 from Ge et al. [52], AD 1949 to 1960 from the National Bureau of Statistics (1950–1961), AD 1961–1985 from Feng et al. [53], and AD 1986–1996 from the Ministry of Land and Resources dataset. The data for AD 1661 to 1933 from Ge et al. [52] were rigorously estimated using Chinese historical taxed cropland area records from historical archives such as *Collections of Historical Governmental Archives* of the Qing Dynasty (《清朝文献通考》), the *Great Qing Unified Records* (《大清一统志》), and *Royal Records of the Qing Dynasty* (《清实录》). The data for AD 1961–1985 from Feng et al. [53] were estimated based on the provincial cropland area data from the National Bureau of Statistics and a correlation analysis between food yields and cropland area.

(2) Provincial population data. Provincial population data for AD 1776, 1820, 1851, 1880, 1910, and 1953 were obtained from Cao and Ge [48]. The authors calibrated and estimated the provincial population for these time points using a range of historical documents, including the *Royal Records in the Qing Dynasty* (《清实录》), the *Great Qing Unified Records* (《大清一统志》), *The History of Qing Dynasty* (《清史稿》), and local chronicles within each province. Provincial population data for 1964, 1982, 1990, and 2000 were obtained from the National Bureau of Statistics.

3.4.2. Estimation of Per Capita Cropland Area

Based on the collected, reconstructed, and revised data, we obtained the provincial per capita cropland area in the middle and lower reaches of the Yellow and Yangtze Rivers from AD 1661 to 1996. The calculation equation is as follows:

$$PCA_k = \frac{C_k}{P_k} \tag{7}$$

where PCA_k is the per capita cropland area of province k for AD 1776, 1820, 1851, 1880, 1910, 1953, 1965, 1980, 1990, and 1999, and C_k and P_k are the cropland area and population data for province k, respectively.

3.5. Data Collaboration in Time and Space

Based on historical records and modern statistical data on cropland areas, household numbers, and population, we estimated the provincial per capita cropland areas for 17 time points over the past millennium, including AD 976 and 1078 during the Northern Song Dynasty, AD 1200 during the Southern Song and Jin dynasties, AD 1294 during the Yuan Dynasty, AD 1393 and 1583 during the Ming Dynasty, and AD 1776, 1820, 1851, 1880, 1910, 1953, 1965, 1980, 1990, and 1999 since the Qing Dynasty. However, as shown in Figure 1, from the Northern Song Dynasty to the present, the provincial administrative divisions within the study area have undergone frequent changes. Not only did the provincial administrative divisions transition from "Lu" to "Province", but the boundaries of the provinces also continuously changed during this period.

To ensure consistency and compare the estimated provincial per capita cropland areas from various historical periods and modern statistical data, we first standardized the modern administrative divisions within the study area into 13 provincial units, considering the evolving nature of historical administrative regions. Subsequently, using these adjusted 13 provincial units as the spatial framework, the provincial per capita cropland areas from different historical periods were integrated into unified administrative units. This estimation was based on the proportion of overlapping areas between the historical provinces across different historical periods and the adjusted provincial units relative to the total area of the adjusted provincial units. The calculation equation is as follows:

$$PCA_{kt} = \delta \cdot \sum_{i=1}^{n} \frac{A_{ont}}{A_k} \cdot PCA_{nt} \tag{8}$$

where PCA_{kt} is the per capita cropland area of province k in year t, n is the number of provinces that overlap with province k, which changes with alternations in dynasties and administrative divisions, PCA_{nt} is the per capita cropland area of province n which overlaps with province k in year t, A_{ont} is the overlapping area of provinces n and k in year t, and A_k is the area of province k in year t. When $n = 1$ and $A_{ot} = A_k$, the per capita cropland area of province A_{ot} is equivalent to the per capita cropland area of province k in year t. δ is the conversion factor between mu and hectares.

4. Results

4.1. Provincial-Level Changes in Per Capita Cropland Area

Our analysis showed that the amount of cropland per person in the provinces located in the middle and lower parts of the Yellow and Yangtze Rivers has generally decreased over the last thousand years (Figure 5). However, due to various factors such as changes

in ruling dynasties, wars, population changes, the types of crops grown, and advancements in agricultural technology, the amount of cropland per person in these provinces has varied over time. In the provinces along the middle and lower reaches of the Yellow River, the changes in cropland per person can be divided into three stages: slow decrease, rapid increase, and fluctuating decrease. Meanwhile, the provinces along the middle and lower reaches of the Yangtze River, apart from the three northern provinces of Anhui, Hu-Ning, and Hubei, showed a similar trend to the five provinces along the middle and lower reaches of the Yellow River, with the amount of cropland per person in all other provinces continuously decreasing over the last millennium.

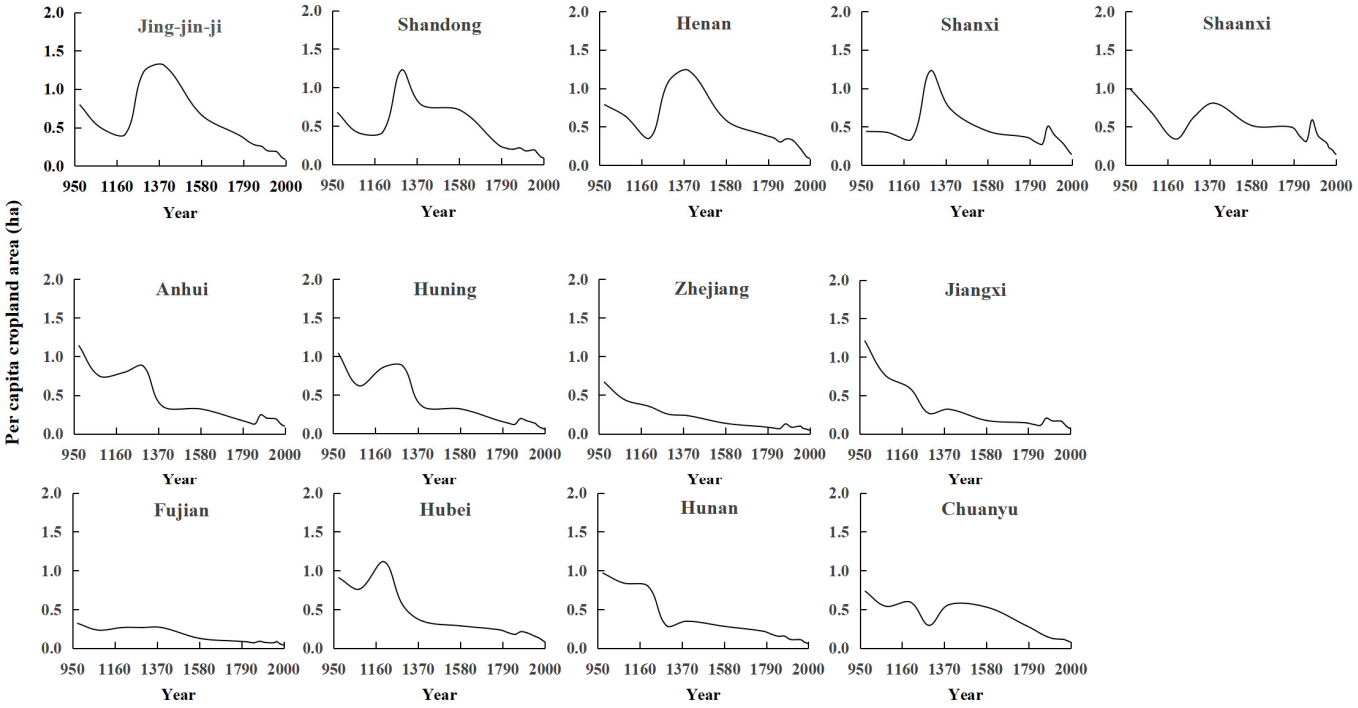


Figure 5. Trends in per capita cropland area change for each province in the middle and lower reaches of the Yellow and Yangtze Rivers over the past millennium.

4.1.1. Changes in the Middle and Lower Reaches of the Yellow River

From AD 976 to 1200, the per capita cropland area in the middle and lower reaches of the Yellow River exhibited a gradual declining trend. The most significant declines were observed in Jing–Jin–Ji and Henan, where the per capita cropland area decreased from 0.79 ha to 0.41 and 0.35 ha, respectively, representing reductions of 0.38 ha and 0.44 ha over 200 years (Figure 5). Despite the impact of the wars of the Song and Jin dynasties on regional agricultural development and population size, the middle and lower reaches of the Yellow River remained agriculturally advanced and densely populated during the Song Dynasty. From the early Northern Song Dynasty to the late Southern Song Dynasty, the regional population grew from 15.35 to 43.48 million. As the population increased and cultivated land resources decreased, the difficulty of land reclamation intensified. Consequently, the strategy of expanding cropland to meet growing food demand became unsustainable. This shifted the focus to improving labor productivity to increase grain output and resulted in a declining trend in the per capita cropland area across the provinces.

During the end of the Southern Song Dynasty, the middle and lower reaches of the Yellow River were heavily affected by wars involving the Yuan, Song, and Jin dynasties. This resulted in the mass extermination of the Han population in these regions, leading to a drastic reduction in population to less than a quarter of its late Southern Song Dynasty level. This caused the widespread abandonment of cropland. The area became a major battleground during the late Yuan Dynasty, leading to further population decline. Al-

though there was some recovery during the early Ming Dynasty, the population remained less than half of that during the late Southern Song Dynasty. Both the Yuan and Ming governments implemented policies to promote agricultural recovery, but due to the significant loss of the agricultural population, early efforts relied on extensive farming methods, resulting in a substantial increase in per capita cropland area from 0.34–0.42 ha to 1.09–1.23 ha (Figure 5). By the Ming Dynasty, the severely depopulated regions of Henan and Jing–Jin–Ji saw their per capita cropland areas increase to 1.23 and 1.31 ha, respectively.

During the Ming Dynasty, the population of the region gradually increased after a period of recovery. By the late Ming period, the population had surpassed that of the late Southern Song Dynasty, reaching 57.93 million. This led to an expansion in cultivation. Population growth exploded during the Qing Dynasty, with the population exceeding 100 million by 1820, reaching 170 million in AD 1953, 270 million in AD 1982, and 340 million in AD 2000. Urbanization led to the conversion of large areas of cropland into construction land, making it difficult for the available cropland resources to support the population. As a result, agricultural productivity was improved through the introduction of new crops, changes in cropping systems, and advancements in agricultural techniques to increase grain yield. However, the per capita cropland area showed a continuous declining trend during this period: it decreased to 0.44–0.71 ha by AD 1583, 0.21–0.37 ha by AD 1820, 0.19–0.29 ha by AD 1953, 0.11–0.20 ha by AD 1980, and 0.08–0.14 ha by AD 1999 (Figure 5). The per capita cropland areas of the Jing–Jin–Ji, Henan, and Shandong provinces fell below 1 ha. As a result, the relationship between people and land became increasingly strained during this period, leading to mounting conflicts and frequent ecological issues.

4.1.2. Changes in the Middle and Lower Reaches of the Yangtze River

Since the Anshi Rebellion of the Tang Dynasty, there have been three major southward migrations, causing the economic center to shift from the middle and lower reaches of the Yellow River to the middle and lower reaches of the Yangtze River. Over the past millennium, the provinces in the middle and lower reaches of the Yangtze River, excluding Anhui, Hunan, and Hubei, have experienced relatively minor impacts from wars between the Yuan, Song, and Jin dynasties. This allowed the population to grow from 20.32 million in the early Northern Song Dynasty to 59.40 million, despite a slight decline to 42.17 million during the Yuan and Ming dynasties. By the late Ming Dynasty, the population exceeded 100 million, reaching 200 million in AD 1820, 260 million in AD 1953, 420 million in AD 1980, and 510 million in AD 2000. While the middle and lower reaches of the Yellow River had a substantial population base after the Tang Dynasty, the middle and lower reaches of the Yangtze River developed rapidly, with its population surpassing that of the Yellow River region by approximately five times during the Yuan Dynasty. Continuous population growth spurred regional agricultural development. However, due to limited cropland resources and explosive population growth, the per capita cropland area showed a continuous declining trend. Particularly in the Zhejiang and Fujian provinces, where cropland resources were scarce, the per capita cropland area decreased from 0.67 ha and 0.32 ha in the early Northern Song Dynasty to 0.25 ha and 0.27 ha by the Yuan Dynasty, then declined to 0.09 ha in the early Qing Dynasty, then to 0.07 and 0.09 ha in AD 1953, respectively. By 1999, the per capita cropland area had dropped to 0.05 ha and 0.04 ha.

4.2. Spatial Patterns of Per Capita Cropland Area

To gain deeper insight into the spatial dynamics of the per capita cropland area changes at the provincial level, we analyzed the per capita cropland areas across the 13 provinces for the years AD 976, 1200, 1393, 1776, 1880, and 1980 using GIS. Corresponding spatial distribution maps were generated (Figure 6).

The spatial patterns of the provincial per capita cropland areas in the traditional agricultural areas of China have undergone significant changes over the past millennium (Figure 6). During the early Song Dynasty (AD 976), the study area had a relatively low

population and abundant cropland resources. Farming methods were still predominantly extensive, resulting in relatively high per capita cropland areas across the 13 provinces in the middle and lower reaches of the Yellow and Yangtze Rivers. Except for the provinces with limited cropland resources due to topography, such as Zhejiang, Fujian, and Shanxi, the per capita cropland area in all other provinces exceeded 0.70 ha, with Anhui, Hu-Ning, and Jiangxi each surpassing 1.00 ha (Figure 6a). By the late Song Dynasty (AD 1200), apart from the Anhui, Hu-Ning, and Hubei provinces, where the per capita cropland areas remained above 0.70 ha due to significant population losses from the wars of the Song and Jin dynasties, all other provinces experienced declines in their per capita cropland areas due to population growth and advancements in agricultural production techniques. In provinces such as Henan, Shanxi, Shaanxi, Zhejiang, and Fujian, the per capita cropland area fell below 0.40 ha (Figure 6b).

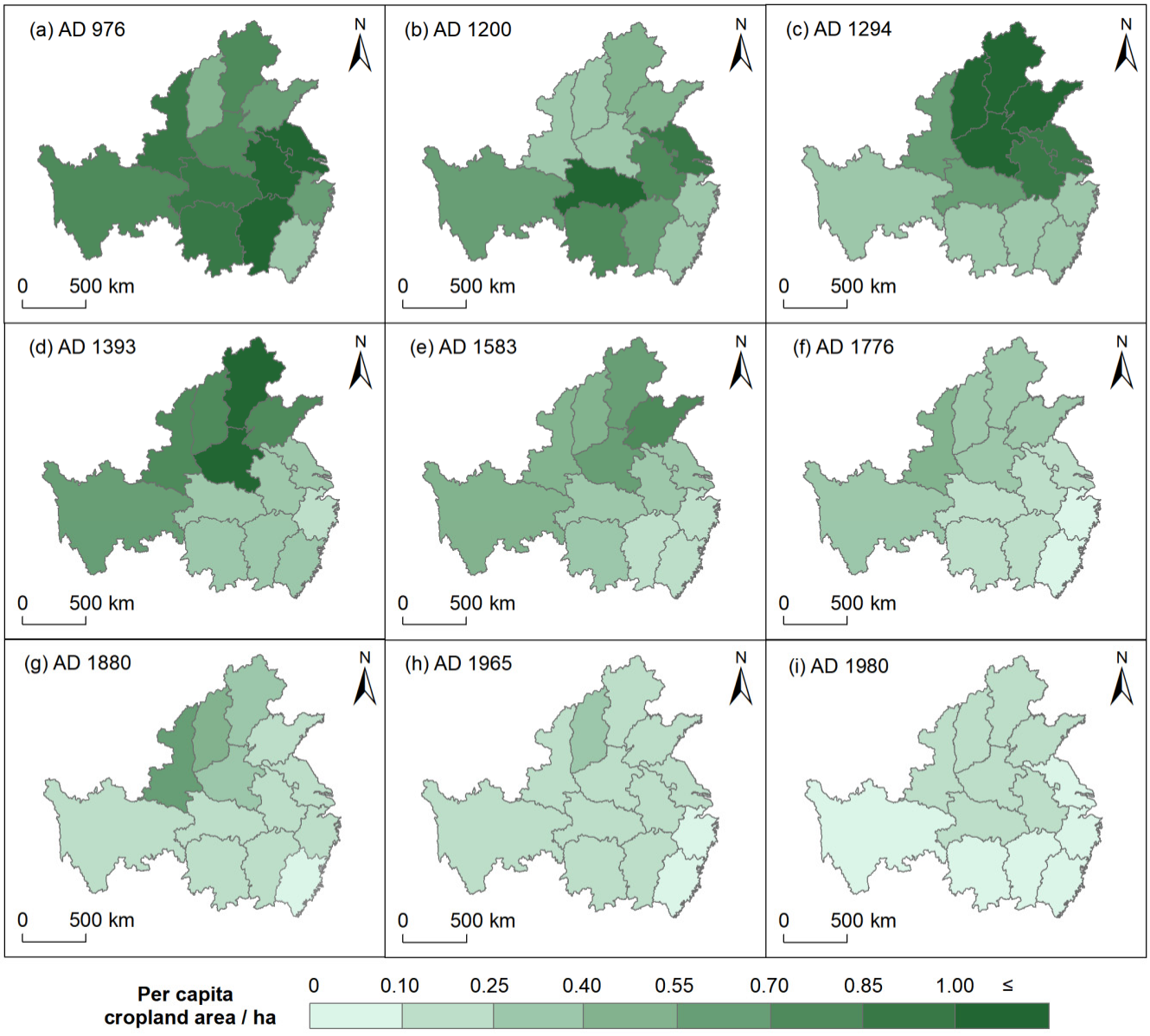


Figure 6. Spatial patterns of per capita cropland area at the provincial level in the traditional agricultural areas of China for AD 976, 1200, 1294, 1393, 1776, 1880, 1965, and 1980.

During the early Yuan Dynasty (AD 1294), a trend of dual-level differentiation in the per capita cropland area appeared among the provinces in the middle and lower reaches of the Yellow River and the middle and lower reaches of the Yangtze River. Except for Shaanxi Province, the per capita cropland area in the middle and lower reaches of the Yellow River exceeded 1.00 ha (Figure 6c). In the middle and lower regions of the Yangtze River, except for the Anhui, Jiangsu, and Hubei provinces, the amount of cropland per person had fallen to below 0.30 ha in all other provinces. This pattern was closely linked to changes in population in both regions. The wars between the Yuan Dynasty and the Song and Jin dynasties affected the population of the area, especially in the middle and lower reaches of the Yellow River. After the Yuan Dynasty was established, the government implemented policies that led to significant population losses in this region. For example, the populations of Jing–Jin–Ji, Shandong, Henan, and Shanxi decreased significantly. The impact of the wars between the Yuan and Ming dynasties meant that the populations of various provinces did not change significantly from those of the late Song Dynasty by the early Ming Dynasty (AD 1393). There was no significant change in the amount of cropland per person among the provinces in the study area. By the late Ming Dynasty (AD 1583), with population recovery, the amount of cropland per person decreased in the provinces along the middle and lower reaches of the Yellow and Yangtze Rivers. The cropland per person in provinces along the middle and lower reaches of the Yellow River ranged from approximately 0.44 to 0.71 ha, while in provinces along the middle and lower reaches of the Yangtze River, it ranged from 0.13 to 0.32 ha (Figure 6e). The pattern of greater cropland per person in the middle and lower reaches of the Yellow River and lower cropland per person in the middle and lower reaches of the Yangtze River remained unchanged.

Since the Qing Dynasty, there has been explosive population growth which has led to tensions in human–land relationships. This highlights conflicts arising from the imbalance between population and cropland resources. As a result, the per capita cropland area in provinces along the middle and lower reaches of both the Yellow and Yangtze Rivers has been decreasing. Despite persistent north–south disparities due to differences in agricultural systems and ongoing improvements in agricultural technology, these differences have gradually diminished. In the early Qing Dynasty (AD 1776), the per capita cropland area in the provinces along the middle and lower reaches of the Yellow River was from approximately 0.25 to 0.50 ha, and along the middle and lower reaches of the Yangtze River, it was from about 0.09 to 0.29 ha (Figure 6f). By the early years of the People's Republic of China (AD 1965), the per capita cropland area in the provinces along the middle and lower reaches of the Yellow River was from around 0.16 to 0.25 ha, and along the middle and lower reaches of the Yangtze River, it was from about 0.07 to 0.14 ha (Figure 6h). In AD 1980, the per capita cropland area in the provinces along the middle and lower reaches of the Yellow River was from approximately 0.11 to 0.20 ha, and along the middle and lower reaches of the Yangtze River, it was from about 0.06 to 0.12 ha (Figure 6i).

5. Discussion

5.1. Comparison with Previous Studies

An analysis of the relationship between population and land use suggests that using population to reconstruct national or regional land use data is common for existing global or regional datasets. Primary studies, including earlier versions of the HYDE and PJ datasets, first established the relationship between population and land use using the quantitative link between modern populations and land use data for the post-1960 period and assumed that per capita land use was nearly constant for the pre-1960 period [13,27]. Based on this conclusion, the per capita cropland values over the past 300 years and millennia were estimated by country using the HYDE and PJ datasets, respectively, and the national- and provincial-level cropland areas were reconstructed using historical population estimates and per capita cropland values.

The earlier versions of the HYDE and PJ datasets used per capita cropland areas of approximately 0.14 ha and 0.15 ha for China over the past 300 years and from AD 800 to

AD 1700, respectively. The KK10 dataset estimates global land areas under anthropogenic land cover changes instead of cropland areas using per capita anthropogenic land use. The latest HYDE 3.2 dataset version highlights that the per capita values for cropland are not constant and may slightly increase or decrease over time as populations increase, technologies improve, and land use intensifies [16]. Based on this assumption, it defines different shapes of per capita cropland curves for different countries, including concave-, bell-, and convex-shaped curves, depending on the limited historical sources. Subsequently, the per capita cropland areas were re-estimated by country, and the basic cropland data were updated in their dataset. Furthermore, HYDE 3.2 considered that the per capita values for cropland in China slightly decreased over time for their study period, and the corresponding values decreased from 0.66 ha in AD 1 to 0.16 ha in AD 1960. For the past millennium, the cropland per capita estimates of China in HYDE 3.2 increased from 0.15 ha for AD 1000 to 0.16 ha for AD 1800, then decreased to 0.15 ha for AD 1980 [16].

This study gathered and analyzed a wealth of historical-document-based data, including taxed cropland areas, cropland inventory areas, military-oriented cropland areas, ordinary cropland areas, household numbers, and population data from the Northern Song Dynasty. Additionally, it examined the historical records of regime shifts, land management systems, tax systems, and changes in land policies to estimate the relationships between population and cropland areas at the provincial level in the traditional agricultural areas of China over the past thousand years. The findings revealed differences in the per capita cropland areas at the provincial level over the study period. The data indicated a general decline in the per capita cropland area in the provinces of the middle and lower reaches of the Yellow and Yangtze Rivers over the past millennium (Figure 5). However, due to various factors such as changes in ruling dynasties, wars, population dynamics, cropping systems, and developments in agricultural technology, variations in the per capita cropland area differed among the provinces of these two regions from AD 976 to 1965.

For the provinces in the middle and lower reaches of the Yellow River, the changes in the per capita cropland area can be characterized in three stages: slow decrease, rapid increase, and fluctuating decrease. Specifically, the per capita cropland areas of the Jing–Jin–Ji, Shandong, Henan, Shanxi, and Shaanxi provinces decreased from 0.79 ha, 0.67 ha, 0.79 ha, 0.44 ha, and 0.99 ha for AD 976 to 0.41 ha, 0.42 ha, 0.35 ha, 0.34 ha, and 0.34 ha for AD 1200, then increased to 1.31 ha, 0.77 ha, 1.23 ha, 0.73 ha, and 0.81 ha for AD 1393, then decreased to 0.16 ha, 0.16 ha, 0.17 ha, 0.25 ha, and 0.23 ha for AD 1965, respectively. In contrast, in the provinces of the middle and lower reaches of the Yangtze River, the per capita cropland area showed a continuous decrease over the past millennium. Especially for the southern provinces of this region, the per capita cropland areas of the Zhejiang, Jiangxi, Fujian, Hunan, and Chuan-Yu provinces decreased from 0.67 ha, 1.21 ha, 0.32 ha, 0.97 ha, and 0.73 ha for AD 976 to 0.07 ha, 0.14 ha, 0.09 ha, 0.11 ha, and 0.11 ha for AD 1965.

We also compared the cropland per capita estimates for each province for AD 976, 1200, 1393, 1776, 1880, and 1965 from this study and for AD 1000, 1200, 1400, 1780, 1880, and 1960 from the HYDE 3.2 dataset and calculated the relative difference ratios between our study and HYDE 3.2. The results indicated that the cropland per capita estimates showed clear differences between the HYDE dataset and our study, and these differences become more pronounced over time. For AD 976, 1294, and 1393, the cropland per capita estimates of our study were 2.1–8.0, 1.7–8.2, and 1.6–8.8 times higher than those reported by the HYDE dataset, respectively (Figure 7). For the past 300 years, the HYDE 3.2 dataset incorporates regional provincial cropland datasets reconstructed by researchers in China, which have reduced the differences in cropland per capita estimates (Figure 7). However, due to uncertainties in the population data within global datasets, there remain discrepancies in cropland per capita estimates. Any variation in cropland per capita estimates, an important parameter used to reconstruct historical cropland areas, can lead to significant uncertainties in reconstruction results. Our results also showed that reconstructing a regional LUCC dataset based on historical data from different areas yielded reliable data.

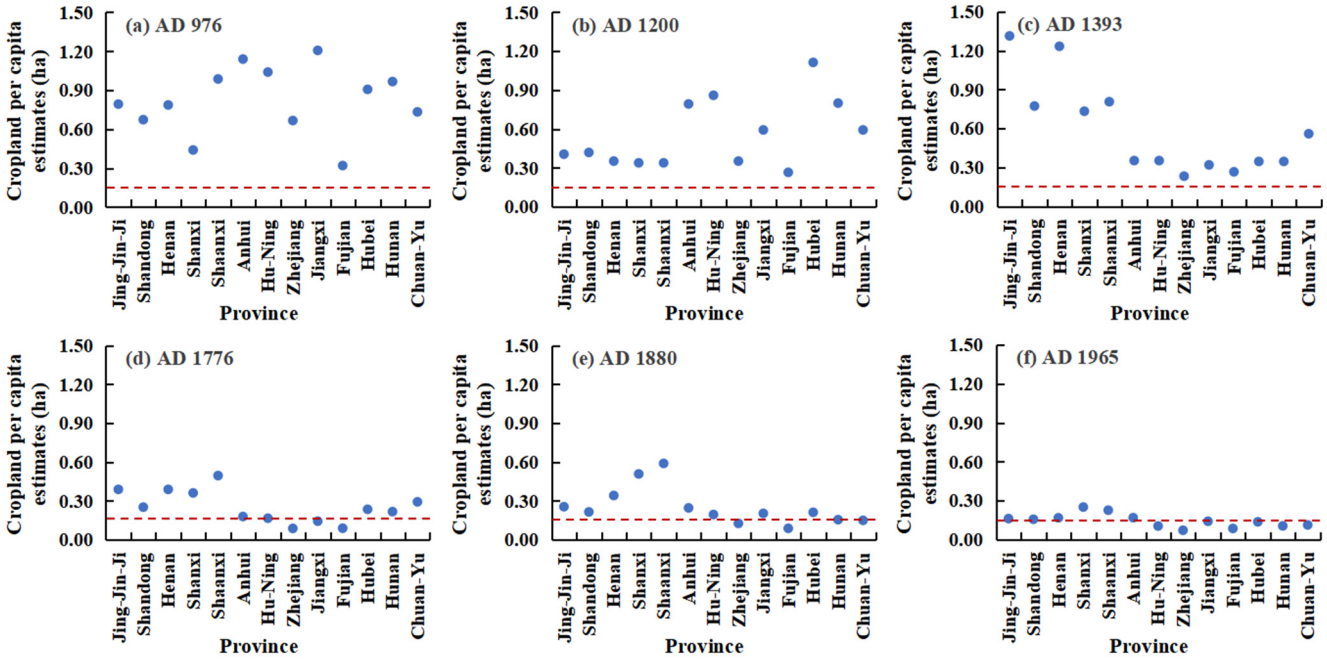


Figure 7. Cropland per capita estimates for each province for AD 976, 1200, 1393, 1776, 1880, and 1965 from our study (blue dots) and for AD 1000, 1200, 1400, 1780, 1880, and 1960 from the HYDE 3.2 dataset (red line).

5.2. Uncertainty Analysis

Although we made an effort to gather the historical records of croplands and populations from each dynasty over the past millennium, comprehensively analyze their characteristics, and estimate the per capita cropland area at the provincial level for the traditional agricultural areas of China, there are still several uncertainties in this study.

The accuracy of historical cropland data is uncertain due to the methods used to collect and record them. Historical documents, such as those on taxed cropland areas, cropland inventory areas, household numbers, and population estimates at different spatial resolutions, are the main sources for estimating per capita cropland areas. Since the validated taxed cropland areas do not always match the actual cropland areas in historical periods, the calibration of these data is necessary. For example, we calibrated the taxed cropland areas of the Song and Ming dynasties based on the ratios between the sporadically recorded taxed cropland areas and cropland inventory areas, as well as the provincial- or county-level proportions of non-cropland areas in the recorded taxed cropland areas. However, the calibration ratios for the provinces in the middle and lower reaches of the Yangtze River during the Song Dynasty were only determined using sporadic county-level data in Liangzhe Province (Lu). Moreover, the proportions of non-cropland areas in the recorded taxed cropland areas during the early Ming Dynasty were also calculated based on sporadic county-level data within the Zhejiang, Southern Zhili, Jiangxi, Fujian, and Huguang provinces. Obtaining additional historical records of the cropland inventory areas for the Song Dynasty and non-cropland areas in the recorded taxed cropland areas for the Ming Dynasty would be helpful. Achieving this will improve the quality of cropland area and per capita cropland area estimations by further clarifying the ratios between the actual cropland area and recorded taxed cropland areas, as well as the proportions of non-cropland areas in the recorded taxed cropland areas.

In this study, we estimated the per capita cropland areas using calibrated cropland areas and population estimates. However, the registration timestamps for the recorded cropland and population data within the same historical period, as well as the administrative units and spatial resolutions of the recorded cropland and population data across different historical periods, did not completely coincide. For time points with recorded provincial

cropland areas and household numbers or population data, we used the cropland registration time as a reference and selected household numbers or population data from the same or a nearby time point to estimate the provincial per capita cropland area. We estimated the per capita cropland area using county-level data within each province and selected the midpoint of the respective study period as the time point for our estimations when only having county-level data. This approach may have resulted in the estimated per capita cropland area representing an average value over a certain historical period, rather than the actual per capita cropland area at a specific time point. To address the inconsistency in the provincial administrative units corresponding to the estimated provincial per capita cropland areas across different historical periods, we adjusted 13 provincial units based on modern provincial administrative units as the spatial framework.

The provincial per capita cropland areas from various historical periods were combined into unified administrative units based on the proportions of the overlapping areas between the historical provinces across different historical periods. This approach assumed that the per capita cropland area remained consistent within each historical provincial administrative unit. However, this method might have led to an underestimation or overestimation of the per capita cropland area due to the close relationship between the per capita cropland area and the natural or social environment. The data processing procedures could have resulted in variations in the estimations.

6. Conclusions

It is important to understand the long-term impact of humans on land cover changes to accurately predict future global climate change. However, the accuracy of current global historical land use scenarios at regional scales is uncertain, as they do not incorporate rich indigenous empirical data to establish the exact temporal–spatial patterns of land use per capita. This study used regional historical taxed cropland areas, cropland inventory areas, household numbers, and population data from the Song Dynasty to the Ming Dynasty, as well as reconstructed and statistical cropland and population data from the past 300 years, to estimate the per capita cropland area at the provincial level in the traditional agricultural areas of China over the past millennium. The results of this study offer a more detailed understanding of the per capita cropland changes in the traditional agricultural areas of China over the past millennium and contribute more regional empirical data on historical per capita land use for the improvement of global land use datasets and the reconstruction of regional land use.

The per capita cropland area in the provinces of the middle and lower reaches of the Yellow and Yangtze Rivers generally showed a declining trend over the past millennium. However, owing to the influence of various factors, such as dynastic alternations, wars, population changes, the types of crops grown, and advancements in agricultural technology, the amount of cropland per person in these provinces has varied over time. The changes in per capita cropland area can be characterized into three stages in the provinces of the middle and lower reaches of the Yellow River: slow decrease, rapid increase, and fluctuating decrease. In the provinces of the middle and lower reaches of the Yangtze River, the per capita cropland area showed a continuous decrease over the past millennium. The per capita cropland areas across the 13 provinces in the middle and lower reaches of the Yellow and Yangtze Rivers were high during the early Song Dynasty. After the Yuan Dynasty, the spatial pattern of the per capita cropland area was higher in the middle and lower reaches of the Yellow River and lower in the middle and lower reaches of the Yangtze River. The corresponding values in the middle and lower reaches of the Yellow River exceeded 1.00 ha, whereas those in the middle and lower reaches of the Yangtze River were below 0.30 ha. This disparity between the higher values in the north and lower values in the south gradually diminished over time. In AD 1980, the per capita cropland area in provinces along the middle and lower reaches of the Yellow River was 0.11–0.20 ha, and along the middle and lower reaches of the Yangtze River, it was 0.06–0.12 ha. We also concluded that the cropland per capita estimates differed in the HYDE and PJ datasets, and these

differences became more prominent over time. For the early Song, Yuan, and Ming dynasties, the cropland per capita estimates of our study were 2.1–8.0, 1.7–8.2, and 1.6–8.8 times higher than those of the HYDE and PJ datasets, respectively. For the past 300 years, the HYDE 3.2 dataset incorporates regional and provincial cropland datasets reconstructed by researchers in China, which have reduced the variations in cropland per capita estimates.

An estimation of land use per capita using historical records of land use and population can provide more detailed and accurate historical information for understanding the interactive relationships between humans and land use. However, this method is applicable only to regions with a long history of agricultural development or historical periods with abundant historical records. Furthermore, due to the impacts of regime changes, territorial and administrative adjustments, and alterations in land systems and tax policies, the meanings of historical records of cropland and population vary significantly across different historical periods and are unevenly distributed in time and space. Consequently, when correcting, estimating, and processing historical data in a spatiotemporal context, the underestimation or overestimation of data is inevitable. Future research can address the uncertainties in estimation results by focusing on the following aspects: first, collecting as many historical records as possible to improve the accuracy of the corrected cropland and population data; second, conducting multi-case studies to enhance the methods for spatiotemporal data processing and minimize errors during this process; and third, comparing and validating results with other evidence-based findings to further increase the credibility of the estimation results.

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