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A New Indicator for Global Food Security Assessment: Harvested Area Rather Than Cropland Area

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Abstract: Cropland area has long been used as a key indicator of food security. However, grain yield is not solely controlled by the area of the cropland. Therefore, we proposed a new indicator to assess food security. Results show that from 1992 to 2004, the global cropland area increased by 840 200 km^2 (99.4%), but the grain yield increased only by 310 million t (29.1%); and from 2004 to 2015, the cropland area decreased by 39 000 km^2 (4.64%), but the grain yield increased by 370 million t (70.84%). This result showed that grain yield was not linearly correlated with cropland area, and delimiting the threshold of cropland protection may not guarantee food security. Combined with further correlation analysis, we found that the increase in the global grain yield was more closely related to the harvested area (R^2 = 0.94), which indicated that the harvested area is a more scientific and accurate indicator than cropland area in terms of guaranteeing food security. Therefore, if governments want to ensure the food security, they should choose a new and more accurate indicator: harvested area rather than cropland area.

Keywords: global change; food security; harvested area; cropland area; grain yield

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1 Introduction

Cropland accounts for 20% of the Earth's surface area, and it is an important material basis for human production and life (Zabel et al., 2019). The population has been steadily increasing, before 2015, however, and the diet structure of humans also has changed. Thus, the global demand for grain has been increasing (Long et al., 2015; Wu et al., 2018). According to the data from the United Nations Food and Agriculture Organization (FAO), the number of people globally suffering from food shortages has continued to increase, and 690 million people are in a state of hunger (Stehfest et al., 2019; Hu Y C et al., 2020). The incidence of global food

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shortages continues to be increasing, which has imposed great pressure on the agricultural ecosystem. Various countries have begun to formulate a series of policies to protect the cropland area.

Economically developed countries and backward countries have adopted completely different ways to increase food production (Yu et al., 2019; Zhang et al, 2021a). For example, cutting down forests and reclaimed grasslands or increasing the sown area of grain to expand the cropland area to obtain more food and meat (Petersen, 2015; Sannigrahi et al., 2018; Li et al., 2021). This approach, however, often leads to soil erosion and desertification and gradually damages the ecological environment. (Ray et al., 2012; Petersen, 2015). In addition, the urbanization in these countries is occupying increasingly high-quality cropland (Sannigrahi et al., 2018; Liu et al., 2020). For the sake of protecting food security, under the background of a reduction in the cropland area, the grain yield can be increased by increasing the harvested area. To achieve this goal, we can use a variety of agricultural management practices, including the efficient use of multiple crops, varieties, fertilizers, irrigation, pesticides, mechanization, and other practices (Minoli et al., 2019; Bajwa et al., 2020). Some of these methods have improved grain yield in some decades (Jägermeyr et al., 2017).

Yu et al. (2019) reported that the relationship between the change in the cropland area and the change in the grain yield is nonlinear, and they estimated the grain production potential at the national level as well as changes in the cropland area. Wu et al. (2018) used a spatially explicit method to quantify the global cropland planting intensity gap (the difference between the potential planting intensity and the actual planting intensity) and proposed that increasing the planting intensity without expanding the cropland area may improve grain yield. Hu Q et al. (2020) identified nine coupling modes of global cropland expansion and intensification based on the global and 30 dataset, quantified the contribution rate to the global food production, and provided strategies for cropland protection and food security on different continents and in different countries.

The ability to identify which strategy is best for improving grain yield is a problem that has been debated for many years. It seems impossible, however, to further expand the cropland area through human activities in the future because cropland area is closely related to biodiversity protection and greenhouse gas emission reductions (Byerlee et al., 2014; Qiu et al., 2020). Thus, it is necessary to assess the consequences of the different production strategies to accurately understand the relationship between global cropland expansion, cropland intensification, and the grain yield (Foley et al., 2011; McNider et al., 2015).

Global land cover products can provide the spatial range of the global cropland area, with spatial resolutions of 300 m to 1 km (Cunningham et al., 2013; Gong et al., 2020). Remote sensing data with high spatial resolution and time information can more accurately estimate and analyze global farmland expansion (Chen et al., 2020; Hu Q et al., 2020). For agricultural intensification, previous studies on the harvested area mainly have focused on the regional scale, and less research has been conducted on the spatial pattern characteristics of the grain harvest area on the global scale (Sakamoto et al., 2005; Gaso et al., 2019).

Understanding how to feed a global population of several billion when the quality and area of the cropland have been decreasing poses a significant challenge. Therefore, a relevant indicator must be drawn up to ensure the food security of each country. We combine high-resolution land use data and grain-related data from 1992 to 2015 to explore the reasons for changes in global grain yield, and at the same time propose a new indicator to assess food security. The purpose of this study was to answer the following questions: 1) What were the temporal and spatial patterns of the global cropland area and grain yield? 2) Which strategy and indicator should we use to ensure food security in the future?

2 Material and Methods

2.1 Data and processing

2.1.1 Land use and land cover data

We obtained global land use and land cover (LULC) data from 1992 to 2015 from the European Space Agency (ESA), with a spatial resolution of 300 m. The latest reprocessing of five global satellite systems was obtained, including NOAA-AVHRR, ENVISAT Advanced Synthetic Aperture Radar (ASAR), SPOT vegetation, and the PROBA-V and MERIS Full Resolution (FR) and Reduced Resolution (RR). This dataset, which has been available online since April 2017, remains one of the most complex global land cover products because of its refined spatial resolution (300 m) and temporal availability (Chen et al., 2019). Efforts were made in this study to assess the consistency of the product with the noted products to minimize the uncertainty in the estimation of the change in the cropland area (Keys, 2005). We used the kappa coefficient, contingency matrix, user error, producer accuracy, overall accuracy, and building procedures to reduce the macro errors to evaluate the statistical accuracy (Wang et al., 2021). Finally, through comparison with other effective validation products, we evaluated the time consistency of the data (See et al., 2015).

2.1.2 LULC classification

The latest global LULC classification divides surface objects into seven categories: cropland, forestland, grassland, wetland, urban construction land, unused land and water bodies. Cropland refers to land where crops are planted, including cropland, newly developed, reclaimed and arranged land, and leisure land (such as rotation land and rotation land). The land is planted mainly with crops (including vegetables), with sporadic fruit trees, mulberry trees, or other trees. Cultivated beaches and sea beaches that can ensure a harvest for one season on average every year also have been considered to be cropland (Portmann et al., 2010).

2.1.3 Grain yield data

We extracted data for the global grain yield and the grain yields of 30 countries with large cropland areas from 1992 to 2015 from the Food and Agriculture Organization Corporate Statistical Database (FAOSTAT) (Tscharntke et al., 2012) to facilitate international comparison and data collection. We selected 14 types of grain as the research object, including wheat, rice, maize, sorghum, barley, buckwheat, rye, fonio, oats, canary seed, millet, quinoa, triticale, cereals, and nes (Agnolucci et al., 2020). We analyzed the relationship between the grain yield and the cropland area from 1992 to 2015 by taking the total grain yield, the grain harvest area, and the grain yield per unit area as the research objects.

$$Y_i = \frac{F_i}{C_i} \tag{1}$$

where Y_i is the yield of year i, F_i is the crop yield acquired from the FAO of year i, and C_i is the cropland area estimated from the European Space Agency's Land Cover Classification System (ESA-LCCS) dataset of year i.

2.2 Methods

2.2.1 Cropland changes

Based on the ESA data, we calculated the cropland area in each year from 1992 to 2015. The Manner-Kendall (M-K) non-parametric test method has been used to study historical and future evolution trends in precipitation, temperature, the gross domestic product (GDP), population, and other factors around the world. In this study, we used the M-K method to calculate the turning point year of the change in the cropland area. The formulas used are as follows:

$$S = \sum_{q=1}^{m-1} \sum_{p=q+1}^{m} \operatorname{sgn}\left(X_p - X_q\right) \tag{2}$$

$$\operatorname{sgn}\left(x_p - x_q\right) = \begin{Bmatrix} +1 & \left(X_p - X_q\right) > 0 \\ 0 & \left(X_p - X_q\right) = 0 \\ -1 & \left(X_p - X_q\right) < 0 \end{Bmatrix} \tag{3}$$

where S is a normal distribution with a mean of 0 and represents the test statistics, and m is the number of samples. For different values of q (i.e., $p \leq m$, $q \neq p$), the distributions of X_p and X_q are different. When the absolute value is greater than 1.28, 1.64, and 2.32, they pass the significance test at the 90%, 95%, and 99% confidence levels, respectively. The trends with $P \leq 0.1$ are statistically significant in this study (Luo et al., 2022).

The year 2004 was the turning point of the change in the global cropland area. We calculated the annual average rate of change of the cropland area (R) before and after 2004 and 2012. The same method was also used in China, India, and the United States:

$$R = \frac{C_i - C_j}{i - j} \tag{4}$$

where R is the rate of change of the global or country's cropland area, i and j represent the year series, and C_i and C_j represent the cropland area in years i and j, respectively.

2.2.2 Correlation calculations

We extracted the cropland area data for 229 countries around the world from remote sensing images and selected the 30 countries with the largest average cropland areas during the study period. These countries dominated the trends of the global cropland area and grain yield. We used histograms to show the grain yields and harvested areas in the 30 major food-producing countries on the map of the global cropland area distribution to better describe the response of the grain yield to the changes in the global cropland area and the cropland intensification (Wu et al., 2020).

We calculated the correlation coefficients to quantitatively describe the response of the grain yield to the changes in the cropland area and harvested area to determine their contributions to the global grain yield (Wu et al., 2020). The correlation was calculated as follows:

$$Q = \frac{\sum_{i=1}^{n} M_i t_i - \frac{1}{n}\sum_{i=1}^{n} M_i \sum_{i=1}^{n} t_i}{\sum_{i=1}^{n} t_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)^2} \tag{5}$$

where Q is the expected value of the linear trend; and n is the study period from 1992 to 2015. M_i is the independent variable corresponding in year i. If the correlation coefficient of the regression equation passed the significance test at the 0.05 and 0.01 confidence levels ($P < 0.05$ and $P < 0.01$), the small probability event occurred, and M_i decreased or increased to significant and highly significant levels, respectively.

$$R^2 = \frac{\mathrm{Cov}(x,y)^2}{\mathrm{Var}(x) \times \mathrm{Var}(y)} \tag{6}$$

where Cov is the covariance and Var is the variance; R^2 ranges from 0 to 1; x is the change in the cropland area or harvested area; and y is the grain yield between 1992 and 2015. Focusing on the results of the calculations, if the value of R^2 is closer to 1, the correlation between the cropland area or the harvested area and the grain yield is stronger.

3 Results

3.1 Distribution and changes of global cropland

The global cropland area in 2015 was 29.78 million km^2, accounting for about 20% of the Earth's land surface according to the data from the European Space Agency's Climate Change Initiative (ESA-CCI) product, with a 300 m resolution, from 1992 to 2015. For the continents, Asia, Europe, Africa, North America, South America, and Oceania accounted for 39%, 18.3%, 16.2%, 12.5%, 11.6%, and 2.4% of the global cropland area, respectively. Asia and Europe contributed the most, accounting for 57.3% of the total cropland area. The global cropland area was mainly distributed in the Amazon Basin, the European Plain, the edge of the Sahara Desert, India, the United States, and southeastern China (Fig. 1). This study shows that the average growth of the global cropland area was derived mainly from conversion of forests (57.5%), grassland (38.3%), and unused land (2.5%) into cropland (Fig. 2). The top five ranked countries were China, Russia, America, India, and Brazil, which had cropland areas of 315.6 million km^2, 293.1 million km^2, 233.9 million km^2, 222.3 million km^2,

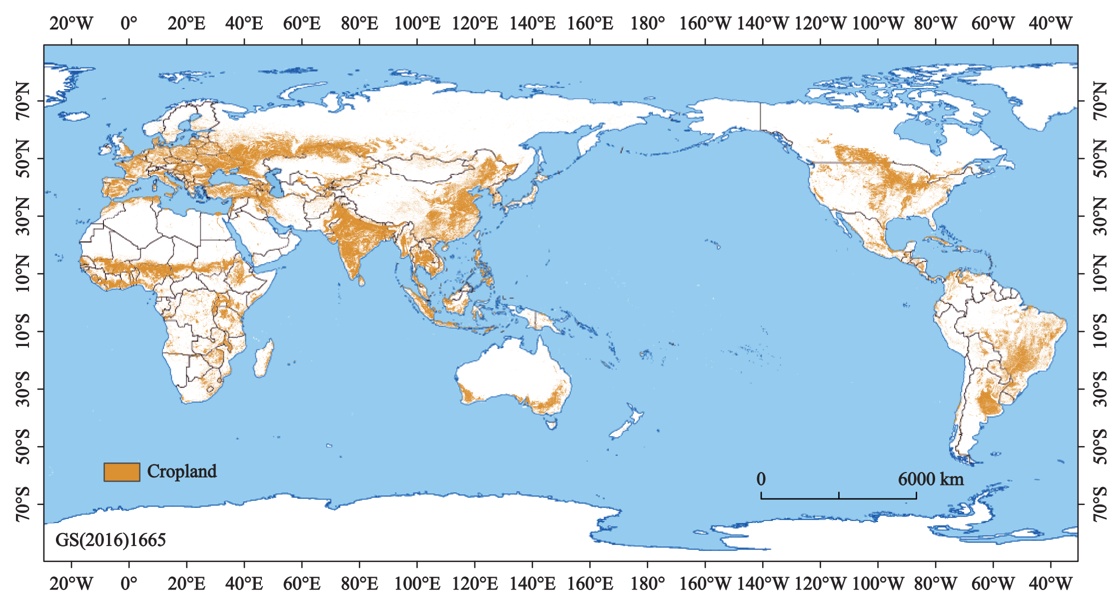

Fig. 1 Distribution of the global cropland in 2015

and 208.9 million km^2, respectively. In general, the cropland area of these five countries accounted for 42.8% of the global cropland area.

According to the cropland data and using the M-K non-parametric test method, we found that the turning year of the cropland area was 2004, and the global cropland area exhibited a three-stage change. It increased by 840 000 km^2 from 1992 to 2004, representing a significant average expansion rate of 70 014.8 km^2/yr. During 2004 to 2012, however, the growth was very slow, with an average annual growth rate of 5500 km^2, and it increased by only 44 000 km^2. The growth rate during 1992–2004 was 13 times faster than that during 2004. After 2012, the cropland area began to decrease at an annual average rate of 13 000 km^2, which was 2.4 times greater than in the previous period. In general, before 2012, the global cropland area initially increased and then began to decrease (Fig. 3a).

Approximately 57.3% of the cropland area was located in Asia and Europe. The increase in the cropland area in Asia was the largest (344 309 km^2), whereas the cropland area in Europe continued to decrease (5336 km^2/yr) (Fig. 3b). Africa's cropland area has increased rapidly over the past few decades (15 000 km^2/yr). We found that the cropland area in North America, South America, and Australia increased first and then increased slowly or decrease, among them, North America has the fastest rate of decline. (Fig. 4). The change in the cropland area on each continent was primarily driven by the development of the large countries (e.g., China and India in Asia and the United States in North America). The increase in the cropland area accelerated in Brazil, Kazakhstan, a few countries in Africa, and other developing countries, but it decelerated in some developed countries, including the United States, FranceIran, Germany and other European countries (Fig. 5)

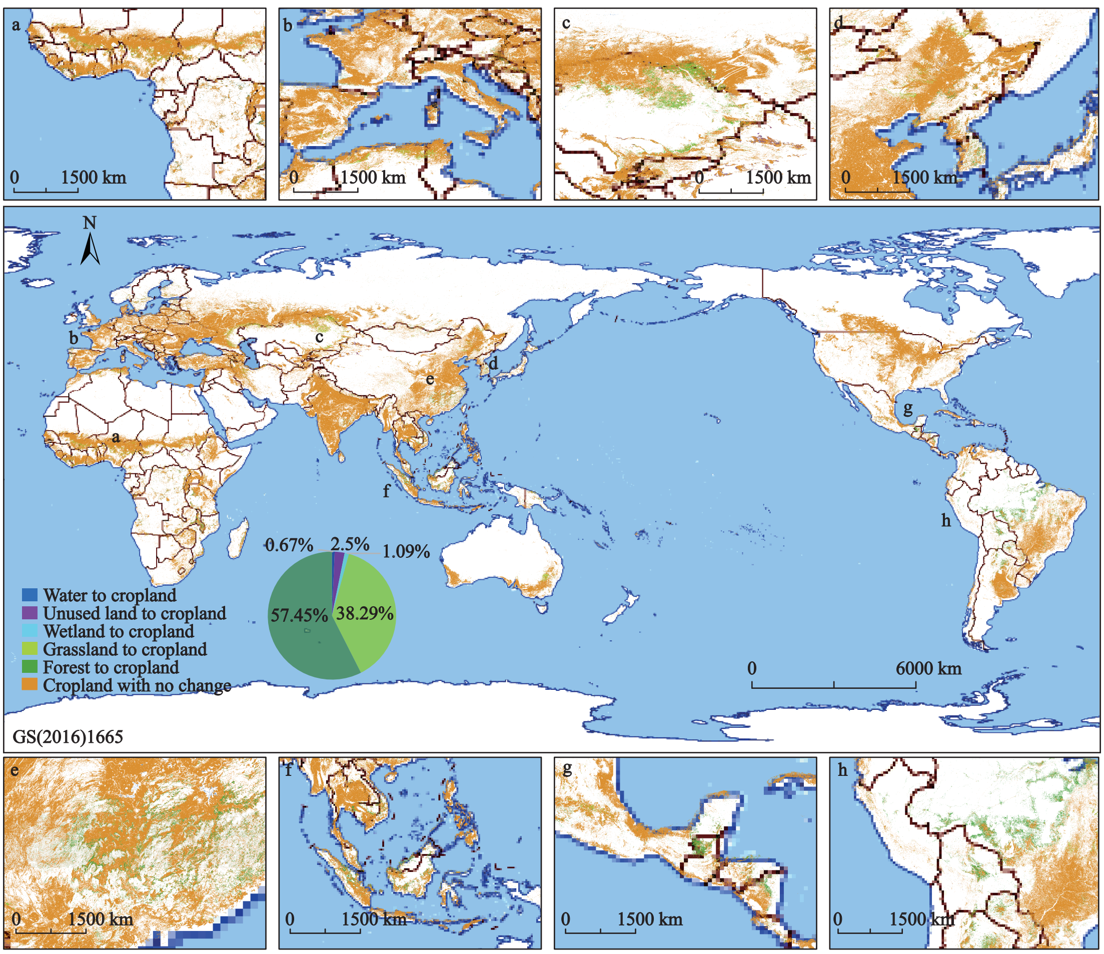

Fig. 2 The transformation of other land types to cropland between 1992 and 2015. Areas with larger cropland changes in (a) Africa, (b) Europe, (c) Central Asia, (d, e) East Asia, (f) Southeast Asia, (g) North America and (h) South America

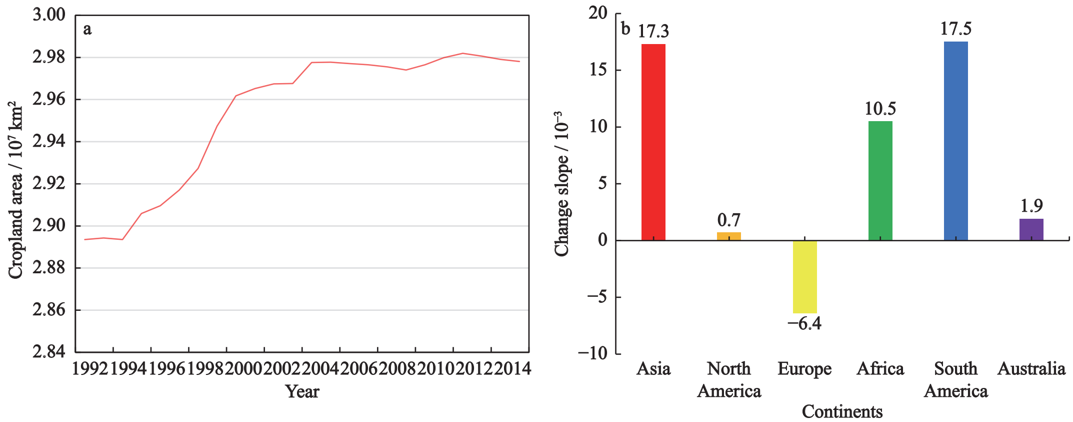

Fig. 3 Dynamic changes of (a) global cropland area and (b) growth rate of each continents from 1992 to 2015

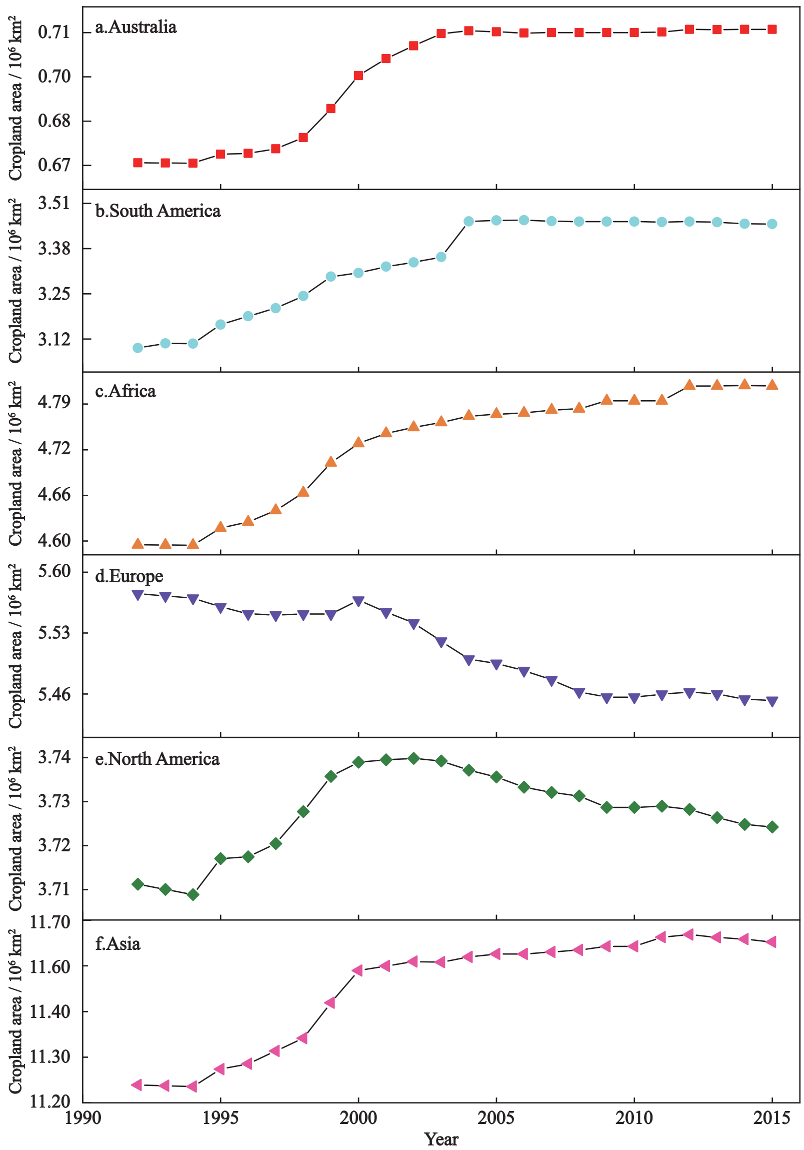

Fig. 4 Changes of cropland area in different continents from 1992 to 2015

(Hu Q et al., 2020). Moreover, we found that the growth rate of the cropland (2.92%) has been considerably lower than the growth rate of the global population (34.6%) over the past few decades, suggesting that the decline in the cropland area has made it difficult to supply enough food for the rapidly growing population (Van Vliet, 2017). This unbalanced relationship between cropland area and population growth has become more pronounced in developing regions (e.g., China and India) (Petersen, 2015). Thus, we should make full use of the cropland area to improve the grain yield.

3.2 Changes in global grain yield and major food producing countries

In 2015, the global grain yield was 3.47 billion t, and the countries with higher grain yields were distributed mainly in Asia, North America, and South America. Among them, China, Russia, the United States, India, and Brazil had grain yields of 620 million t, 103 million t, 430 million t, 280 million t, and 110 million t, respectively. China, the United States, and India contributed the most, accounting for 38.6% of the world's grain yield from only 26% of the global cropland. China was particularly prominent, contributing 18% of the global grain yield from only 10.6% of the global cropland area. India contributed 8.2% of the world's grain yield from only 7.5% of the global cropland, and the United States contributed 12.5% of the grain yield from 7.9% of the global cropland. Among the three major food-producing countries, China's contribution rate was far greater

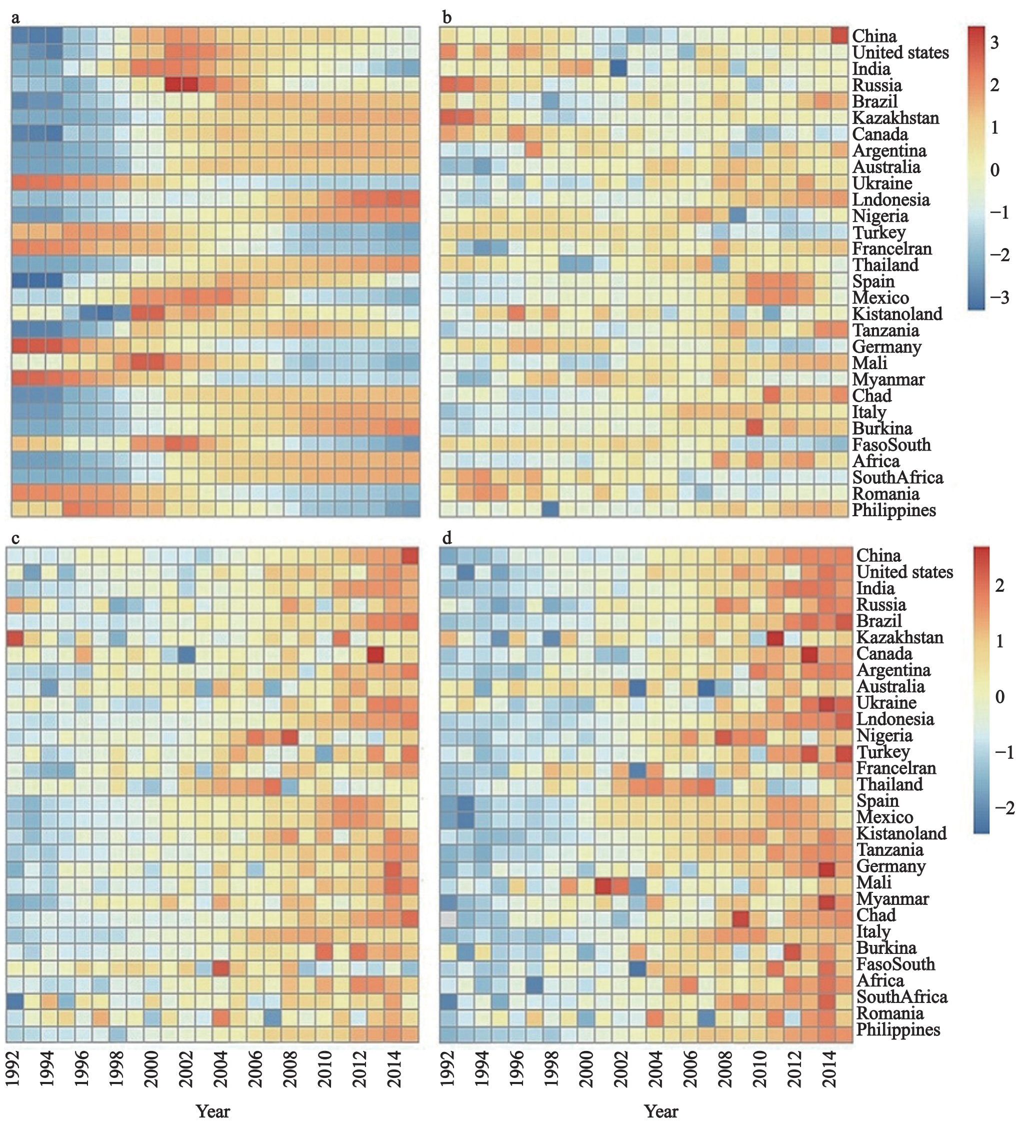

Fig. 5 Spatial map of grain yield and harvested area of the 30 major food producing countries in 2015

than that of the United States and India (Fig. 6).

The yield per unit area is an important factor of the grain yield. From 1992 to 2015, the global grain yield per unit area increased from 29 700 to 41 700 kg/km^2, representing a net increase of 40% and an average annual growth rate of 5 t/km^2 (i.e., a rapid growth rate). The global grain yield increased by 1.1 billion t at an annual average rate of 46 million t. In addition, we found that the growth rate of the grain yield was significantly different before and after 2004 and was contrary to the growth trend of the cropland area whether in major food producing countries or on a global scale (Fig. 5, Fig. 7). For example, the global cropland area increased by 840 000 km^2 before 2004, and the global grain yield increased by only 320 million t. The cropland area decreased by 39 000 km^2 at an annual average rate of 13 000 km^2 after 2012, but the grain yield increased by 370 million t (Fig. 7). The changes in the cropland area and the grain yield were not consistent and synchronous. There was, however, a good linear relationship between the harvested area and the grain yield, especially after 2004.

3.3 Correlation between grain yield and cropland and harvested area

The rapid decrease in the global grain harvest area before 2004 may have affected the growth rate of the grain yield. Therefore, we fitted and analyzed the correlations between the global cropland area and grain yield, and between global harvested area and grain yield after 2004. We found that these correlations had R^2 values of 0.23 and 0.94, respectively (Fig. 8). The data showed that the fitting degree between the grain yield and the harvested area was much higher than that between the grain yield and the cropland area, suggesting that the impact of the harvested area on the grain yield was much greater. For example, the global harvested area decreased before 2004, resulting in the slow growth of the grain yield, with an average annual growth rate of only 27 million t. After 2004, the harvested area increased by 7720 km^2 with a fast growth rate and the global grain yield increased rapidly, with an average annual growth rate of 71 million t, which was 2.6 times that during the previous period (1992–2004) (Fig. 7).

China, the United States, and India are the world's largest food-producing countries, and their grain yields have accounted for a large proportion of the global grain yield over the years. We found that the cropland area of these three countries all reached the maximum values before 2004 and then decreased rapidly. Their grain yields increased rapidly after 2004, however. For example, after 2004, China's cropland area decreased by 21 000 km^2, but its total grain yield increased by 216 million t; the cropland area of the United States decreased by 11 000 km^2, but its total grain yield increased by 42.9 million t; and India's cropland area decreased by 11 000 km^2 with an average annual rate of decrease of 1031.8 km^2, but its total grain yield in-

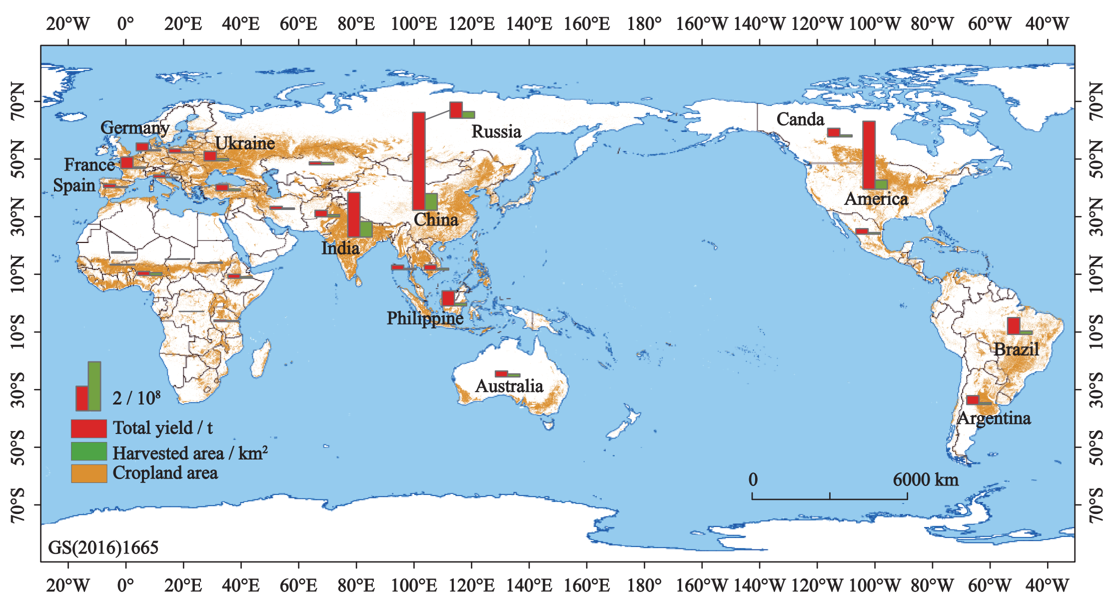

Fig. 6 Global changes of cropland and major global food indicators from 1992 to 2015

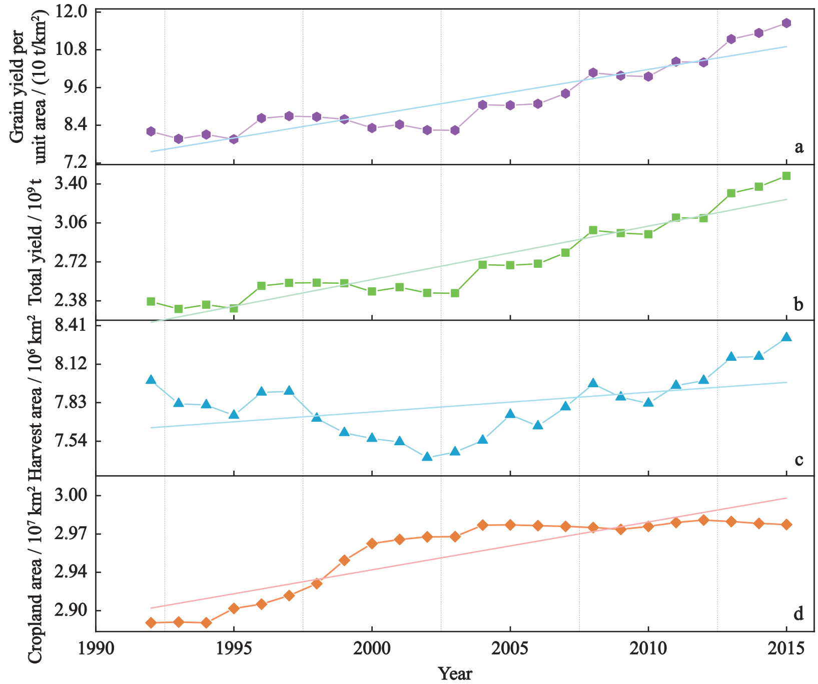

Fig. 7 Changes of (a) cropland area, (b) harvest area, (c) grain yield and (d) yield per unit area in 30 countries from 1992 to 2015

creased by 54 500 million t (Fig. 9).

To further understand the importance of the grain harvest area to the grain yield, we studied the relationships between the cropland area, harvested area, and grain yield in China, India, and the United States after 2004. The results of the fitting analysis revealed that the grain yield and the cropland area were significantly negatively correlated in China, the United States, and India, but the grain yield was positively correlated with the harvested area. Moreover, the fitting degree of the correlation between the harvested area and the grain yield in China was close to 1 (R^2 = 0.97), which indicated that the harvested area greatly affected the grain yield (Fig. 10).

In contrast, whether on a global scale or among the three major food producing countries, the decrease in the cropland area did not lead to a decrease in the grain yield. Thus, further emphasizing and protecting only the cropland area may not guarantee food security, and the harvested area is a new and more scientific indicator than the cropland area to evaluate food security.

4 Discussion

4.1 Reasons for the change of global cropland area

The global cropland area expanded rapidly before 2004. During this period, the level of scientific and technological development was slow, and the rapid growth of the population required the conversion of a great deal of land into cropland to improve the grain yield and to maintain basic production and living standards (Lambin et al., 2013; Meyfroidt et al., 2013). Before 2004, however, the growth of the global grain yield was very slow, and the expansion of cropland did not drive the rapid growth of the grain yield. One reason for this is that the harvested area in the developed countries continued to decrease and the growth rate of the grain yield in the developing countries slowed down (Hubbard, 2013). In terms of the planting structure, with the continuous adjustment of agricultural planting methods in various countries, during this period of cropland utilization, the cropland area used to produce oil, cotton, sugar, hemp, and other non-grain crops increased, whereas the cropland area used for grain yield decreased (Fig. 11), the average yield of non-grain crops was three times that of grain crops (Phalke et al., 2020; Zhang et al., 2021b).

After 2004, global urbanization accelerated, occupying most of the high-quality cropland. Because of the influences of urban expansion and ecological restoration policies (such as China's policy of returning farmland to forest and grassland), the cropland area began to gradually decrease (Schneider, 2012; Han et al., 2020). The changes in the cropland area in Europe and Africa ex-

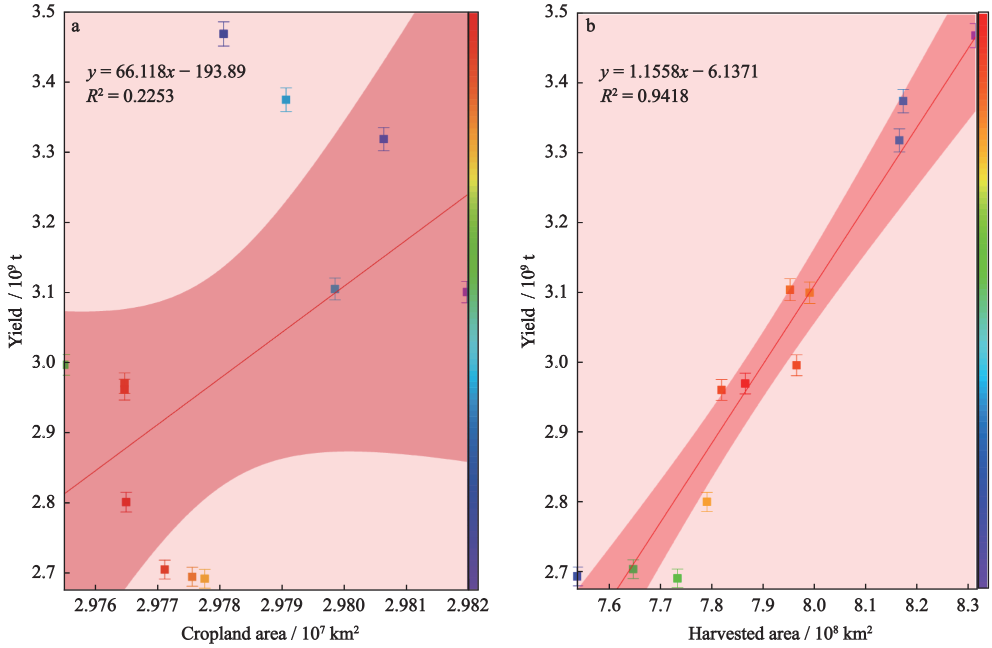

Fig. 8 Fitting analysis chart of global yield with cropland area (a) and harvest area (b). Slope < 0 (> 0), indicating that the two independent variables are negatively (positively) correlated, the width of red shadow represents the value of R^2 and the correlation between independent variable

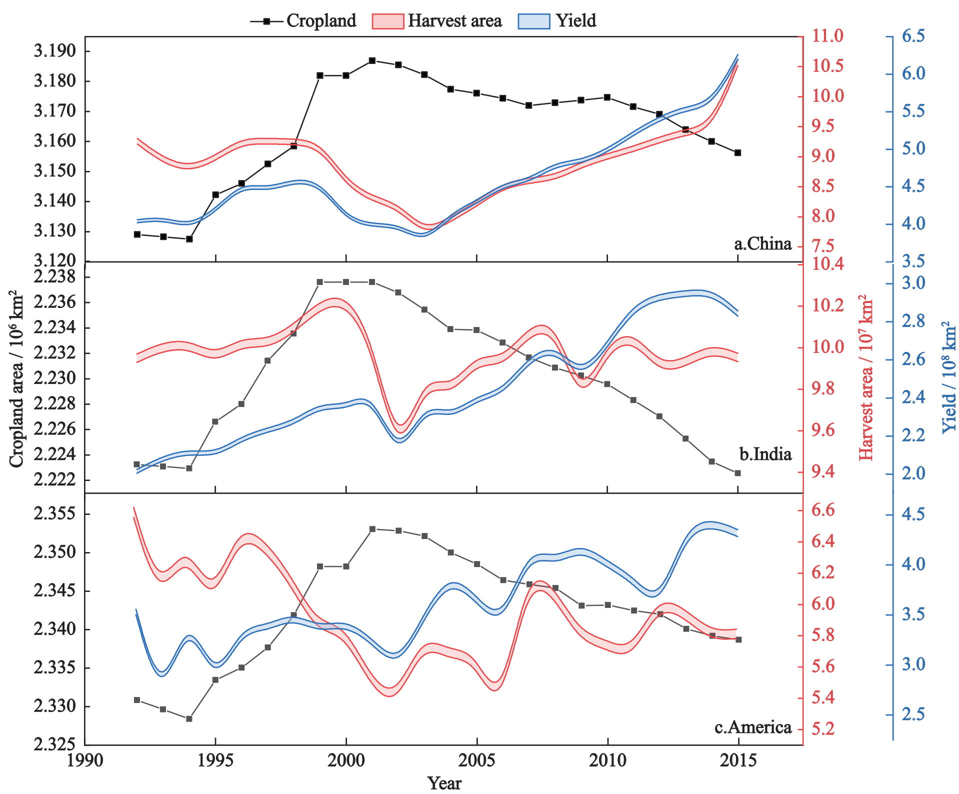

Fig. 9 Cropland area, grain harvest area and yield map of (a) China, (b) India and (c) America. The pink and blue bands are the effect of adding error bars to the variables

hibited the opposite trend, and the cropland area in Europe continuously decreased. This gradual reduction may have been related to the level of economic development (Schierhorn et al., 2014). Rich countries tend to

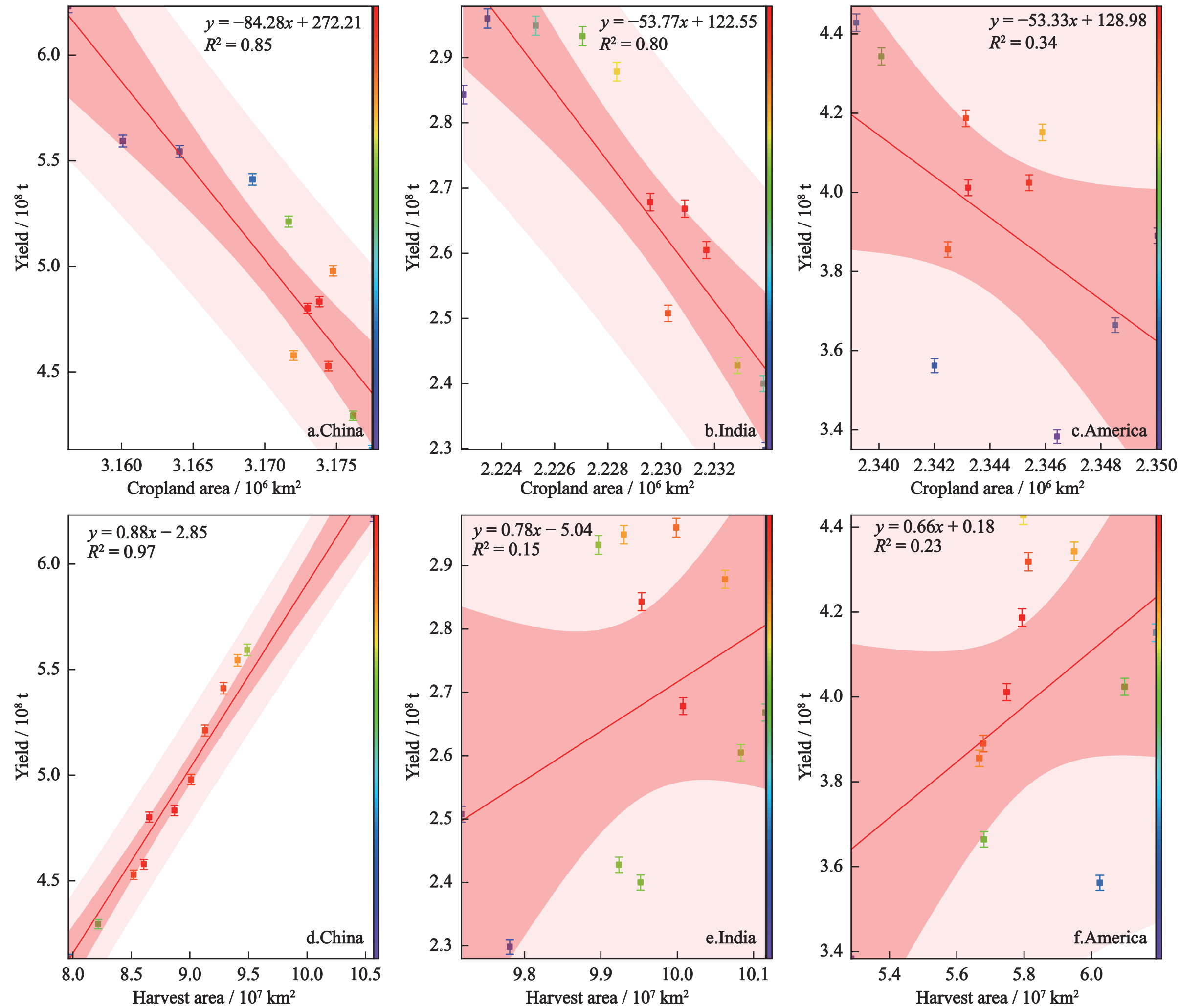

Fig. 10 Fitting analysis chart of grain yield, cropland and harvest area in China, the United States and India. Slope < 0 (> 0), indicating that the two independent variables are negatively (positively) correlated, the width of red shadow represents the value of R^2 and the correlation between independent variable

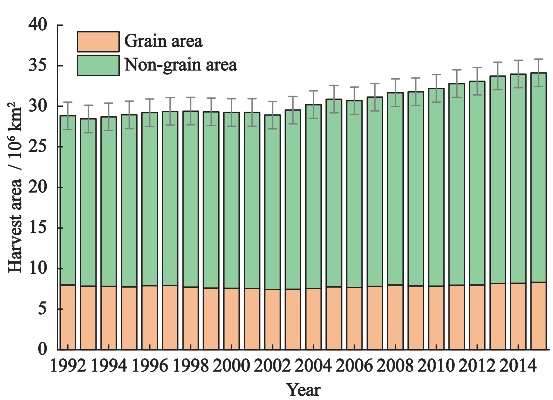

Fig. 11 Global harvest area of the grain and non-grains from 1992 to 2015

transfer land use to other countries by increasing food imports, which may lead to less cropland in developed countries and more land for urban expansion (d'Amour et al., 2017; Lin, 2019). The cropland land area in Africa continued to grow during the study period. Because of the slow economic development of Africa, in most countries, the cropland land area is expanded through reclamation and deforestation to ensure food security. According to the FAO's report on the global forest resource assessment in 2020, the annual net rate of loss of Africa's forest was the largest, up to 3.9 million ha (Zeng et al., 2018). This trend was similar to the early development model of many countries, that is, sacrificing the ecology and environment to develop the economy and feed the population. Previous studies also have reported this large-scale cropland expansion, which resulted in massive deforestation, loss of grassland, and some natural disasters (Mechiche-Alamiand-

Abdi, 2020).

4.2 Cropland management and food security assessment

Against the backdrop of a decrease in the global cropland area, the increase in the grain yield was 2.6 times greater than that before 2004 (Yu et al., 2018). During this period, the improvement in the agricultural mechanization level, irrigation, chemical fertilizers, and other technical methods made the grain harvest area grow faster, and the invention of hybrid rice contributed more to the yield. For example, the growth of China's grain harvest area from 2005 to 2015 was mainly due to changes in farmland management, including changes in the crop planting structure, rice water management, the multiple cropping index, increases in fertilization, and irrigation measures (Carlson et al., 2017).

Agricultural planting is greatly affected by the farmers' willingness to implement the recommended practices, however, and the phenomenon of non-grain cropland is becoming increasingly serious (Yang, 2021). Farmers are more willing to plant non-grain crops, such as tea, traditional Chinese medicine, and rapeseed to obtain more benefits. This leads to the reduction of the grain harvest area and does not guarantee food security (Sacks et al., 2010). For example, China has implemented the policy of reserving at least 1.8 billion mu (1 mu = 666.67 m^2) of red line cropland to ensure food security, but this policy ignores the proportion of grain crops in the 1.8 billion mu of cropland, which will largely determine the amount of grain yield (You, 2012). If the harvested area and production of non-food crops are far greater than that of the grain crops, China's food security will be negatively affected (Hu Y C et al., 2020). Therefore, it is not enough to guarantee only the 120 million ha of cropland, and what is planted in this cropland is also important, that is, the amount of grain harvest area.

We found a negative correlation between the grain yield and the cropland area. The grain yield, however, was strongly positively correlated with the grain harvest area. With the acceleration of global urbanization, construction land (e.g., housing, transportation, and reservoirs) often encroaches on agricultural production land. Once the cropland area is occupied, it is difficult to restore the underlying surface to usable cropland. It seems unlikely that the cropland area will be expanded further in the future (Van Vliet et al., 2017). In addition, increasing the grain harvest area may provide another promising method of improving the grain yield, which will largely compensate for the decrease in the global cropland area caused by future industrialization and urbanization (Tilman et al., 2002).

5 Conclusions

In this study, based on a global land cover dataset, we used correlation analysis to reveal the distributions of, changes in, and relationships between the global cropland area and the grain yield at different spatial scales (continent and country scales) from 1992 to 2015.

Between 1992 and 2015, the global cropland area increased by 2.19%. The abrupt change year of the global cropland area was 2004. After 2012, the average annual decrease of 13 000 km^2 was 2.4 times that during 2004–2012. Correlation between the cropland area and the grain yield was poor, whereas the fitting degree between the grain harvest area and the grain yield was high (R^2 = 0.94), indicating that the grain harvest area was an important factor affecting the grain yield. So only emphasizing and protecting the cropland area can not ensure food security at the national level. When evaluating food security, the harvested area is a new and more scientific indicator than the cropland area. From 1992 to 2015, the area of non-grain cropland in China has significantly increased at a rate of about 27%, the problem of damage to the cultivated layer caused by non-grain crops has become increasingly prominent. Without doubt, Governments of various countries should formulate the size of the grain harvest area as a new indicator of food security, rather than directly delineate the size of the cropland. Optimizing the layout of grain production, strengthening supervision, reducing the conversion rate of non-grain farmland, and increasing the harvest area of grain crops can ensure food security.

The results of this study provide important information and data for developing countries to use to ensure their own food security. They also can be used to promote our understanding of global environmental change. In our research, however, the resolution of the remote sensing data was not very high, which may have led to inaccurate estimates of the cropland area. In addition, the sizes of the grain yield and harvested area are greatly affected by climate change and human activities.

With the acceleration of global urbanization and the improvement of the accuracy of land use data, future research should focus on continuous temporal analysis of hot spots where the cropland expanded and was lost from 2000 to 2020 and were conversions with other land use categories have occurred.

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