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Grain Self-Sufficiency Capacity in China's Metropolitan Areas under Rapid Urbanization: Trends and Regional Differences from 1990 to 2015

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Abstract: Urbanization brings significant changes to the urban food system. There is growing attention to food self-sufficiency in metropolitan areas for the concern of greenhouse gas (GHG) mitigation in food transportation. In China, grain self-sufficiency in metropolitan areas is also an important issue for grain security and involves coordination among contradictory policy goals. Based upon a comprehensive statistical analysis of 70 metropolitan areas in mainland China, we investigated the regional differences in the trends of grain self-sufficiency capacity in these areas from 1990 to 2015. The findings show a trend of decline in 3/4 of metropolitan areas, mainly located in the rapidly urbanizing eastern coastal areas and in the West. The increase of self-sufficiency mainly occurred in the North, in areas either specialized in grain production or originally low in grain self-sufficiency. The enlarging contradiction of decreasing supply and rising demand explained the sharp decrease in self-sufficiency, while the increase in self-sufficiency was due to the increase in supply. Land productivity contributed more significantly than land availability to supply change. There was a tradeoff between urban expansion (rather than economic growth) and grain production in metropolitan areas. Our results provide implications to future research and policy-making for grain production management in China's metropolitan areas.

Keywords: grain; self-sufficiency; metropolitan area; urbanization; trend; regional difference; China

1. Introduction

Over 55% of the world's population now lives in urban areas, and the number of big cities continues to grow [1]. Urbanization brings significant changes to the urban food system, from a self-sufficient system conforming to Von Thünon's theory to an industrialized one marked by highly concentrated food demands, increasing competition for land from non-agricultural uses, and mass transportation of agricultural produce [2]. Local food provisioning in metropolitan areas is more commonly replaced by distant food from national and global markets, especially in the Global North [3]. Though there are worldwide efforts to preserve peri-urban farmlands against urban encroachment, the initial reasons are usually not linked to local food, but rather to the high productivity of the prime farmlands and other benefits such as open spaces [4–8]. Meanwhile, adaptation of peri-urban farming systems is required to meet the changing demands of urban populations. There are two broad categories of adaptation. The first is to make peri-urban agricultural production more environmentally sustainable and resilient [9,10]. The second is to improve the socio-economic performance of peri-urban agricultural systems, with strategies focusing on advantages in an urban environment, such as diversification, specialization, and short food supply chains [11–15]. More and more scholars claim local food as an important benefit

to urban population and an effective support for the revitalization of peri-urban agriculture [11,14]. Nevertheless, local food here mainly concerns fruit and vegetables or organic food. It emphasizes on the embedded environmental, social, and economic value in the food rather than the significance of food self-sufficiency. Some diversification strategies toward non-productive activities, e.g., horse farms and hobby farms, have even weakened food production in peri-urban areas [16,17].

However, there is growing attention to food self-sufficiency in metropolitan areas in recent years. As the concept of urban metabolism has gained importance in the sustainability of cities, the question of whether locally grown food offers a more sustainable urban food system has arisen [18]. The flow of embedded environmental impacts and ecosystem services along with food transportation has begun to receive wide attention [19,20]. In some countries in North America and Europe, optimizing local production around urban areas to maximize food self-sufficiency has already been integrated into policies as a potential way to reduce GHG emissions and to improve food autonomy [21,22]. A growing number of studies has conducted assessments of food supply–demand balance [23,24] or food self-sufficiency capacity [21,22,25,26] in metropolitan areas across broad food categories (grains, vegetables, fruit, meat, etc.). Another motive for research on food self-sufficiency is rooted in the concern for food supply in natural disasters or extreme weather events when distant food supply is impossible, and the research interest is specifically on nutritional self-sufficiency with a focus on fresh vegetables and fruit [27,28].

Most of the world's urbanization now occurs in developing countries [29]. The rapid growth of urban populations, accompanied by extensive and unplanned urban expansion, makes urban food supply in developing countries a big challenge for food security [3,30]. Dependence on distant food is no longer a good solution when there is an increasing awareness of urban metabolism. Some scholars also think that increasing dependence on the import of food (i.e., grains) by Asian countries, especially India and China, is very likely to affect food prices in the world market and aggravate global food crises [31,32]. Grain security has always been at the heart of the food security agenda of China [32,33]. Consumed as staple food and feedstuff, grains have never grown less important in China, even with income-related improvements in diet [34–36]. China pursues a self-sufficiency rate of 95% for grains since the publication of the Medium- and Long-Term Plan for National Food Security in 2008 [33]. However, the grain self-sufficiency rate has dropped to approximately 10% lower than the national target in recent years, for which urban expansion plays an important role, and metropolitan areas are hotspots of urban expansion [37]. China's metropolitan areas are mainly located in the eastern plains, where the climate condition and land quality are very suitable for agricultural production. Therefore, optimizing grain production in China's metropolitan areas to maximize food self-sufficiency is not only meaningful for GHG mitigation in food transportation but also important for food security at the national level.

In fact, grain production in China's metropolitan areas is confronted with contradictory policies (Figure 1), and the trends in self-sufficiency capacity can be very different among metropolitan areas. In China, the top-down regulation of national goals and policies plays a dominant role in land use and other activities. Policies targeting grain security and farmland conservation are mutually reinforcing and have positive effects on grain production in metropolitan areas [38–40]. The articles of those polices are actually carried out at the county and township levels in metropolitan areas, such as the direct subsidy for grain production, the annual quotas of farmland conversion, and the prime farmland protection districts [38]. The policy of provincial self-sufficiency for grains and ineffectiveness of the land conversion quotas trading initiative [40] compels attention from the provincial governments to the advantages of metropolitan areas in producing grains, such as the fertile soil and the long cultivation history. However, there are usually failures in farmland conservation because of the conflicts with the economic growth target [41,42]. For example, it is not rare to see farmland conversion driven by the so-called "land financing" of municipal governments, which consider land transfer to be a lucrative fiscal source [43,44]. Furthermore, the policies for environmental protection are becoming increasingly more stringent. On the one hand, the requirement for increasing urban green spaces

and ameliorating urban environment is used as a reason for cutting back on farmlands and grain production. For example, in 2014, Beijing, the capital city, planned to cut down over half of its grain cultivation area before 2020 mainly for afforestation in plains to reduce irrigation water use [45]. On the other hand, there is a growing concern for the environmental impacts of land reclamation in remote, vulnerable areas [46] and the northward shift of grain production to regions facing chronic water shortages [36,37,46]. The policy of returning marginal farmlands to forests or grasslands might indirectly spur efforts to preserve fertile farmlands in metropolitan areas. Finally, the movement of agricultural modernization and the adaptation of peri-urban agriculture to changing urban demands (e.g., diversification) [47,48] may further increase the variations among the metropolitan areas with regards to grain production.

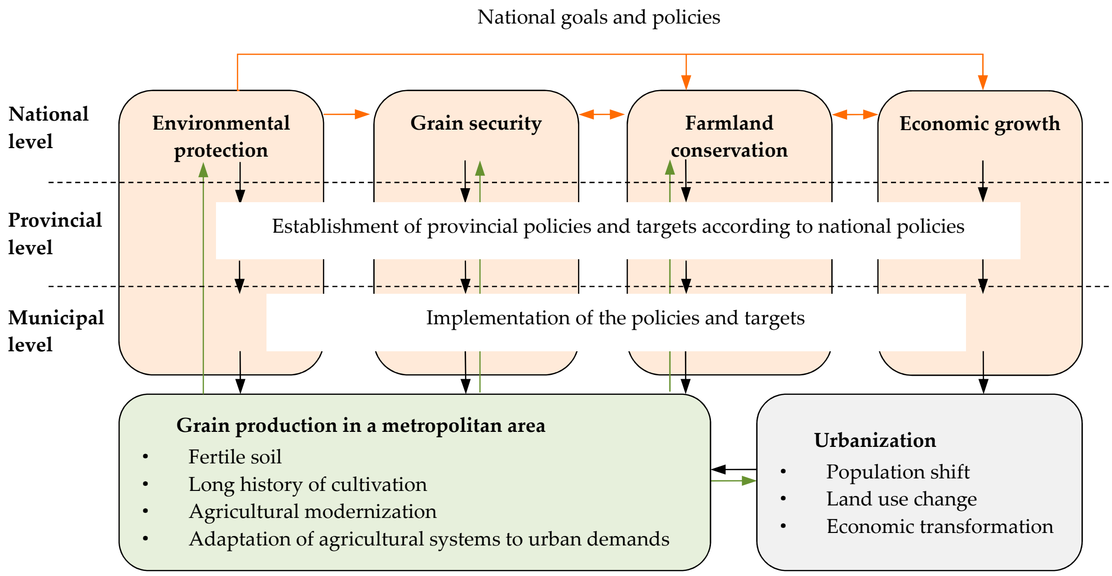


Figure 1. A conceptual framework for the contradictory policies affecting grain production in China's metropolitan areas (adapted from [38–40]). The yellow boxes represent the top-down regulation of national policies with different targets; the green box represents the agricultural system in a metropolitan area; the grey box shows the influences of urbanization. The dashed lines signify the different levels of the policy-makers and performers. The black arrows show the effecting paths of different policies on the grain production in a metropolitan area; the green arrows show the feedback of the latter on national goals and the urbanization process in the region; the orange arrows show the interaction between different policy targets.

This study aims to quantitatively investigate the regional differences in the trends of grain self-sufficiency capacity in China's metropolitan areas from 1990 to 2015. The objective is to contribute to China's grain security and coordination among different policy targets at the national level by optimizing the management of grain production in metropolitan areas. The study is about comparisons among metropolitan areas across China, without looking into the spatial pattern within a city. The specific objectives include analyzing the trends in grain self-sufficiency capacity, providing explanations for the trends by decomposing the contributions of the changes in supply and demand, and examining the impacts of urban development on the trends of grain self-sufficiency. Finally, we discuss the implications of the results for policy-making, the differences between China's metropolitan areas and some metropolitan areas in the Global North with regards to grain production, and limitations of the study.

2. Materials and Methods

2.1. Study Areas

A metropolitan area is a functional complex composed of a large city and the outlying suburbs closely linked to the central city [49,50]. The key steps in defining a metropolitan area include the identification of the central city and the delimitation of its hinterland boundary. Although different methods and criteria can be used [49–51], administrative boundaries are the most commonly used criteria in the literature [11,52–54].

In China, cities can be at different administrative levels, including provincial level cities, prefecture-level cities, and county-level cities. The municipality that governs the city has jurisdiction over a much larger territory also encompassing its surrounding suburban and rural counties. The municipality is expected to promote the coordinated development within its boundary. Therefore, the municipality of a large city can be considered as having the structure of a metropolitan area. According to the New Standard of City-Size Classification released by the State Council of China in 2014, cities of more than 1 million people within their built-up areas are classified as large cities, and the number of large cities in mainland China was 70 based upon the most recent census data [55]. Among the 70 municipalities, Shanghai, Beijing, Tianjin, and Chongqing are provincial municipalities, and the rest are all prefecture-level ones.

However, the territory of a municipality sometimes encompasses remote rural counties that have weak linkage with the central city. The actual boundary of a metropolitan area often lies between the boundary of the built-up area and that of the municipality [56,57]. We took the municipal boundaries as the maximum limit of the metropolitan areas and adopted the Gravitational Model of Economic Linkages method to remove the rural counties that were weakly linked to the central city [58,59] (See Appendix A for detailed computing process). The boundaries and locations of the 70 studied metropolitan areas are shown in Figure 2. The boundaries of developed metropolitan areas were similar to their municipal boundaries (e.g., Beijing in Figure 2b) while those underdeveloped metropolitan areas in the West and in the North were significantly smaller than their municipal administrative areas (e.g., Chongqing in Figure 2b). Though the influences of megacities such as Beijing, Shanghai, and Shenzhen possibly surpassed their administrative boundaries, we did not consider that for the limited data and the important role of administrative units in China's policies.

The locations of the metropolitan areas were close to the large rivers of China, namely the Yellow River, the Yangtze River, and the Pearl River, and the rim of the Bohai Gulf (Figure 2a). Three large megalopolises composed of adjacent metropolitan areas formed around Beijing, Shanghai, and Shenzhen-Guangzhou. The 70 metropolitan areas had an average area of 6723 km^2 and a resident population of 6.1 million people in 2015. These metropolitan areas took up only 4.9% of the total land area of China, but comprised 30.8% of the total population and 12% of arable lands in 2015 (24.2% and 13.7% in 1990, respectively).

2.2. Data Sources

The land use data (30 m × 30 m) were obtained from the Resource and Environment Data Cloud Platform of the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences. The data were produced from satellite images and available for the years 1990, 1995, 2000, 2005, 2010, and 2015 [60]. The land use data were clipped by the limits of metropolitan areas in ArcGIS 10.2 and imported into Fragstat 4.0 to calculate the area of metropolitan areas and arable lands. The data of grain production, resident population, and GDP at the county-level in 1990, 1995, 2000, 2005, 2010, and 2015 were acquired from the statistical yearbooks of China. Rectification of the statistical data was made for metropolitan areas when there were changes in administrative divisions from 1990 to 2015. The administrative boundaries in 2015 were adopted as the statistical standard. The analysis and calculations were carried out in PASW Statistics 18 and Excel 2010.

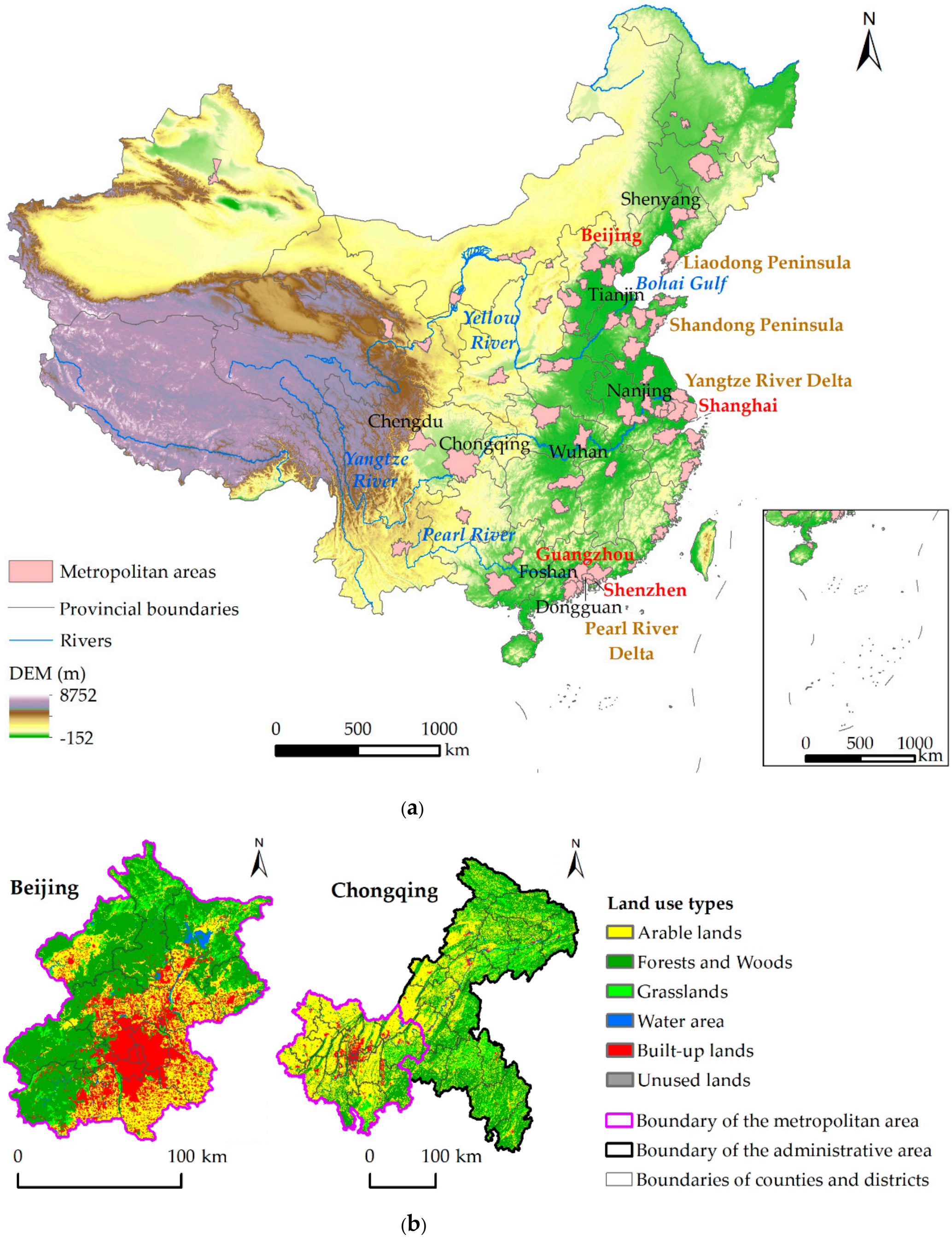


Figure 2. The 70 studied metropolitan areas in mainland China. (**a**) Location of the 70 metropolitan areas. The metropolitan areas with central cities of more than 5 million people were annotated with black and red text. Among them, Beijing, Shanghai, Shenzhen, and Guangzhou were the largest metropolitan areas in China. Around Shanghai and Shenzhen-Guangzhou, two large megalopolises were formed in the Yangtze River Delta and the Pearl River Delta, respectively. In the North and around the Bohai Gulf, Beijing, Tianjin, with metropolitan areas in Liaodong Peninsula, and Shandong Peninsula formed the third megalopolis of China. (**b**) Land use maps of Beijing and Chongqing in 2015 given as examples. The boundary of Beijing metropolitan area was the same as its administrative boundary. A large part of the counties in the administrative Chongqing were excluded from the metropolitan area.

2.3. Methodology

The study was designed to include three steps: First, we analyzed the overall trends and the spatial pattern of the trends in grain self-sufficiency capacity of the metropolitan areas. Then, to give explanations for the trends, we investigated the changes in the supply–demand structure for grains, and the contribution ratios of the changes in the supply and the demand. Finally, we examined the impacts of urban expansion and economic growth on the trends in grain self-sufficiency in metropolitan areas. The indicators used in this study are shown in Figure 3.

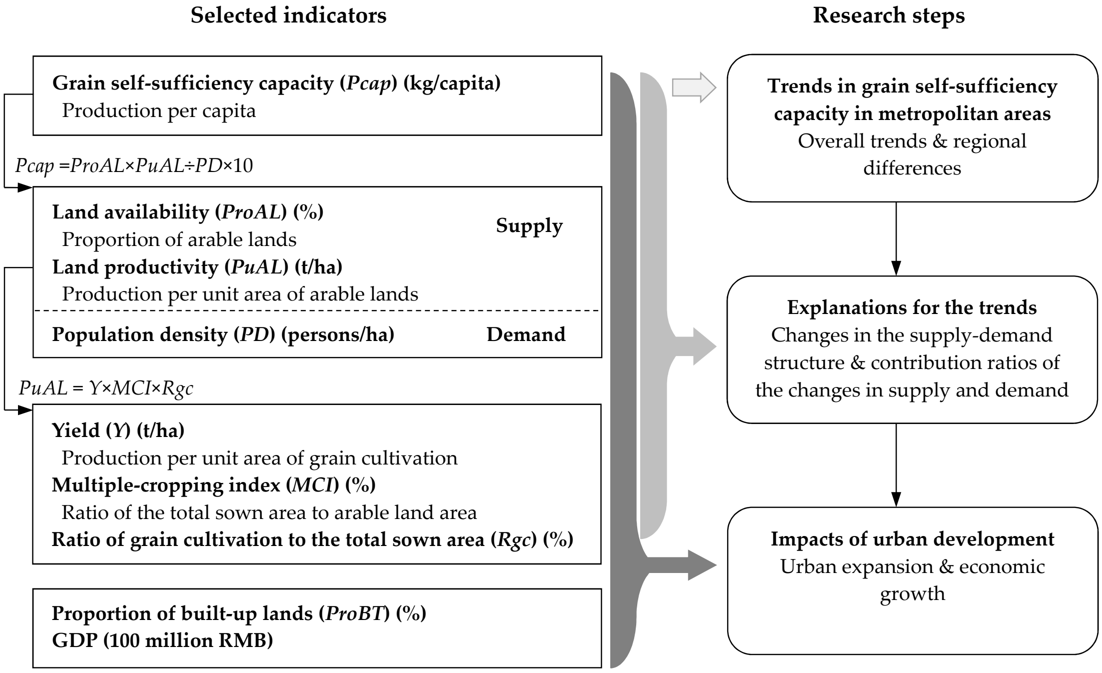


Figure 3. Flowchart of analysis and selection of indicators. The wide grey arrows signify the indicators used in each analysis.

We used the per capita production (*Pcap*) (kg/capita) to define the grain self-sufficiency capacity in the metropolitan areas (Figure 3), which does not mean the consumption of only local food [61]. In China, grains mainly include rice, wheat, maize, sorghum, millet, other cereals, soybeans, and potatoes. Beans and tubers are included in grains in China's statistic yearbooks and policy documents (e.g., the draft of the Grain Law). We followed this classification method. According to the Outline of Medium- and Long-Term Plan for National Food Security of China (2008–2020), China's per capita consumption of grains was 388 kg/capita in 2007 and could reach 395 kg/capita in 2020. The State Food and Nutrition Consultant Committee of China suggested 437 kg/capita as the ideal level for grain consumption [62]. Thus, we consider that a metropolitan area achieves grain self-sufficiency with $Pcap > 437$ kg/capita in this study.

The demand of grains was reflected by population density (*PD*). The supply of grains was determined by land availability (*ProAL*) and land productivity (*PuAL*). Land productivity was further determined by three factors, namely yield (*Y*), multiple-cropping index (*MCI*), and the ratio of grain cultivation to total sown area (*Rgc*). The *Y*, *MCI*, and *Rgc* are influenced by the progress in agricultural technology, willingness of farmers and market fluctuations [62,63]. The indicator of land productivity reflects the difference in the use of arable lands, and can respond more quickly than land availability to the impacts of human activities. For the analysis on the impacts of urban development, we used the proportion of built-up lands to indicate urban expansion and GDP to indicate economic growth.

The indicators were calculated based upon the grain production, population, area of corresponding land use type, area of grain cultivation, and total sown area (See Appendix B for detailed computing

process). All nine indicators were calculated for the 70 metropolitan areas in 1990, 1995, 2000, 2005, 2010, and 2015. We also calculated the annual change rate as shown in Equation (1) for each indicator in all metropolitan areas.

$$r_X = \text{Slope}\ (X)/\text{Average}\ (X) \times 100, \quad (1)$$

where X represents the time-serial value of the indicators (X = *Pcap*, *PuAL*, *ProAL*, *PD*, *Y*, *MCI*, *Rgc*, *ProBT*, GDP) from 1990 to 2015, i.e., $X = (x_{1990}, \ldots, x_{2015})$, r_X represents the annual change rate of the indicator (%/year). Average (X) and Slope (X) are functions for calculating the mean of X and its slope with respect to year.

Then, we quantified the contribution ratios of the changes in *PuAL*, *ProAL*, and *PD* to the change of *Pcap* ($C_{X\text{-}Pcap}$), and the contribution ratios of the changes in *Y*, *MCI*, and *Rgc* to the change of *PuAL* ($C_{X\text{-}PuAL}$) in the metropolitan areas by comparing r_{PuAL}, r_{ProAL}, -r_{PD} to r_{Pcap}, and r_Y, r_{MCI}, r_{Rgc} to r_{PuAL}, as shown in Equations (2) and (3). The theory behind the method is that the change rates of the *Pcap* and *PuAL* can be estimated by the sum of the change rates of their determinants, as explained in Appendix C [64,65].

$$C_{X\text{-}Pcap} = r_X/r_{Pcap}\ (X = ProAL, PuAL, PD), \quad (2)$$

$$C_{X\text{-}PuAL} = r_X/r_{PuAL}\ (X = Y, MCI, Rgc), \quad (3)$$

The contribution ratio of the PD growth was quantified with the opposite of its annual change rate since the growth of PD contributes negatively to the change of the per capita production.

We used the Kruskal-Wallis Test and Coefficient of Variation (CV) for the analysis of trends and variations among metropolitan areas, and we used the Spearman Correlation analysis for the relationship between indicators, i.e., between grain supply and demand, and between the change rates of the self-sufficiency, supply, and demand of grains, and the rates of urban expansion and GDP growth. Non-parametric methods were used because the data did not conform to a normal distribution.

3. Results

3.1. The Trends of Grain Self-Sufficiency Capacity in China's Metropolitan Areas

3.1.1. Overall Trends of Grain Self-Sufficiency Capacity

Though the 70 metropolitan areas only accounted for 5% of the total land area of China, they were responsible for 21% of the total grain production in China in 1990. However, the proportion of these metropolitan areas in China's total grain production dropped to 14.2% in 2015. This suggests that the metropolitan areas had gradually lost their comparative advantage to rural areas in grain production. On average, the grain production in a metropolitan area declined from 1.3 million tons in 1990 to 1.2 million tons in 2015, whereas its population size increased from 4 million people to 6.1 million people in the same period. Thus, the average grain self-sufficiency capacity in China's metropolitan areas substantially decreased.

Among individual metropolitan areas (Figure 4a), most did not achieve full self-sufficiency for grains, i.e., per capita production > 437 kg/capita, and the median level of per capita production steadily dropped from 304 kg/capita in 1990 to 143 kg/capita in 2015. The number of metropolitan areas with self-sufficiency capacity below 25%, i.e., per capita production < 109.3 kg/capita, increased from 7 to 28 in this period. The results of the Kruskal-Wallis Test indicated that the differences among the years were significant (Figure 4a), which suggests the overall level of grain self-sufficiency capacity in China's metropolitan areas decreased dramatically. However, the highest level of per capita production increased from 852 kg/capita in 1990 to 955 kg/capita in 2015. Only one metropolitan area had per capita production > 800 kg/capita in 1990–2010, and the number increased to 3 in 2015. It should also be noted that a turning point emerged in 2005. The per capita production in the top quartile increased after 2005. The number of metropolitan areas with full self-sufficiency capacity decreased from 13 in 1990 to 7 in 2005, then increased again to 10 in 2015. The change rates of grain self-sufficiency capacity

varied and were negative in about 3/4 of the metropolitan areas (Figure 4b). The results of the CV (Figure 4c) suggested a significant increase in the variations among metropolitan areas.

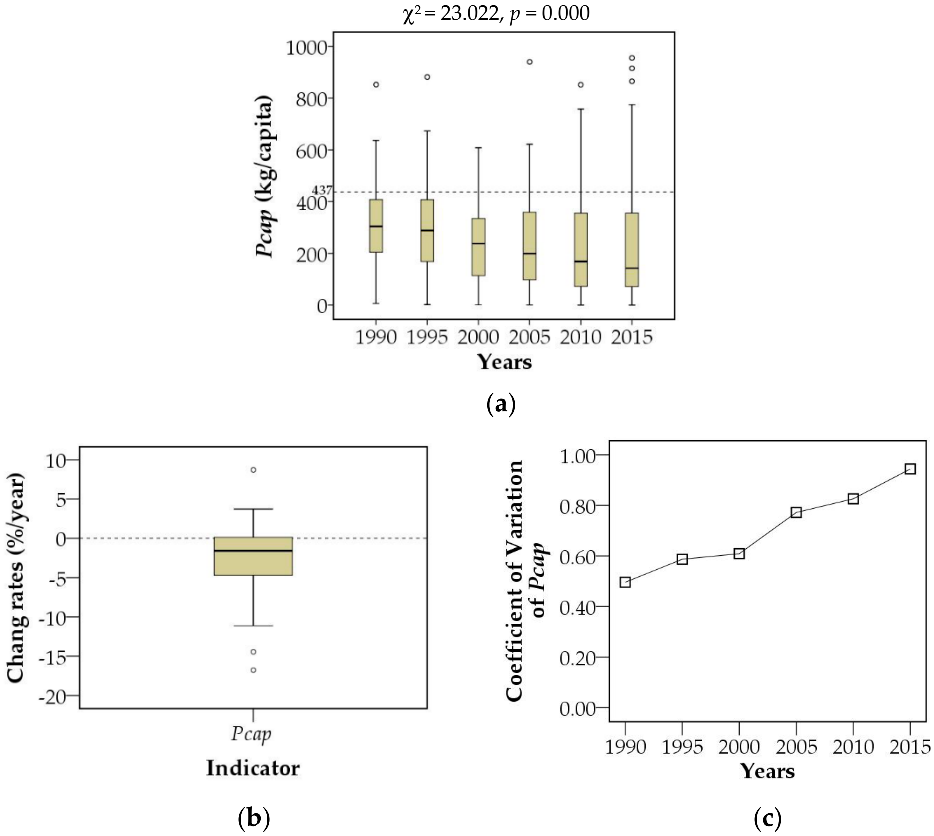


Figure 4. Distribution and variations of grain self-sufficiency capacity in China's metropolitan areas from 1990 to 2015. (**a**) Distribution of per capita grain production (*Pcap*). The dashed line indicates the level of full self-sufficiency (*Pcap* > 437 kg/capita). The χ^2 and p on top of the figure show the Chi-square and p value of the Kruskal-Wallis Test among different years. (**b**) Distribution of the change rates of *Pcap* from 1990 to 2015 in the metropolitan areas. The dashed line shows the division between positive and negative trends. (**c**) Coefficient of Variation of *Pcap* in different years.

3.1.2. Regional Differences in the Trends of Grain Self-Sufficiency Capacity

We combined the positive or negative change rate of self-sufficiency from 1990 to 2015 and the original level of self-sufficiency in the 1990s to reveal the spatial pattern of the trends in grain self-sufficiency in the metropolitan areas across China (Figure 5). The result suggested a general decline of grain self-sufficiency in the three large megalopolises, i.e., the Pearl River Delta, the Yangtze River Delta, and the area around Bohai Gulf, in metropolitan areas originally with low, medium, or high self-sufficiency. The increase of grain self-sufficiency mainly occurred in Northeastern China and in the areas between the two megalopolises around Bohai Gulf and in the Yangtze River Delta. The increasing trends in these metropolitan areas, which had a high or medium self-sufficiency in the 1990s, signified the best situation in terms of grain self-sufficiency capacity. Several small metropolitan areas in Northern China also showed some improvements in grain self-sufficiency, which were originally short of grain production. Other metropolitan areas in the West and South of China all showed decreasing trends in grain self-sufficiency. Among them, Urumqi and Xining in Northwestern China originally had a low self-sufficiency; the four metropolitan areas in the Southwestern China were slightly better with an originally medium self-sufficiency; the metropolitan areas in between (e.g., Chengdu and Chongqing) were originally high in self-sufficiency, but the situation could also be alarming with regard to the absolute decline in grain production.

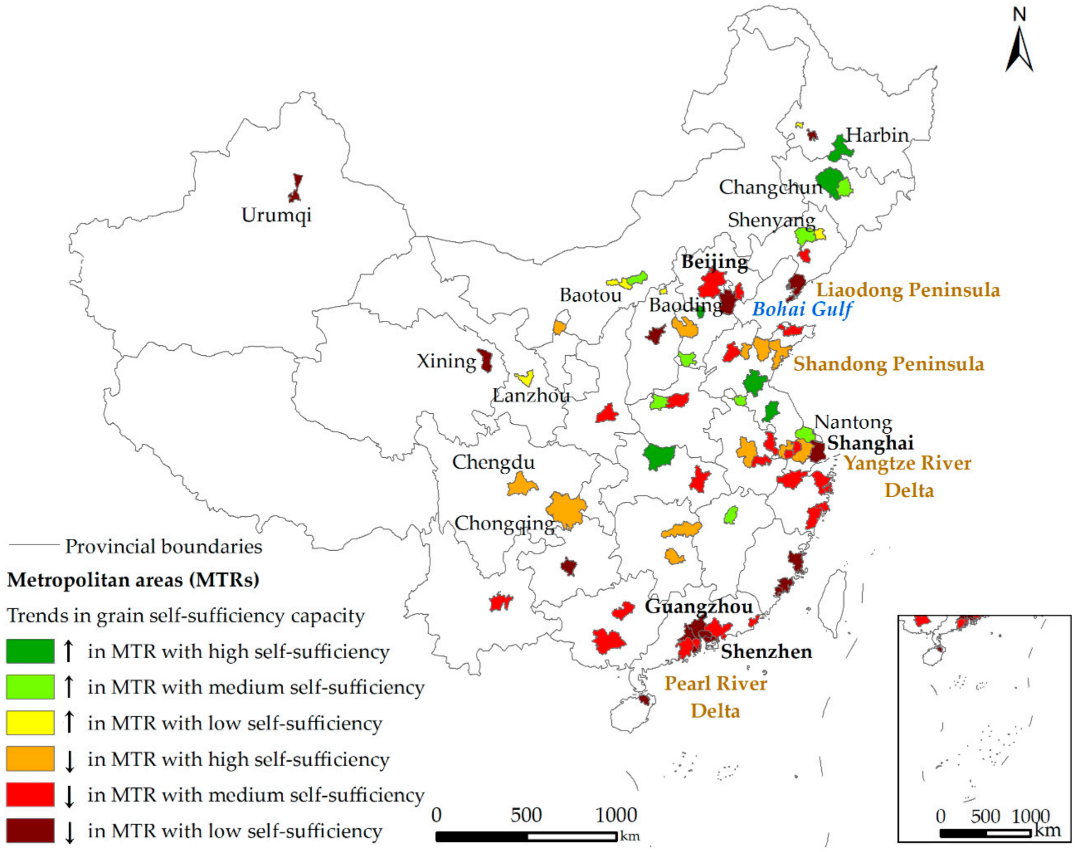


Figure 5. Spatial pattern of the trends in grain self-sufficiency capacity in China's metropolitan areas from 1990 to 2015. The metropolitan areas were originally classified as having high self-sufficiency (>90%), medium self-sufficiency (50%–90%), and low self-sufficiency (<50%), based upon the ratio of their average per capita grain production in 1990 and 1995 over 437 kg/capita. The trends were defined according to whether the annual change rate of per capita production from 1990 to 2015 was positive or negative.

Table 1 shows the changes in per capita grain production in some representative metropolitan areas for the major trends in grain self-sufficiency. The results suggested that the decrease in the center of the megalopolises was the most dramatic, especially in Shenzhen, which lost almost all its grain production capacity. Chengdu and Chongqing were both regional central cities in Western China and had very close levels of grain self-sufficiency in the 1990s, but apparently, the decline of grain self-sufficiency in Chengdu was much quicker than in Chongqing. Urumqi, Xining, Baotou, and Lanzhou represented the metropolitan areas with poor conditions for grain production in North and Northwestern China; however, the results suggested that their trends in grain self-sufficiency could be different. Harbin and Changchun were among the metropolitan areas with the highest grain self-sufficiency in China. Nantong and Baoding were the only metropolitan areas with increasing grain self-sufficiency among the neighbors of Shanghai and Beijing, respectively. Shenyang in the north of the Liaodong Peninsula was the only one with increasing grain self-sufficiency among the metropolitan areas with central cities of more than 5 million people.

Table 1. Changes in per capita grain production (*Pcap*) in selected metropolitan areas with different trends in grain self-sufficiency from 1990 to 2015.

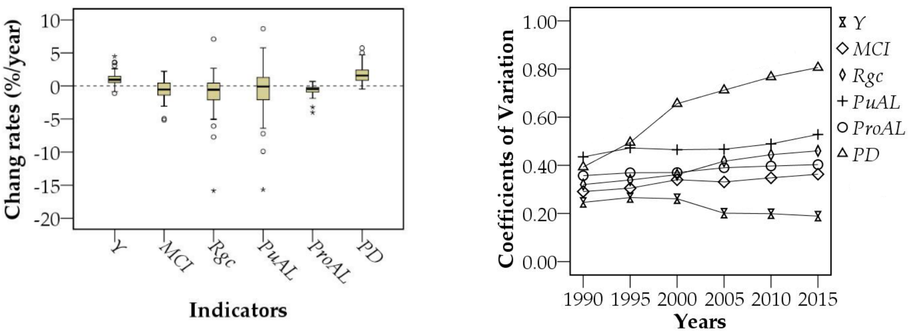
Trends of Grain Self-Sufficiency	Metropolitan Areas	*Pcap* (kg/capita)		Change Rate of *Pcap* (%/year)
		1990	2015	
Decrease in the center of the megalopolises	Beijing	245	29	−7.6
	Shanghai	183	46	−6.0
	Shenzhen	49	0.004	−17
	Guangzhou	190	33	−7.3
Decrease in traditional grain production regions in the West	Chengdu	406	154	−4.1
	Chongqing	410	297	−1.2
Decrease in areas with low self-sufficiency in Northwestern China	Urumqi	85	36	−4.2
	Xining	223	84	−3.2
Increase in traditional grain production regions in Northeastern China	Harbin	514	775	0.3
	Changchun	852	955	0.3
Increase in the periphery of the megalopolises	Nantong	304	468	1.2
	Baoding	364	391	0.1
	Shenyang	362	320	0.1
Improvement in the North	Baotou	132	375	3.7
	Lanzhou	58	79	1.0

3.2. Contributions of the Changes in Grain Supply and Demand to the Trends of Grain Self-Sufficiency Capacity in China's Metropolitan Areas

3.2.1. Changes in the Supply–Demand Relationship for Grains in China's Metropolitan Areas

Over the study years, the supply and demand of grains in China's metropolitan areas changed in different ways (Figure 6a). Land availability for grain production only had a slight decrease in most of the metropolitan areas. The change of land productivity for grains varied among the metropolitan areas remarkably. Almost half of the metropolitan areas had increased trends and the other half had decreased trends in land productivity for grains. The PD increased significantly in most of the metropolitan areas. The results of the Coefficients of Variation (Figure 6b) suggested that the variations among metropolitan areas increased dramatically in PD but only slightly increased after 2005 in land productivity and land availability for grains. As for the three determinants of land productivity, the growth of grain yield in most of the metropolitan areas reduced the variation among metropolitan areas while the different change rates of the ratio of grain cultivation to the total sown area increased the variations among metropolitan areas (Figure 6a,b).

The Spearman Correlation analysis (Table 2) showed that the growth of PD in the metropolitan areas negatively correlated with the changes in land availability and land productivity for grains ($p < 0.001$) and also negatively correlated with the change in grain yield ($p < 0.01$) and the change in the ratio of grain cultivation to total sown area ($p < 0.001$). Meanwhile, the change in land availability positively correlated with the change in land productivity ($p < 0.001$) and the changes in the three determinants of land productivity, especially with the change in the ratio of grain cultivation to total sown area ($p < 0.001$). The results implied a trend toward a polarization effect, which meant that the metropolitan areas with higher PD would have smaller proportion of arable land and lower land productivity for grains.



(a) (b)

Figure 6. Change rates and variations of the indicators related to grain supply and demand in the metropolitan areas from 1990 to 2015. (**a**) Distribution of the change rates of grain yield (*Y*), multiple-cropping index (*MCI*), ratio of grain cultivation to the total sown area (*Rgc*), land productivity (*PuAL*), land availability (*ProAL*), and population density (*PD*) in the metropolitan areas from 1990 to 2015. The dashed line shows the division between positive and negative trends. (**b**) Coefficients of variation of these indicators in different years.

Table 2. Spearman correlation coefficients between the supply and demand indicators for grains in China's metropolitan areas from 1990 to 2015.

Indicators		1990	1995	2000	2005	2010	2015	Change Rates
PD-	*ProAL*	0.356 **	0.217	0.125	0.026	−0.075	−0.096	−0.565 ***
	PuAL	0.38 **	0.257 *	0.23	−0.105	−0.207	−0.205	−0.525 ***
	Y	0.144	0.138	0.226	0.134	−0.06	−0.097	−0.344 **
	MCI	0.131	0.146	0.206	0.105	0.1	0.21	−0.029
	Rgc	0.148	0.096	−0.151	−0.312 **	−0.303 *	−0.35 **	−0.572 ***
ProAL-	*PuAL*	0.257 *	0.239 *	0.298 *	0.515 ***	0.615 ***	0.645 ***	0.613 ***
	Y	0.298 *	0.3 *	0.278 *	0.464 ***	0.536 ***	0.515 ***	0.307 **
	MCI	−0.078	−0.133	−0.096	0.076	0.102	0.118	0.261 *
	Rgc	0.203	0.242 *	0.205	0.304 *	0.367 **	0.431 ***	0.587 ***

* Correlation is significant at the 0.05 level (2-tailed); ** at the 0.01 level; *** at the 0.001 level.

The polarization effect was partly proved by the results of the Spearman Correlation analysis between the original indicators in multiple years (Table 2). The results showed that the land availability and land productivity for grain production both positively correlated with PD in the metropolitan areas in 1990 ($p < 0.01$). The positive relationship between the supply and demand of grains gradually turned to an insignificant but negative one from 2005. The ratio of the grain cultivation to total sown area showed a significant negative correlation with PD from 2005 ($p < 0.01$), which implied that the metropolitan areas with higher demand of grains had an increase in other crops or less decrease in other crops than grain cultivation. The metropolitan areas with higher land availability also had higher land productivity for grains. This positive correlation strengthened from 1990 ($R = 0.257$, $p < 0.05$) to 2015 ($R = 0.645$, $p < 0.001$). The same trend was also observed for grain yield ($R = 0.298$, $p < 0.05$ in 1990 and $R = 0.515$, $p < 0.001$ in 2015) and the ratio of grain cultivation to total sown area ($R = 0.203$, not significant in 1990 and $R = 0.431$, $p < 0.001$ in 2015). The polarization effect not only resulted from the scale effect but also the fact that metropolitan areas with smaller proportion of arable land gave less importance to grain production.

3.2.2. Contributions of the Changes in Supply and Demand to the Trends in Grain Self-Sufficiency

Figure 7a presented the spatial pattern of the contributions of grain supply and demand to the trends in per capita grain production in China's metropolitan areas. The increase of per capita grain production in all 19 metropolitan areas (in green in Figure 7a) mainly resulted from the increase in supply. More specifically, the increase in land productivity was more important than the change in

land availability. The increase in land productivity had an average contribution ratio of 410%, while the change in land availability had an average contribution ratio of −92%. Though four metropolitan areas also had increased land availability and another four had decreased PD, their contributions to the increase of per capita grain production were relatively small.

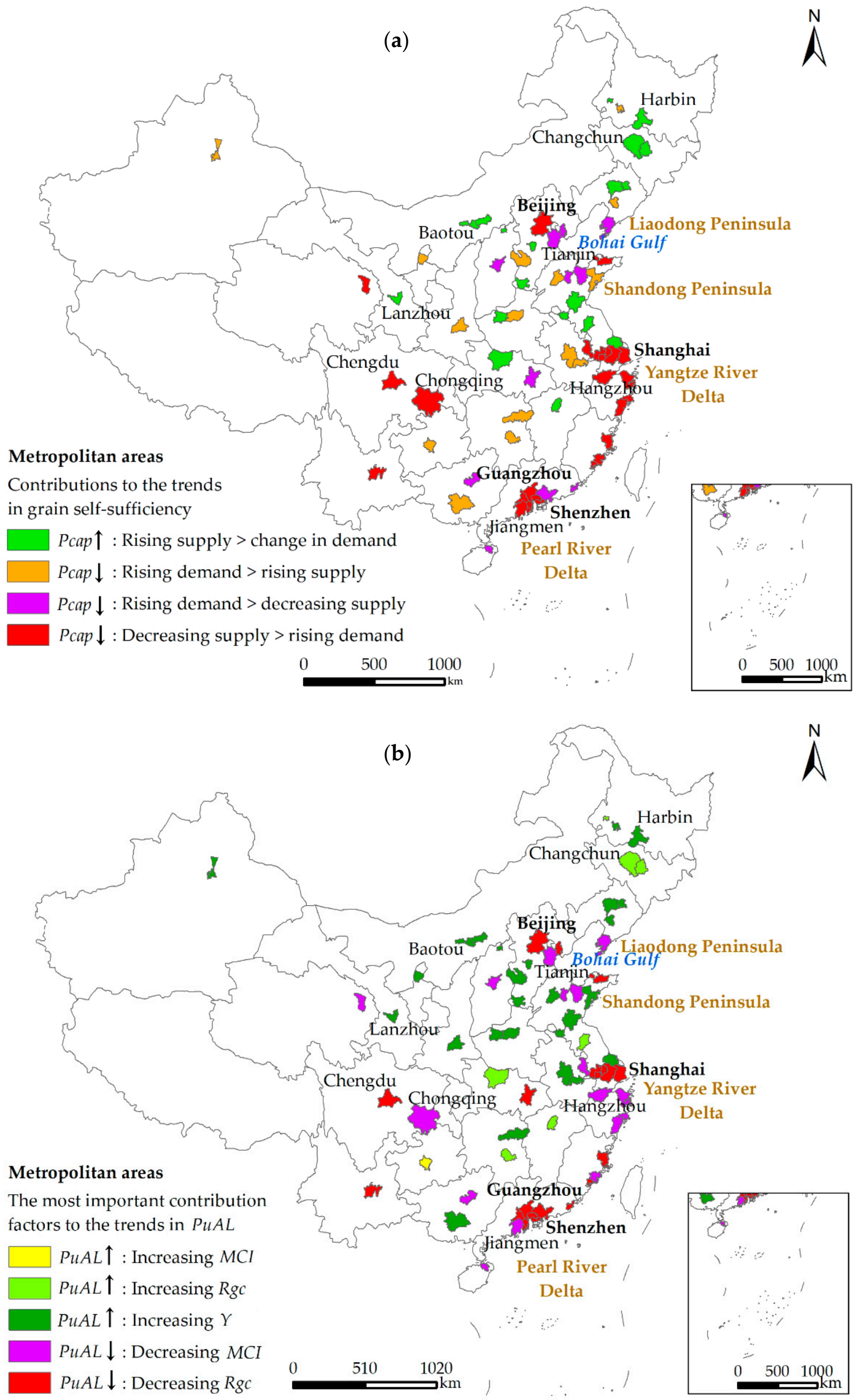


Figure 7. Spatial pattern of the contributions of grain supply and demand to the trends in grain self-sufficiency capacity in China's metropolitan areas from 1990 to 2015. (**a**) Contributions to the trends in per capita grain production (*Pcap*) in metropolitan areas. (**b**) The most important contribution factors to the trends in land productivity for grains (*PuAL*). *Y*: grain yield, *MCI*: multiple-cropping index, *Rgc*: ratio of grain cultivation to the total sown area.

The decreasing trend of per capita production in 15 metropolitan areas (in brown in Figure 7a) was because the contribution of rising demand surpassed the increasing supply. The average contribution ratios of the changes in PD, land availability, and land productivity were 250%, 69%, and −220%, respectively. The increase of grain supply came from the increase in land productivity.

The other 36 metropolitan areas had decreasing land availability, decreasing land productivity, and increasing PD, which all positively contributed to the decrease of per capita production. Among them, the decline in 11 metropolitan areas (in purple in Figure 7a) was because the contribution of the rising demand surpassed the decrease in supply. The average contribution ratio of the rising population density was 64% in these areas, and the average contribution ratios of land availability and land productivity were 17% and 16%, respectively. In the remaining 25 metropolitan areas (in red in Figure 7a), the reason for the decrease in grain self-sufficiency was related to the contribution of the decreasing supply surpassing the rising demand. Again, the most important contributing factor was the decrease in land productivity, which accounted for 52% to the change of per capita production. The average contribution ratio of land availability was only 18%.

As for the change in land productivity, we found that the most important contribution factors to the increase of land productivity were the increasing yield in 26/34 metropolitan areas (in dark green in Figure 7b, average contribution ratio = 560%). The most important contribution factors to the decrease of land productivity were the decreasing MCI in 16/36 metropolitan areas (in purple in Figure 7b, average contribution ratio = 317%) and the decreasing ratio of grain cultivation to total sown area in 20/36 metropolitan areas (in red in Figure 7b, average contribution ratio = 138%).

As seen in Figure 7, we found that the contradiction between an increasing demand and a decreasing supply mainly occurred in the eastern coastal areas and in Western China. In the three large megalopolises (i.e., the Pearl River Delta, the Yangtz River Delta, and the areas around Bohai Gulf), metropolitan areas in the center (e.g., Beijing, Shanghai, Shenzhen, and Guangzhou) had a decrease in land productivity mainly due to the decrease in the ratio of grain cultivation to total sown areas. Metropolitan areas in the peripheral part of the megalopolises (e.g., Tianjin, Hangzhou, and Jiangmen) had decreasing land productivity due to the decrease in the MCI.

Table 3 shows the changes in indicators related to grain supply and demand in some representative metropolitan areas with regards to contributions to grain self-sufficiency. The results suggested that the absolute quantity of changes in all the indicators were the most dramatic in the center of the megalopolises (i.e., Beijing, Shanghai, Shenzhen, and Guangzhou). Hangzhou and Jiangmen, neighbors of Shanghai and Shenzhen, respectively, had significant decreases in the MCI though their population densities did not change as much as their giant neighbors. Tianjin, south-east of Beijing, was a typical example of the metropolitan areas with decreasing grain self-sufficiency due to population growth. Compared to Chongqing, Chengdu was more similar to the metropolitan areas in the center of the megalopolises in the eastern coastal areas. Finally, for the increase of grain self-sufficiency and land productivity, the examples of Harbin, Changchun, Baotou, and Lanzhou showed that there was not much room for improvement in the MCI, because of the poor physical conditions in the North.

3.3. Impacts of Urban Expansion and Economic Growth on Grain Self-Sufficiency in China's Metropolitan Areas

The above results suggested that the greatest reduction in grain self-sufficiency capacity was in the metropolitan areas of the most rapidly growing cities in the eastern coastal areas. The results in Table 4 indicated the relationship between the change of grain self-sufficiency and urban development in metropolitan areas, i.e., GDP growth and urban expansion. The results may help to examine whether there was a "tradeoff" between grain production and economic development in metropolitan areas.

Table 3. Changes in indicators related to grain supply and demand in selected metropolitan areas with different primary contribution factors to the trends in grain self-sufficiency from 1990 to 2015.

Characteristics in Regard to Contributions to Grain Self-Sufficiency		Metropolitan Areas	*PD* (Persons/ha)		*Y* (t/ha)		*MCI* (%)		*Rgc* (%)	
			1990	2015	1990	2015	1990	2015	1990	2015
Enlarging contradiction between rising demands and decreasing supply	In the center of the megalopolises	Beijing	6.6	13.3	5.5	6.0	140	80	58.2	33.9
		Shanghai	16.8	30.4	5.9	6.9	200	180	43.2	24.9
		Shenzhen	8.8	60.4	4.6	4.9	200	160	22.6	0.04
		Guangzhou	9.0	19.3	5.2	4.9	170	280	49.3	15.5
	In the periphery of megalopolises	Tianjin	8.2	14.8	4.0	5.2	130	120	46.5	45.5
		Hangzhou	4.9	8.1	4.8	6.0	270	140	40.3	23.5
		Jiangmen	4.0	5.3	5.0	4.9	220	180	44.9	40.8
	In the West	Chengdu	7.9	12.6	5.4	6.3	210	160	46.0	37.6
		Chongqing	5.7	6.8	4.1	5.2	210	150	41.2	42.5
Increasing self-sufficiency because of rising land productivity	High self-sufficiency	Harbin	4.9	5.4	4.8	7.4	100	100	75.8	79.1
		Changchun	3.3	4.1	6.3	7.6	100	80	59.3	85.5
	Low self-sufficiency	Baotou	3.6	5.5	2.1	4.7	130	140	45.0	89.4
		Lanzhou	4.3	6.8	1.5	3.7	100	120	57.7	45.7

Table 4. Correlation and regression analyses between the trends in the grain self-sufficiency capacity and urban expansion and GDP growth in the metropolitan areas from 1990 to 2015.

Indicators	r_Y	r_{MCI}	r_{Rgc}	r_{PuAL}	r_{ProAL}	r_{PD}	r_{Pcap}	r_{GDP}
				Spearman's Correlation Coefficients				
r_{GDP}-	−0.056	−0.1	−0.048	−0.111	−0.077	0.198	−0.11	1
r_{ProBT}-	−0.26 *	−0.239 *	−0.39 **	−0.504 ***	−0.634 ***	0.486 ***	−0.552 ***	0.354 **
				Simple Linear Regression Models (r_{ProBT} as independent variable)				
$a(r_{ProBT})$	−0.202 *	−0.243 *	−0.748 **	−1.175 ***	−0.275 ***	0.369 ***	−1.63 ***	0.322 **
Constant	1.606	0.037	1.031	2.629	0.13	0.706	1.807	7.693
R Square	0.066	0.059	0.123	0.208	0.252	0.158	0.269	0.13

* Correlation is significant at the 0.05 level (2-tailed), ** at the 0.01 level; *** at the 0.001 level. r_{GDP} was calculated with adjusted GDP by deflator (1990 = 100).

The change rates of the supply, demand, and self-sufficiency indicators of grains were all significantly correlated with the rate of urban expansion but not with the growth of GDP (Table 4). As revealed by the Simple Linear Regression Models, when the rate of urban expansion increased by 1%, the growth rate of GDP would be increased by approximately 0.322% ($p < 0.01$) and the decrease rate of per capita grain production would be accelerated by 1.63% ($p < 0.001$). Accelerated increase of built-up lands resulted in not only a faster increase of PD ($a = 0.369$, $p < 0.001$) and loss of arable lands ($a = -0.275$, $p < 0.001$) but also a more remarkable decrease of land productivity of grains ($a = -1.175$, $p < 0.001$).

Thus, there was a tradeoff between urban expansion (rather than economic growth) and grain production in China's metropolitan areas. The contribution of urban expansion to economic growth was considerably smaller than its impact on the loss of grain production.

4. Discussion

4.1. Implications for Policies Related to Grain Production in China's Metropolitan Areas

Despite the overall declining trend of grain self-sufficiency, there were still 19 out of 70 metropolitan areas, mainly located in Northern China, which experienced rising trends. The four metropolitan areas with the highest self-sufficiency capacity (average per capita production > 500 kg/capita) were important areas in commercial grain production. The increasing trends in those areas were the reflection of an ongoing specialization process in agricultural production in China. There was also an improvement in some metropolitan areas with low self-sufficiency capacity. These were mainly old industrial or resource-dependent cities in Northern China. It has been reported that some resource-dependent cities are turning to modern agriculture for the transition of their economic systems [66]. The decrease in

grain self-sufficiency capacity mainly occurred in the eastern coastal areas, especially the megalopolises of the Yangtze River Delta, the Pearl River Delta, and the rim of Bohai Gulf. These were the core areas of urbanization in China. This pattern is consistent with studies at the provincial levels [62] and county levels [67] across China. Several metropolitan areas in the West also experienced sharp decreases in grain self-sufficiency. A possible reason for this might be that those areas, as provincial capitals, were also hotspots of urban expansion [37]. Therefore, the results suggested the necessity of differentiating the management strategies for food systems among the metropolitan areas. It is inappropriate to form a concept of a metropolitan area without local grain supply based solely upon the examples of metropolitan areas in the major megalopolises.

However, the megalopolises of the Yangtze River Delta, the Pearl River Delta, and the rim of Bohai Gulf do provide typical models which increasingly marginalize grain production. The potential for grain self-sufficiency is very limited in those metropolitan areas even from the perspective of two alternative strategies for food supply currently proposed in China, which are "Storing Grain in Land (Cang Liang Yu Di)" and "Storing Grain in Technology (Cang Liang Yu Ji)". The former emphasizes the preservation of a certain amount of qualified arable lands so that the metropolitan area has the capacity to produce enough grains when needed. The latter relies on progress in agricultural technology to improve land use efficiency and compensate the loss of arable lands. Nevertheless, metropolitan areas with low grain self-sufficiency capacity, e.g., Beijing, Shanghai, Guangzhou, and Shenzhen, have very limited availability of arable lands and thus little potential for improvement. The improvement in grain yield is also limited in metropolitan areas undergoing significant loss of arable lands. An alarming issue is that the development of more urban clusters or megalopolises is set to be the main direction of China's future urbanization by the National New-Type Urbanization Plan (2014–2020) [68,69]. The 20 planned urban clusters (known as "urban agglomeration" in China) will take up a large part of China's fertile arable lands. If all the future urban clusters follow the development path of the current megalopolises in the Yangtze River Delta and the Pearl River Delta, it will be a great risk to the grain security of China.

The results in the analysis of urban impacts (Section 3.3) suggested that the tradeoff is between urban expansion and grain production rather than economic growth and grain production. In the Yangtze River Delta and the Pearl River Delta, adjacent metropolitan areas of different sizes and development levels had similarly rapid decreases in grain self-sufficiency capacity. This reflects the effects of the regional policies and is also in accordance with Sinclair's [2] model in terms of the anticipation of urban encroachment. Therefore, what the policy-makers really need with regards to the tradeoffs between urban development and grain production in metropolitan areas is to optimize land use planning and make urban expansion more land efficient. There is also an urgent need to integrate agricultural production within the agenda of urban development and, especially, the development of urban clusters.

Finally, the contribution of arable land loss to the change of grain self-sufficiency capacity was relatively small in all metropolitan areas. In areas with remarkable loss of arable lands, urban expansion had an even greater impact on land productivity for grains. Previous studies focused more on the impacts of arable land loss [40,46,47,70,71]. However, our study showed that more research and management efforts are needed for the influences of land use on grain self-sufficiency. The possible reasons for the decrease in the MCI might be abandonment or deintensification of cultivation. The underlying causes of abandonment include the fragmentation of arable lands, lack of labor, uncertainty of the future, and the rising of non-productive recreational agriculture in peri-urban areas [47,48,63,72]. The reasons for the decrease in the ratio of grain cultivation to total sown areas might be the shift to vegetables or cash crops for higher profits or a sharper decrease in grains than vegetables and cash crops. In particular, metropolitan areas in the peripheral part of the megalopolises should be more cautious about the underlying problems of land abandonment and deintensification. Those metropolitan areas in the center of the megalopolises should pay more attention to the cultivation shift to cash crops.

4.2. A Brief Comparison with Some Metropolitan Areas in the Global North

Not all countries in the Global North are in a similar situation as China, where big cities are concentrated in the most important agricultural regions for grain production. For example, the USA and Canada have vast high-quality agricultural lands in inland areas for commercial grain production, while most of their important cities are in coastal areas. Though less densely inhabited than China and most European countries, the USA and Canada have had important policy concerns for farmland loss due to urbanization since the 1970s [5,6,8,73,74]. However, they strive to preserve farmland for protection of open spaces and other benefits, in addition to food and commodity production in a broad sense [5]. Since grains can be easily transported and agricultural production is highly specialized at the national level in the USA and Canada, grains are not particularly emphasized in the study of food self-sufficiency in metropolitan areas [21].

Comparisons between China and European countries are relatively more interesting with regards to grain production in metropolitan areas. Major metropolitan areas such as Paris, Berlin, and Milan are in the historical zones of grain production. They are also profoundly influenced by the Common Agricultural Policy (CAP) of the European Union, which was started in the 1960s with an initial focus on promoting grain production [75]. These metropolitan areas are also faced with the conflicts between grain production and the targets of economic growth, urbanization, and environmental protection. It would be interesting to know how these areas coordinate among multiple targets, with a different system from China's top-down regulation regime (Figure 1).

The Greater Paris Region (Ile-de-France Region) is the largest metropolitan area in France; it consists of 18% of the total population and 30% of the GDP in France with only 2% of the country's land, but it still has an intensive grain production. According to the Annual Agricultural Statistics of France, 48% of the total area consisted of arable lands in the Greater Paris Region and the proportion of grain cultivation was 72% in 2014. Its per capita grain production was 281 kg/capita in 2014, about 10 times that of Beijing and 6 times that of Shanghai. The grain supply has surpassed demand in the Greater Paris Region-based upon the French diet [76]. Grain supply surpassing demand has also been reported in other metropolitan areas such as Berlin and Milan [23].

Taking the Greater Paris Region as an example, its differences with China's major metropolitan areas such as Beijing, Shanghai, and Guangzhou can be interpreted from four aspects. Firstly, due to the completed agricultural modernization and the CAP policy, agriculture in Paris has developed a large-scale, highly mechanized intensive agriculture of grains and oil crops [77]. Paris was able to benefit early from the proximity to the urban market, diffusion of technology, and farm consolidation [4]. China's agricultural modernization is still in progress. The small household agriculture has difficulties in resisting the impacts of urbanization. Secondly, urban areas have been quite stable in Paris since the 1980s after the most rapid population growth and urban expansion in the 1960s [4]. China's major metropolitan areas are under greater pressures from ongoing urbanization. Grain production is at risk of further decline due to the needs of future urban expansion. Thirdly, China has a different land tenure and policy system from that of Paris. China's top-down management system makes it much easier to implement large-scale developing projects or agricultural structural adjustments. Finally, food production is being further incorporated into landscape service and biodiversity management along with the reform of the CAP policy and the establishment of Agri-Urban Programs in the Greater Paris Region [4,6,78,79]. Beijing's top-down afforestation program on farmlands in the plain [45] implies that China's metropolitan areas still consider agriculture in a contradictive position with environmental concern.

However, the metropolitan areas under the CAP regime are criticized for sending a large part of their grain production to national and international markets and having caused significant loss of specialized farms for fruit and vegetables [11]. On the contrary, China's metropolitan areas are actually dominated by subsistence agriculture. The municipal government is accountable for vegetable self-sufficiency and the reallocation of farmlands from grain production to fruit and vegetables is

encouraged [38,45], so the loss of farmland does not influence much on vegetables and fruit in terms of cultivation area in China's metropolitan areas.

4.3. Limitations of the Study

To achieve a comprehensive comparison among metropolitan areas across China, the study did not consider the difference among different grains and the spatial variation within the cities. However, it is very likely that the trends of self-sufficiency differ among the grains and districts within the city. For example, previous studies about Beijing suggested a sharper decrease in wheat than maize, despite a general decline in all grains, and the trends also varied among the near, middle, and far suburbs [47,80]. Future research can specifically focus on these questions in selected metropolitan areas. Instead of weight-based analysis, future research can also look further into the issue of nutrition self-sufficiency, which responds more directly to public health [27,28]. Next, our study did not consider the influences of the food supply chains [11], the change of diets [30], or the expansion of metropolitan areas. What remains to be investigated are the consequences of the change in grain self-sufficiency in metropolitan areas such as the change of GHG emission in urban food system and the change of water resource demands of peri-urban agriculture [80]. Finally, we did not analyze in detail the reasons for the changes in land productivity of grains. For example, the decrease in the ratio of grain cultivation to total sown areas can result from a sharper decrease in grains than vegetables and cash crops, or a shift of grain to vegetables and cash crops. The reason for the decrease in the MCI can be different across regions. Future research can improve these limitations with specific studies and field investigations in selected metropolitan areas.

5. Conclusions

Based upon a comprehensive statistical analysis of 70 metropolitan areas in mainland China, we quantitatively investigated the regional differences in the trends of grain self-sufficiency capacity in these areas from 1990 to 2015. The findings showed that first, there was insufficient grain production and a declining trend of grain self-sufficiency capacity in most metropolitan areas. However, about 1/4 metropolitan areas had increasing grain self-sufficiency during this period. The decrease in grain self-sufficiency mainly occurred in the rapidly urbanizing eastern coastal areas, especially in the megalopolises of the Yangtze River Delta, the Pearl River Delta, and the rim of Bohai Gulf, as well as some provincial capital regions in the West. The increase of self-sufficiency mainly occurred in the North, in metropolitan areas highly specialized in grain production or originally low in grain self-sufficiency. Then, the grain supply and demand structure changed toward a polarization effect, which meant that metropolitan areas with higher population densities had smaller proportion of arable land and lower land productivity of grains. The enlarging contradiction between the rising demand and the decreasing supply provided an explanation for the decreasing trend in grain self-sufficiency in the eastern coastal areas and in the West. The increasing self-sufficiency in the North mainly resulted from the growing supply. More specifically, the change in land productivity was more important than land availability in the contributions to supply change, including the increase in the North and the decrease in the eastern coastal areas. The increase of land productivity mainly resulted from the increase in grain yield, while the decrease of land productivity was primarily led by the decrease in the MCI or the ratio of grain cultivation to total sown area. Finally, there was a tradeoff between urban expansion (rather than economic growth) and grain production in China's metropolitan areas.

Based on the findings, some main implications for future research and policy-making include: (1) differentiation among the metropolitan areas for the management of food systems; (2) cautions about the impact on grain security in the development of more urban clusters or megalopolises in future urbanization in China; (3) land use optimization to make urbanization more land efficient and integrated with grain production; (4) investigation and regulation on arable land use in peri-urban areas, especially on land abandonment and the shift in the cultivation system; (5) comparison with other metropolitan areas in the world to understand the different types of relationships between

megacities and food production; and (6) research in specific metropolitan areas on the differences among grains and spatial variations within cities, the impacts of the declining grain self-sufficiency capacity in metropolitan areas, and other questions.

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Appendix A

The Gravitational Model of Economic Linkages method for the identification of the boundaries of metropolitan areas was carried out as follows:

The strength of the economic linkage between the central city and each of its peripheral counties in the same municipality was calculated according to Equation (A1) for the year 2015. The area of the central city means the districts covered by the contiguous built-up area where the municipal government was located.

$$Eco\_R_i = \left(\sqrt{(P_0 \times G_0)}\sqrt{(P_i \times G_i)}\right)/{dist_i}^2 \; (i = 1, 2, \ldots, n), \tag{A1}$$

where Eco_R_i is the economic linkage strength between the central city and the ith peripheral county of the same municipality (1000 persons·billion RMB/km^2). P_0 and P_i represent the urban population in the central city and the permanent resident population in the ith county (1000 persons), respectively. G_0 and G_i represent the GDP in the central city and the ith county (billion RMB), respectively. $dist_i$ represents the shortest road distance between the ith county and its central city (km). n is the number of the peripheral counties in the same municipality.

The criteria "$Eco\_R_i \geq 20$" or "$10 \leq Eco\_R_i < 20$ and Eco_R_i takes up > 10% in ΣEco_R_i of a municipality" were used for the selection of peripheral counties being kept in the metropolitan areas. The criteria were set based upon the distribution and range of the Eco_R_i values and the values of the largest metropolitan areas, such as Beijing, Shanghai, Guangzhou, and Shenzhen. Exclaves were not included.

Appendix B

The calculation methods of the indicators used in this study were shown in Equations (A2)–(A9).

$$Pcap = Q/P \times 1000, \tag{A2}$$

$$PuAL = Q/A_{AL}, \tag{A3}$$

$$ProAL = A_{AL}/A \times 100, \tag{A4}$$

$$ProBT = A_{BT}/A \times 100, \tag{A5}$$

$$PD = P/A, \tag{A6}$$

$$Y = Q/A_{GC}, \tag{A7}$$

$$MCI = A_{TS}/A_{AL} \times 100, \tag{A8}$$

$$Rgc = PuAL/(Y \times MCI), \tag{A9}$$

where Q is the total production of grains (t); P is the number of permanent residents (persons); A is the total area of the metropolitan area (ha). A_{AL}, A_{BT}, A_{GC} and A_{TS} are the area of arable lands (ha), the area of built-up lands (ha), the area of grain cultivation (ha) and the total sown area (ha), respectively. All indicators were calculated for the 70 metropolitan areas in 1990, 1995, 2000, 2005, 2010, and 2015. The Y and MCI were calculated at the municipal level and used for the metropolitan areas due to data unavailability.

Appendix C

The change rates of per capita grain production (*Pcap*) and land productivity (*PuAL*) can be estimated by the sum of the change rates of their determinants as explained below:

It can be derived from Equation (A10) that the change rate of the *Pcap* is approximately equal to the sum of the change rates of *ProAL*, *PuAL*, and the opposite of *PD* (Equations (A11)–(A15)).

$$Pcap = PuAL \times ProAL \div PD \times 10, \tag{A10}$$

$$\ln(Pcap) = \ln(PuAL) + \ln(ProAL) - \ln(PD) + \ln 10, \tag{A11}$$

$$\mathrm{d}\ln(Pcap)/\mathrm{d}t = \mathrm{d}\ln(PuAL)/\mathrm{d}t + \mathrm{d}\ln(ProAL)/\mathrm{d}t - \mathrm{d}\ln(PD)/\mathrm{d}t, \tag{A12}$$

$$(\mathrm{d}Pcap/\mathrm{d}t)/Pcap = (\mathrm{d}PuAL/\mathrm{d}t)/PuAL + (\mathrm{d}ProAL/\mathrm{d}t)/ProAL - (\mathrm{d}PD/\mathrm{d}t)/PD, \tag{A13}$$

$$(\mathrm{d}X/\mathrm{d}t)/X \times 100 \approx \mathrm{Slope}(X)/\mathrm{Average}\ (X) \times 100 = r_X, \tag{A14}$$

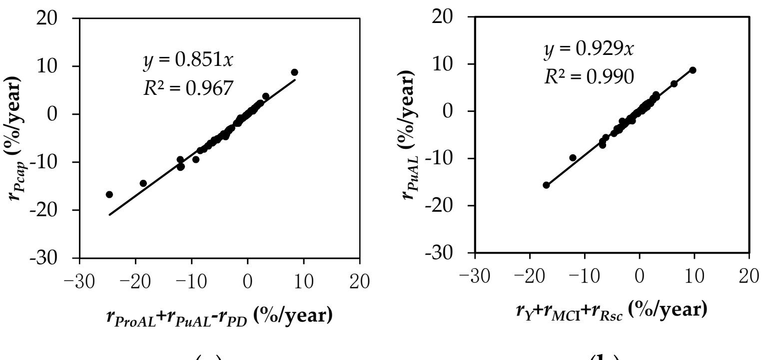
$$r_{Pcap} = r_{PuAL} + r_{ProAL} - r_{PD}. \tag{A15}$$

In the same way, it can be obtained from Equation (A16) that the change rate of the *PuAL* is approximately equal to the sum of the change rates of Y, MCI, and Rgc (Equation (A17)).

$$PuAL = Y \times MCI \times Rgc, \tag{A16}$$

$$r_{PuAL} = r_Y + r_{MCI} + r_{Rgc}. \tag{A17}$$

Figure A1 showed that the sum of the change rates of the contributing factors had good explanatory power for the change rates of *Pcap* and *PuAL*.



(**a**) (**b**)

Figure A1. The explanatory power of the contributing factors to the trends in grain self-sufficiency capacity in China's metropolitan areas. (**a**) The linear regression between the annual change rate of per capita production (r_{Pcap}) and the sum of the change rates of the production per unit area of arable land (r_{PuAL}), proportion of arable area (r_{ProAL}), and the opposite of population density ($-r_{PD}$) in metropolitan areas from 1990 to 2015; (**b**) The linear regression between r_{PuAL} and the sum of the change rates of yield (r_Y), the multiple-cropping index (r_{MCI}), and the ratio of grain cultivation to total sown area (r_{Rgc}) in metropolitan areas from 1990 to 2015.

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