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Quantifying the Impacts of Grain Plantation Decline on Domestic Grain Supply in China During the Past Two Decades

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Abstract: An adequate food supply is a core issue for sustainable development worldwide. Amid greater instability in the food supply triggered by more armed conflicts, trade disputes, and climate change, a decline in grain cultivation area still plagues many regions. China, a major food producer globally, is a case in point. The truth is that at the moment, the formulation and implementation of policies as well as academic discussions regarding this issue are predominantly based on the sown area of grains, overlooking the fundamental role co-played by population, yield efficiency, and sown area in determining food supply. Furthermore, the commonly used indicator, the non-grain cultivation rate, fails to directly reflect the impact of the phenomenon on the grain supply. To address these gaps, this study introduces trend-change detection and factor-contribution analysis, uses long-term grain sown area data to identify regions with significant grain retreat, and quantifies the relative influence of population shifts, crop yield improvements, and sown area changes on food supply. Key findings include the following: China's total grain production maintained steady growth from 2003 to 2023, far exceeding conventional food security thresholds. Temporary reductions in grain sown area (2015–2019, 2021–2022) were offset by rising yields, with no substantial decline in supply. Twelve provinces/municipalities, Beijing, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, Guizhou, Shaanxi, Ningxia, Sichuan, Chongqing, and Hainan, exhibited substantial declines in grain plantation. However, Sichuan and Shaanxi achieved counter-trend growth in food supply, while Ningxia and Guizhou experienced frequent fluctuations. The sown area was not always the dominant factor in per capita grain availability. Yield increases neutralized cropland reduction in Sichuan, Shaanxi, Guizhou, and Ningxia, whereas population inflows outweighed the sown area effect in the other eight provinces. The study concludes that China's grain cropland reduction has not yet posed a threat to national food security. That said, the spatial concentration of these affected regions and their ongoing output reductions may raise domestic grain redistribution costs and intensify inter-regional conflicts over cropland protection. Meanwhile, population influx plays a similarly important role to that of grain plantation decline in the grain supply. Considering that, we believe that more moderate measures should be adopted to address the shrinkage of grain planting areas, with pre-set food self-sufficiency standards. These measures include, but are not limited to, improving productivity and adopting integrated farming. Methodologically, this work lowers distortions from normal annual cropland fluctuations, enabling more precise identification of non-grain production zones. By quantifying the separate impacts of population, crop yield,

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and sown area changes, it supplements existing observations on grain cropland decline and provides better targeted suggestions on policy formulation and coordination.

Keywords: food security; non-grain production; grain supply; population flow; crop yield

1. Introduction

An adequate food supply is not only a critical strategic issue for fostering economic growth, social stability, and national security, but is also a fundamental component of sustainable development. How to maintain food security has always been high on the agenda of academics and government officials around the world [1,2]. Since 2014, the number of people suffering from hunger worldwide has steadily increased, reaching approximately 690 million by 2019 [3]. Alleviating hunger and enhancing food security have thus emerged as core priorities under the 2030 Sustainable Development Goals [4–6]. While boosting food production is pivotal in combating hunger, intensified trade tension, armed conflicts, market volatility, and climate change have made global food production and security more fragile. Ensuring basic food self-sufficiency is therefore highly imperative [3,7]. Currently, croplands worldwide are facing great challenges as farmers abandon grain plantations to seek higher incomes. Notably, regions such as Southeast Asia and sub-Saharan Africa are seeing large-scale expansion in the cultivation of biofuel and cash crops [8,9]. In response, developed nations, including the United States and Canada, have conducted extensive monitoring of both food and non-food crops [10]. Such trends pose a significant threat to the sustainability of global food production and the efforts to meet the zero hunger objective [11]. To address these challenges, many scholars have proposed initiatives such as advancing farmland intensification [12], restructuring crop planting systems [13], enhancing high-efficiency agricultural technologies [14], strengthening agricultural policy incentives [15], reforming global agricultural trade systems [16], and curbing food waste [17].

China is the most populous country and one of the largest food producers in the world. At the same time, its per capita arable land area is only 40% of the world average, with generally low land quality and a severe shortage of reserved resources [18,19]. Since the founding of the country in 1949, food security has consistently been one of the key priorities of the central government. Thanks to decades of effort, sown area, planting intensity, and yield efficiency increased [20,21]. That doubled China's total grain production, making significant contributions to global food security [22,23]. By the early 21st century, China met the food security standard of the Food and Agriculture Organization of the United Nations [24]. However, scholars have observed contradictory developments over the past 20 years, that is, the northward expansion and the southward contraction in grain cultivation [25–27]. Driven by economic benefits, more traditional food crops have been replaced by high-economic-value activities such as tree planting, aquaculture, and cultivation of fruit trees and tea [28]. According to some researchers, more than 25% of China's cropland is no longer dedicated to grain production, and this percentage may be even higher in economically advanced or rapidly developing cities [29]. In response to that, China has rolled out a series of policies, and established a local responsibility system [30,31], aiming to safeguard domestic food self-sufficiency by maintaining or expanding the area dedicated to grains [7,32].

In fact, food supply is the result of a dynamic interaction between sown area, yield efficiency, and population [33]. Back in the early 2000s [34], the issue of grain plantation decline had already caught the attention of governors and scholars. However, the time-

series data indicate that the total output and supply of grains have continued to grow [35]. This proves that the increase in yield efficiency of grains has effectively countered the risk directly caused by the shrinkage of grain cropland on food supply [36]. Starting in 2016, China has incorporated a series of specific cropland policies into its 13th Five-Year Plan, such as the application of advanced agricultural technologies [37] and the development of high-standard farmland [38], for better crop yield and food security. However, when it comes to practice, rigid area-focused methods tend to be adopted, which overlook market forces. This leads to over-governance and a failure in addressing the fundamental imbalance between economic and agricultural developments [39]. What is more, the existing academic evaluation results regarding grain plantation variation are not convenient for policymakers to refer to. Most of them are performed based on the ratio of non-grain planting area to total sown area [40,41]. However, there are annual fluctuations in both grain and non-grain plantation. This makes the conclusions incomparable between regions or periods [42–45]. In some major grain-producing regions, such as Heilongjiang and Inner Mongolia, larger cropland areas actually lead to an exaggeration of the grain plantation decline level [46].

Meanwhile, China's population has experienced a new trend of change over the past ten years. After decades of growth, the total population has nearly stopped growing and will not change significantly in the near future. Furthermore, people have gradually gravitated to a few developed provinces or regions [47,48]. This means that the total grain demand in China will stay at the current level, and the negative impacts of non-grain production could either be mitigated or aggravated by population movement. At this point, most studies are conducted from the perspective of total food production. They either analyze the previous data on the total yield to explore changes in agricultural production patterns [49], or examine the spatio-temporal changes in the supply–demand balance based on population [11,50]. Therefore, an in-depth study of the interaction among grain sown area, yield efficiency, and population is of great necessity, in particular on a regional scale. On top of that, analyzing the reduction in grain cropland from the perspective of the food supply has high scientific and practical significance for designing cropland policies and ensuring food security.

Out of the aforementioned considerations, this study was designed with time-series statistics at the provincial level. Trend detection and attribution analysis were adopted as qualitative and quantitative methods, respectively, to accurately identify key areas with grain plantation shrinkage, and to quantify the effects of factors such as population and crop yield on China's food supply. By doing that, we aim to answer three questions: (1) Where did the decrease in grain planting area occur? (2) How has the grain supply in the regions suffering a grain plantation decrease changed? (3) To what extent has the reduction in grain sown area impacted the intra-grain supply?

2. Technical Contents

2.1. Study Area and Definition of Grain Plantation Decline

According to the current official statistical standards of China and academic conventions, grains generally include rice, maize, wheat, and other coarse grains such as millet, sorghum, oats, barley, and buckwheat [24,51]. Among them, rice, maize, and wheat play a fundamental and critical role in the food supply, dietary structure, and industrial production of China and even the globe. Accounting for over 90% of the total grain production, these three crops have been key subjects in Chinese cropland policies. The central government of China has even initiated the concept of "non-grain production" (NGP), which shows its great attention to the retreat of these grains [43]. With that, this study adopts these three crops as representatives of grains, and defines the reduction in their total sown area as NGP.

It has to be mentioned that Qinghai and Tibet are not included for the following reasons: (1) They own few croplands. (2) The main crops and staple foods for people there are not rice, maize, or wheat. (3) The production of these three crops constitutes a negligible proportion of the national total. All data were downloaded from the National Bureau of Statistics of China (https://www.stats.gov.cn). The technical details are described in the following sections.

2.2. Technical Routine

To address the aforementioned questions, this study was designed with three research components (Figure 1). The first part is identifying the regions with grain plantation decline. In previous studies, the most common practice was to segment time spans. For example, the time span of 20 years can be divided into 5-year or 10-year intervals with segmented data selected. This approach has been widely used in research involving long-term land-use change on multiple scales, including those on cultivated land [52–54]. It is clear that this method is likely to overlook critical moments of abrupt changes in data. The indicator "grain-to-crop sown area ratio" is specially designed to characterize the phenomenon. Mathematically, as it is simultaneously influenced by the annual fluctuations in cropping intensity, cultivated land area, and grain planting, the results are not comparable in terms of time and space. For instance, despite increases in both total cultivated land area and grain sown area, the level of non-grain conversion may still rise [43,46,55]. Therefore, we introduce a trend detection method to evaluate the shifts in grain sown area in a quantitative way (Section 2.3.2). Three scenarios can be anticipated: (1) A phased increase or decrease, that is, a period of decline followed by recovery or even a surpassing of the original level, or the opposite. (2) A continuous increase or decrease, that is, a consistent trend without significant reversals. (3) The combination of (1) and (2), that is, at least two trend changes or continuous minor fluctuations within a reasonable range. The regions with either phased or continuous declines in grain plantation are targets in the following discussions, and the trend detection method is detailed in Section 2.3.2.

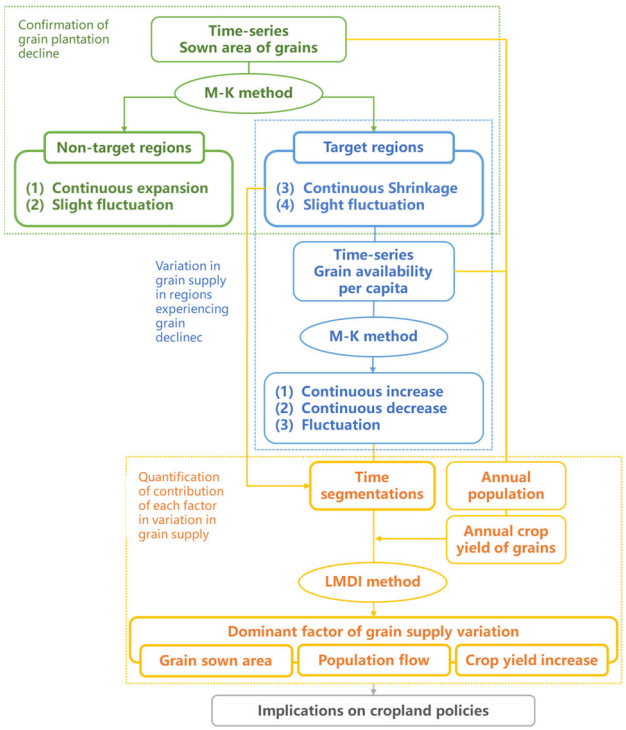


Figure 1. Technical routine.

The second component focuses on the fluctuations in grain supply in targeted regions. This part uses annual per capita grain availability (Ga) as the indicator of grain supply. It is not only widely used in official and academic discussions [56,57], but also has a direct mathematical relationship with sown-area, population, as well as crop yield (Ga = Ag × Yield/Population), which could facilitate the quantification of the contributions of the three factors to the changes in grain supply in subsequent discussions. Due to considerations similar to those described above, as well as for the continuity of the research, the same trend detection method is employed to understanding the trend variation in Ga.

The final section describes the quantification of the impacts of various factors, i.e., crop yield, population, and, particularly, Ag shrinkage on grain supply. The method Logarithmic Mean Divisia Index (LMDI) is introduced to decompose the contributions of each factor to the annual change rate of Ga. The following discussion is based on the abrupt trend change identified in the former parts. Details of the LMDI method are provided in Section 2.3.3.

2.3. Data and Methodologies

2.3.1. Data

Based on the technical routine, data on grain sown area, crop yield, total output of rice, maize, and wheat, and population are required. We performed the research on the time span of 2003 to 2023 for three reasons: (1) Farmers' abandonment of grain plantation was originally reported in the early 2000s [58]. (2) China met the food security baseline around 2005 and since then has maintained a high level of grain self-sufficiency [59]. (3) The statistics are only updated to 2023, which is an objective limitation. All research data were obtained from the annual provincial statistics published on the website of China's National Bureau of Statistics. To maintain consistency with previous similar studies on the food supply, we adopted a resident population in our study [33]. Additionally, there was no need for preprocessing as official data were already verified before they were released.

2.3.2. Mann–Kendall Method

The Mann–Kendall (M-K) method, which was initially proposed and further developed by Mann and Kendall [60], is a non-parametric statistical test, featuring simplicity in the calculation of ranks of data. It is suitable for analyzing time series with unstable central trends, as it does not require samples to follow a specific distribution, and is robust against outliers. Moreover, it can be effectively applied to analyze sequence data of both categorical and ordinal variables [61]. The M-K method has been widely accepted in trend-related studies in various fields, including hydrology [62], meteorology [63], and environment studies [64].

The temporal data from these studies exhibit a high degree of similarity with land-use change: they change gradually over time, with normal interannual fluctuations, and great sudden events such as natural disasters or wars may lead to abrupt trend shifts. So, they are also introduced in the discussion on land-use change [65]. Considering that, we attempt to apply M-K method in this study to identify changes in Ag and Ga. The calculation process comprises four steps:

(1) Calculate the expected meanalculate the expected mean (E) and variance (Var) of the data sequence. n is the count of the data sequence.

$$E = n(n+1)/4 \quad (1)$$

$$Var = n(n-1)(2n+5)/72 \quad (2)$$

(2) Work out the rank sequence (S_k) as well as its expected mean and variance, and then derive the trend statistics (UF_k).

$$S_k = \sum_{r=1}^{k} r_i \ (k = 2, 3, \ldots\ldots, n)$$
$$r_i = \begin{cases} +1, & if\ x_i > x_j \\ 0, & if\ x_i \leq x_j \end{cases} \quad (3)$$
$$(x_i\ is\ the\ i^{th}\ element\ of\ the\ data\ sequence)$$

$$UF_k = [S_k - E(s_k)] / \sqrt{Var(s_k)} \quad (4)$$

(3) Derive the UF_k of the inverse data sequence (UF_b), that is, repeat the steps (1)–(2) for the inverse data sequence.

(4) Determine the critical values at a given significance level (usually $\alpha = 0.05$; the corresponding critical values are ± 1.96); the mutation points are verified by comparing UF_k and UF_b with the critical values.

In the above results, a positive (negative) UF_k indicates growth (decline) in the data sequence, and the further away from 0 it is, the more significant is the change in the data sequence. Therefore, for data that consistently decreases or increases, the M-K method will not indicate a trend reversal when the data monotonically changes. If a intersection point between UF_k and UF_b falls within a given critical range, it is considered a trend mutation—Generally, the critical range is determined to be $[-1.96, 1.96]$ by a typically adopted significance level of 0.05. However, it is important to underline that the intersection time indicates a significant trend change occurs, but not the starting point of the trend change that actually precedes the moment [66,67].

2.3.3. Logarithmic Mean Divisia Index

The Logarithmic Mean Divisia Index (LMDI) method was originally referred to as Divisia Index Decomposition (DID) when it was created in 1924. It labels each decomposed factor as a continuous and differentiable function of time, differentiates them with respect to time, and then decomposes the influence of changes in each factor on the target variable. It was finally developed as LMDI by Ang et al. in 2005 [68]. LMDI has seen widespread application in areas such as industry, economics, environment and energy studies [69–71].

Built on the Divisia Index method, the LMDI method identifies and quantifies the contributions of various factors to the target indicator, and compares their respective impacts. It avoids unexplained residuals during the decomposition process, and, consequently enhances analytical accuracy, as it does not produce residuals. It remains robust even in the presence of zero or negative values. The LMDI method embraces both additive and multiplicative forms, which are suitable for calculating the impacts of indicators with additive and multiplicative relationships, respectively.

$$E = x_1 * x_2 * \ldots\ldots * x_n$$
$$x_i\ means\ the\ i^{th}\ factor\ impacts\ the\ target\ variable\ E \quad (5)$$

$$D_i = \left(E^t - E^0 / E^t\right) * \left(\ln(x_t / x_0) / \ln\left(E^t / E^0\right)\right)$$
$$D_i \text{ means the contribution of } x_i \text{ in the variation of } E \text{ during 0 to } t. \quad (6)$$

Since Ga, Ag, population, and Yg exhibit multiplicative relationships, the multiplicative form of the LMDI method is used to calculate the influence of changes in grain production and population on those in Ga (Equations (5) and (6)). Notably, population is introduced as reciprocal of Ga as it is inversely proportional to Ga.

3. Results

3.1. A Phase-Specific and Moderate Decline in Grain Plantation in China: Negative but Limited Impact on Domestic Grain Supply

Figure 2 showcases the temporal changes in Ag and Ga across China from 2003 to 2023. For Ag (Figure 2a), 2015 marks a turning point: Before 2015, Ag demonstrated a consistent upward trend, with an increase of nearly 40% compared to its value in 2003. Subsequently, Ag underwent a phased decline over four years. It began to rebound in 2019 and returned to the 2018 level by 2021. Therefore, the annual changes in the absolute value of Ag imply that the time spans from 2015 to 2019 and from 2021 to 2022 are the phases when a grain plantation decline occurred. Nevertheless, the outcomes of the M-K test support that Ag maintained an increasing trend without reversal, that is, the declines observed between 2015 and 2019 and 2021 and 2022 were normal fluctuations.

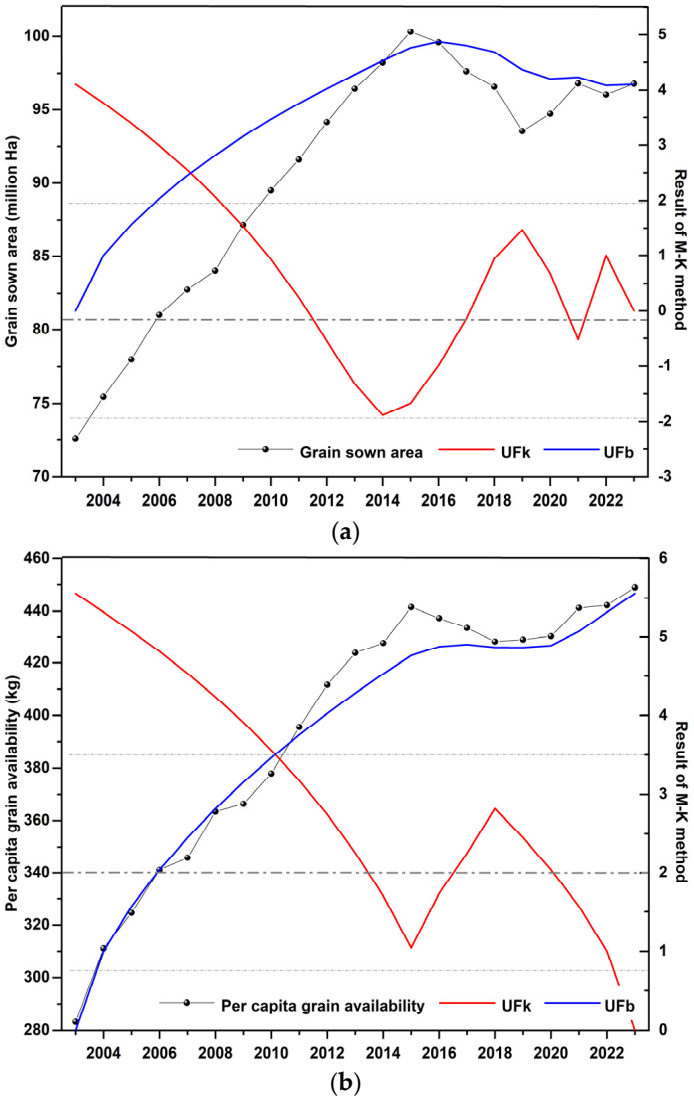


Figure 2. The temporal changes in total sown area and annual availability per capita of grain (rice, maize, and wheat), and the results of the Mann-Kendall (M-K) test during 2003–2023. (**a**) Grain sown area (Ag). (**b**) Per capita availability of grains (Ga).

The M-K method presents a similar but more moderate trend for Ga, which is presented in Figure 2b. From 2015 to 2019, Ga dropped from 441.49 kg in 2015 to approximately 428 kg (specifically, 428.15 kg in 2018 and 428.95 kg in 2019), with annual change rates ranging between −1.24% and 0.19%. That is, the population flow or crop yield had a more positive

impact on Ga during the years with a decline in the grain sown area. This phenomenon was particularly pronounced between 2021 and 2022. Rather than declining in tandem with Ag, Ga rebounded and exceeded the historical high recorded in 2015.

The LMDI method further clarified the contributions of each factor to Ga's annual variation during years with a decline in Ag (Table 1): Ag served as the primary negative factor propelling the changes in Ga, while population growth continuously imposed a negative influence on Ga as well. However, these effects were largely offset by the increases in Yg. From 2015 to 2019, Yg was the only factor contributing to Ga, and it even registered increases during the periods of 2018–2019 and 2020–2021.

Table 1. Annual variation in Ga and contributions of Ag, population, and Yg.

Period	Annual Variation of Ga (Ga, %)	Contributions (%)		
		Grain Sown Area (Ag)	Population	Yield of Grains Per Unit (Yg)
2015–2016	−0.94	−0.73	−0.65	0.43
2016–2017	−0.87	−1.98	−0.55	1.67
2017–2018	−1.24	−1.06	−0.38	0.20
2018–2019	0.19	−3.21	−0.35	3.76
2021–2022	0.23	−0.80	0.06	0.98

3.2. Continuous Retreat of Grains in 2/5 Provinces: The Rich Get Richer, While the Poor Get Poorer

As the M-K test indicates, the decrease in grain plantation is not a nationwide but a regional phenomenon, occurring at the provincial level. There are 12 provinces (i.e., Beijing, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Shaanxi, and Ningxia) that either maintained a declining trend or exhibited a trend shift in Ag during the study period (Figure 3).

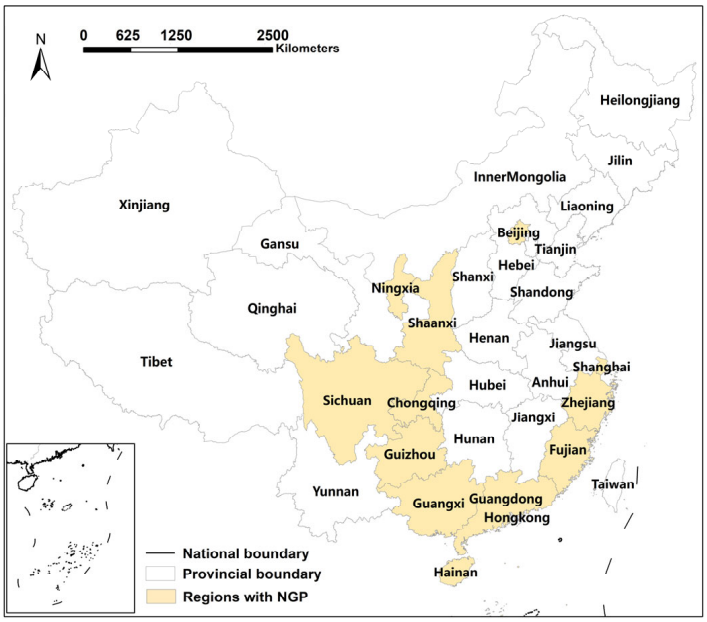


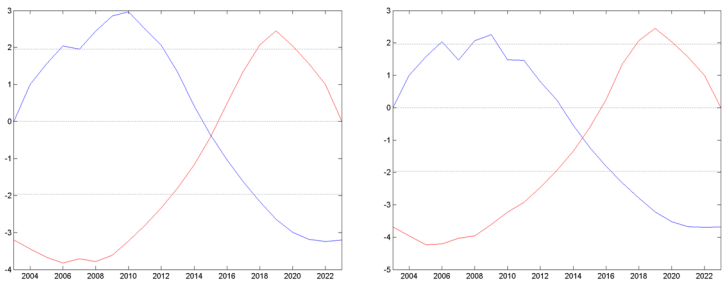
Figure 3. Provinces with grain plantation decreases.

Figure 4 presents the M-K test results regarding Ag in these 12 provinces. Among them, Guizhou stands out, as its Ag values underwent multiple substantial trend changes (2004–2005, 2008–2009, and 2018–2019). Specifically, its Ag experienced a brief decline

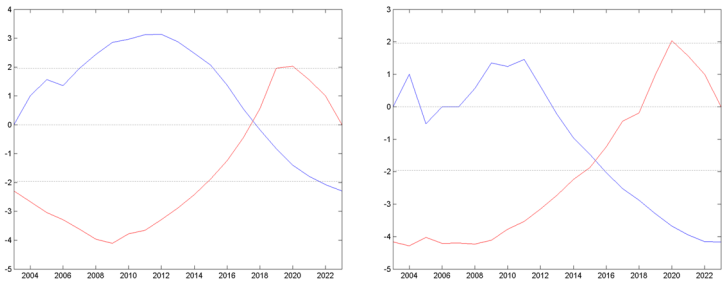
around 2005, followed by a rebound. Then it reached its peak in 2014, amounting to 1938 thousand hectares. The upward trend persisted between 2017 and 2018. Subsequently, it witnessed a significant decline and stabilized at its lowest level, which was 1305 thousand hectares ±5% after 2019.

In the remaining 11 provinces, Ag either increased for a certain period followed by a decline or maintained a downward trend. Five of them, Beijing, Shanghai, Zhejiang, Guangdong, and Shaanxi, each exhibited one significant trend shift, in 2015, 2017–2018, 2008–2009, 2010–2011, and 2016–2017, respectively. Before their shifts, Ag in Beijing, Shanghai, and Shaanxi exhibited significant increases. Their respective peaks, amounting to 212 thousand hectares, 187 thousand hectares, and 2493 thousand hectares, occurred between 2009 and 2010. Their lowest values were recorded in the period from 2019 to 2020 at 42 thousand hectares, 113 thousand hectares, and 2235 thousand hectares, respectively. After 2020, there were mild recoveries. Yet, none of them reached the levels of 2016. In contrast, Zhejiang did not see a notable increase prior to the shift. Its highest value (1159 thousand hectares) was recorded in 2005, while its lowest value (748 thousand hectares) was in 2016. And there was a slight recovery after 2016. The other six regions, namely Fujian, Guangxi, Hainan, Sichuan, Chongqing, and Ningxia, did not display significant trend shifts. Among them, Fujian, Guangdong, Guangxi, Hainan, and Sichuan underwent fluctuations in the initial stage of the study period and then maintained a downward trend, which was similar to the situation in Zhejiang. Chongqing and Ningxia kept declining over the entire study period. For the majority of these provinces, the highest values were recorded in the early stage (before 2006), whereas the lowest values predominantly emerged after 2018 (Table 1).

Overall, Ag in NGP provinces ultimately experienced significant declines, and this trend had not reversed by the end of the study period. Even though annual data reveal that some provinces, like Beijing, Zhejiang, and Shanghai, had a slight recovery by the end of the study period, the Ag in these provinces remained at low levels and was far from reaching the levels of 2003.

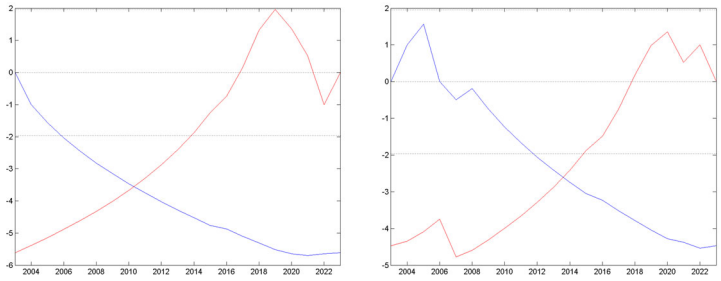


(**a**) Beijing

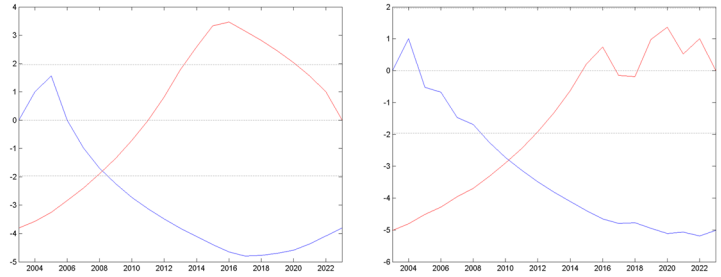


(**b**) Shanghai

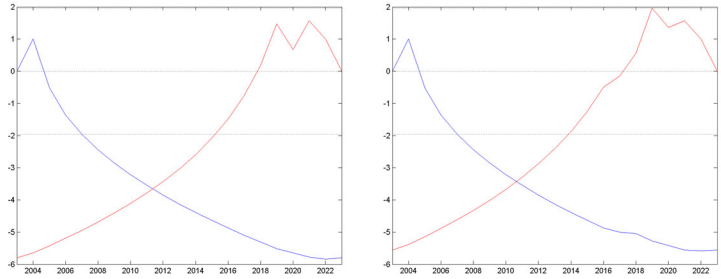
Figure 4. *Cont.*



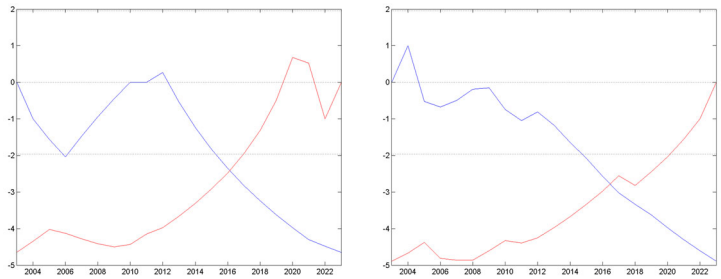
(**c**) Chongqing



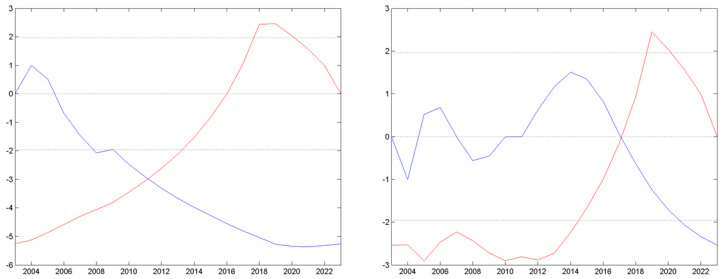
(**d**) Zhejiang



(**e**) Fujian

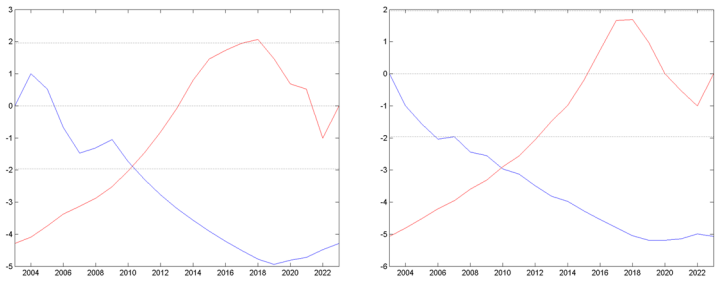


(**f**) Hainan

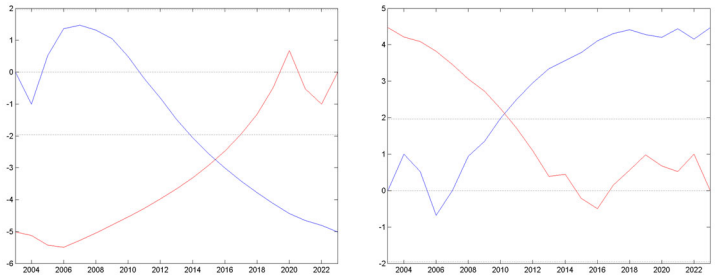


(**g**) Guangxi

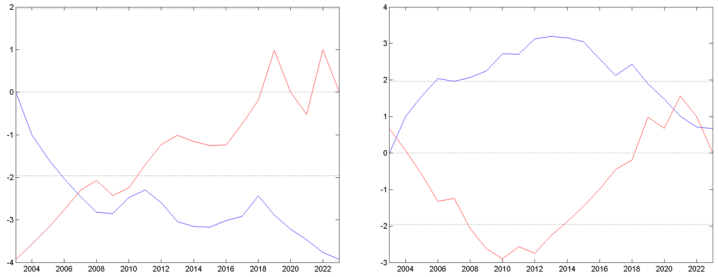
Figure 4. *Cont.*



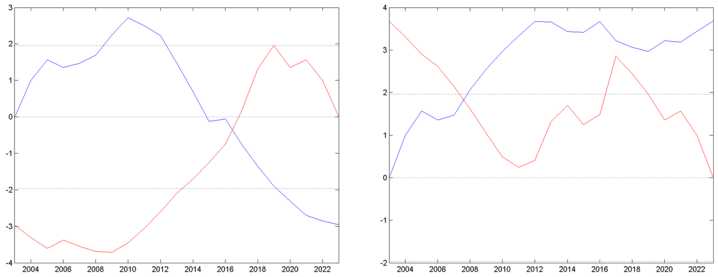
(**h**) Guangdong



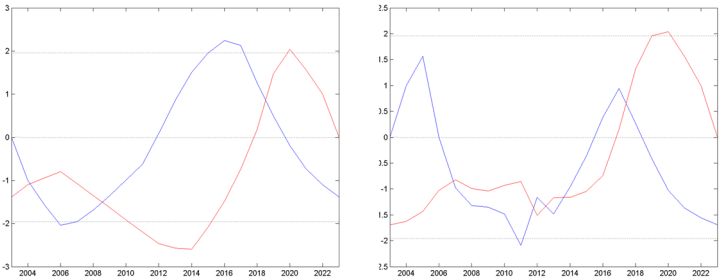
(**i**) Sichuan



(**j**) Ningxia



(**k**) Shaanxi



(**l**) Guizhou

Figure 4. Results of the Mann–Kendall (M-K) detection in provinces with a grain plantation decrease or fluctuation. (The left and right images in each subgraph present the M-K results for Ag and Ga, respectively. The blue line is UF_k and red line represents UF_b).

3.3. Provinces with Grain Plantation Decline Do Not Always Experience Intra Supply Shrinkage

The changes in Ga differ from those in Ag. Figure 4 presents the M-K results for Ga in the 12 target regions. Among them, both Guizhou and Ningxia saw multiple trend shifts in Ga, yet the timings differed: In Guizhou, the trend shifts were concentrated in the mid-stage of the study period, which indicated the substantial annual fluctuations in Ga. After the final trend shift that occurred between 2017 and 2018, the values of Ga stabilized within the range of 173–190 kg/(person* year), which was approximately 25–32% lower than the peak value recorded during the study period (253 kg/(person* year). In Ningxia, the trend shifts took place at the beginning and end of the study period, presenting an initial upswing and a subsequent decline in Ga. The peak value, amounting to 492 kg/(person* year), was recorded in 2012. Following a trend shift around 2020, Ga settled at approximately 450 kg/(person* year). Notably, the inverse trend between Ga and Ag indicated the dominant influence of population or Yg on Ga over the course of the study period.

Beijing, Shanghai, Guangxi, and Shaanxi each demonstrated a single trend shift in Ga, yet the specific patterns differed. The trend of Ga in Shaanxi ran counter to that of Ag, with the lowest value recorded in 2003, amounting to 230 kg/(person* year). Ga started to rise approximately in 2007–2008, and then maintained a stable level within the range of 270–290 kg/(person* year). In Beijing, Shanghai, and Guangxi, the trend shifts emerged in the periods of 2014–2015, 2015–2016, and 2017–2018, respectively, after which Ga continued to decline. The ultimate levels of Ga in Guangxi and Shaanxi were standing at around 250–270 kg/(person* year), but the highest values of Ga in Beijing and Shanghai were 68 kg/(person* year) and 57 kg/(person* year), respectively, with their lowest values accounting for only 19–42% and 63–72% of their peaks.

In the remaining six provinces, no trend shifts in Ga were observed. Among them, Sichuan witnessed a steady growth in Ga over the 20-year study period. Specifically, Ga increased by approximately 13%, rising from around 300 kg/(person* year) at the beginning of the study period to around 335 kg/(person* year) after 2021. In contrast, Zhejiang, Fujian, Guangdong, Hainan, and Chongqing exhibited a continuous decrease in Ga. Their highest Ga values all emerged between 2003 and 2005, and their lowest emerged after 2016. In the last few years, they sustained the lowest Ga levels at 82–85 kg/(person* year), 97–100 kg/(person* year), 88–92 kg/(person* year), 122–133 kg/(person* year), and 233–238 kg/(person* year), respectively.

3.4. The Contraction of Plantation Does Not Always Dominate the Variation in Grain Supply: A Battle with Sustained Crop Yield in Alliance with Population Influx

According to the timing of trend shifts of Ag and Ga, there are multiple stages of each province, with different primary factors affecting Ga (Table 2). In Sichuan, Shaanxi, and Ningxia, Ga kept rising even when Ag was on the decline, which suggested that Ag was not the key factor propelling the changes in Ga during the non-grain conversion period. Throughout the study period, the population in these three provinces continued to increase as well, indicating that Yg was the main factor driving the changes in Ga. What makes Shaanxi special is that even with non-grain conversion predominantly occurring after 2016, it still saw Ga increase mainly due to increasing Yg.

In Beijing and Shanghai, non-grain conversion mainly took place during the periods from 2014 to 2016 and 2015 to 2019, in which it played a dominant role in driving the changes in Ga. Before that, the concentrated population inflow was the primary factor for Ga changes. After that, the population reached a stable state, with Ag slightly increasing (though still below initial levels) and Yg declining.

Table 2. Sudden trend shifts in Ag and Ga, indicated by LMDI test.

Regions	Stages	Ga (%)	Contributions (%)		
			Ag	Population	Yield
Beijing	2003~2014	−18.95	−0.18	−36.03	17.26
	2014~2016	−18.77	−30.29	−0.99	12.51
	2016~2023	−11.43	1.29	0.39	−13.11
Shanghai	2003~2015	−8.52	19.14	−31.63	3.97
	2015~2019	−20.38	−30.36	−0.83	10.82
	2019~2023	5.05	7.35	−0.25	−2.05
Chongqing	2003~2023	−15.63	−28.27	−11.92	24.56
Zhejiang	2003~2008	−11.38	−12.61	−6.64	7.87
	2009~2023	−30.50	−11.16	−19.11	−0.23
Fujian	2003~2023	−36.02	−37.00	−14.33	15.31
Hainan	2003~2023	−33.38	−37.98	−20.68	25.27
Guangxi	2003~2016	−1.60	−16.99	0.00	15.39
	2017~2023	−1.06	−0.59	−2.40	1.93
Guangdong	2003~2010	−22.65	−8.71	−13.46	−0.48
	2011~2023	−13.54	−3.72	−15.51	5.68
Sichuan	2003~2023	15.04	−5.26	−2.49	22.79
Ningxia	2005~2023	14.44	−13.26	−24.48	52.18
Shaanxi	~2007	9.00	4.32	−1.02	5.70
	2008~2016	11.55	−0.13	−4.34	16.02
	2017~	7.33	−0.31	−1.27	8.91

Among the other provinces (except for Guizhou), only one trend shift took place, with both Ag and Ga fluctuating before declining or maintaining a downward trend. Though Ag exerted a substantial influence on Ga, population and Yg seemed to be more decisive in driving Ga changes. This is manifested in the diminishing disparity among the relative contributions of Ag, population, and Yg to Ga changes. In some regions or time spans (i.e., Zhejiang, Guangdong, Guangxi, and Hainan), Ag was no longer the dominant factor.

Guizhou stands out among the NGP provinces with frequent trend shifts (Figure 4). From 2004 to 2019, the trend shifts of Ag or Ga indicated significant year-to-year fluctuations. Figure 5 shows the calculated annual change rates of Ga and its influencing factors in the province, revealing that the fluctuations in Ga were mainly propelled by Yg. During the final trend shift (2017–2019), Ag witnessed a concentrated decrease and subsequently emerged as the dominant factor in Ga changes.

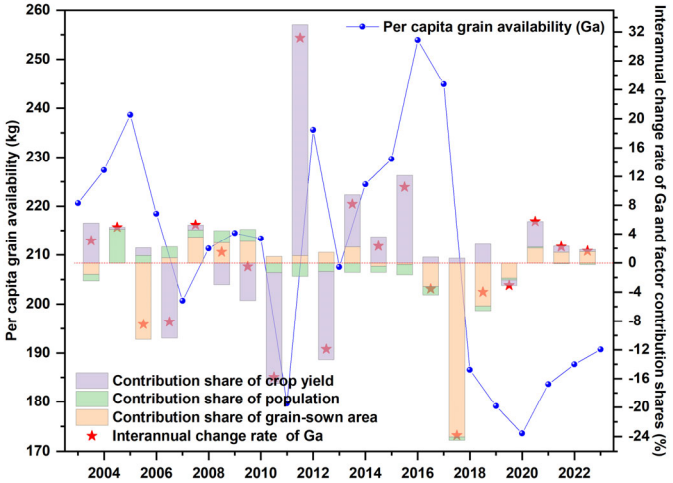


Figure 5. Interannual change rates and factor contribution shares from 2003 to 2023 in Guizhou.

4. Discussions and Conclusions

4.1. Conclusions

Based on the results, we propose the following three conclusions: First of all, amid the shrinkage of grain plantation areas, yield growth has played a prominent *compensatory role*. Considering the widely accepted threshold for food security (400 kg per capita) [42,45,58], and the high proportion of rice, maize, and wheat of China's total grain output (85–90%) [72–74], the safety benchmarks for these three grains are estimated to be 340 kg–360 kg per capita. With that, China reached the food security target around 2007 and has since then maintained sustained growth [20]. Since 2014, Ga has been stabilized at 435 kg ±15 kg. With a limited potential for substantial yield and population increases [75], we estimate that 15–20% of grain croplands could be reallocated in flexible ways, such as fallow rotation or diversified agricultural uses [76]. This could actually contribute to balancing the conservation and utilization of cultivated land, as well as the optimization of food supply, for two reasons: (1) Ecological imperative: decades of expansion and overuse of cropland have led to widespread degradation of soil quality and ecosystem [77–79]. (2) Dietary transition: since 2010, China has been less self-sufficient in oilseed, soybean, sugar, and dairy products, combined with less dietary dependence on grains as the primary calorie source [80,81]. These have made it necessary for agricultural production to be more diversified and focused on quality.

Secondly, the flexible surplus area indicates that when dealing with NGP, it is possible to use moderate approaches to strike a balance between economic interests and grain production, rather than to over-rely on expanding or restoring grain cultivation. For instance, Liu et al. and Qiu et al., based on historical land-use data, underline the importance of yield gap and cropping intensity in addressing NGP [43,46]. That is consistent with Shen's suggestion on enhancing the utilization of winter fallow fields [13]. Many regions have also continued to innovate with integrated farming, such as rice–fish and rice–crayfish co-culture modes, which have proven to be effective [82]. Furthermore, leveraging but not over-relying on the global food trade has long been acknowledged as an ideal option to improve the domestic food supply [83].

However, there are still red lines for local governments regarding the decrease in grain plantation and supply. Most of the provinces with grain retreat are intrinsically vulnerable in the national grain supply system. With the exception of Ningxia, Sichuan, and Shaanxi, the other nine provinces have all witnessed substantial declines in Ga. These provinces are predominantly spatially concentrated in the southeastern–southwestern regions. This spatial pattern discloses two crucial implications: (1) Since there are increases both in national grain sown area and production, the spatial cluster of NGP provinces in the southeastern–southern area has promoted the northward movement of the geographic center of the grain production of the whole country. (2) The combination of diminished local production and enlarged population within NGP regions has aggravated regional supply shortfalls, thereby making it imperative to intensify grain redistribution. This evolving production–marketing paradigm has resulted in higher circulation costs [55], over-concentrated vulnerability to natural disasters, rising pressure on other provinces to protect arable land, and even the potential for higher administrative tension between grain-producing and grain-consuming regions [84,85]. Therefore, ensuring a certain level of grain self-sufficiency remains vital to these provinces. But no consensus on that has been achieved among scholars or government officials. We propose to maintain the self-sufficiency of basic grain production in certain regions. For instance, it is advised to support Beijing by the Beijing–Tianjin–Hebei region, and Shanghai by the Yangtze River Delta. This approach will not over-burden NGP provinces in terms of the balance of provincial land use or the cost of grain transportation [86].

4.2. Future Issues

Based on the above conclusions, how to implement fallowing will be an important issue, which involves three aspects: quantity, space, and order. Among these, quantity and space have been widely discussed by technical indicators, such as food supply and demand, and the state of cultivated land [87,88]. But to make fallowing work, it is still necessary to coordinate policies [89]. The northwest, north, and southeast coastal areas are in urgent need of fallowing due to ecological pressure or excessive development [76]. Considering the insufficient and continuously declining grain plantation and production in the southeastern coastal areas, fallowing in these areas will surely involve grain transportation, which will then affect other provinces in their cropland use. Meanwhile, the decrease in cropping intensity in double-cropping regions has led to recessive grain retreat, which is particularly evident in the provinces without extra grains, including the southern NGP provinces [90]. Therefore, more attention should be paid to the balance between seasonal and annual fallowing, producing and consuming areas, and fallowing and grain planting recovery, especially in the southern NGP provinces.

Going ahead, we believe that the guiding role of population mobility in food allocation should be included as a key issue in the design of cropland policy. On one hand, numerous studies have confirmed and quantified that the expansion of cultivated land and increase in grain production mainly occurred in Northeast and Northwest China, and have led to a persistent northward shift of the geographical distribution center of grain production over the past few decades [43,91,92], but the role of shrinking grain planting areas in this process has received little attention. On the other hand, China's total population stabilized, and a polarized migration trend at the county level began to emerge around 2020, which is expected to intensify in the coming years [93,94]. The coexistence of cropland–abandonment and urban–agricultural spatial conflicts has arisen [95]. These suggest that the impact of grain planting and population dynamics on food supply may become more complex, along with spatial agglomeration patterns different from those observed over the past two decades, potentially leading to more drastic shifts in food allocation and land use.

4.3. Comparisons and Limitations

By using time-series sown area and trend tracing methods, a new approach is explored for identifying the retreat of grain plantation, which has two key advantages: (1) The results are comparable among regions and time spans as it minimizes the impact of normal fluctuations in variables by detecting trend changes. (2) The results are more practical as the approach facilitates the observation of the actual impacts of grain cultivation area decline within the framework of food supply security. Our results differ from similar studies in two ways: The reduction in grain plantation is understood as a regional phenomenon, mainly occurring in 12 provinces, including Beijing, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, Sichuan, Ningxia, Chongqing, Guizhou, Hainan, and Shaanxi. It more accurately identifies the NGP regions targeted by China's land-use policies, which is in line with the recent findings of Tan et al. [96]. Furthermore, this research is the first to explicitly quantify the impacts of the declining grain cultivation area on the food supply in relation to population migration and yield efficiency increases. It fills the gaps in NGP studies, thereby facilitating the formulation of policies aimed at multi-objective optimization.

However, we acknowledge that this study still has some limitations. The major one is the ignorance about the differences in regional output and demand for various grains. Statistics show that there are still significant gaps in crop yield among provinces despite the widespread and continuous increases in each crop over the past 40 years. During the study period, the average yield efficiency of rice, maize, or wheat in the lowest-producing provinces was only about 50–60% of the highest, with southern regions

generally outperforming northern ones [97]. As the identified NGP regions in this study are concentrated in the south, this limitation may have overestimated the negative impacts of NGP on the grain supply in these provinces. Moreover, the neglect of the caloric supply capacity of various foods and regional variations in grain consumption may introduce bias as well. Research shows that due to adjustments in dietary structure, the calories provided by grains have significantly decreased compared to a decade ago. The increasing intake of sugars, vegetables, and fruits has greatly compensated for the calories lost from grains in some provinces [98].

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