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# Opportunistic Market-Driven Regional Shifts of Cropping Practices Reduce Food Production Capacity of China

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**Key Points:**
- Substantial shifts in the regional cultivation patterns have occurred in China
- Macroshifts have reduced food production by 1.02% nationally each year
- The spatial shifts were accompanied by major changes in crop species composition

**Supporting Information:**
- Supporting Information S1

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**Abstract** China is facing the challenge of feeding a growing population with the declining cropland and increasing shortage of water resources under the changing climate. This study identified that the opportunistic profit-driven shifts of planting areas and crop species composition have strongly reduced the food production capacity of China. First, the regional cultivation patterns of major crops in China have substantially shifted during the past five decades. Southeast and South China, the regions with abundant water resources and fewer natural disasters, have lost large planting areas of cropland in order to pursue industry and commerce. Meanwhile, Northeast and Northwest China, the regions with low water resources and frequent natural disasters, have witnessed increases in planting areas. These macroshifts have reduced the national food production by 1.02% per year. The lost grain production would have been enough to feed 13 million people. Second, the spatial shifts have been accompanied by major changes in crop species composition, with substantial increases in planting area and production of maize, due to its low water consumption and high economic returns. Consequently, the stockpile of maize in China has accounted for more than half of global stockpile, and the stock to use ratio of maize in China has exceeded the reliable level. Market-driven regional shifts of cropping practices have resulted in larger irrigation requirements and aggravated environmental stresses. Our results highlighted the need for Chinese food policies to consider the spatial shifts in cultivation, and the planting crop compositions limited by regional water resources and climate change.

## 1. Introduction

Food production and consumption in China exert a strong influence on the global food security and markets. Although accounting for only 6% of the global arable land, China feeds more than 1.3 billion people and generates 24% of the total food production in the world (U.S. Department of Agriculture [USDA], 2017). China is the leading producer of rice over the globe, accounting for 30% of the world's rice production (USDA, 2017). Moreover, China is also the leading producer of wheat and the second largest producer of maize, producing 17% and 23% of the global wheat and maize, respectively (USDA, 2017). Therefore, crop production in China has significant implications beyond the country's borders. For example, the crop failure due to winter drought in eastern China's wheat-growing season of 2011 forced China to substantially increase the import of wheat, which led to a doubling of wheat prices in the international market, made bread prices tripled in the world's largest wheat importer Egypt, and indirectly resulted in a civil unrest (Sternberg, 2012).

Because of its national and global significance, China's food production has been closely monitored and examined. The temporal trends and spatial patterns of grain production in China, as well as their driving forces, have been studied extensively at regional and national scales (C. Q. Chen et al., 2011; Tao et al., 2014; Yuan et al., 2014). Numerous studies have reached a consistent conclusion that China is facing the challenge of feeding its growing population with declining water resources and changing climate (Tao et al., 2014; Zhao et al., 2017). A previous study showed that China experienced yield stagnation more acutely than other countries, with more than half of the areas dedicated to cultivation of maize, rice, wheat, and soybeans failing to achieve yield improvement (Ray et al., 2012). In addition, the country's rapid economic development has led to an increased domestic food consumption and an intensified utilization of the limited arable land base (Zhou et al., 2014). These have forced the Chinese government to abandon its long-held policy of grain self-sufficiency and to increase the grain imports (Figure S1 in the supporting information).

Numerous studies predominantly examined the impacts of climate variability on grain production, and none, to our knowledge, has investigated the effects of profit-driven cross-region shifts in cropping areas and crop composition on the food production in China. For hundreds of years, South and Southeast China were the most important grain production areas because of abundant rainfall. Since the implementation of the Reform and Opening Up policy starting in 1979, the Chinese government attached importance to economic development. As a result, large areas of grain-producing cropland in South and Southeast China have been replaced by urbanization (J. Y. Liu et al., 2003) or converted to other land use types with higher economic returns (Cao, Lv, et al., 2014). On the contrary, the crop practices substantially increased in the Northeast and Northwest China largely driven by the expansion of irrigation agriculture, where it turns out to be a new center of grain production.

However, market-driven regional shifts of crop practices did not match with the patterns of water availability and climate change. The regions of Southeast and South China with abundant water resources lost large planting areas of cropland in order to pursue industry and commerce. Meanwhile, the regions of Northeast and Northwest China with deficient water resources increased the crop practices. In addition, rising studies reported that natural disasters in the Northeast and Northwest China are more frequent than in the South and Southeast China (Shi & Kasperson, 2015; Yuan et al., 2014). This research therefore strives to answer the scientific question of how the market-driven regional shifts of cropping practices impact food production of China through the interactions with water resource and climate change. Addressing and quantifying this impact will greatly improve our mechanistic understandings of food production capacity and its responses to national policy and climate change.

## 2. Materials and Methods

In order to quantify the impacts of spatial shifts in planting areas on crop production in China, we calculated potential crop production by assuming no spatial shifts in planting area. First, it was assumed that all regions will retain the constant shares of planting areas to the entire country:

$$r_i = \frac{\text{Area}_{i,1960}}{\text{Area}_{T,1960}} \tag{1}$$

where $r_i$ is the proportion of planting area of the $i$th province accounting for the entire country, $\text{Area}_{i,1960}$ is the mean values of planting areas of the $i$th province in 1960, and $\text{Area}_{T,1960}$ is total planting areas of the entire country in 1960.

The potential planting area ($\text{AreaP}_{i,j}$, $i$th province at $j$th year, and $j$ starting from 1961), assuming no spatial shifts, can be calculated as

$$\text{Area}P_{i,j} = r_i \times \text{Area}_{T,j} \tag{2}$$

where $\text{Area}_{T,j}$ is the total planting area of entire country at $j$th year.

The potential production of the $i$th province at $j$th year ($\text{Prod}P_{i,j}$) can be calculated as the following equation by actual per unit area yield of the $i$th province at $j$th year ($\text{YPA}_{i,j}$) from the statistical yearbook.

$$\text{Prod}P_{i,j} = \text{Area}P_{i,j} \times \text{YPA}_{i,j} \tag{3}$$

The impacts of the spatial shifts of planting areas on crop production in China can be quantified using the differences between $\text{Prod}P_{i,j}$ and actual statistical production ($\text{Prod}A_{i,j}$).

In addition, this study investigated the impacts of regional shifts of planting areas on irrigation. The crop irrigation requirement ($\text{Crop}_{\text{Irri}}$, mm) is defined as the depth (or amount) of water needed to meet the water loss through evapotranspiration. In other words, it is the amount of water needed by various crops to grow

**Table 1**
*Data Sources for This Study*

| Data | Duration | References |
|---|---|---|
| Grain yield and planting area | 1960–2014 | Chinese Agricultural Yearbook |
| Irrigation area | 1972–2014 | Chinese Agricultural Yearbook |
| Natural disaster | 1960–2014 | Chinese Agricultural Yearbook |
| Agricultural import and export | 2000–2013 | Yearbook of Chinese Customs |
| Cropland conversion | 2000–2009 | China Land and Resources Statistical Yearbook |

optimally. Reference crop evapotranspiration is calculated based on the Penman-Monteith model (Allen et al., 1998) shown below

$$\mathrm{Crop}_{\mathrm{Irri}} = \mathrm{ET}_{\mathrm{Crop}} - \mathrm{Prec} \tag{4}$$

$$\mathrm{ET}_{\mathrm{Crop}} = \mathrm{ET}_0 \times K_c \tag{5}$$

$$\mathrm{ET}_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} U(e_s - e_a)}{\Delta + \gamma(1 + 0.34U)} \tag{6}$$

where $\mathrm{ET}_{\mathrm{crop}}$ is crop evapotranspiration (mm/day), $\mathrm{ET}_0$ is reference crop evapotranspiration (mm $\mathrm{day}^{-1}$), $K_c$ is crop coefficient, $R_n$ is the net radiation on the crop surface (MJ/$\mathrm{m}^2$/day), $G$ is the soil heat flux (MJ/$\mathrm{m}^2$/day), $T$ is air temperature at 2 m height (°C), $U$ is the wind speed at 2 m height (m/s), $e_s$ is the saturation vapor pressure (kPa), $e_a$ is the actual vapor pressure (kPa), $\Delta$ is the curve slope of saturated vapor pressure versus air temperature (kPa/°C), and $\gamma$ is the psychromentric constant (kPa/°C). This study used the $K_c$ values commended by the Food and Agriculture Organization (http://www.fao.org/docrep/S2022E/s2022e00.htm#Contents; Tables S3–S6). The province-level phenophases of crop species was collected from the crop planting database of Ministry of Agriculture of the People's Republic of China (http://202.127.42.157/moazzys/nongshi.aspx). We simulated the crop irrigation requirements from 1960 to 2014 using an interpolated temperature, precipitation, wind speed, vapor pressure deficit (Yuan et al., 2015), and the reanalysis data set of $R_n$ (Global Modeling and Assimilation Office, 2004). All simulations were conducted at the province level, and the meteorological variables were averaged based on the province boundary.

A global data set of Palmer Drought Severity Index (PDSI) at 2.5° resolution was used to investigate long-term drought trends in China (Jacobi et al., 2013). The PDSI is the most prominent index of meteorological drought used worldwide. The PDSI incorporates antecedent and current moisture supply (precipitation) and demand (evapotranspiration) in a hydrological accounting system. The PDSI was additionally used to quantify long-term changes in global and regional drought events (Yuan et al., 2014). Table 1 lists the sources of all statistical data used in this study.

## 3. Results

The arable land resources in China have experienced significant changes in time and space. The area of grain cultivation decreased by more than 9%, from 120 million hectares (mha) in the1960s to 106 mha in the 2000s (Figure 1). Most regions, especially the major grain production areas with abundant water resources (i.e., Southeast, South, and North China), have witnessed acute decline in planting areas (Figure 1). In contrast, planting area in regions with low water resources, such as the Northeast, Northwest, and Southwest China, has increased in recent years (Figure 1).

As a result, cropping area shares shifted substantially across the regions over time. On average, the planting area in Southeast China decreased from 27.9% of the entire country in the 1960s to 25.1% averaged for 2000–2014 (Figure S2e). The proportion of planting area in the South China, North China, Loess Plateau, and Tibetan Plateau also declined over time (Figures S2i, S2c, S2f, and S2d). However, the shares of other regions (i.e., the Northeast, Northwest, and Southwest China) increased. For example, Northeast China only accounted for 10.5% of the total planting area in the 1960s, which increased to 15.7% in the 2000s (Figure S2a). As a result, the distribution of grain production shifted greatly. The contribution of crop production in Southeast China to the national total decreased from 35.3% in the 1960s to 28.5% in the 2000s. In contrast, the proportion of overall crop production in the Northeast and Northwest increased by 9.9% and 2.6%, respectively over the same period (Figures S2a and S2b).

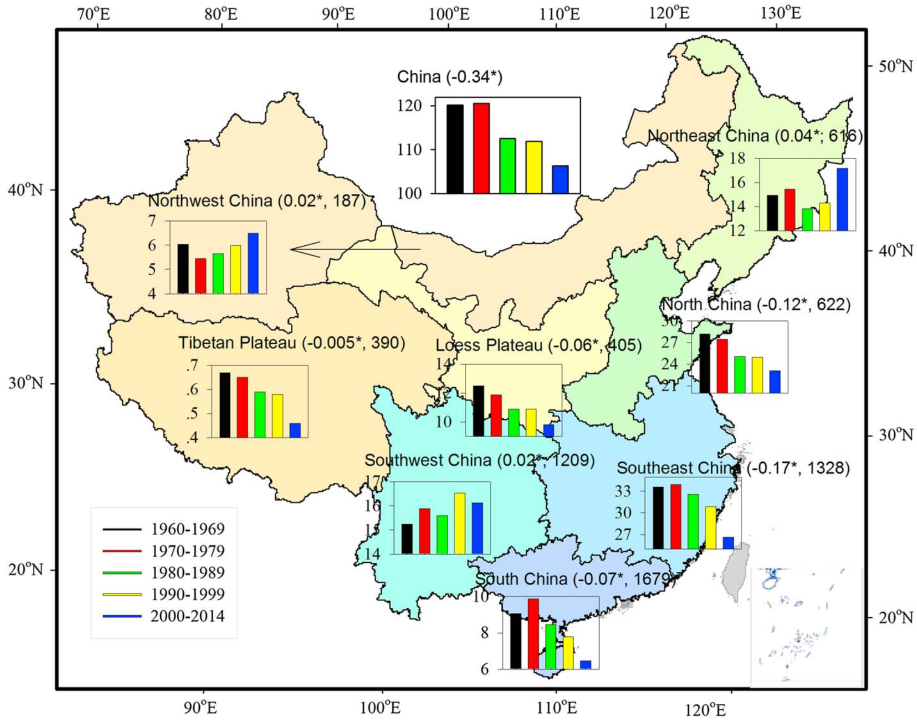


**Figure 1.** Decadal changes of the grain planting area in eight regions (denoted in different colors) over China. Area is in million hectares (mha). The values in parentheses indicate the annual change rates (mha/year, left) and the mean annual precipitation over the entire areas (mm, right) from 1960 to 2014. Asterisk indicates that the trend of change is statistically significant ($p < 0.05$).

Besides the regional shifts in cropping area shares, the proportions of the three major grains (i.e., rice, wheat, and maize) and the crop composition experienced substantial changes as well. In the main traditional rice production areas of Southeast, South, and Southwest China, the planting areas of rice significantly decreased, while increasing trends were observed in the Northeast, Northwest, and North, where water is highly limited (Table S1 and Figure S3a). The planting areas of maize significantly increased in all regions (Figure S3c and Table S1), particularly in the Northeast and North with an increasing rate by more than 0.1 mha/year (Table S1). In contrast, the planting areas of wheat only significantly increased in the North (Figure S3 and Table S1) but significantly decreased in other regions (i.e., Northeast, Northwest, South, and Loess Plateau).

Nationally, the planting areas of maize increased continuously since 1960, but the planting areas of other crops either decreased or remained stable (Figures 2a, S4a, and S5a). The share of maize planting area increased from 11.51% in 1960 to 32.93% in 2014, becoming the largest among all grain crops (Figure S4a). Maize production increased continuously with the share reaching 35.53% in 2014 (Figure S4b), and the production shares of rice and other grains gradually decreased (Figure S4b). Maize production dominated the increases of grain production that 43% (even more than 75% from 1990) increase of grain production can be attributed to maize production since 1960 (Figure S5c).

Agricultural areas are often affected by disasters that are not evenly distributed in China. Higher fractions of croplands are affected by natural disasters in the northern regions with substantially increased proportion of planting area than in the southern regions with decreased cropland shares (Figure 3e). Averagely for 1960–2014, natural disasters impacted cropland area in the Northeast and Northwest by 32% and 33%, respectively (Figure 3e). These percentages were substantially higher than those for most of the southern regions, where the affected rates were generally smaller than 25%. The disaster-stricken areas increased significantly over time in all regions except the North. The highest increasing rates were 0.49 and 0.61%/year, respectively, in the Northeast and Northwest coupled with the largest increases of planting areas (Figure 3e). Most natural disasters were related to climate change in the Northeast and Northwest areas. More than 75% of natural disasters were extreme climate events, such as droughts and floods (Figure S6). Using the PDSI, we identified significantly increasing droughts in Northeast, North, and Southwest China over the past few

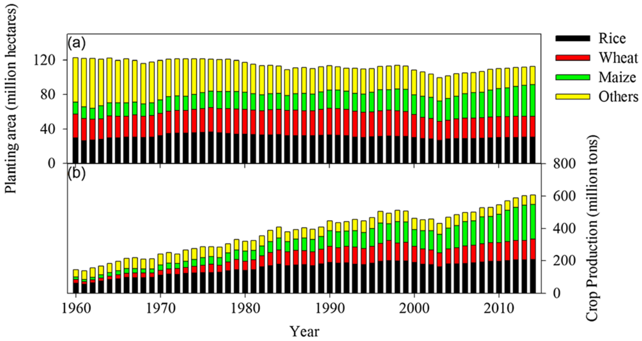


**Figure 2.** Changes in planting areas (a) and crop production (b) of the grain crops over the entire country for 1960–2014.

decades (Figure S2). With the existing low availability of water resources, extreme climate events such as droughts and interannual variability of precipitation brought more difficulty for rain-fed agriculture in the northern regions.

The macroshifts in cropping area in China significantly reduced the national crop production by 5.11 million tons annually from 1961 to 2014 (Figure 4). Comparatively, the realized mean increasing rate of the annual total crop production in China was 2.78% during the same period. Without the reduction from regional shifts in cropping area, the increasing rate in the annualized grain production would be 3.8% (36% higher than the realized rate). The lost grain production would have been enough to feed 13 million people on average at 386.60 kg/year per-capita grain consumption rate (Tang & Li, 2012). A significant decrease in grain production was observed from 1960 to 2014, especially after 1984 when grain production decreased by 0.81 million t/year ($y = -0.81x + 1{,}597$, $R^2 = 0.93$, $p < 0.01$). The negative impacts were particularly evident and strong during the past decades in most regions, except for Northeast, Southwest, and Northwest China (Figure S7).

The increases in cropping area in the Northwest, North, and Northeast were largely driven by the expansion of irrigation agriculture. Water resources in China are unevenly distributed with a general abundance in the

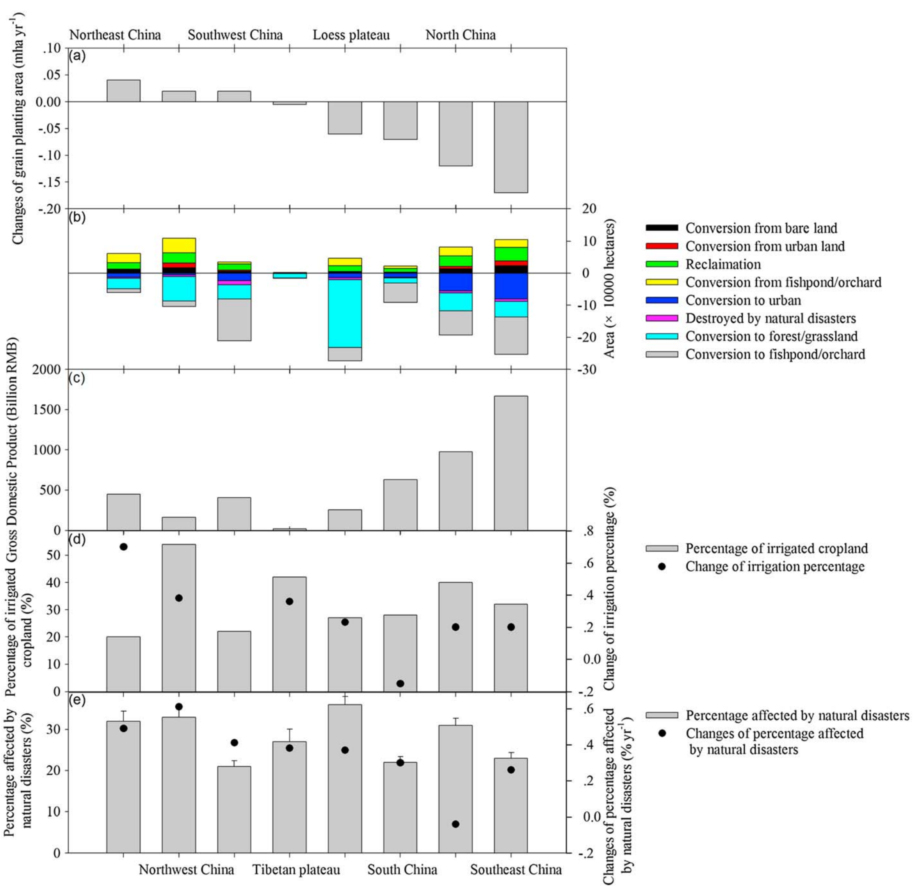


**Figure 3.** Comparisons of grain planting areas changes (a), land use changes (b), gross domestic product (c), the percentage of irrigated areas and changes (d), the percentage of planting areas affected by natural disasters, and (e) changes over the eight regions. Data source: (a) plant area data are from the Chinese Agricultural Yearbook of 1960–2014; (b) land cover change data are from the China Land and Resources Statistical Yearbook of 2000–2009; (c) gross domestic product data are from the National Database by National Bureau of Statistics of China of 1960–2014 (http://data.stats.gov.cn/english); (d) irrigated cropland area are from the Chinese Agricultural Yearbook of 1972–2014; (e) natural disaster data are from the Chinese Agricultural Yearbook of 1960–2014.

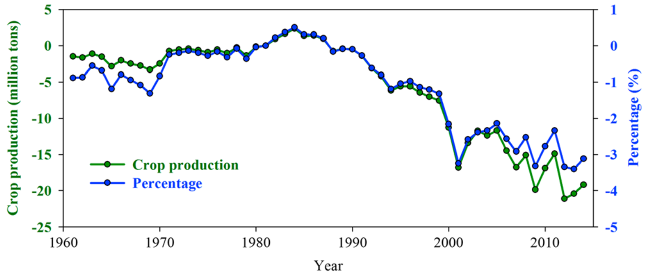


**Figure 4.** Changes in crop production (million tons) driven by macrogeographic shifts in planting area in China. Percentage indicates the ratio of the decreased crop production to the statistical yield of the whole country (see section 2).

southern regions and a relative deficiency in the northern regions (Figure 1). Average annual precipitation in the Northwest, North, and Northeast is 187, 622, and 616 mm/year, respectively for 1960–2014 (Figure 1). The amounts are insufficient or marginal for crop production. Given the low amount and high interannual variability of precipitation, crop production in these areas strongly depends on irrigation. Model simulations showed larger crop irrigation requirements over Northwest, North, and Northeast China than other regions (Figure S8). In fact, averaged for 1972–2014, irrigated area in the Northeast, North, and Northwest accounted for 20, 40, and 54% of the national arable area, respectively (Figure 2d). The Northeast and Northwest, with the fastest extension of planting areas, showed the largest increasing rates of irrigation area (Figure 2d). The spatial shifts of planting area increased crop irrigation over the entire country by 1.87% in the 1960s to 31.14% in 2000–2014 (Figure 5). Especially, the Northeast and Northwest showed substantial increases in cropland irrigation resulting from increased planting areas and changes in crop types (Figure S9).

## 4. Discussion

### 4.1. Causes for Regional Shifts of Cropping Area and Composition

The geographic shifts of cropping area and crop composition in China shown in this study have been largely controlled by national policies and market conditions. Trying to produce enough food to feed China's large population, the Chinese government has used grain production as the core indicator of the regional development status since the 1950s. Agricultural reclamation, nationally initiated in the 1960s, has resulted in increases in planting area throughout the 1960s to 1970s (Figure 1). Since 1979, the areas of North, Southeast, and South China with the earliest implementation of the Reform and Opening Up policy have become the major regions of economic and industrial development with the highest gross domestic production (Figure 2c) and the largest cropland losses (Figure 2a). Province-level statistical data averaged over 2000–2009 showed that more than 28% and 31% of cropland was converted for urban development in North and Southeast China, respectively; 38–66% of cropland was converted for uses with higher economic profits such as aquaculture and timber production in North, Southeast, and South China (Figure S9). Net increases in cropland occurred in areas of Northeast and Northwest China, benefiting from the reclamation and conversion from economic forests (Figure 2b).

Ecological engineering programs have also substantially affected the planting areas in China (Cao, Ma, et al., 2014). The six key ecological engineering programs (e.g., the Three Norths Shelter Forest System Project, the Natural Forest Conservation Program, and the Grain to Green Program) are unprecedented in China's ecological and environmental history in terms of geographic extent, government budget, and social mobilization (D. Liu et al., 2014). For example, the Grain for Green Project (GGP) launched in 1999 returns cultivated land across China to forest or perennial grassland, in order to reduce water and soil erosion (Feng et al., 2015; Lu et al., 2017). This project has been implemented in more than 2,000 counties across 25 provinces and autonomous regions. About 8.68 million hectares of cropland have been converted to forests from 1999 to 2010 according to statistical data (Deng et al., 2012). These programs have led to a substantial decrease in cropland area.

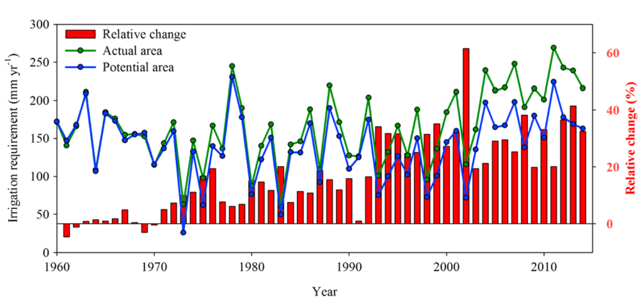


**Figure 5.** Comparison of cropland irrigation requirements under the actual (*A*, denoted by green lines) and potential planting areas (*P*, denoted by blue lines). Red bars indicate the relative change of irrigation requirement: (*P* − A)/*A*.

The changes in planting areas of the three staple crops have been driven by their market conditions and adaptation to water availability. Although Northeast and Northwest China witnessed increases in planting areas, the limited water resources strongly restricted the selection of crop types able to be planted. The previous study showed that rice and wheat require equivalent amounts of water for a unit yield (0.97 $m^3$ $H_2O$/kg yield), which is almost the double of the water requirement for maize production (0.55 $m^3$ $H_2O$/kg yield) (Zwart & Bastiaanssen, 2004). According to province-level statistics, the cost

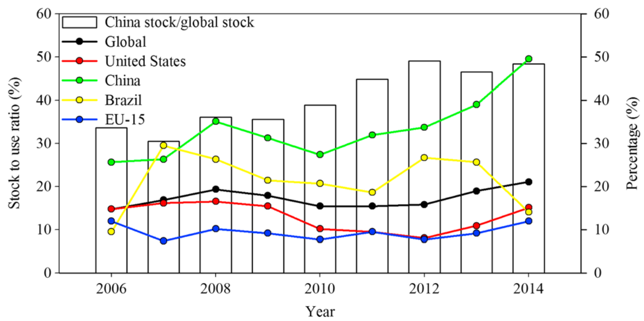


**Figure 6.** The stock to use ratios of maize over the global and the sample countries (solid lines) and the percentages of maize stock in China to the global stock (bars) for 2006–2014.

of irrigation for maize was much lower than for wheat and rice over all regions (Table S2). On average, the cost of irrigation for wheat and rice was 1.78 and 2.88 times that of maize. However, maize profit was 2.40 times higher than that of wheat averaged for all regions (Table S2). The largest share of planting area of maize in the Northeast, Northwest, and North can therefore be attributed to its low water requirements and high economic returns.

### 4.2. Impacts of Regional Shifts of Crop Practices

The competition for resources between agricultural and nonagricultural sectors and across regions has been intensified by the rapid industrialization, urbanization, strong income growth, and population expansion. The Chinese government mandates that the country should never has less than 120.19 mha of arable land without setting province-based minimum targets. This study showed substantial regional shifts in crop cultivation and the subsequent impacts on crop yield in China. Northeast and Northwest China are replacing the southern regions to be the most important grain production areas. However, the limitations of water resources availability and the frequent natural disasters, particularly in the northern regions, have decreased the national total crop production by 1.02%, which offsets the rising rate of crop yields in China (Figure 4). It is imperative to consider regional shifts of planting area as an integral part of regional and national strategies to sustain and improve national food production and cope with the global and regional environmental changes.

Regional shifts of planting areas have partly determined the changes of crop compositions and stimulated the growth of maize production. Recent increase of maize production in China, however, greatly exceeds its domestic demand, resulting in huge stockpiles of maize. As a consequence of these changes, China's food production has changed the global trading market. For example, China has changed from a net importer to exporter of maize since 2003. However, in recent years, China is forced to import wheat to meet the shortages in domestic demand (Figure S1). The ratio of stock to use for maize in China is the highest among all major maize producing countries in recent years (Figure 6). China has 48% of global maize stockpile (Figure 6). One analyst estimated that more than 20 million metric tons of China's maize are "so moldy or deteriorated that they are no longer suitable for human consumption or feed use," which will probably result in losses of more than $10 billion USDA, 2016). The government has realized the overproduction of maize and announced to reduce 3.33 million hectares of maize cultivation areas in the Northeast, North, Northwest, and Southwest by 2020 (Ministry of Agriculture of the People's Republic of China, 2015).

In addition, the increases of planting area in Northeast and Northwest China strongly depend on the expended irrigation conditions because of the low rainfall. It is very important to realize that the expansion of irrigation-based agriculture has resulted in many negative environmental consequences, such as the depletion of water resources, water pollution, and soil salinization. The increase in cropping areas in these regions has substantially increased the agricultural uses of water and therefore aggravated the shortages of water resources for other uses. Ground water withdrawal for crop production in the North has led to a rapid decline in the water table (−0.8 m/year) since the 1970s (Shen et al., 2013). Recent study highlighted that groundwater in the North and Northwest has been stressed or overstressed due to the high population and irrigation demand (Richey et al., 2015). Moreover, irrigation has led to soil salinization on about 9 mha of arable lands in the northern regions, adversely affecting the cropland quality and crop yield (W. P. Chen et al., 2010). How long and how extensive this irrigation-based agriculture can be sustained across various regions in China is a major scientific question that requires immediate attention.

How to strategically optimize crop production areas and crop composition in the face of a changing climate to secure food supply in the future is a major challenge for our society in general and China in particular. The food production capacity of China is expecting to decline due to climate and other environmental changes. For example, an analysis using an agroclimate model showed that, without additional irrigation, China's grain production in 2025 would be reduced to 72% of the level in 2010, highlighting the critical dependence of China's food security on future climate regimes and irrigation (Heilig et al., 2000). Climate system models have predicted more pronounced water shortages in North and Northeast China (Wang et al., 2013), likely putting more strict constraints on future cropping and species selection. Moreover, a recent study showed negative temperature impacts on crop yield at the global scale that each degrees Celsius increase in global mean temperature would, on average, reduce global yields of wheat by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1% (Zhao et al., 2017). Northeast and Northwest China, the regions with the largest increases in air temperature, have witnessed increases in planting areas (Figure S10). Optimizing regional patterns of cropping practices in the face of a changing climate is a grand challenge that must be addressed urgently at regional to national levels. Current practices are not sustainable for food production, given the increasing reliance on irrigation-based agriculture, accelerated drawdown of groundwater resources, more frequent extreme climate events, and worsening environmental conditions.

## 5. Conclusion

This study showed that market-driven shifts of cropping practices across regions have caused an annual loss of 5.11 million tons of grain production averaged over 1960–2014, enough to feed 13 million people. The shifts have created unintended consequences on water availability and the environment, directly challenging the sustainability of China's food production. Meanwhile, regional shifts of plating areas have altered the crop compositions. Jointly driven by the high profits and low water requirement, the planting areas of maize have substantially increased. Consequently, maize production has dominated the increases of grain production. Since 1960, 43% increase of grain production was attributed to maize production. This contribution reached even more than 75% since 1990. However, maize production has exceeded the domestic demand, which in turn creates huge stockpiles. We argue that regional shifts of cropping practices should be an integral part of regional and national strategies in dealing with national and global food security in the face of global and regional environmental changes.

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## References

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome, Italy.
Cao, S. X., Lv, Y., Zheng, H. R., & Wang, X. (2014). Challenges facing China's unbalanced urbanization strategy. *Land Use Policy*, *39*, 412–415.
Cao, S. X., Ma, H., Yuan, W. P., & Wang, X. (2014). Interaction of ecological and social factors affects vegetation recovery in China. *Biological Conservation*, *180*, 270–277.
Chen, C. Q., Lei, C. X., Deng, A. X., Qian, C. R., Hoogmoed, W., & Zhang, W. J. (2011). Will higher minimum temperatures increase corn production in Northeast China? An analysis of historical data over 1965–2008. *Agricultural and Forest Meteorology*, *151*, 1580–1588.
Chen, W. P., Hou, Z. N., Wu, L. S., Liang, Y. C., & Wei, C. Z. (2010). Evaluating salinity distribution in soil irrigated with saline water in arid regions of northwest China. *Agricultural Water Management*, *97*, 2001–2008.
Deng, L., Shangguan, Z. P., & Li, R. (2012). Effects of the Grain-For-Green Program on soil erosion in China. *International Journal of Sediment Research*, *27*, 120–127.
Feng, Q., Ma, H., Jiang, X. M., Wang, X., & Cao, S. X. (2015). What has caused desertification in China. *Scientific Reports*, *5*, 15998. https://doi.org/10.1038/srep15998
Global Modeling and Assimilation Office (2004). *File specification for GEOSDAS gridded output version 5.3*.
Heilig, G. K., Fischer, G., & van Velthuizen, H. T. (2000). Can China feed itself? An analysis of China's food prospects with special reference to water resources. *The International Journal of Sustainable Development and World Ecology*, *7*, 153–172.
Jacobi, J., Perrone, D., Duncan, L. L., & Hornberger, G. (2013). A tool for calculating the Palmer drought indices. *Water Resources Research*, *49*, 6086–6089.
Liu, D., Chen, Y., Cai, W. W., Dong, W. J., Xiao, J. F., Chen, J. Q., et al. (2014). The contribution of China's Grain for Green Program to carbon sequestration. *Landscape Ecology*, *29*, 1675–1688.
Liu, J. Y., Liu, M. L., Zhuang, D. F., Zhang, Z. X., & Deng, X. Z. (2003). Study on spatial pattern of land-use change in China during 1995–2000. *Science in China Series D: Earth Sciences*, *46*, 373–384.
Lu, C. X., Zhao, T. Y., Shi, X. L., & Cao, S. X. (2017). Ecological restoration by afforestation may increase groundwater depth and create potentially large ecological and water opportunity costs in arid and semiarid China. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2016.03.046
Ministry of Agriculture of the People's Republic of China (2015). (MOA), "The guidance on structural adjustment in maize over the several areas", Publications, 07B100307201500876). Retrieved from http://www.moa.gov.cn/govpublic/ZZYGLS/201511/t20151102_4885037.htm
Ray, D. K., Ramankutty, N., Mueller, N. D., West, P. C., & Foley, J. A. (2012). Recent patterns of crop yield growth and stagnation. *Nature Communications*, *3*, 1293. https://doi.org/10.1038/ncomms2296
Richey, A. S., Thomas, B. F., Lo, M. H., Reager, J. T., Famiglietti, J. S., Voss, K., et al. (2015). Quantifying renewable groundwater stress with GRACE. *Water Resources Research*, *51*, 5217–5238.
Shen, Y. J., Li, S., Chen, Y. N., Qi, Y. Q., & Zhang, S. W. (2013). Estimation of regional irrigation water requirement and water supply risk in the arid region of Northwestern China 1989–2010. *Agricultural Water Management*, *128*, 55–64.
Shi, P. J., & Kasperson, R. (2015). *World atlas of natural disaster risk*. Berlin, Heidelberg: Springer-Verlag, Beijing Normal University Press.
Sternberg, T. (2012). Chinese drought, bread and the Arab Spring. *Applied Geography*, *34*, 519–524.
Tang, H. J., & Li, Z. M. (2012). Study on per capita grain demand based on Chinese reasonable dietary pattern. *Scientia Agricultura Sinica*, *45*, 2315–2327.
Tao, F. L., Zhang, Z., Xiao, D. P., Zhang, S., Rotter, R. P., Shi, W. J., et al. (2014). Responses of wheat growth and yield to climate change in different climate zones of China, 1981–2009. *Agricultural and Forest Meteorology*, *189-190*, 91–104.

U.S. Department of Agriculture (2016). China's decision to end corn floor price shakes grain and feed market, Publication CH16027, USDA. Retrieved from https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Grain%20and%20Feed%20Annual_Beijing_China%20-%20Peoples%20Republic%20of_4-8-2016.pdf

U.S. Department of Agriculture (2017). World agricultural production, Publication WAP 02-17, USDA. Retrieved from https://apps.fas.usda.gov/psdonline/circulars/production.pdf

Wang, J. X., Huang, J. K., & Yan, T. T. (2013). Impacts of climate change on water and agricultural production in ten large river basins in China. *Journal of Integrative Agriculture*, *12*, 1267–1278.

Yuan, W. P., Liu, D., Dong, W. J., Liu, S. G., Zhou, G. S., Yu, G. R., et al. (2014). Multiyear precipitation reduction strongly decreases carbon uptake over northern China. *Journal of Geophysical Research: Biogeosciences*, *119*, 881–896. https://doi.org/10.1002/2014JG002608

Yuan, W. P., Xu, B., Chen, Z. Q., Xia, J. Z., & Xu, W. F. (2015). Validation of China-wide interpolated daily climate variables from 1960 to 2011. *Theoretical and Applied Climatology*, *119*, 689–700.

Zhao, C., Liu, B., Piao, S. L., Wang, X. H., Lobell, D. B., Huang, Y., et al. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, *114*, 9326–9331.

Zhou, Z. Y., Liu, H. B., & Cao, L. J. (2014). *Food consumption in China: The revolution continues*. Northampton, MA: Edward Elgar Publishing, Inc. https://doi.org/10.4337/9781782549208

Zwart, S. J., & Bastiaanssen, W. G. M. (2004). Review of measured crop water productivity values for irrigated wheat, rice, cotton and maize. *Agricultural Water Management*, *69*, 115–133.