Land use change and environmental stress of wheat, rice and corn production in China

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1. Introduction

In China, providing enough food for its population of 1.3 billion is an important challenge. There has been increasing concern about China’s food supply and the country’s ability to feed itself (Song, 1997). While Brown (1995, 2004) warns that the rising dependence on grain imports in China might affect the international food price significantly, others have argued that the country is capable of producing the grain it needs in the 21st century (Rosegrant, Agcaoili-Sombilla, & Perez, 1995; Song, 1997). This debate, which intensified after the 2008 food crisis (Heady & Fan, 2008), mostly revolves around China’s grain production due to the essential role grains play in the Chinese diet. For the past few years, world grain production has fallen short of consumption, which drew world grain stocks down to the lowest level in 30 years at the end of 2004 (Brown, 2004).

China is a major player in the world grain market and some of the shortfalls originate in China. Between 1950 and 1998, China increased its grain production from 90 to 434 million tons. Production peaked in 1998, but declined between 1998 and 2003, partly due to the loss of significant arable land because of urbanization, large-scale ecological restoration programs and increased water shortages (Liu & Savenije, 2008). However, China’s grain production increased starting in 2003 to reach a record high of 440 million tons in 2008. The total decline of China’s grain production, from 434 million tons in 1998 to 363 million tons in 2003,
represented a drop of more than 70 million tons in five years (FAOSTAT, 2010). To put it in perspective, this amount is more than Canadian grain production in 2003 and the combined exports of Canada, Australia, and Argentina (Brown, 2004). For this reason, grain production in China has attracted intense research interest (Fischer & Sun, 2001; Kaufmann & Seto, 2001; Mannin, 1995; Rosenzweig, Parry, Fischer, & Frohberg, 1993).

The increase in grain productivity, the primary source of production growth in the last few decades, relied heavily on the intensive use of fertilizers and pesticides (Huang & Rozelle, 1995). In China, grain production, in particular the associated land use change, is also closely related to global climate change. The country is the second largest CO2 emitter—just after the United States. Agricultural production contributes significantly to the emission of greenhouse gases. For example, rice paddies and ruminant livestock release methane and the application of large amounts of low grade fertilizers in crop production increases atmospheric nitrous oxide (Cheng, Han, & Taylor, 1992; Ellis, Lin, Yang, & Cheng, 2000; Fischer & Sun, 2001; Tong, Hall, & Wang, 2003). Consequences of the increase in grain productivity include soil degradation, water scarcity, and severe pollution in major grain production areas, as well as the declining efficiency of the fertilizer application. The negative impact of this on the health of natural resource bases, which China’s past grain productivity success has depended on, raises the question as to whether or not China can continue its grain self-sufficiency (Rozelle, 2008). The National Development and Reform Commission (NDRC, 2006) reiterated the country’s goal to stabilize the grain self-sufficiency rate above 95% and attain the capacity to produce 540 million tons of grains,1 by the year 2020. Is such a goal achievable?

This paper intends to analyze the land use change and environmental stress of grain production in China. The second section describes the main county-level data set (1980–2003) and the major methods used in the analysis. In the third section, the study looks at aggregate changes in land use since the early 1960s, and links these changes to overall policy changes. Then, in the fourth section, the study uses county-level panel data from 1980 to 2003 and GIS (Geographical Information System) graphical tools to show that there are important spatial shifts in grain production over time—changes that represent a move away from the traditional “granary of China”. The fifth section uses a spatial econometric model to investigate the drivers of grain production shifts. In the sixth section, we establish a correlation between grain production and environmental degradation through the use of two environmental stress indicators: soil degradation and water scarcity, which we map and analyze in combination with (county-based) grain production. We conclude the study with policy recommendations.

2. Data and methods

The primary dataset used in this study is Chinese county-level crop production statistics. Our dataset contains annual data (1980–2003) from the Ministry of Agriculture and the National Bureau of Statistics and covers all of mainland China’s counties. It includes the basic production statistics for major agricultural products such as rice, wheat, corn, soybean, cotton, potato, oil crops, sugar, vegetable, livestock, and fishery products. We verified the data with a wide variety of sources to fill in data gaps and address data inconsistencies. The main work undertaken was to link the county data to our county GIS boundary file so that we could map the crop production. This involved linking counties in the statistic dataset to the same counties in the GIS file, as well as accounting for the changing county boundaries from year to year. The cleaned dataset covers all the counties within 30 provinces2 of mainland

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1 China’s definition of grain includes coarse grains, rice, wheat, soybeans, and potatoes. This differs from the grain definition used in this paper, which includes only rice, wheat and corn. Using the Chinese definition, grain production amounted to 529 million tons in 2008.

2 We have called autonomous regions such as Xinjiang also provinces for reasons of simplification. Chongqing is included in Sichuan province. Taiwan is not included here.

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China. The total number of counties varies from year to year due to administrative changes. The number varies from 2400 to over 3200, but we finally settled on 2475 consistent counties from 1980 to 2003. In this paper, we take a narrow definition of grain to only include three main crops: rice, wheat and corn, all three of which are widely produced across China. These three crops make up 47% of the total sown area in 2003. Fig. 1 shows all 30 provinces and the regional groupings in China.

We used two methods in this paper: the centroid method for spatial dynamic analysis of land use change in grain production and the random effects panel data model to analyze the drivers of such land use change at the provincial level.

2.1. Centroid method

We applied the centroid method in order to more precisely measure land use change of grain production in China. This method estimates the location (longitude and latitude) of the centroid of Chinese grain areas and looks at the dynamics of the centroid during the period examined. The steps are:

(a) The central point (i.e. centroid, the center of gravity under a uniform distribution of weight) of each county is calculated using a standard GIS procedure (http://arcscripts.esri.com/details.asp?dbid=13091. Accessed July 2009).
(b) The grain area in each county is assigned to the centroid of that county in each year from 1980 to 2003.
(c) The centroid of Chinese grain production is the weighted average of all counties’ centroid. The weight is the crop harvested area for that county.
(d) The centroid is presented by its longitude and latitude, and a change of the centroid represents the overall land use change in each crop.

2.2. Random effects panel data model

There are various drivers for land use change of grain production: the rapid urbanization of the southeast, east and south, particularly the coastal region; the subsequent increase in land prices; and increased demand from growing cities for other non-bulk food products such as vegetables and fruits (but also meat). These caused a shift in these areas from land-intensive production to labor-intensive production that resulted in the shift of low-value production, such as grain, to the north-northeast, where the population is smaller and land more widely available. Assuming that crop production dynamics for each crop (wheat, rice and corn) differ across provinces, we estimated a random effects panel data model at the provincial level, which is specified as follows (Cameron & Trivedi, 2005):

\[ y_{it} = x_{it}' \beta + v_i + \nu_{it}, \forall i = 1, \ldots, N \text{ and } t = 1, \ldots, T \]  

\( y_{it} \) is the crop production for province \( i \) in period \( t \)

\( v_i \) is the province-specific effect measuring unobserved geographical heterogeneity, which is independently and identically distributed (iid) with mean 0 and variance \( \sigma_v^2 \)

\( \nu_{it} \) is the error term iid with mean 0 and variance \( \sigma_\nu^2 \), independent from both \( x_{it} \) and \( v_i \)

\( \beta \) is the parameter vector to be estimated.

The equivalent spatial specification of Eq. (1) is given by

\[ y_{it} = x_{it}' \beta + v_i + \phi_{it} \]  

\[ \phi_{it} = \rho \sum_{j=1}^{N} w_{ij} \phi_{jt} + \epsilon_{it} \]

where

\( \phi_{it} \) reflects the spatially autocorrelated error term;
\( \rho \) represents production spillover from one province to another;
\( w_{ij} \) are elements of the spatial weight matrix \( W \) that describes geographical proximity among countries. For convenience, matrix \( W \) is row-standardized.

Eq. (2) is estimated using a procedure developed by Elhorst (2009). The matrix \( x_{it} \) includes the following explanatory variables:

- **Cultivated land**: Providing food for a growing population is the critical task for Chinese agriculture. Throughout the study period, over half of cultivated land is used for grain production; therefore we expect a strong correlation between land expansion and crop production.
- **Ratio of rural population to arable land**: This variable is used as proxy for land availability. In general, rural labor is another production factor and so it may positively affect grain production. However, there is a rural labor surplus in China, so we expect...
the effect may be negative (i.e. grain production to decrease as the number of rural population per available land increases) or no effect at all.

- **Ratio of urban population to total population:** This is a proxy for urbanization. As urbanization increases, the demand for food will also increase, which will eventually lead to an increase in crop production; it will also have an effect on diversification towards animal husbandry, for which more corn is needed.

- **Research expenditures:** As pointed out by Fan, Zhang, and Zhang (2002), agricultural research and development (R&D) has been a major factor in explaining agricultural production growth in China. Since we could not disaggregate research expenditures by crops, we are using the aggregate amount. We assume that public policy towards agriculture is positively correlated with production expansion. R&D expenditure is used as an indicator of public policy.

- **Binary variables for regional effect:** The dynamics of crop production is not uniform across regions. Regions have experienced sustained production growth, stagnated, or experienced crop production decreases. Failure to capture these regional differences may lead to biased estimates.

3. Overall land use change in rice, wheat and corn productions

Land use change in China is strongly affected by government land- and crop-specific policies, grain prices, rural-to-urban labor migration, and urban-industrial growth. Furthermore, natural disasters such as drought and flood can have a severe impact on land use patterns. Until the late 1970s, all agricultural land in China was managed by cooperatives, people’s communes and state farms, and production was controlled and distributed through state policy and state-led organizations (Lin & Ho, 2003; Tong et al., 2003). Only after the implementation in the late 1970s of the household responsibility system in rural areas, could Chinese peasants decide for themselves what to plant and how to manage their agricultural production based on their own understanding of soil/water conditions and market needs. Based on these land policy changes in China, we could divide the four decades of land use change into six phases (Fan et al., 2002; Tong et al., 2003): Economic Adjustments (1961–1965), the Cultural Revolution (1966–76), the Household Responsibility System (1978–85), Second Phase Reform (1986–95), “Governor’s Grain Bag Responsibility” System (1995–98), and New Development in Agricultural Policy (1999–2008).

**Fig. 2** shows the harvested areas for rice, wheat and corn for the period of 1960–2008. During this period, China’s grain area varies from 67 million hectares to 86 million hectares. The changes of grain areas are closely related to Chinese agricultural policy changes. The Great Famine of 1959–61 led to the government’s implementation of an (“Agriculture First”) adjustment and consolidation policy. Although corn and wheat areas increased only marginally, rice area increased from 25 to 30 million hectares. Despite policy failures and political chaos during the Cultural Revolution, Chinese grain areas increased from 70 to 83 million hectares. Much of this increase, however, was the result of the irrational use of land. For example, the so-called policy to “create croplands by encroaching the lake area” and deforestation for cereal production dramatically changed the Chinese landscape (Tong et al., 2003). In 1978, China introduced the “household responsibility system”, which dismantled the people’s communes’ system. The grain area declined considerably due to the increase in other types of crops such as cash crops and vegetables, which were more remunerative for the peasants.

Significant grain productivity improvements led to the growth in output, but also to a considerable decrease in grain prices. The Second Phase of Reform (1986–95) was designed to further liberalize agricultural pricing and marketing systems. During this...
period, the government increased grain production financing by subsidizing fertilizers and raising state procurement prices for cereals. However, while this policy had considerable positive effects on the areas of corn and rice, it did not have positive effects on wheat (Fig. 2).

The 1990s marked a new development stage in China as urbanization and industrial growth attracted an increasing proportion of the rural labor force to urban and suburban areas. Rice and wheat areas declined while corn areas increased. The late 1993 grain price surge led to the central government’s adoption of the “Governor’s Grain Bag Responsibility” policy (Carter, Zhong, & Cai, 1996), which aimed to promote provincial grain self-sufficiency. As shown in Fig. 2, such administrative measures succeeded in stabilizing or even raising grain areas during this period. However, the effect did not last: Since 1998, China has continued to lose rice and wheat areas and the corn areas increased only slightly. By 2003, total grain area in China was only 72.8 million hectares, 16% less than the peak that had been reached in 1998. Grain production in 2003 dropped to 363 million tons, which is 18% less than in 1998 (FAOSTAT, 2010).

4. Spatial and temporal patterns of grain production

The space–time dynamics of grain acreage shifts as a result of changes in agricultural and macroeconomic policies is not well understood. In this section, we explain these dynamics using several factors.

Fig. 3. Grain production regions in China. (1) 1980–82 average (2) 2001–03 average.
4.1. Spatial pattern of land use changes of grain production

The county-level panel data on rice, wheat, and corn production allow us to investigate the temporal–spatial change of grain production. Fig. 3 shows the relative share of each county in national grain production in the early 1980s (average 1980–82) and 2002 (average 2001–03). Two clear patterns emerge. The first pattern is that there are two clusters of grain production. The first area includes the northeast of the Jilin province, the south of the Heilongjiang province and north of the Liaoning province. Additionally, the grain production zones in central and eastern China, including Shandong, Jiangsu, Anhui, Henan, northern Zhejiang, northern Jiangxi, and the eastern parts of the Hubei, Hunan, Guangxi and Sichuan provinces, form a relatively large area.

The second clear pattern that emerges is the northward shift of grain production since the early 1980s. In 1980, the majority of top grain production counties, defined as those counties whose grain productions are over 0.15% of national total, were concentrated in central and eastern China, such as, for example, in and around the corridor between the Yellow and Yangtze rivers. By 2003, the top grain production counties were located mostly in northeast China. Though central and eastern China remain important grain production zones, the shares of grain production in many counties within these zones decreased during this period. This is particularly true for those counties in the Jiangsu, Zhejiang, and Guangdong provinces as well as several counties in Sichuan and Hunan provinces. As a result of the production decline in many more southern counties, there has been a clear northward move of grain production areas between 1980 and 2003 (Fig. 3). In addition, western (and northwestern) provinces such as Xinjiang, Qinghai, and Gansu have increased their grain production considerably. Many counties in these provinces did not grow grain at all in 1980, but grew significant amounts of grain by 2003.

We also examined the changes in grain production from the point of view of land use by estimating the annual growth rates of planted areas of rice, wheat and corn throughout the 1980–2003 period. Fig. 4 (in four parts) presents the annual growth rates of planted areas of the three major grains separately and that of the aggregated grain planted area. There is considerable spatial heterogeneity of land use changes in grain production. Both grain area expansion and area loss are widespread across China. Northeast China, the North China Plain, and central China have all expanded grain areas more than 10% per year between 1980 and 2003. However, many counties within the same regions have lost grain areas during this period. For example, many counties along the central strip from Hebei and Shanxi to Yunnan province have been reducing grain areas as shown in Fig. 4(1). Western provinces, such as Xinjiang, Qinghai and even Tibet show high grain area growth rates—10% per year. On one hand, this reflects

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3 Notice the unit of the share is double percentage, which is 1/10,000.
their relatively low initial grain areas. On the other, these western Chinese provinces provide considerable scope for agricultural expansion. Xinjiang could even become the “California” of China (Tso, 2004).4

The aggregated grain area growth hides the heterogeneity among individual crops. The three other maps in Fig. 4 show the annual area growth rates for rice, wheat and corn individually. The rice area expansion is more limited than the other two crops. Areas planted with rice are growing in the northeast and parts of Henan and Shandong provinces, while rice areas in much of the rest of China are actually declining or stagnant. In particular, rice areas in coastal and central regions are quickly decreasing. Wheat and corn expansion covers broader regions. Notably, many counties in Inner Mongolia experience growth rates of over 10% in corn and wheat, while the provinces of Heilongjiang and Xinjiang considerably reduced their wheat areas.5 Corn areas expanded considerably in southeast China around Jiangxi province, while area expansion in rice and wheat is quite limited in the same region. This corn increase is due to the fact that corn is becoming an important resource for animal feed, for which the demand has expanded dramatically since the 1990s.

These maps provide a useful visualization of the spatial patterns and trends between the two snapshot periods selected for this study. To obtain a more quantitative sense of the observed changes, we summarize the land use change from 1980 to 2003. Table 1 shows the percentage change by comparing crop areas in 1980 to those in 2003. We divided China into seven regions (Fig. 1) according to the agro-ecological conditions (Fan & Pardey, 1997; You, Rosegrant, Wood, & Sun, 2009). From 1980 to 2003, rice and wheat areas decreased by about one-fifth while corn area increased by about one quarter. The total grain area decreased by a moderate 7.6% between 1980 and 2003. This overall picture, however, hides tremendous spatial variation among crops and across the country. All seven regions in China planted more corn and less wheat in 2003 in comparison to 1980. Northeast and northwest China planted more rice in 2003, but the rest of China planted less rice, which resulted in an overall decline in rice area. The northeast provinces lost 86.1% of their wheat areas, but increased their rice and corn areas by 222.7 and 35.9% respectively. The wheat areas in the four southern provinces decreased by as much as 86.2%, and the rice area decreased by 31.3% between 1980 and 2003. Even with a 23.6% corn area increase, the south has a net loss of 30.5% of grain areas. The central provinces lost between 19.1 and 53.3% of their rice and wheat acreage, while the southeast and northwest regions gained more than 50% of corn areas. The area losses in the south and central regions are likely due to ecological recovery programs, which include a large-scale sloping land conversion program, agricultural diversification and urban and infrastructure development (See Qu et al., 2011—for this issue). The increase in rice and corn area in the northeast is largely due to the conversion of large wetlands to crop land in the so-called “Three River Plain” area (Tong et al., 2003).

4 As we shall see in part six, the water shortage problems that California is currently facing, are similarly severe in north and western China. South-western Xinjiang, where there is much cotton and grain production is a case in point (Spoor & Shi, 2008).

5 The latter phenomenon can be explained for Xinjiang by the further expansion of cotton (at the expense of wheat).

4.2. Spatial dynamics analysis

We used the centroid method to investigate the dynamic changes of grain production. This method calculates geographic locations of the centroids of rice, wheat and corn areas from 1980–2003. The movements of these centroids, expressed in longitude and latitude, could clearly show the average land use change of grain production. For example, an increase of latitude means movement from south to north, while an increase of longitude represents movement from west to east. Fig. 5 presents the centroid movements for rice, wheat, corn and grain as a whole.

Fig. 5(1) shows the overall increase of central latitudes for rice, wheat and corn. This represents the distinct south–north movement. The rice centroid has the lowest latitude, the corn centroid has the highest latitude, and wheat falls somewhere in between. The distance between the rice and wheat centroids is about 6°, which is about 700 km. The centroid of corn is around N37°, 2° north of the centroid of wheat. These three centroids share similarities in terms of the west–east direction, as shown in Fig. 5(2). The centroid of corn has the highest longitude, almost 1 to 2° higher than those of rice and wheat. These latitude and longitude movements represent the overall trend of land use change in Chinese grain production. There is significant northward

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Table 1

<table>
<thead>
<tr>
<th>Region</th>
<th>Rice (%)</th>
<th>Wheat (%)</th>
<th>Corn (%)</th>
<th>Grain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>222.67</td>
<td>−86.13</td>
<td>35.86</td>
<td>21.49</td>
</tr>
<tr>
<td>North</td>
<td>−9.27</td>
<td>−5.90</td>
<td>17.48</td>
<td>2.56</td>
</tr>
<tr>
<td>Northwest</td>
<td>40.56</td>
<td>−37.59</td>
<td>83.73</td>
<td>−4.15</td>
</tr>
<tr>
<td>Central</td>
<td>−19.06</td>
<td>−53.32</td>
<td>17.55</td>
<td>−21.84</td>
</tr>
<tr>
<td>Southeast</td>
<td>−30.56</td>
<td>−1.07</td>
<td>68.25</td>
<td>−15.77</td>
</tr>
<tr>
<td>Southwest</td>
<td>−5.09</td>
<td>−14.37</td>
<td>0.64</td>
<td>−5.93</td>
</tr>
<tr>
<td>South</td>
<td>−31.29</td>
<td>−86.25</td>
<td>23.58</td>
<td>−30.45</td>
</tr>
<tr>
<td>China</td>
<td>−16.06</td>
<td>−24.84</td>
<td>25.94</td>
<td>−7.65</td>
</tr>
</tbody>
</table>

Note: The seven regions in China are: northeast (Heilongjiang, Liaoning, and Jilin), north (Beijing, Tianjin, Hebei, Henan, Shandong, Shanxi, and Shaanxi), northwest (Inner Mongolia, Ningxia, Xinjiang, Tibet, Qinghai, and Gansu), Central (Jiangxi, Hunan, and Hubei), southeast (Shanghai, Jiangsu, Zhejiang, and Anhui), southwest (Sichuan, Guizhou, and Yunnan), and south (Guangxi, Fujian, Hainan, and Guangdong).
movement of the rice centroid (slope = 0.043, $R^2 = 0.37$, $p < 0.005$) and of the corn centroid (slope = 0.021, $R^2 = 0.29$, $p < 0.01$), which implies that rice and corn production move 0.073 (5 km/year) and 0.041 (3 km/year) latitude degrees northward per year respectively. With the wheat production center almost staying at the same latitude, the movement of rice and corn centroids represents a 4 km/year ($R^2 = 0.53$, $p < 0.004$) northward movement for grain production between 1980 and 2003. The west–east (i.e. inland–coastal) movement is not statistically significant except for rice. The rice centroid has an eastward movement (slope = 0.03, $R^2 = 0.46$, $p < 0.003$), which is 2 km/year. This reflects the large rice area shift to the northeast. The Northeast region in China locates far more eastward than the Central and all the southern regions, which were the primary rice production zones in the 1980s and 1990s.

5. Drivers of the grain production shift

Land use changes in China are strongly affected by the government’s land policies, grain prices, urbanization and labor migration and many other factors. Using a provincial panel dataset, we estimated both the non-spatial and spatial panel data models described in Section 2.2. As reported in Table 2, evidence of positive spatial correlation was found for wheat and corn production, which confirms the clustering of grain production; a marginal change in the production in neighboring provinces significantly affects a given province’s own production. Estimation results also suggest that the variability in crop production induced by province-specific attributes as measured by the fraction of variance due to the province-effect is substantially stronger for wheat (0.470) and corn (0.451) than for rice (0.293). For both non-spatial and spatial specifications, cultivated land plays a major role in the production of all three crops. A one percent increase in the cultivated land area increases wheat production by

![Fig. 5. Latitudinal and longitudinal movement of the centroids of rice, wheat and corn in China. (1) Latitude (2) Longitude.](image)
more intensive use of physical inputs such as irrigation, fertilizer and pesticides (Fan & Pardey, 1997; Huang & Rozelle, 1995). While institutional change such as the household responsibility system and urbanization significantly increased grain production between 1980 and 2003. Many researchers have studied the sources of this growth in productivity (Fan & Pardey, 1997; Huang & Rozelle, 1996; Lin, 1992).

6. Environmental degradation of grain production bases

China has dramatically increased its grain production since 1980. Most growth originates from productivity improvement; the total grain area increased between 1980 and 2003. Many researchers have studied the sources of this growth in productivity (Fan & Pardey, 1997; Huang & Rozelle, 1996; Lin, 1992). While institutional change such as the household responsibility system and technology are important contributing factors, the productivity increase relied heavily on increasing production intensity and the more intensive use of physical inputs such as irrigation, fertilizer and pesticides (Fan & Pardey, 1997; Huang & Rozelle, 1995). Intensive input use and poor natural resource management in the pursuit of yield growth puts great pressure on crop land. Huang and Rozelle (1995) estimated that such environmental stress problems can cause grain yields to decline—half of which is due to

| Table 2 |
| Estimation results a. |

<table>
<thead>
<tr>
<th>Coefficient (S.E.)</th>
<th>Coefficient (S.E.)</th>
<th>Coefficient (S.E.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neighbor’s production</td>
<td>0.094*</td>
<td>0.022</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>1.126***</td>
<td>0.013</td>
</tr>
<tr>
<td>Rural pop/arable land</td>
<td>-0.046</td>
<td>0.027</td>
</tr>
<tr>
<td>Urbanization</td>
<td>0.073*</td>
<td>0.04</td>
</tr>
<tr>
<td>Research expenditure</td>
<td>0.185***</td>
<td>0.01</td>
</tr>
<tr>
<td>Regional effect (default = Northeast)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>0.282</td>
<td>0.152</td>
</tr>
<tr>
<td>Northwest</td>
<td>0.434***</td>
<td>0.162</td>
</tr>
<tr>
<td>Central</td>
<td>0.045</td>
<td>0.182</td>
</tr>
<tr>
<td>Southwest</td>
<td>0.195</td>
<td>0.171</td>
</tr>
<tr>
<td>South</td>
<td>-0.307*</td>
<td>0.187</td>
</tr>
<tr>
<td>Intercept</td>
<td>-2.080***</td>
<td>-0.21</td>
</tr>
<tr>
<td>Adjusted R-squared</td>
<td>0.97</td>
<td></td>
</tr>
<tr>
<td>#Obs.</td>
<td>660</td>
<td></td>
</tr>
<tr>
<td>LM test for no spatial lag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-spatial</td>
<td>80.8 (0.00)</td>
<td></td>
</tr>
<tr>
<td>Spatial</td>
<td>0.26(0.61)</td>
<td></td>
</tr>
<tr>
<td>Notes:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• All variables (except binary variables) are in logarithmic form so that coefficients can be interpreted as elasticities.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• S.E.: standard error; *** means statistical significance at 10, 5 and 1%.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• See the note of Table 1 for regional definitions.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a Unlike the non-spatial specification, the spatial specification could not handle the number of missing values in Qinghai and Hainan provinces; as a result, they were dropped from the sample.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1.13 (1.07) percent, rice production by 0.96%, and corn production by 1.10 (0.99) percent—results that seem normal for land-intensive crops. These elasticities help to understand the fact that where land becomes more readily available (such as in the North and Northeast), grain areas will grow faster over time. Land intensive production will gradually migrate towards relatively “land abundant” regions.

Furthermore, our estimation results suggest that a 1% increase in the ratio of rural population to arable land is expected to decrease wheat production by 0.05% for both non-spatial and spatial specifications. The spatial model shows a significantly (at 5%) negative effect of the ratio of rural population to arable land on rice production. This is expected as labor intensive and HYV (high yield variety)-oriented production becomes more attractive. No significant effect of the ratio of rural population to arable land is found on corn production. As discussed before, the different results among the three crops is due to the huge rural surplus labor in China. Urbanization has a positive significant effect on wheat and corn production, most likely caused by the shifting demand patterns towards higher quality food consumption, but does not show any significant effect on rice. Research expenditures significantly influence the production of all three crops: a one percent increase in government spending in research leads to a 0.17-0.19% increase in wheat production, a 0.14-0.15% in rice production, and a 0.18% in corn production. These results confirm that the regional shifts in grain land use patterns are also partly induced by government policy. Finally, evidence of significant regional-specific effects is also established. Indeed, compared to the northeast region (the default), the production of wheat is significantly higher in the north and northwest regions and significantly lower in the southern regions (except the southeast) when accounting for spatial correlation. A similar result is found for corn, but no significant difference is observed between the northeast and north. As for rice, the only significant difference is observed in the northwest region, where rice production is lower than in the northeast region. This, however, is rather trivial result as rice is grown much less in the northwest region because of unsuitable climate conditions.

salinity effects. Tong et al. (2003) concluded that the grain yield increases with increasing fertilizer use but that the yield increase per unit fertilizer use for rice, wheat and corn decreased significantly. In this part, we look at the conditions of water and soil resources of grain production using the latest data from the Millennium Ecosystem Assessment (2005).

Soil is the primary environmental stock that supports agriculture, and, consequently, soil condition is a central factor in determining the current state and future productive capacity of an agro-ecosystem (Wood, Sebastian, & Scherr, 2001). The diversity of soil degradation causes, processes, and consequences presents challenges in defining useful indicators to describe its status. The most comprehensive regional data on soil degradation in China is from the Assessment of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD). In this study, local experts used a standardized assessment framework (Van Lynden & Oldeman, 1997; Wood et al., 2001) and national maps to assess the degree of yield loss associated with four types of soil degradation: water erosion, wind erosion, physical degradation, and chemical degradation (Van Lynden & Oldeman, 1997). Fig. 6 presents ASSOD data on the severity of soil degradation within agricultural land for China. The map shows that wind and water erosion, chemical deterioration and salinization are widespread in China. Comparing this map with Fig. 2, we can immediately see that the major grain production areas are the same areas where soil degradation is worst. Soil degradation is caused by chemical deterioration in Northeast China, and by physical degradation and water erosion in the North China Plain and in the middle Yangtze River basin. Extreme wind erosion and chemical degradation occur in Inner Mongolia and along its boundary with the provinces of Ningxia, Shaanxi, Shanxi and Hebei. The region is the source for the “heavy dust break-out” which befalls Beijing almost every year, and reaches as far as Japan and South Korea. Table 3 summarizes the different soil degradation classes by their severity levels: 13.1 and 43.7% of cropland in China has “extreme” or “strong” soil degradation; 29.1% of Chinese cropland experiences strong water erosion, and 10.7% strong physical degradation (Table 3). Since planted area of the three grain crops is over 60% of total crop land, grain production is a critical contributing factor to soil degradation in China.

Water availability and reliability are increasingly critical constraints to food production in China. China produces 75% of total grain and 90% of all products on only 45% of irrigated farmland annually (Fischer & Sun, 2001). Almost 100% of rice, 56% of wheat and 40% of corn are irrigated in China (Liu & Savenije, 2008). Irrigation is one of the critical factors for increasing grain productivity as well as increasing cropping intensity. Agriculture accounts for the greatest proportion of withdrawals from surface and groundwater resources. Decreased river flows and falling ground water tables, in particular in the 3-H (Huang, Huai and Hai) river basins are pervasive in irrigated areas. Rapid expansion in irrigated area within the Yellow River basin over the last five decades have led to water abstractions in excess of total basin runoff, completely cutting off discharge to the highly environmentally sensitive downstream estuary area during some dry years.

To gain a better understanding of water availability and uses in China’s grain producing regions, we use the water reliability indicators resulting from the IMPACT-WATER model developed by Rosegrant, Msangi, and Sulser (2006) for 2000–2010. The

![Fig. 6. Soil degradation within cropland in China.](source: Assessment of the Status of Human-Induced Soil Degradation in South and Southeast Asia (ASSOD) (van Lynden and Oldeman 1997). PAGE agricultural extent: Wood et al. 2000.)
IMPACT-WATER model divides China into 15 food production units according to major river basins. Water supply and demand and crop production are first assessed at the river-basin scale. Crop production is then summed to the national level, where food demand and trade are modeled. The water supply for crops is determined by taking account of water availability as well as other demands from residents, livestock, industries and pre-committed flows to environmental, ecological, and navigational uses. Water reliability for crop production is simply defined as:

\[
\text{Water reliability} = \frac{\text{supply}}{\text{demand}}
\]

This measure gives a sense of the degree to which water demand is met each year, for each crop in each food production unit.

### Table 3
Soil degradation in Chinese crop land.

Source: Author’s calculation based on: (1) ASSOD (Van Lynden & Oldeman, 1997) (2) Wood et al. (2001).

<table>
<thead>
<tr>
<th>Dominant degradation type</th>
<th>Impact (percentage of agricultural land)</th>
<th>Non/Low</th>
<th>Moderate</th>
<th>Strong</th>
<th>Extreme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water erosion a</td>
<td>12.5</td>
<td>14.4</td>
<td>29.1</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Wind erosion b</td>
<td>0.2</td>
<td>1.7</td>
<td>2.4</td>
<td>2.6</td>
<td></td>
</tr>
<tr>
<td>Chemical degradation c</td>
<td>8.1</td>
<td>5.4</td>
<td>1.4</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Physical degradation d</td>
<td>0.5</td>
<td>0.5</td>
<td>10.7</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>21.3</td>
<td>22.0</td>
<td>43.7</td>
<td>13.1</td>
<td></td>
</tr>
</tbody>
</table>

- a Water erosion includes: loss of topsoil and terrain deformation.
- b Wind erosion includes: loss of topsoil by wind action, terrain deformation, and overblowing.
- c Chemical degradation includes: fertility decline and reduced organic matter content, salinization/alkalinization, dystrification/acidiﬁcation, eutrophication, and pollution.
- d Physical degradation includes: compaction, crusting and sealing, waterlogging, lowering of the soil’s surface, loss of productive function, and aridiﬁcation.

Finally, we combined the grain production information in Fig. 2 with the above soil degradation and available water scarcity data. We deﬁned water scarcity as a situation in which more than half of water demand from crop production is not met. A county has a soil degradation problem if more than 20% of crop land falls into the four types of soil degradation listed in Fig. 6. The superposition of grain production level and the natural resource conditions provides insight into the spatial pattern of the sustainability of grain production in China. Fig. 7 shows the status of soil degradation and water scarcity for Chinese grain production regions. The map shows where there are serious environmental stresses on Chinese grain production. The North China Plain, China’s bread basket, has both severe water scarcity and serious soil deterioration. The northwest region of Xinjiang, the “California of China”, has already shown signs of both soil quality deterioration and water shortage. Central China, another center of China’s grain production, has sufficient water but soil erosion, land salinization and declining soil fertility are widespread.

### Table 4
Water reliability indicators in major river basins in China.

<table>
<thead>
<tr>
<th>River basin</th>
<th>Water reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All crops</td>
</tr>
<tr>
<td>Heilongjiang</td>
<td>1.00</td>
</tr>
<tr>
<td>Yaluzangbu</td>
<td>1.00</td>
</tr>
<tr>
<td>Yangtze</td>
<td>1.00</td>
</tr>
<tr>
<td>Ganges</td>
<td>0.89</td>
</tr>
<tr>
<td>Haihe</td>
<td>0.33</td>
</tr>
<tr>
<td>Huaihe</td>
<td>0.31</td>
</tr>
<tr>
<td>Yellow</td>
<td>0.58</td>
</tr>
<tr>
<td>Indus</td>
<td>0.98</td>
</tr>
<tr>
<td>Lancang(Mekong)</td>
<td>1.00</td>
</tr>
<tr>
<td>Inner Mongolia</td>
<td>0.21</td>
</tr>
<tr>
<td>Ob River</td>
<td>0.17</td>
</tr>
<tr>
<td>Southeast Coast Rivers</td>
<td>0.98</td>
</tr>
<tr>
<td>Songhuajiang</td>
<td>1.00</td>
</tr>
<tr>
<td>Yilihe</td>
<td>0.50</td>
</tr>
<tr>
<td>Pearl</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Northeast China is mixed, with slightly more than half of the counties experiencing some soil degradation; the rest has no soil and water stresses so far. Judging only from these two parameters, we can clearly see that the hotspots of natural resources deterioration correspond to the major grain production areas.

7. Conclusion

Using detailed grain crop data at county level for an extended period (1980–2003), we have shown that there are significant shifts in grain production from the traditional grain producing areas in the central, south and east regions, towards the north and northeast regions—although the former still remain the most important areas. Within this overall shift, there is a high degree of variability within each region. We identified some key factors that explain the observed grain production shifts. These factors include: cultivated land availability, degree of urbanization and R&D policies targeting agriculture.

In the traditional “granary” of China, intensification of production was the only strategy to dramatically increase production, the consequence of which is substantial negative environmental stress represented by high degrees of soil salinity and water shortages. However, the shift towards even more environmentally fragile zones, which have relatively more land but more limited water resources, might rapidly increase the environmental stress—in particular water availability—in these areas. Since most grain production in China is dependent on irrigation, this observed shift will put heavy pressure on the existing resource base.

The conclusion, based on the combination of our results on grain area shifts presented in Fig. 4 [(1)–(4)] and environmental stress indicators, is rather grim. We namely observed a movement of grain crops (which depend largely on irrigation) to those areas where environmental stress is caused by water shortages. In the North China Plain, water tables have been falling considerably since the 1990s. Official statistics for the North China Plain show that during the period 2000–2006 the groundwater level on average declined in 61% of the monitoring sites while the level increased in the remaining 39% (Qu et al., 2011—this issue). Hence, the shift away from the already-fragile agro-ecological areas in the traditional “granary” areas to the north and northeast might be seen at first sight as environmentally desirable. However, when analyzing the natural resources base in these areas, it becomes clear that such a shift may not be sustainable.

We have shown in this paper that the spatial shift can be significantly explained by available land, degree of urbanization and government policies. This means the spatial shift is partly market-induced and partially policy-induced. There is a risk that similar processes of resource degradation are to be expected in the “new” areas where grain is migrating. Government policies should therefore be focused on avoiding such processes; more attention should be paid in R&D policies to the stimulation of water saving techniques, land conservation and appropriate crop-mix changes. These might still provide sufficient grain production, but will not worsen—and hopefully improve—the already fragile land and water resource base in and northeast regions.

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