Science of the Total Environment 716 (2020) 137119

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

# Impact of spatiotemporal change of cultivated land on food-water relations in China during 1990–2015

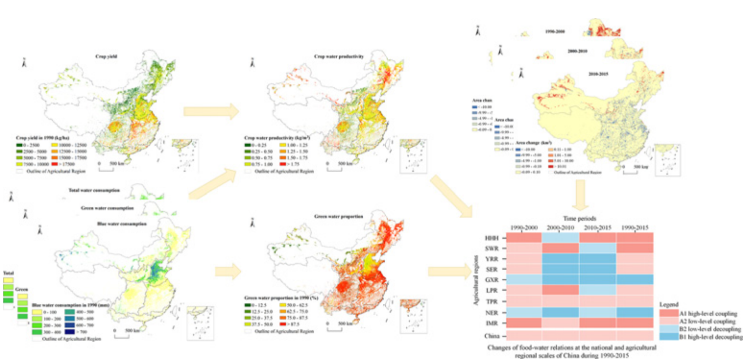
Xue Wang [a,*], Liangjie Xin [a], Minghong Tan [a,b], Xiubin Li [a,c], Jiayue Wang [a]

[a] Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[b] International College, University of Chinese Academy of Sciences, Beijing 10049, PR China
[c] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 10049, China

## HIGHLIGHTS

- We developed new spatially explicit datasets for constant food crop yield and constant food crop water production in China.
- Cultivated land change resulted in a rough decrease in average food crop yield in China during 1990–2015.
- Cultivated land change resulted in decreases in average $ET_a$ and $ET_{green}$ a, and an increase in $ET_{blue}$ in China during 1990–2015.
- Cultivated land change resulted in an increase of average CWP and a decrease in average GWP in China during 1990–2015.
- Cultivated land change resulted in a low-level coupling food-water relations, with a negative environmental effect in China.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

*Article history:*
Received 29 October 2019
Received in revised form 30 January 2020
Accepted 3 February 2020
Available online 4 February 2020

Editor: Jay Gan

*Keywords:*
Land use change
Crop yield
Crop water productivity
Green water proportion
China

## ABSTRACT

The spatiotemporal change of cultivated land can exert significant effects on food production and the associated water consumption. The quantification of these effects is meaningful for guiding relevant policies. However, few studies have explored systematic methods assessing changes of food production and water consumption and the relations between them, caused by cultivated land change. This study developed new spatially explicit datasets for constant food crop yield and constant food crop water consumption, combining agricultural statistical data, the China-AEZ model, and the GIS spatial analysis method, and estimated the impact of cultivated land change on food crop production, food crop water consumption and food-water relations characterized by two major indicators, i.e., crop water productivity (CWP) and green water proportion (GWP), in China during 1990–2015. The results showed that the increase of approximately 0.80% in cultivated land area in China resulted in a decrease of approximately 0.37% in average food crop yield per unit area, an increase of approximately 1.97% in blue water consumption per unit area ($ET_{blue}$), and continuous decreases in both total water consumption per unit area ($ET_a$) and green water consumption per unit area ($ET_{green}$), with overall rates of 2.41% and 3.11%, respectively, at the national scale from 1990 to 2015. Concurrently, the average CWP continuously increased with an overall rate of 2.06%, while the average GWP continuously decreased with an overall rate of 0.86% at the national scale. A low-level coupling trend of food-water relations was concluded, together with a negative environmental effect. The food-water relations were getting even worse in major cultivated land expansion areas and during the later period of 2000–2015. The findings of this study can be useful for providing a deep understanding of food-water relations corresponding to cultivated land change and giving suggestions for the sustainable development of cultivated land and the integrated management of water resources.



* Corresponding author.
*E-mail address:* wangxue@igsnrr.ac.cn (X. Wang).

https://doi.org/10.1016/j.scitotenv.2020.137119
0048-9697/

## 1. Introduction

Cultivated land is widely known as the basis of food production. To provide more food, the global area of cultivated land has been increased by 12% over the last 50 years (Food and Agriculture Organization of the United Nations (FAO), 2011). The newly added cultivated land is mainly derived from areas with forest, shrub, grassland and sparse vegetation (Lambin and Meyfroidt, 2011; Tan and Li, 2019). Moreover, cultivated land has been converted into other land use types, i.e., forest, settlement and grassland, mainly attributed to land abandonment, urban expansion and environmental policy (Lambin and Meyfroidt, 2011; van Vliet et al., 2015; Li and Li, 2016; Tan and Li, 2019). The spatiotemporal change of cultivated land has become one of the major manifestations of global land use change, which can exert impacts on not only food production but also the associated water consumption and the relations between them (Ewert et al., 2005; Foley et al., 2005; Foley et al., 2011; Zuo et al., 2018).

China is a typical country experiencing spatiotemporal changes of cultivated land. With the rapid development of industrialization and urbanization in China, cultivated land has been lost, and the area of high-quality cultivated land occupied by built-up areas totaled approximately $300 \times 10^4$ ha from 1996 to 2009 (Kong, 2014). This first occurred in the more developing East China and then expanded to the less developing Central and West China (Liu et al., 2014b). The decrease in the quantity of cultivated land has aroused much attention across China, and the government has implemented a set of programs aiming to maintain the cultivated land requisition-compensation balance (Song and Pijanowski, 2014). However, the quality of the land converted to and from cultivated land usually varies, and therefore, the cultivated land productivity at the national scale has changed along with the quantity of cultivated land, which may impact China's and even the world's secure supply of food. In this context, the quantification of the impact of cultivated land change on food production has become the research interest of many scholars, whose evaluation methods and/or study periods vary with each other, resulting in inconsistent conclusions (Yan et al., 2009; Liu et al., 2014c; Song and Liu, 2016; Xu et al., 2017; Li et al., 2018).

In addition to food crop production, China's cultivated land change can also exert an impact on food crop water consumption because the crops or cropping systems adopted on cultivated land and their water consumption vary across the country (Liu et al., 2007b, 2009a). More specifically, the consumed water of food crops has different composition with regard to water sources across China (Liu and Yang, 2010). Green water and blue water are generally used for food crop production; the former refers to the precipitation directly consumed by plants to produce biomass (Rockström et al., 2007), which is more plentiful in Southeast China than in Northwest China, while the latter is from surface water bodies and groundwater, which is a supplement to green water through irrigation (Hoekstra and Mekonnen, 2012). Blue water plays a vital role in crop production and increasing crop yields, especially for crops in Northern China (Liu et al., 2007a). In this context, the spatiotemporal change of cultivated land can exert impacts on “colorful” water uses associated with food production. In other words, cultivated land change can bring about changes in not only blue water consumption but also green water consumption for food production. However, there was a very small number of studies paying attention to changes of blue water consumption caused by cultivated land change in China, and the quantification of changes in green water consumption was even marginalized by such studies(Huang et al., 2012; Zuo et al., 2018), mainly because the opportunity cost of blue water is much higher than that of green water, and the overuse of blue water, especially that drawn from underground, were more likely to cause disasters and environmental problems (Liu and Yang, 2010; Wang et al., 2015). Considering that both green and blue water are important for food production, water use assessments are incomplete without considering green water (Liu et al., 2009a).

Besides food production and the associated water consumption, relations between them, i.e., food-water relations, may also change due to the spatiotemporal change of cultivated land in China. Defined as the ratio of crop yield and water consumption, crop water productivity (CWP) combines the two important and interrelated processes in food crop production systems and is therefore regarded as an integrated indicator relating to food-water relations (Liu et al., 2007a; Lu et al., 2016). Previous studies focused mainly on the impacts of different irrigation regimes on the CWP, using site experiments or crop models, with the aim to give suggestions for the improvement of CWP with less irrigation at local or regional scales (Li and Ren, 2019; Zhang et al., 2019b; Zhou and Zhao, 2019). (Liu et al., 2007a; Huang et al., 2019). There were also studies relating to the modelling of CWP for specific food crops, e.g., wheat, at national scale, using large-scale food production models (Liu et al., 2007a; Huang et al., 2019). However, few studies considered the quantitative evaluation of changes in CWP for general food production from the perspective of the spatiotemporal changes of cultivated land at the national and subnational scales in China. In addition, as the CWP does not take into account the structure of colorful water uses, the green water proportion of consumptive water use (GWP), which is an effective tool to assess both the role of green water in food crop production and the impacts of colorful water uses on the environment, should also be evaluated to better characterize the food-water relations in China (Liu et al., 2009a; Page et al., 2011; Wang et al., 2015; Lu et al., 2016). However, few studies have explored the methodology for such quantifications.

Considering the above shortcomings, in this study, we developed a new integrated approach to assess the impacts of spatiotemporal change of cultivated land on food production and water consumption and the relations between them in China. The main objectives of this study were to (1) analyze the impact of the spatiotemporal change of cultivated land on food production and colorful water consumptions at the national and subnational scales in China during 1990–2015 and (2) specify the changes in food-water relations characterized mainly by the CWP and GWP in China. Combining agricultural statistical data, the China-AEZ (Chinese edition of Agro-Ecological Zones) model, and geographical information system (GIS), a new spatially explicit food crop yield dataset and a new spatially explicit food crop water consumption dataset of China were developed. The impacts of cultivated land change on food crop production, food crop water consumption, CWP and GWP during 1990–2015 were quantified. This study addresses the food-water nexus relating to land use change and has global significance. The main findings of this study are meaningful not only for meeting the demands for the sustainable development of cultivated land and integrated management of water resources in China but also for providing a reference for future studies in similar areas worldwide on the food-water effects of the spatiotemporal change of cultivated land.

## 2. Materials and methods

### 2.1. A general theory framework for the impact of cultivated land change on food-water relations

In this study, we focused on the impact of cultivated land change on food production and water consumption and the relations between them by ignoring the temporal variations of climate and agricultural practices on cultivated land throughout China. Therefore, new spatially-explicit datasets for constant actual food crop yield, colorful food crop water consumptions, CWP and GWP were constructed for quantification of these impacts. In this context, the spatial heterogeneities of the above datasets can be regarded as the fundamental reasons for the generation of the impacts of cultivated land change in China. When spatiotemporal changes of cultivated land happened, values of food crop yield, colorful water consumptions, and the two major indicators representing food-water relations, i.e., CWP and GWP, in areas experiencing expansion of cultivated land are very likely different with those in areas suffering shrinkage of cultivated land within regions. Besides, the direction and magnitude of the changes can also be affected by the areas of cultivated land increased and decreased within regions. Therefore, the spatiotemporal changes of cultivated land should have resulted in changes of not only food crop production and colorful water consumptions but also the relations between them at the national and sub-national scales of China.

In theory, changes of food-water relations can be roughly categorized into four trends: (1) When both CWP and GWP increase, the water productivity improves together with a larger contribution of green water in total water consumption. Considering the low opportunity cost of green water and the low negative environmental influences of green water use, the food-water relation presents a significant "high-level coupling" trend. (2) When CWP increases but GWP decreases, the improvement of water productivity is accompanied by decline of the contribution of green water in total water consumption. Therefore, although the food-water relation presents a coupling trend, this trend is not perfect because higher burden is exerted on the environment by more dependency on blue water. We define it as the "low-level coupling" trend. (3) When CWP and GWP both decrease, water productivity decreases together with higher dependency on blue water for food production, which is also more likely to trigger environmental problems. Therefore, the food-water relation takes on a "high-level decoupling" trend. (4) When CWP decreases but GWP increases, the situation is not so bad as that described above, and is defined as the "low-level decoupling" trend.

### *2.2. Data preparation*

The spatial and temporal resolution of the datasets used in this study are listed in Table 1.

The land use data were obtained from the National Earth System Science Data Sharing Infrastructure (Chinese Academy of Sciences, 2019), with a resolution of 30 arc *sec*. They were updated regularly at five-year intervals from 1990 to 2015 with standard procedures based on Landsat TM/ETM+ images (Liu et al., 2014a). The land use data can be grouped into six major classes: cultivated land, woodland, grassland, water body, built-up area and unused land. The cultivated land maps for the years 1990, 2000, 2010, and 2015 were derived from the above national land-use database, which were not only used to identify the spatiotemporal change of cultivated land but also applied as major inputs for the China-AEZ model.

Meteorological data, including monthly maximum and minimum temperature, precipitation, wind speed, relative humidity, and sunshine duration for the period 1981–2010, were obtained from the China Meteorological Administration (2012). The 30-year average monthly data for each of the above meteorological factors were first calculated and then interpolated to all of China using the thin plate smoothing spline method (Hancock and Hutchinson, 2006). These interpolated data were also major inputs for the China-AEZ model.

Soil data and the Digital Elevation Model (DEM) data were also major inputs for the China-AEZ model. Soil data, with a resolution of 30 arc *sec*, were obtained from the Institute of Soil Science, Chinese Academy of Sciences (IIASA/FAO, 2012). DEM data, with a resolution of 3 arc *sec*, were obtained from the Shuttle Radar Topography Mission (SRTM) database (CGIAR-CSI, 2006). The DEM data were resampled to 30 arc sec before use in the China-AEZ model.

Irrigated and rainfed crop areas, with a resolution of 5 arc minutes, were obtained from the global data set of monthly irrigated and rainfed crop areas around the year 2000 (MIRCA 2000 data) (Portmann et al., 2010). However, crops grown on newly added cultivated land after 2000 were not considered by these data. Therefore, using these data and the spatial statistics tool in ArcGIS 10.4, we calculated the proportions of irrigated areas to total areas sown for major food crops at the county level, which were primary parameters for the quantification of food crop water consumption across China. Using this method, we can fill up the missing data on newly added cultivated land, though the spatial resolution decreased. We assumed that the proportions for one crop remain the same within counties.

The ratio of irrigated area to cultivated land area, with a resolution of 30 arc *sec*, was obtained from the Chinese Academy of Agricultural Sciences (2016). It was applied when simulating the potential food crop yield, which was a primary parameter for the quantification of food crop production in China.

County-level agricultural statistical data, including the cultivated land area, total production and sown area of food crops for the years 1990, 2000, 2010, and 2015, were also obtained from the Chinese Academy of Agricultural Sciences (2016). These data were used to calculate the multiyear average food crop yield and the multiyear average proportions of areas sown with major food crops at the county level, which were key elements in developing the spatially explicit food crop yield dataset and the spatially explicit food crop water consumption dataset of China, respectively.

The geographical boundaries used in this study included the boundaries of the county and agricultural region, which were both derived from the National Earth System Science Data Sharing Infrastructure (Chinese Academy of Sciences, 2019). The most recent county boundary in 2014 was applied throughout the study, and all changes in county boundaries during 1990–2015 were revised accordingly. A total of 2340 counties were included, with Taiwan, Hong Kong, and Macao excluded due to lack of data. A total of 9 agricultural regions were segmented based on agricultural production characteristics and physical-geographical environment (Fig. 1), aiming to characterize the spatial heterogeneity of changes in food-water relations relevant to the spatial shift of cultivated land within China.

**Table 1**
Datasets used in this study.

| Datasets | Spatial reference | Source |
|---|---|---|
| 1. Land use data | 30 arc *sec* | Chinese Academy of Sciences (2019) |
| 2. Meteorological data | 839 stations | China Meteorological Administration (2012) |
| 3. Soil data | 30 arc *sec* | IIASA/FAO (2012) |
| 4. Digital Elevation Model (DEM) | 30 arc *sec* | CGIAR-CSI (2006) |
| 5. Irrigated and rainfed crop areas | 5 arc minutes | Portmann et al. (2010) |
| 6. Ratio of irrigated area to cultivated land area | 30 arc sec | Chinese Academy of Agricultural Sciences (2016) |
| 7. Agricultural statistical data | County | Chinese Academy of Agricultural Sciences (2016) |
| 8. Geographical boundaries | County/Agricultural region | Chinese Academy of Sciences (2019) |

### *2.3. A brief description of the China-AEZ model*

The Chinese edition of the Agro-Ecological Zones (China-AEZ) model was applied in developing new spatially explicit datasets for constant food crop yield and constant food crop water consumptions. This model was developed during the major NSFC-IIASA cooperation project: *Assessing the impact of climate change and incentive human activities on China's agro-ecosystem and its supply potentials (2010—2012)* (Tian et al., 2011; Tian et al., 2012). It can simulate crop growth and water balance processes occurring throughout the soil-plant-atmosphere continuum, by taking into consideration of climate, soil, and terrain conditions. It can be used to obtain potential yield and water consumption, i.e., the total volume of water consumed in terms of evapotranspiration (ET), including green and blue water consumption/evapotranspiration ($ET_{green}$ and $ET_{blue}$), of a variety of crops (Wang et al., 2015; Xu et al., 2019). Specifically, the methodology for the calculation of potential yields is based on ecophysiological principles, while ET is estimated using the crop

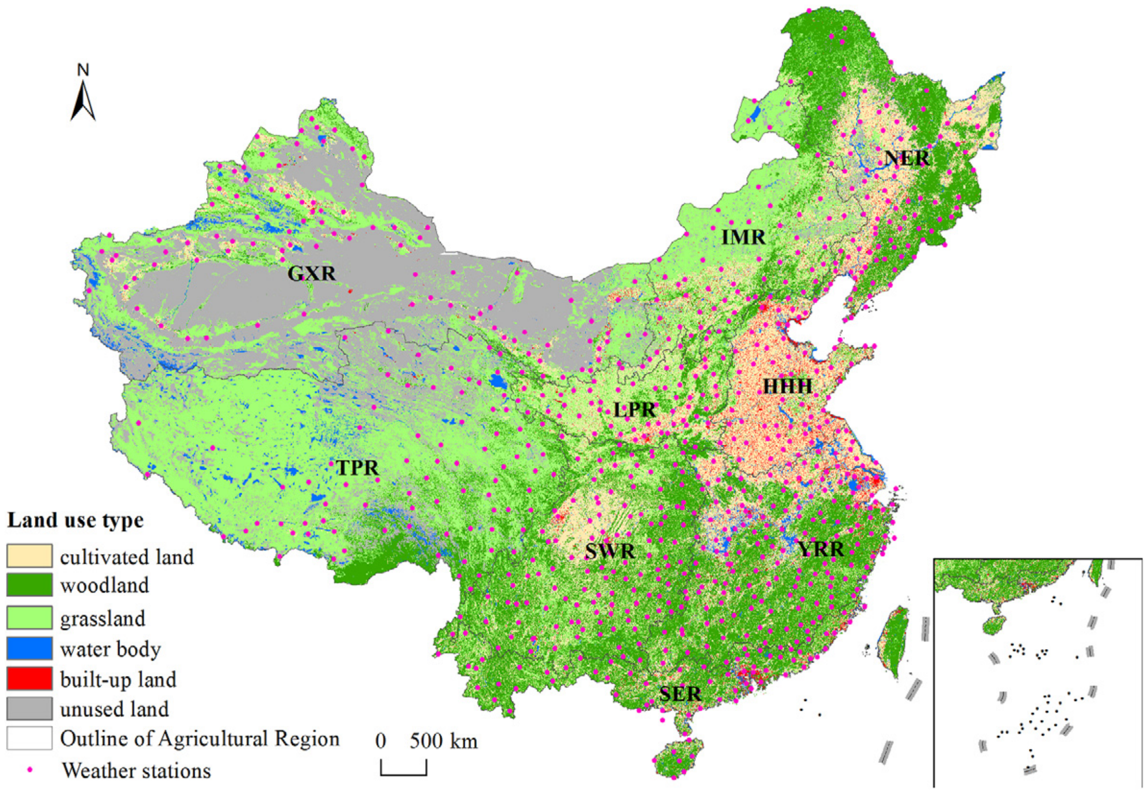



**Fig. 1.** Map of agricultural regions: HHH, SWR, YRR, SER, GXR, LPR, TPR, NER, and IMR represent the Huang-Huai-Hai region, the Southwest China region, the Middle-lower Yangtze River region, the Southeast China region, the Gansu-Xinjiang region, the Loess Plateau region, the Tibetan Plateau region, the Northeast China region, and the Inner Mongolia region, respectively.

coefficient method recommended by FAO. The details of the China-AEZ modelling methodology can be found in IIASA/FAO (2012).

*2.4. Food crop yield dataset at the pixel level*

The spatially explicit constant food crop yield dataset of China, with a resolution of 30 arc *sec*, was developed using the statistical food crop yield at the county level, the potential yield estimated using the China-AEZ model, and a GIS spatial analysis method.

The food crop yield of county *i* was first calculated using the following formulas:

$$Yield_i = \frac{1}{4}\sum_{m=1}^{4}\left(\frac{\sum_{k=1}^{5} p_{imk}}{\sum_{k=1}^{5} s_{imk}} \times MCI_{im}\right) \tag{1}$$

$$MCI_{im} = \frac{\sum s_{imn}}{s_{cul}} \tag{2}$$

where $Yield_i$ is the average food crop yield per unit area (kg/ha) of 4 years (1990, 2000, 2010, and 2015) for county *i*. The subscript *m* is the code for the years, and $m = 1, 2, 3$, and 4. The multiyear average food crop yield is used to reduce fluctuations of climate variation between years. $\sum_{k=1}^{5} p_{imk}$ and $\sum_{k=1}^{5} s_{imk}$ are the sums of productions and sown areas of major food crops of county *i* in year *m*, respectively. The subscript *k* refers to the food crop type. In this study, wheat, maize, rice, soybean, and potato were selected as major food crops in China because they represent more than 90% of China's total food output (Liu et al., 2014b). Therefore, $k = 1, 2, 3, 4$, and 5. According to the National Bureau of Statistics of the People's Republic of China (2016), potato production should be first converted at a scale of 5:1 before it is added to the total production. The multiple cropping index (MCI) was applied to convert the average yield of food crops to the total yield of food crops per unit area of cultivated land. $MCI_i$ equals the ratio of the total area of agricultural crops sown (including food crops and other cash crops) ($\sum s_{imn}$) to the area of cultivated land ($s_{cul}$) in county *i*.

The food crop yield at the pixel level was then estimated, combined with the potential yield of food crops per unit area simulated by the China-AEZ model and the GIS spatial analysis method. The formula is presented below:

$$Yield_{ij} = \frac{PY_{ij}}{\overline{PY_i}} \times Yield_i \tag{3}$$

where $Yield_{ij}$ refers to the average food crop yield per unit area (kg/ha) of pixel *j* in county *i*. $PY_{ij}$ refers to the potential yield of food crops of pixel *j* in county *i*, and $\overline{PY_i}$ refers to the average potential yield of food crops of county *I*, obtained using the GIS spatial analysis method. The simulated potential yield of food crops was previously used to assess the impact of cultivated land change on food crop production potential in China (Liu et al., 2014c; Xu et al., 2017). Although the simulated potential yield per unit area was nearly 1.55 times as much as the actual yield (the statistical one), an excellent correlation was found between the simulated potential yield and the actual yield at the county level, taking the year 2010 as an example (Liu et al., 2014b). The spatial heterogeneity of simulated potential yield can be a good reflection of the spatial variation of actual yield. Therefore, the potential yield of food crops per unit area was applied, and a new spatially explicit constant food crop yield dataset of China was developed accordingly (Fig. 2a). When simulating potential food crop yield per unit area, the same procedure as Liu et al. (2014c) was adopted in this study.

*2.5. Food crop water consumption dataset at the pixel level*

A spatially explicit constant food crop water consumption dataset for China, including not only total water consumption ($ET_a$) but also $ET_{green}$ and $ET_{blue}$ for food crops on cultivated land in China, with a resolution of

30 arc *sec*, was developed using the formulas listed as follows:

$$ET_{a,ij} = \sum_{k=1}^{5} (P_{ik} \times ET_{a,ijk}) \times \overline{MCI_i} \quad (4)$$

$$ET_{green,ij} = \sum_{k=1}^{5} (P_{ik} \times ET_{green,ijk}) \times \overline{MCI_i} \quad (5)$$

$$ET_{blue,ij} = \sum_{k=1}^{5} (P_{ik} \times ET_{blue,ijk}) \times \overline{MCI_i} \quad (6)$$

where $ET_{a,\ ij}$, $ET_{green,\ ij}$ and $ET_{blue,\ ij}$ refer to the average total water consumption, green water consumption and blue water consumption of food crops (mm) for 4 years (1990, 2000, 2010, and 2015) in pixel $j$ of county $i$, respectively. $\overline{MCI_i}$ refers to the 4-year average multiple cropping index of county $i$. $P_{ik}$ refers to the 4-year average proportion

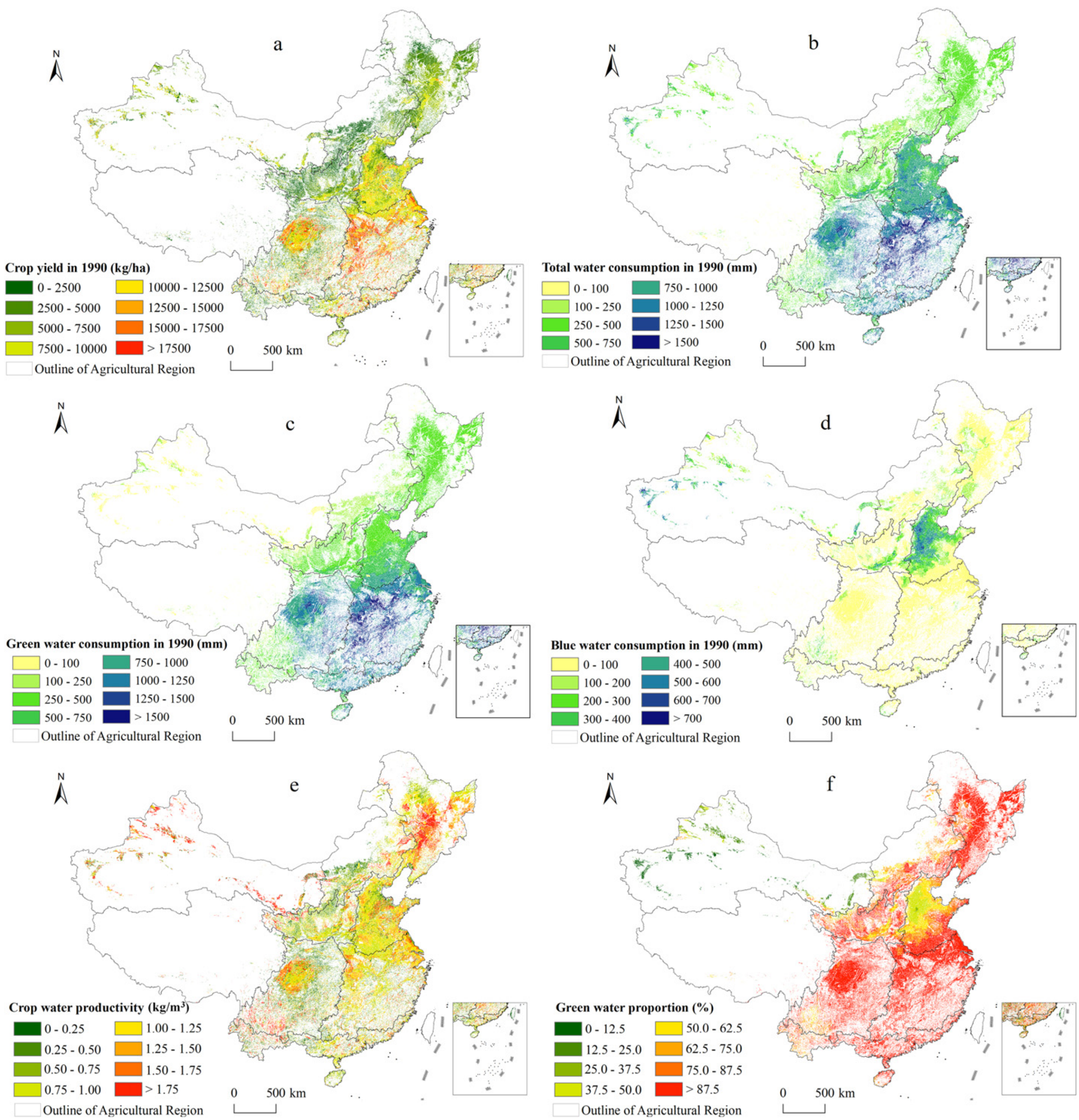



**Fig. 2.** The spatial distributions of crop yield (a), total water consumption (b), green water consumption (c), blue water consumption (d), crop water productivity (e) and green water proportion (f) on cultivated land in 1990.

of sown area of major food crop $k$ to the total sown area of 5 major food crops and is calculated using the following formula:

$$P_{ik} = \frac{1}{4}\sum_{m=1}^{4}\frac{s_{imk}}{\sum_{k=1}^{5} s_{imk}} \tag{7}$$

where $s_{imk}$ refers to the sown area of food crop $k$ in county $i$ in year $m$; $m = 1, 2, 3$, and 4. $ET_{a,\ ijk}$, $ET_{green,\ ijk}$ and $ET_{blue,\ ijk}$ refer to the total water consumption, green water consumption and blue water consumption of food crop $k$ (mm) in pixel $j$ of county $i$, respectively. They are calculated using the following formulas:

$$ET_{a,ijk} = ET^{irr}_{a,ijk} \times IRR_{ik} + ET^{rfd}_{a,ijk} \times (1 - IRR_{ik}) \tag{8}$$

$$ET_{green,ijk} = ET^{irr}_{green,ijk} \times IRR_{ik} + ET^{rfd}_{green,ijk} \times (1 - IRR_{ik}) \tag{9}$$

$$ET_{blue,ijk} = ET^{irr}_{blue,ijk} \times IRR_{ik} \tag{10}$$

where
$IRR_{ik}$refers to the proportion of irrigated area to the total area of food crop $k$ sown in county $i$, which is calculated using the MIRCA 2000 data. Here, we assumed that $IRR_{ik}$ is homogeneous at the county level for the same food crop. $ET^{irr}_{a,\ ijk}$, $ET^{irr}_{green,\ ijk}$ and $ET^{irr}_{blue,\ ijk}$ refer to the total water consumption, green water consumption and blue water consumption of food crop $k$ (mm) in pixel $j$ of county $i$ under the irrigation condition, respectively; $ET^{rfd}_{a,\ ijk}$ and $ET^{rfd}_{green,\ ijk}$ refer to the total water consumption and green water consumption of food crop $k$ (mm) in pixel $j$ of county $i$ under the rainfed condition, respectively.

The ET indicators of the 5 major food crops were separately estimated using the China-AEZ model. Details of the China-AEZ modelling methodology for crop evapotranspiration can be found in one of our previous studies, taking winter wheat in the North China Plain as an example (Wang et al., 2015). In this study, we apply the ET values under the average climatic conditions during 1981–2010 to offset the influence of extreme weather incidents. The results of the China-AEZ model have been validated (Supplementary Fig. 1).

Finally, we obtained constant food crop $ET_a$, $ET_{green}$ and $ET_{blue}$ on cultivated land at the pixel level in China (Fig. 2b-d).

### 2.6. Crop water productivity and green water proportion

The CWP at the pixel level can be calculated as the ratio of food crop yield to total water consumption:

$$CWP_{ij} = 10 \times Yield_{ij}/ET_{a,ij} \tag{11}$$

where $CWP_{ij}$ refers to the food crop water productivity (kg/m$^3$) of pixel $j$ in county $i$. $Yield_{ij}$ and $ET_{a,\ ij}$ refer to the food crop yield (kg/ha) and total water consumption (mm) of pixel $j$ in county $i$, respectively. The constant 10 is used to convert mm into m$^3$/ha.

The GWP at the pixel level can be calculated as follows:

$$GWP_{ij} = ET_{green,ij}/ET_{a,ij} \times 100\% \tag{12}$$

where $GWP_{ij}$ refers to the green water proportion (%) for food crops in pixel $j$ of county $i$. $ET_{green,\ ij}$ and $ET_{a,\ ij}$ refer to the green water consumption (mm) and total water consumption (mm) for food crops in pixel $j$ of county $i$, respectively.

A higher CWP indicates a higher water use efficiency in food crop production on cultivated land, while a smaller CWP means that more water resources are consumed when achieving the same food crop yield. In terms of GWP, a higher value indicates a larger proportion of $ET_{green}$ to $ET_a$ in food crop production on cultivated land and correspondingly a more friendly environmental effect because the use of green water instead of blue water places less pressure on the local water supply system, and vice versa. The spatial distributions of CWP and GWP are shown in Fig. 2e-f.

## 3. Results

### 3.1. Spatiotemporal change of cultivated land in China

The total area of cultivated land increased from approximately $177.18 \times 10^4$ km$^2$ in 1990 to $178.60 \times 10^4$ km$^2$ in 2015, with an increasing rate of 0.80%. There was a larger amount of cultivated land increment during 1990–2000, resulting in a larger area of cultivated land in 2000 ($180.05 \times 10^4$ km$^2$) than in 2015, and a continuous decrease in cultivated land area occurred during 2000–2015. Spatially, during 1990–2000, the new cultivated land was mainly located in Northeast China, while the decrease in cultivated land mainly occurred in the eastern coastal area of China, especially the mostly developed Beijing-Tianjin-Hebei region, Yangtze River Delta region, and Pearl River Delta region (Fig. 3). During 2000–2010 and 2010–2015, the spatial distributions of the changing area of cultivated land were nearly the same (Fig. 3): large-scale new cultivated land was located in Northwest China, followed by Northeast China; decrements continued in the eastern coastal area of China, and they occurred in large amounts in the central and western areas of China, implying a spread of cultivated land loss from the eastern coastal area to the central and western areas in China.

In terms of agricultural regions, their changing trends in cultivated land area varied (Fig. 4). The YRR, the HHH, the SWR and the SER all suffered continuous decreases during 1990–2015. In comparison, the areas of cultivated land in the NER and the GXR continued to increase during 1990–2015. Specifically, during 1990–2000, the increment in the NER was $2.86 \times 10^4$ km$^2$, much larger than the increment in the GXR ($0.34 \times 10^4$ km$^2$); in contrast, during 2000–2015, the increments in the GXR added up to $1.94 \times 10^4$ km$^2$, much larger than the increments in the NER ($0.34 \times 10^4$ km$^2$). The other three agricultural regions, i.e., the IMR, the LPR, and the TPR, increased in terms of the area of cultivated land during 1990–2000 and then decreased during 2000–2015, resulting in net increases in the IMR and the TPR and a net decrease in the LPR during 1990–2015.

### 3.2. Changes in food crop production and food crop water consumption

During 1990–2015, the spatial change of cultivated land resulted in a 0.37% decrease in the average food crop yield at the national scale. This was mainly attributed to the decreases of average food crop yield in the GXR and the NER, while the average food crop yield in the other agricultural regions all experienced increments during 1990–2015 (Fig. 5a). The changing trends were not consistent within the entire study period. With respect to the period 1990–2000, there was a 0.72% increase in average food crop yield at the national scale, and most of the agricultural regions, except the NER, experienced increments in average food crop yield. Then, the average food crop yield at the national scale began to decrease, and the rates equaled 0.51% and 0.57% during 2000–2010 and 2010–2015, respectively. Specifically, the average food crop yields in the eastern regions, including the HHH, the YRR, the SER and the NER, together with the GXR, all changed to decrease during 2000–2010 and continued decreasing during 2010–2015, while those in the SWR, the LPR, and the TPR did not decrease until the period 2010–2015. Only the average food crop yield in the IMR continued to increase during 1990–2015 (Fig. 5a).

With the spatiotemporal change of cultivated land, both the average $ET_a$ and the average $ET_{green}$ of food crops in China continued decreasing during 1990–2015, with overall rates of 2.41% and 3.11%, respectively. With respect to agricultural regions, the average $ET_a$ and the average $ET_{green}$ in the SER, the LPR, the TPR, and the NER all showed general decreasing trends during 1990–2015. In comparison, approximate increases both in the average $ET_a$ and the average $ET_{green}$ occurred in the YRR, the HHH, the SWR, and the IMR. In the GXR, the changing trends

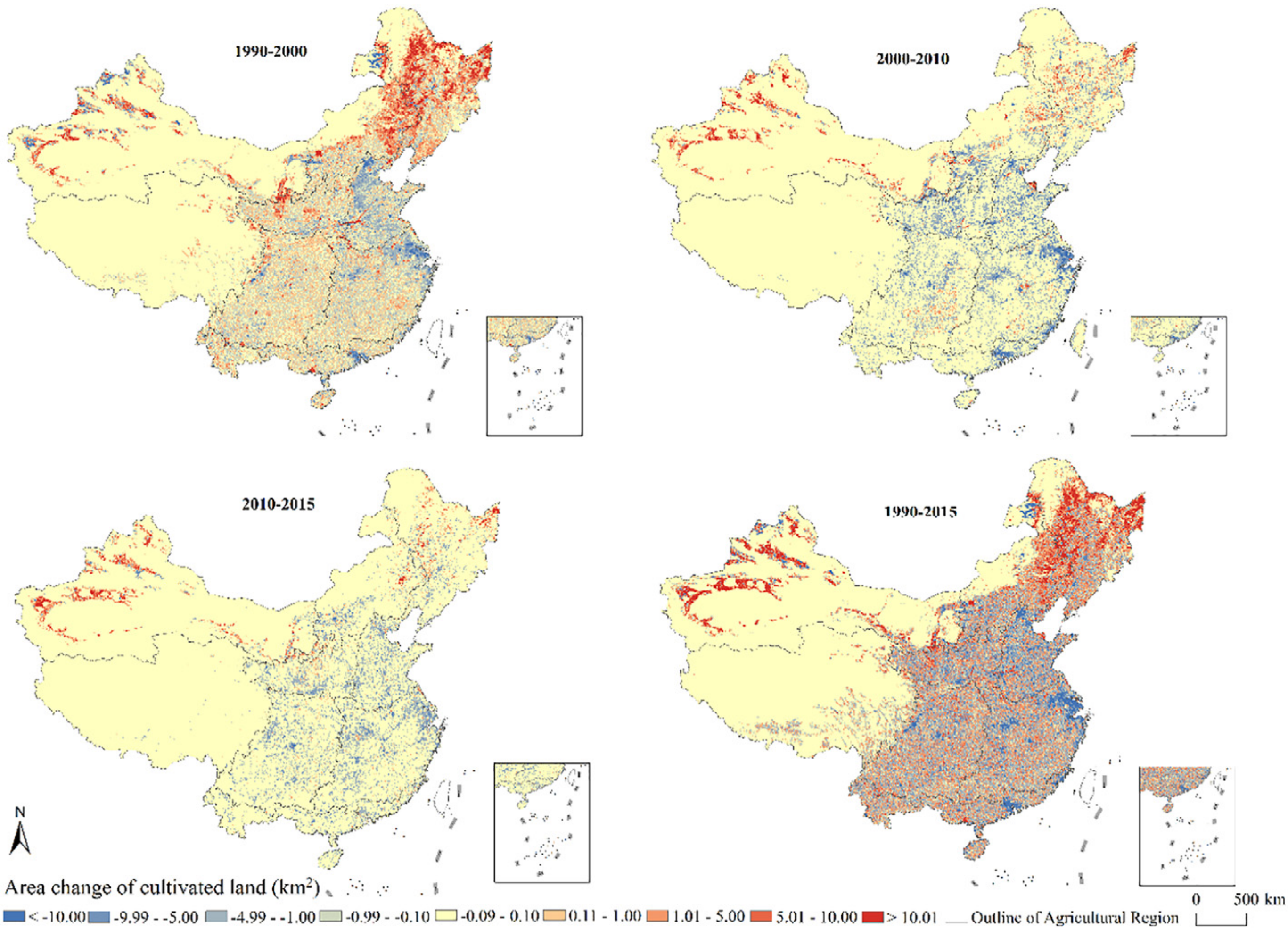



**Fig. 3.** Area change of cultivated land at a scale of 10 × 10 km$^2$ across China during 1990–2015.

in the average $ET_a$ and the average $ET_{green}$ were the opposite, with the former being positive and the latter being negative (Fig. 5b and c).

The average $ET_{blue}$ of food crops first decreased 0.53% during 1990–2000 and then increased during 2000–2015, resulting in a total 1.97% increase at the national scale during 1990–2015. During 1990–2000, decreases of the average $ET_{blue}$ occurred in most of the agricultural regions, except the YRR and the GXR, and the decreasing rate in the NER was the greatest (2.50%). Then, the changing trends in the IMR increased during 2000–2015, while the changing trends in the other agricultural regions remained the same as those during 1990–2000. According to Fig. 5d, the increment of the average $ET_{blue}$ in the GXR (with an increase rate of 4.64%) was most obvious across China during 1990–2015.

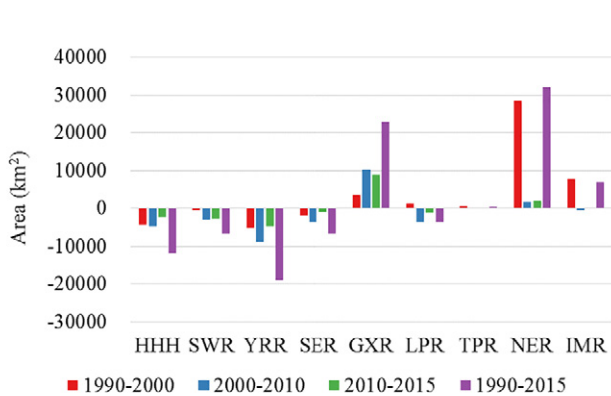



**Fig. 4.** Area change of cultivated land in agricultural regions during 1990–2015.

### 3.3. Changes in food crop water productivity and green water proportion

During 1990–2015, the cultivated land change resulted in a continuous improvement in the average CWP at the national scale, with a total ratio of 2.06%. Spatially, 7 of the 9 agricultural regions experienced rough or continuous improvements in average CWP (Fig. 5e). Specifically, in the HHH, the SWR, the YRR, and the SER, the improvements occurred mainly during 1990–2000, and continuous declines occurred during 2000–2015. The average CWP in the TPR and the IMR continuously increased during the entire period. In contrast, the GXR and the NER, i.e., the regions with major increments of cultivated land area, suffered continuous decreases in average CWP during 1990–2015 (Fig. 5e).

In contrast to the changing trend in average CWP, the average GWP continued to decrease from 85.90% in 1990 to 85.04% in 2015 in China. According to Fig. 5f, during 1990–2015, the declines in average GWP in two agricultural regions, the GXR and the NER, were the most obvious, with total decreasing values equal to 2.20% and 1.42%, respectively. In addition, the SER, the YRR, and the TPR suffered continuous decreases in average GWP during 1990–2015. In comparison, the average GWP in the HHH, the IMR, and the SWR increased during 1990–2015, and the total increasing value in the HHH (0.14%) was the largest.

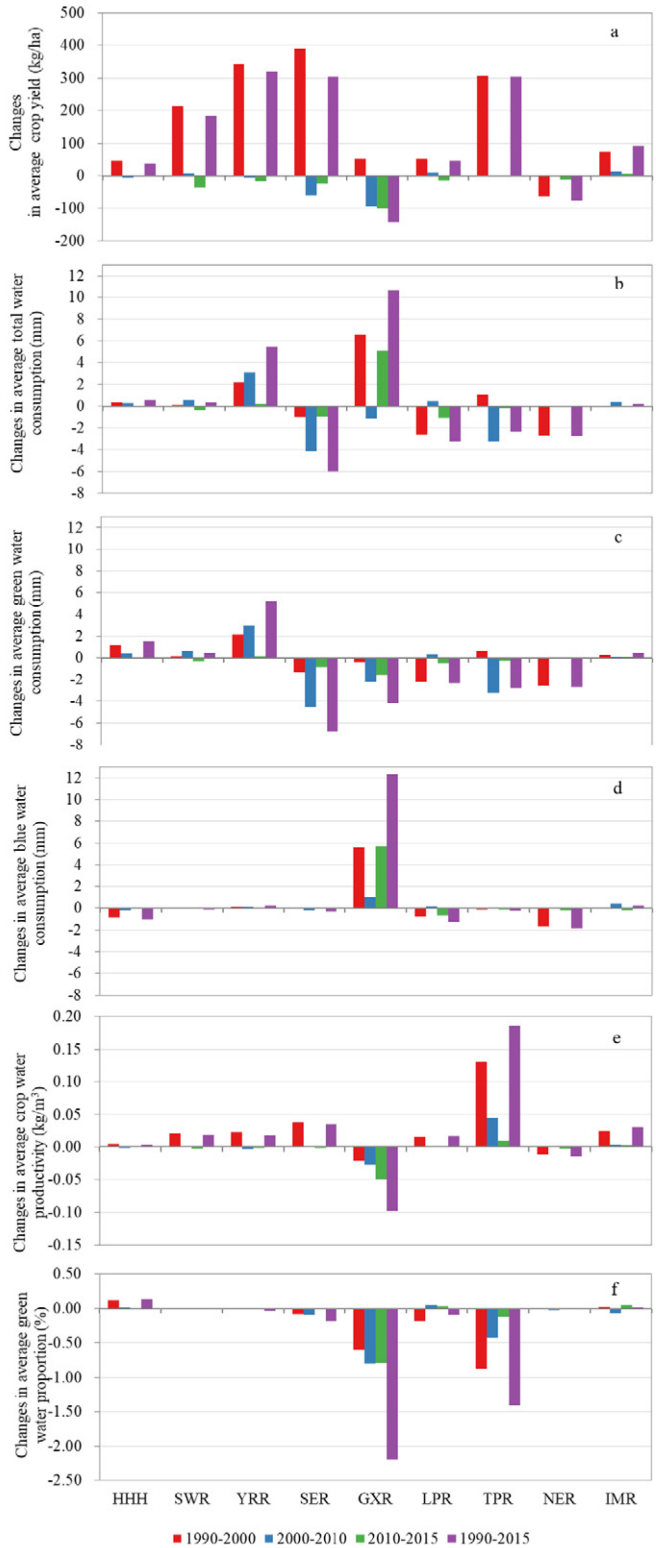



**Fig. 5.** Changes in average crop yield (a), average total water consumption (b), average green water consumption (c), average blue water consumption (d), average crop water productivity (e), and average green water proportion (f) in agricultural regions of China.

### *3.4. Changes in food-water relations at the national and agricultural regional scales*

According to the changes in CWP and GWP described in Section 3.3 and the four trends previously defined in Section 2.1, trends in food-water relations at the national and agricultural regional scales of China during 1990–2015 were concluded and showed in Fig. 6.

At the national scale, a continuous low-level coupling trend was concluded during 1990–2015. In terms of agricultural regions, during 1990–2015, a high-level decoupling trend for food-water relations was concluded in the NER and the GXR, the major regions contributing to the expansion of cultivated land in China. In comparison, other regions all showed coupling trends in food-water relations. Specifically, a high-level coupling trend was spotted in the HHH, the SWR and the IMR, while a low-level coupling trend was found in the YRR, the SER, the LPR, and the TPR.

The coupling trends of food-water relations were not consistent for agricultural regions in different time periods. All agricultural regions, except the GXR and the NER, showed coupling trends in food-water relations during 1990–2000. However, during 2000–2015, food-water relations in agricultural regions suffering large-area shrinkage of cultivated land changed to decoupling trends. Specifically, a high-level decoupling trend for food-water relations occurred in the YRR and the SER, while a roughly low-level decoupling trend was found in the HHH and the SWR. In comparison, the changing trend was roughly low-level coupling in the TPR and the IMR during 2000–2015, where the average CWP roughly increased while the average GWP roughly decreased. In the LPR, a rough improvement in the average CWP was accompanied by a rough increment in average GWP, resulting in a rough high-level coupling trend in food-water relations during 2000–2015.

## 4. Discussion

### *4.1. Major driving forces of the spatiotemporal change of cultivated land in China*

The spatiotemporal changes of cultivated land in China were not consistent during the study period of 1990–2015: the total area of cultivated land increased during 1990–2000 and decreased during 2000–2015; the changing trends of cultivated land area were also different among agricultural regions. In this context, the major driving force also varies with time and space. Specifically, during 1990–2000, the exploitation of cultivated land in the NER made a significant contribution to the spatiotemporal change of cultivated land across China. The major driving forces can be attributed to (1) the increasing food demand caused by population growth in this region; (2) the development of agricultural technology, especially irrigation equipment; and (3) relevant promotional policies, such as the dry farmland to paddy policy in Heilongjiang Province during the 1990s, which promoted the expansion of paddy (Bai et al., 2005; Yan et al., 2016). Concurrently, cultivated land loss, mainly occurring in the eastern coastal area of China, can be regarded as a result of urban sprawl in these frontier zones of economic development and urbanization (Zhang et al., 2019a).

During 2000–2015, the cultivated land area in China continued to decrease. Spatially, the loss of cultivated land occurred not only in the more developed eastern coastal area but also in the less developed central and western areas of China. The spread of cultivated land loss can be attributed to two major drivers: rapid urbanization and ecological protection policies, such as the Sloping Land Conversion Program (SLCP). Due to the initiation of the western development strategy and the new rural construction strategy, the urbanization rate rose sharply across China after the year 2000, resulting in a large amount of high-quality cultivated land being occupied by construction land in the eastern coastal area and the central and western areas of China (Liu et al., 2014a). The SLCP, launched in 1999, was the largest land retirement/afforestation program in China, aiming to reverse desertification and soil erosion and foster regional socioeconomic development through returning cropland distributed on steep slopes to forest or grassland (Komarek et al., 2014; Chen et al., 2015). The SLCP has facilitated the retirement of cultivated land across China and was therefore regarded as another major cause of cultivated land loss (Chen et al., 2008; Wang

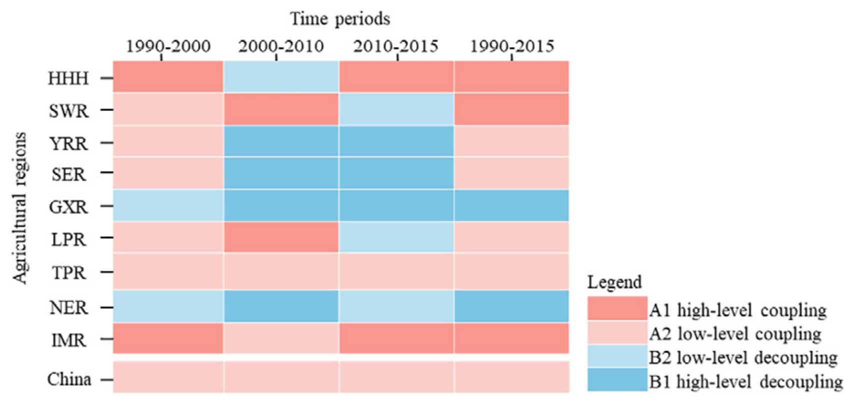



**Fig. 6.** Changes of food-water relations at the national and agricultural regional scales in China during 1990–2015.

et al., 2017). Notably, a considerable amount of sloping cultivated land with poor productivity was reported to be abandoned proactively by farmers (Zhang et al., 2014; Xin and Li, 2018), which also contributed to the decrease of cultivated land, especially in the remote sloping area of China. In addition, the government has made great efforts in curbing the reduction of cultivated land loss through initiating a set of farmland protection policies (Cheng et al., 2015); however, we have reservations about the effects of these policies based on the results of our study.

Cultivated land exploitation in the NER continued, but the area was smaller during 2000–2015 due to the insufficiency of arable land resources in this region. In addition, a larger amount of new cultivated land was exploited in the GXR mainly from grassland, desert, and alkaline land (Song and Zhang, 2015; Maieryemu et al., 2017; Zhou et al., 2017). The major driving forces included population growth and the improvement of agricultural techniques, especially irrigation and drainage techniques, the latter promoting water availability in potential expansion areas and acting as the key driving force in the GXR, where the climate is dry (Song and Zhang, 2015; Maieryemu et al., 2017; Zhou et al., 2017). In addition, local preferential policies, for example, including the provision of low-interest or interest-free loans and the exemption of cultivated land income taxes, together with the elimination of agricultural taxes and provision of agricultural subsidies initiated by the central government of China, were regarded as major driving forces (Chen et al., 2010). Moreover, the call for the scale management of agricultural crops due to their relatively high effectiveness also contributed to the expansion of cultivated land in this region (Zhu and Li, 2011; Li et al., 2018).

### 4.2. Policy implications on improvement of food-water relations across China

A continuous low-level coupling trend of food-water relations was concluded at the national scale of China during 1990–2015, implying that the improvement in the average CWP of China is not very encouraging, considering the negative environmental influences of potential blue water overexploitation caused by the decline of GWP. Besides, changes of food-water relations were not consistent among agricultural regions and in different time periods, which showed even decoupling trends in major cultivated land expansion areas during the whole study period and in major cultivated land shrinkage areas during the later period of 2000–2015. In this context, in order to improve the food-water relations across China, policies aiming for the sustainable development of cultivated land and conservation of water resources should be conducted in accordance with the spatiotemporal changes of cultivated land and the corresponding changing trends of food-water relations, especially in major cultivated land expansion areas and major cultivated land shrinkage areas.

In major cultivated land expansion areas, including the NER and the GXR, where a high-level decoupling trend of food-water relations occurred, policies should be focused on the improvement of both CWP and GWP on both existing and potential cultivated land. Conservation tillage techniques, such as straw retention, strip tillage, sub soiling, and zero tillage, should be encouraged because they are considered to improve CWP compared with conventional tillage (Hu et al., 2015; Zhang et al., 2015). Different water management strategies should be adopted to improve the GWP because the water resource endowments were not the same in the NER and the GXR. Strategies including abandoning blue water-intensive crops, boosting the price of irrigation water, and adopting water-saving irrigation are suggested to reduce the blue water use for food crop production in the GXR, where natural precipitation is rather limited (Han, 2017; Shen and Wu, 2017; Jiang and Wang, 2019). In the NER, where natural precipitation is relatively abundant, green water management, including reinforcing and improving the construction of rainwater harvesting infrastructure and biotechnological advances, should be conducted (Liu et al., 2009a; Cai et al., 2020), together with the above-mentioned strategies for the conservation of blue water in this region.

In major cultivated land shrinkage areas, including the HHH, the SWR, the YRR and the SER, where decoupling trends of food-water relations occurred during the later period of 2000–2015, high attention should be paid to the protection of cultivated land with high CWP. In addition to the restriction of occupation of cultivated land by construction land, the major content of existing farmland protection policies (Cheng et al., 2015), the protection of cultivated land with high values of CWP should be integrated into farmland protection policies. Considering specific measures, a timely and spatially explicit accounting of CWP on cultivated land was suggested, together with conservation tillage techniques, water-saving irrigation techniques, and scientific fertilization techniques (Qin et al., 2010; Xue et al., 2019). Besides decreases of CWP, decreases of GWP also occurred in the YRR and the SER. Although values of GWP were larger than 90% in the above two regions, attentions should be paid to the declining role of green water in food crop production and strategies on green water management should also be strengthened in these regions with abundant natural precipitation (Liu et al., 2009a; Cai et al., 2020).

### 4.3. Uncertainty of our assessments

When assessing the impact of cultivated land change on food-water relations in China, we developed a spatially explicit constant food crop yield dataset and a spatially explicit constant food crop water consumption dataset, using the average food crop yield per unit area and the average proportions of sown area of 5 major food crops to the total sown area of these food crops in 4 years (1990, 2000, 2010, and 2015) at the county level, respectively, to reduce the fluctuations of climate variation between years. In addition, ET values for the 5 major food crops under the average climatic conditions during 1981–2010 were adopted, offsetting the influences of extreme weather incidents, and the irrigation ratios for the 5 major food crops in around 2000 were adopted for all years considered in the study. Therefore, the changes in food crop production, food crop water consumption, and food-water relations characterized by CWP and GWP quantified can be regarded as the main results of the spatiotemporal change of cultivated land.

Nonetheless, the uncertainty of our assessments represents four aspects. First, when constructing the spatially explicit constant datasets for both food crop yield and water consumption, four-year average agricultural data in 1990, 2000, 2010 and 2015 were applied, rather than data for consecutive years. The latter approach, with no obvious growth trends, was regarded as more applicable for calculating average yield and water consumption for food crops on cultivated land and isolating the uncertainty of the impact of spatial land shift (Li et al., 2018). Even so, the former approach would be constrained by data availability and climate fluctuation between years (Li et al., 2018). In addition, 5 crops, namely, wheat, maize, rice, soybean, and potato, were selected as major food crops in China. The results may be varied when more food crops are included in the assessment framework. However, the change may be not significant because the ratio of the aggregate production of the 5 food crops in total food production was more than 90% in China (Liu et al., 2014b). Thirdly, due to poor data availability, the proportions of irrigated areas to total areas sown for major food crops at the county level at around 2000 were obtained using the MIRCA 2000 data, which were primary parameters for the quantification of food crop water consumption across China. Using the county-level data, we filled up the missing data on newly added cultivated land at an expense of reducing the spatial resolution. Considering the improvement in irrigation conditions, especially in northern China (Wang et al., 2019), the changing trends of blue water consumption and GWP for food crop production may be correct but their values may be underestimated and overestimated, respectively, in this study. Thus, updated irrigation data for food crops were highly needed for a more precise quantification of the impacts of spatiotemporal change of cultivated land on food crop water consumption and food-water relations. Finally, there is uncertainty in the China-AEZ model for the TPR. To date, there are few specific types of crops in the TPR, whose phonological calendars and essential parameters may vary from those in areas with lower attitudes. Therefore, much effort must be made to revise the relative parameters for crops to make the China-AEZ model more applicable, especially in the TPR. However, the corresponding influence on the results of this study at the national scale may be neglected because cultivated land area in the TPR accounted for no more than 1% of the total cultivated land area in China.

## 5. Conclusion

Assessing the impacts of cultivated land change on food-water relations would be meaningful for both understanding the land-food-water nexus and providing pertinent suggestions for policy-makers. This study proposed a new assessment framework for quantifying changes in food-water relations characterized by two major indicators, i.e., the CWP and GWP, due to the spatiotemporal change of cultivated land in China. First, features of cultivated land change in China were characterized based on land use data at five-year intervals during 1990–2015. Second, a spatially explicit constant food crop yield dataset and a spatially explicit constant food crop water consumption dataset were developed, combining agricultural statistical data at the county level, the China-AEZ model and the GIS spatial analysis method. Moreover, the CWP and GWP at the pixel level were calculated using the above datasets. Finally, changes in the average CWP and GWP, together with changes in food crop production and food crop water consumption, were estimated at the national scale. The results indicated that cultivated land area first increased by 1.62% during 1990–2000 and then continuously decreased during 2000–2015, resulting in a total increase of 0.80% at the national scale during 1990–2015. Correspondingly, the changing trends of average food crop yield and average $ET_{blue}$ at the national scale were opposite before and after the year 2000: the average food crop yield changed from increasing to decreasing and resulted in a decrease of approximately 0.37%, while the changing trend of average $ET_{blue}$ was the reverse, with a total increase of 1.97% during 1990–2015. In comparison, cultivated land change resulted in a continuous decrease in $ET_a$ and $ET_{green}$, with overall rates of 2.41% and 3.11%, respectively. With respect to the two indicators reflecting food-water relations, at the national scale, a continuous increase in average CWP, with an overall rate of 2.06%, coupled with a continuous decrease in average GWP, with an overall amount of 0.86%, was estimated during 1990–2015. The results showed that the general improvement in average CWP was accompanied by lower land productivity and greater reliance on blue water instead of green water in China during the study period, especially during 2000–2015, implying a low-level coupling of food-water relations and a negative environmental effect. The food-water relations even showed decoupling trends in areas with major cultivated land expansion, i.e., the NER and the GXR, during the whole study period and in areas with major cultivated land shrinkage, including the HHH, the SWR, the YRR and the SER, during 2000–2015. Based on the results of this study, policy implications for the sustainable development of cultivated land and the optimum management of water resources were proposed in accordance with the spatiotemporal changes in cultivated land and the corresponding changes in food-water relations.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.137119.

## Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, 'Impact of spatiotemporal change of cultivated land on food-water relations in China during 1990-2015'.

## Acknowledgements

We are grateful to Prof. Günther Fischer from the International Institute for Applied Systems Analysis (IIASA) for his help in utilization of the China-AEZ model. This research is supported by the National Natural Science Foundation of China (Grant No. 41701092) and the National Key Research and Development Program of China (No. 2017YFE0104600).

## References

Bai, S., Zhang, S., Zhang, Y., 2005. Stages and determinants of farmland development and driving forces in Duerbote County during the past 50 years. Resources Science 27, 71–76 (in Chinese).

Cai, J., He, Y., Xie, R., Liu, Y., 2020. A footprint-based water security assessment: an analysis of Hunan province in China. J. Clean. Prod. 245, 118485. https://doi.org/10.1016/j.jclepro.2019.118485.

CGIAR-CSI, 2006. NASA Shuttle Radar Topographic Mission (SRTM). available at. http://srtm.csi.cgiar.org/.

Chen, C., Xie, G., Zhen, L., Leng, Y., 2008. Long-term dynamics of cultivated land resources and their driving forces of Guyuan City in upper reaches of Jinghe River. Chin. Geogr. Sci. 18, 33–40.

Chen, H., Wu, S., Feng, X., 2010. Study on the changes of cultivated land and the driving factors in Xinjiang based on RS and GIS. Journal of Natural Resources 25, 614–624 (in Chinese).

Chen, H., López-Carr, D., Tan, Y., Xi, J., Liang, X., 2015. China's grain for green policy and farm dynamics: simulating household land-use responses. Reg. Environ. Chang. 16, 1147–1159.

Cheng, L., Jiang, P., Chen, W., Li, M., Wang, L., Gong, Y., Pian, Y., Xia, N., Duan, Y., Huang, Q., 2015. Farmland protection policies and rapid urbanization in China: a case study for Changzhou City. Land Use Policy 48, 552–566.

China Meteorological Administration, 2012. China Meteorological Data Sharing Service System. available at. http://cdc.cma.gov.cn/.

Chinese Academy of Agricultural Sciences, 2016. National Agricultural Scientific Data Sharing Center (AgriData). available at. http://www.agridata.cn/.

Chinese Academy of Sciences, 2019. National Earth System Science Data Sharing Infrastructure. available at. http://www2.geodata.cn/.

Ewert, F., Rounsevell, M.D.A., Reginster, I., Metzger, M.J., Leemans, R., 2005. Future scenarios of European agricultural land use. Agric. Ecosyst. Environ. 107, 101–116.

FAO, 2011. The State of the world's Land and Water Resources for Food and Agriculture (SOLAW): Managing Systems at Risk (Rome, Italy).

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., 2005. Global consequences of land use. Science 309, 570–574.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockstrom, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Han, J., 2017. A Study on the Influential Factors of Water Requirement of Crops in Hexi Region and the Optimal Distribution of Water Resources. Master's thesis. Lanzhou University.

Hancock, P.A., Hutchinson, M.F., 2006. Spatial interpolation of large climate data sets using bivariate thin plate smoothing splines. Environ. Model Softw. 21, 1684–1694.

Hoekstra, A.Y., Mekonnen, M.M., 2012. The water footprint of humanity. Proceedings of the National Academy of Sciences (PNAS) 109, 3232–3237.

Hu, F., Chai, Q., Gan, Y., Yin, W., Zhao, C., Feng, F., 2015. Characteristics of soil carbon emission and water utilization in wheat/maize intercropping with minimal/zero tillage and straw retention. Sci. Agric. Sin. 49, 120–131 (in Chinese).

Huang, J., Bradley, G.R., Xu, C.C., Zhang, H.L., Chen, F., 2012. Cropping pattern modifications change water resource demands in the Beijing metropolitan area. J. Integr. Agric. 11, 1914–1923.

Huang, J., Ridoutt, B.G., Thorp, K.R., Wang, X., Lan, K., Liao, J., Tao, X., Wu, C., Huang, J., Chen, F., Scherer, L., 2019. Water-scarcity footprints and water productivities indicate unsustainable wheat production in China. Agric. Water Manag. 224.

IIASA/FAO, 2012. Global Agro-ecological Zones (GAEZ v3.0). IIASA, FAO, Laxenburg, Austria and Rome, Italy.

Jiang, G., Wang, Z., 2019. Scale effects of ecological safety of water-saving irrigation: a case study in the arid Inland River basin of Northwest China. Water 11.

Komarek, A.M., Shi, X., Heerink, N., 2014. Household-level effects of China's sloping land conversion program under price and policy shifts. Land Use Policy 40, 36–44.

Kong, X., 2014. China must protect high-quality arable land. Nature 506, 7.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. U. S. A. 108, 3465–3472.

Li, X., 2005. Agricultural Irrigation Water Requirement and its Regional Characteristic in China. Master's thesis. Tsinghua University.

Li, S., Li, X., 2016. Progress and prospect on farmland abandonment. Acta Geograph. Sin. 71, 370–389 (in Chinese).

Li, P., Ren, L., 2019. Evaluating the effects of limited irrigation on crop water productivity and reducing deep groundwater exploitation in the North China plain using an agro-hydrological model: II. Scenario simulation and analysis. J. Hydrol. 574, 715–732.

Li, Y., Li, X., Tan, M., Wang, X., Xin, L., 2018. The impact of cultivated land spatial shift on food crop production in China, 1990-2010. Land Degrad. Dev. 29, 1652–1659.

Liu, J., Yang, H., 2010. Spatially explicit assessment of global consumptive water uses in cropland: green and blue water. J. Hydrol. 384, 187–197.

Liu, J., Wiberg, D., Zehnder, A.J.B., Yang, H., 2007a. Modeling the role of irrigation in winter wheat yield, crop water productivity, and production in China. Irrig. Sci. 26, 21–33.

Liu, J., Zehnder, A.J.B., Yang, H., 2007b. Historical trend in China's virtual water trade. Water Int. 32, 78–90.

Liu, J., Zehnder, A.J.B., Yang, H., 2009a. Global consumptive water use for crop production: the importance of green water and virtual water. Water Resources Res 45. https://doi.org/10.1029/2007WR006051.

Liu, J., Kuang, W., Zhang, Z., Xu, X., 2014a. Spatiotemporal characteristics, patterns and causes of land use changes in China since the late 1980s. Acta Geograph. Sin. 69, 3–14 (in Chinese).

Liu, L., Xu, X., Chen, X., 2014b. Assessing the impact of urban expansion on potential crop yield in China during 1990–2010. Food Security 7, 33–43.

Liu, L., Xu, X., Liu, J., Chen, X., Ning, J., 2014c. Impact of farmland changes on production potential in China during 1990–2010. J. Geogr. Sci. 25, 19–34.

Lu, Y., Zhang, X., Chen, S., Shao, L., Sun, H., 2016. Changes in water use efficiency and water footprint in grain production over the past 35 years: a case study in the North China plain. J. Clean. Prod. 116, 71–79.

Maieryemu, Y., Maimaiti, S., Aishan, T., Ruzemaimaiti, M., et al., 2017. Spatial-temporal characteristics of cropland in the Ugan-Kuqa river delta oasis. Sci. Agric. Sin. 50, 3506–3518 (in Chinese).

National Bureau of Statistics of the People's Republic of China, 2016. China Statistical Yearbook. Chinese Statistics Press, Beijing (in Chinese).

Page, G., Ridoutt, B., Bellotti, B., 2011. Fresh tomato production for the Sydney market: an evaluation of options to reduce freshwater scarcity from agricultural water use. Agric. Water Manag. 100, 18–24.

Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000-global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. Glob. Biogeochem. Cycles 24. https://doi.org/10.1029/2008GB003435.

Qin, J., Hu, F., Li, D., Li, H., Liu, J., Yu, R., 2010. The effect of mulching, tillage and rotation on yield in non-flooded compared with flooded rice production. J. Agron. Crop Sci. 196, 397–406.

Rockström, J., Lannerstad, M., Falkenmark, M., 2007. Assessing the water challenge of a new green revolution in developing countries. Proc. Natl. Acad. Sci. U. S. A. 104, 6253–6260.

Shen, D., Wu, J., 2017. State of the art review: water pricing reform in China. International Journal of Water Resources Development 33, 198–232.

Song, W., Liu, M., 2016. Farmland conversion decreases regional and national land quality in China. Land Degrad. Dev. 28, 459–471.

Song, W., Pijanowski, B.C., 2014. The effects of China's cultivated land balance program on potential land productivity at a national scale. Appl. Geogr. 46, 158–170.

Song, W., Zhang, Y., 2015. Expansion of agricultural oasis in the Heihe River basin of China: patterns, reasons and policy implications. Physics and Chemistry of the Earth, Parts A/B/C 89–90, 46–55.

Tan, M., Li, Y., 2019. Spatial and temporal variation of cropland at the global level from 1992 to 2015. Journal of Resources and Ecology 10.

Tian, Z., Liang, Z.R., Shi, J., Fischer, G., Gu, T.T., 2011. Analysis of impact on China wheat potential productivity of climate change during 1961-2010. Chinese Agricultural Science Bulletin 29, 61–69.

Tian, Z., Zhong, H.L., Sun, L.X., Fischer, G., Liang, Z.R., 2012. Estimating potential yield of wheat production in China based on cross-scale data-model fusion. IEEE 4th International Symposium on Plant Growth Modeling, Simulation, Visualization and Applications, pp. 388–395.

van Vliet, J., de Groot, H.L.F., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. Landsc. Urban Plan. 133, 24–36.

Wang, X., Li, X., Fischer, G., Sun, L., Tan, M., Xin, L., Liang, Z., 2015. Impact of the changing area sown to winter wheat on crop water footprint in the North China plain. Ecol. Indic. 57, 100–109.

Wang, C., Zhen, L., Du, B., 2017. Assessment of the impact of China's sloping land conservation program on regional development in a typical hilly region of the loess plateau: a case study in Guyuan. Environmental Development 21, 66–76.

Wang, J., Zhu, Y., Sun, T., Huang, J., Zhang, L., Guan, B., Huang, Q., 2019. Forty years of irrigation development and reform in China. Australian J. Agr. Resource Econ. 59, 1–24.

Xin, L., Li, X., 2018. China should not massively reclaim new farmland. Land Use Policy 72, 12–15.

Xu, X., Wang, L., Cai, H., Wang, L., Liu, L., Wang, H., 2017. The influences of spatiotemporal change of cultivated land on food crop production potential in China. Food Security 9, 485–495.

Xu, H., Tian, Z., He, X., Wang, J., Sun, L., Fischer, G., Fan, D., Zhong, H., Wu, W., Pope, E., Kent, C., Liu, J., 2019. Future increases in irrigation water requirement challenge the water-food nexus in the northeast farming region of China. Agric. Water Manag. 213, 594–604.

Xue, L., Khan, S., Sun, M., Anwar, S., Ren, A., Gao, Z., Lin, W., Xue, J., Yang, Z., Deng, Y., 2019. Effects of tillage practices on water consumption and grain yield of dryland winter wheat under different precipitation distribution in the loess plateau of China. Soil Tillage Res. 191, 66–74.

Yan, H., Liu, J., Huang, H.Q., Tao, B., Cao, M., 2009. Assessing the consequence of land use change on agricultural productivity in China. Glob. Planet. Chang. 67, 13–19.

Yan, F., Zhang, S., Kuang, W., Du, G., Chen, J., Liu, X., Yu, L., Yang, C., 2016. Comparison of cultivated landscape changes under different management modes: a case study in Sanjiang plain. Sustainability 8, 1071.

Zhang, Y., Li, X., Song, W., 2014. Determinants of cropland abandonment at the parcel, household and village levels in mountain areas of China: a multi-level analysis. Land Use Policy 41, 186–192.

Zhang, Y., Li, J., Guo, Z., Yue, Z., 2015. Simulated responses of winter wheat yield and soil moisture to different conservation tillage practices in Weibei highlands, Northwest China. Chin. J. Appl. Ecol. 26, 800–808 (in Chinese).

Zhang, C., Zhong, S., Wang, X., Shen, L., Liu, L., Liu, Y., 2019a. Land use change in coastal cities during the rapid urbanization period from 1990 to 2016: a case study in Ningbo City, China. Sustainability 11.

Zhang, P., Wei, T., Li, Y., Zhang, Y., Cai, T., Ren, X., Han, Q., Jia, Z., 2019b. Effects of deficit irrigation combined with rainwater harvesting planting system on the water use efficiency and maize (Zea mays L.) yield in a semiarid area. Irrig. Sci. 37, 611–625.

Zhou, H., Zhao, W., 2019. Modeling soil water balance and irrigation strategies in a flood-irrigated wheat-maize rotation system. A case in dry climate, China. Agric. Water Manag. 221, 286–302.

Zhou, D., Wang, X., Shi, M., 2017. Human driving forces of oasis expansion in northwestern China during the last decade: a case study of the Heihe River basin. Land Degrad. Dev. 28, 412–420.

Zhu, H., Li, Y., 2011. An empirical analysis of the causes of farmland expansion in Northwest China. Prog. Geogr. 30, 615–620 (in Chinese).

Zuo, L., Zhang, Z., Carlson, K.M., MacDonald, G.K., Brauman, K.A., Liu, Y., Zhang, W., Zhang, H., Wu, W., Zhao, X., Wang, X., Liu, B., Yi, L., Wen, Q., Liu, F., Xu, J., Hu, S., Sun, F., Gerber, J.S., West, P.C., 2018. Progress towards sustainable intensification in China challenged by land-use change. Nature Sustainability 1, 304–313.