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Conversions between natural wetlands and farmland in China: A multiscale geospatial analysis

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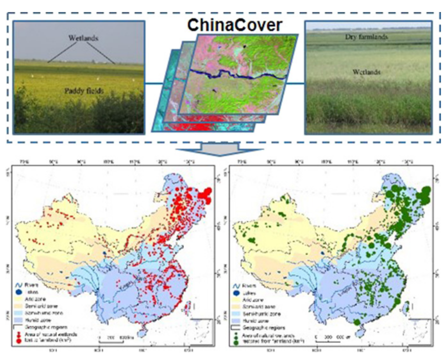
HIGHLIGHTS

- Conversions between natural wetlands and farmland in China were quantified.
- About 60% of China's lost natural wetlands were due to agricultural encroachment.
- Natural wetland conversion to farmland was highest in Northeast China (85.4%).
- A total of 1369 km^2 of natural wetlands were restored from farmland during 1990–2010.
- China must develop place-based sustainable management policies for natural wetlands.

GRAPHICAL ABSTRACT



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ABSTRACT

Agricultural activity is widely recognized as a leading driver of natural wetland loss in many parts of the world. However, little is known about the spatiotemporal patterns of conversion between natural wetlands and farmland in China. This information deficiency has limited decision-making for the sustainable management of natural wetland ecosystems. In this study, we explicitly quantified bidirectional natural wetland-farmland conversions during the periods of 1990–2000 and 2000–2010 at multiple spatiotemporal scales. Our results revealed that about 60% (15,765 km^2) of China's lost natural wetlands were due to agricultural encroachment for grain production, 74.7% (11,778 km^2) of which occurred from 1990 to 2000. Natural wetland conversion to farmland was highest in Northeast China (13,467 km^2 or 85.4%), whereas the natural wetlands in Northwest China demand extra attention because of a notable increase of agricultural encroachment. Natural wetlands in the humid zone experienced tremendous agricultural encroachment, leading to a loss of 10,649 km^2, accounting for 67.5% of the total agriculture-induced natural wetland loss in China. On the other hand, a total of 1369 km^2 of natural wetlands were restored from farmland, with 66.3% of this restoration occurring between 2000 and 2010, primarily in Northeast China and the humid zone. Although a series of national policies and population pressure resulted in agricultural encroachment into natural wetlands, there are also policies and management measures protecting and restoring natural wetlands in China. The spatial differences in natural wetland-farmland conversions among

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different geographic regions and climatic zones suggest that China must develop place-based sustainable management policies and plans for natural wetlands. This study provides important scientific information necessary for developing such policies and implementation plans.

1. Introduction

Agricultural activity is the leading anthropogenic force driving the loss of natural ecosystem (Ramankutty and Foley, 1998;Qiu, 2011; Asselen et al., 2013), causing serious ecological consequences, such as habitat degradation (Zhao et al., 2006; Wimberly et al., 2018), biodiversity loss (An et al., 2007; Cramer et al., 2017; Yang et al., 2017), water quantity and quality declines (Fang et al., 2005; Scanlon et al., 2007), and reduced carbon sequestration (Saunders et al., 2012; Man et al., 2017). To respond to these emerging environmental problems, the first necessary step is to quantify the spatiotemporal patterns of agricultural encroachment into natural areas.

Wetlands cover approximately 6% of the terrestrial surface and provide important and diverse benefits to people around the world (MA, 2005; Zedler and Kercher, 2005; Keddy, 2010). However, significant wetland loss due to human activity, including agricultural encroachment (Rebelo et al., 2009; Reis et al., 2017), urbanization (Li et al., 2014; Hartig and Bennion, 2017), and aquaculture (Richards and Friess, 2016), has occurred in recent decades. Despite efforts to restore natural wetlands for human well-being (Wang et al., 2012; MA, 2005), more than half of the global wetlands have disappeared during the last century (Davidson, 2014). Agricultural encroachment is dominantly responsible for wetland loss, undermining the capacity of natural wetlands to deliver ecosystem services (Asselen et al., 2013; Wang et al., 2015; Beuel et al., 2016). Therefore, spatially explicit assessments of the natural wetland loss due to agricultural conversion are extremely important for wetland conservation and restoration.

A large number of regional studies have reported that the loss of natural wetlands worldwide is largely caused by crop cultivation for food production, such as in southwestern Australia (Davis and Froend, 1999), the Sanjiang Plain in China (Wang et al., 2011; Song et al., 2014), North and South Dakota in the United States (Johnston, 2013), and Kampala in the Uganda (Isunju and Kemp, 2016). However, these studies varied in both temporal scale and wetland definition, indicating that new evidence for natural wetland loss due to agricultural encroachment at larger scales is needed. Compared to other human threats (e.g., urbanization), it is easier to restore natural wetlands lost to agricultural encroachment because the soil seed bank is conserved (Neff et al., 2009; Wang et al., 2017). Therefore, an accurate quantification of the conversion between natural wetlands and farmland at large scales is critical to understanding the sustainability of global wetland ecosystems.

China holds approximately 10% of global wetlands (Niu et al., 2009, Hu et al., 2017) and one-fifth of the world population (about 1.4 billion people), but only 7% of global farmland (Liu and Diamond, 2005; Lu et al., 2015). For both food production and economic growth, extensive natural wetlands have been cultivated due to negligence and underestimation of their tremendous ecological values (Gong et al., 2010; Song et al., 2012; Chen et al., 2015). Despite the consensus that dramatic farmland expansion has destroyed substantial natural wetlands (Niu et al., 2009), knowledge gaps exist in mapping and quantifying agricultural encroachment into natural wetlands across the country. We still do not know how much natural wetlands have been cultivated to farmland in China. Additionally, we know little about the spatiotemporal patterns of natural wetland reclamation or restoration. This information deficiency has limited spatially explicit decision-making for wetland conservation and rehabilitation (Wang et al., 2012; Reis et al., 2017). A more generalized understanding of the patterns and processes underlying the conversion between China's natural wetlands and farmland will be helpful in designing sustainable national policies for protecting and restoring natural wetlands (Nguyen et al., 2017).

In this study, we aim to document the spatiotemporal patterns of both China's agricultural encroachment into natural wetlands and the restoration from farmland to natural wetlands from 1990 to 2010. Specifically, we intend to reveal the hotspot areas of these conversions, and to examine how these conversions vary across geographic regions and climatic zones. We also identify key socioeconomic driving forces of natural wetlands-farmland conversions and make recommendations for sustainable wetland management.

2. Data and methods

2.1. Remote sensing datasets

Remote sensing can both help us characterize the current status of land cover and, through the use of time series data, help us to determine changes on the land surface (Ozesmi and Bauer, 2002; Tian et al., 2017). These advantages make remote sensing the best way to identify the conversion between different land cover categories. After the establishment of China' socialist market economic system in the early 1990s, China began to develop rapidly and experienced dramatic land cover changes (Zhang et al., 2014a). To investigate the ecological changes, the Chinese Academy of Sciences (CAS) has established the China National Land Cover Database (ChinaCover) based on multi-source and multi-seasonal satellite images (Zhang et al., 2014a; Ouyang et al., 2016). And the ChinaCover was published as atlas in 2017 (Wu et al., 2017). Datasets for natural wetlands and farmland in 1990, 2000, and 2010 used in this study were extracted from the ChinaCover. In this study, the natural wetlands refer to the wetlands consisting of vegetation cover types including forested swamp, shrub swamp, and marshes. Natural water bodies (i.e., rivers and lakes) were excluded from our analysis. This database does not separate inland and coastal wetlands because there is no generally accepted boundary between them, and satellite images do not always cover low tidal areas for the entire coast line. Farmland was classified into dry farmland and paddy field.

The detailed information for classification and validation of ChinaCover was introduced in Zhang et al. (2014a). An object-oriented classification approach was used to differentiate various classes of land cover. In the process, a hierarchical classification tree (i.e., Fig. 1a) and various rules (i.e., Fig. 1b) were designed to identify natural wetlands and farmland. The normalized difference vegetation index (NDVI) and normalized difference water index (NDWI) played important roles in the identification of natural wetlands, whereas the phenologic features and object shape/texture contributed largely to the recognition of farmland. Additionally, the geographic and climatic features (Fig. 1c) were considered to establish different rules (Fig. 1b) for identifying natural wetlands and farmland across the country. Visual editing based on the knowledge of natural wetlands in various research teams of CAS largely contributed to the classification. In addition, a great number of field samples carried out by CAS and samples from Google Earth images were used to improve the classification accuracy. The overall accuracy of ChinaCover is greater than 94%. Specifically, producer's accuracy is 89% for natural wetlands and 90% for farmland, while user's accuracy is 86% for natural wetlands and 89% for farmland. The dataset of ChinaCover represents the most accurate mapping of China's land cover during the past decades and thus were used in this study. Fig. 2 shows the distribution of China's natural wetlands and farmland in 2010.

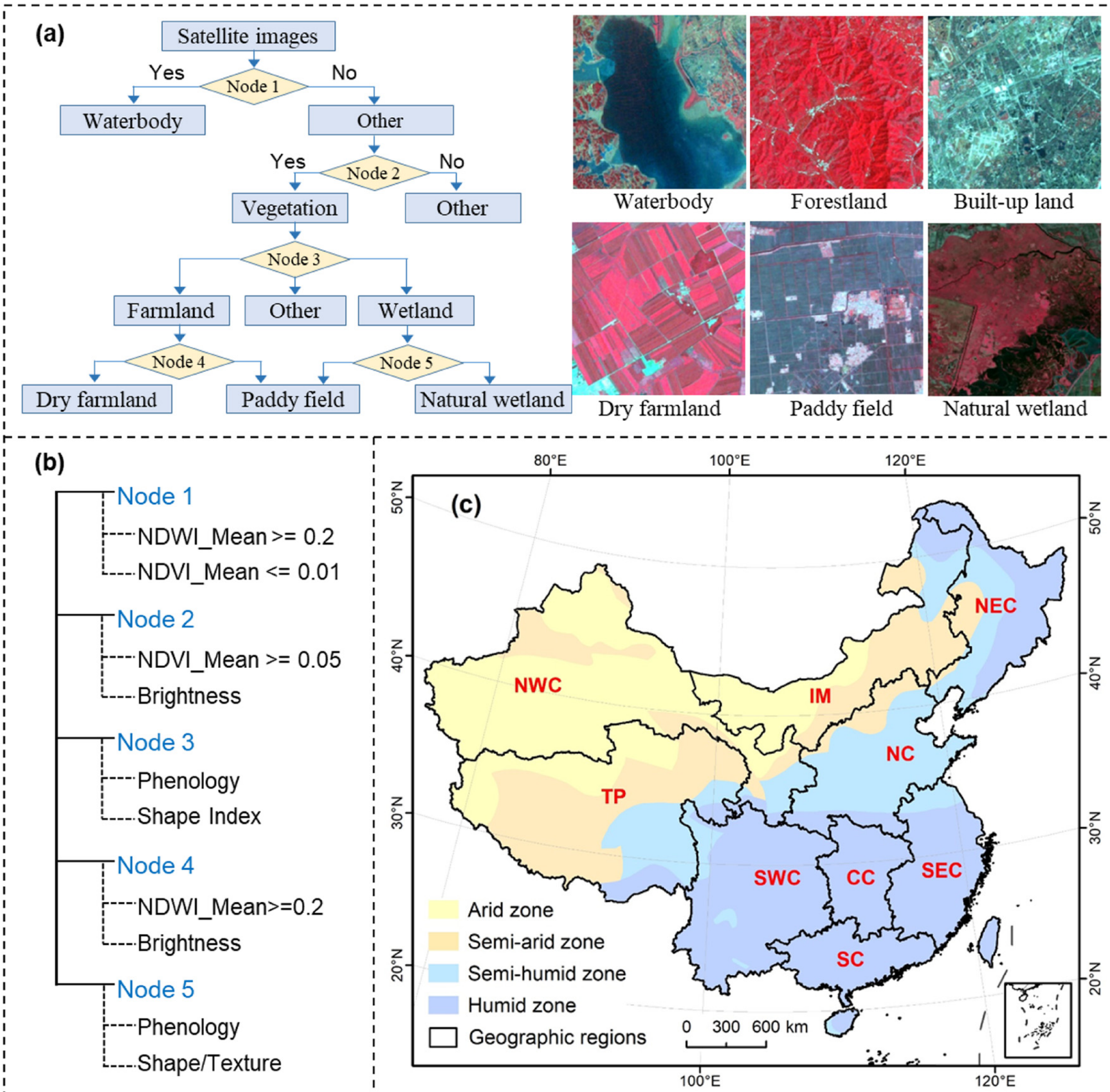

Fig. 1. Classification approach for identifying natural wetlands and farmland: (a) a hierarchical classification tree and image example; (b) example for heterogeneous rules at different levels; (c) spatial pattern of geographic regions and climatic zones in China; NEC denotes Northeast China, IM denotes Inner Mongolia, NWC denotes Northwest China, NC denotes North China, TP denotes Tibet-Qinghai Plateau, CC denotes Central China, SEC denotes Southeast China, and SC denotes South China.

2.2. Data analysis

In this study, we quantified the changes by intersecting the natural wetlands and farmland layers in ArcGIS software (ESRI version 9.3). A conversion matrix analysis was employed to calculate the areas converted between the natural wetlands and farmland. Converted areas within each county were then mapped to document the spatial pattern and hotspot areas. For a better understanding of the patterns and processes in conversion between the natural wetlands and farmland, we quantified both the areas where natural wetlands encroached by crop cultivation and the areas where natural wetlands were restored from farmland during two periods, 1990–2000 and 2000–2010, in each geographic region and climatic zone. Specifically, we compared the spatially variable changes among the geographic regions and climatic zones. We also calculated encroachment and recovery for both dry farmland and paddy field.

Additionally, we summarized policies related to agricultural development and wetland conservation and relevant statistical datasets from the Chinese Statistical Yearbook in 2011, including total grain production, gross domestic product (GDP) for agriculture, and total population. The temporal changes in policies and statistical datasets were used to discuss the driving forces controlling the conversions between natural wetlands and farmland. Finally, management suggestions were presented based on our results and discussion.

3. Results

3.1. Geospatially variable agricultural encroachment into natural wetlands

Fig. 3 shows that the natural wetlands converted to farmland were clustered in the east and scattered in the west. Specifically, three hotspot regions including Northeast China, the North China Plain, and the middle and lower reaches of the Yangtze River experienced intensive agricultural encroachment into natural wetlands (Fig. 3). Additionally, the loss of natural wetlands induced by agricultural encroachment was more notable in the humid and semi-humid zones. A total of 15,765 km^2 of natural wetlands were destroyed due to crop cultivation from 1990 to 2010, of which 74.7% (11,778 km^2) occurred in the first decade, and 25.3% (3987 km^2) occurred in the second. Agricultural encroachment contributed to 60% of the area's decline in natural wetlands

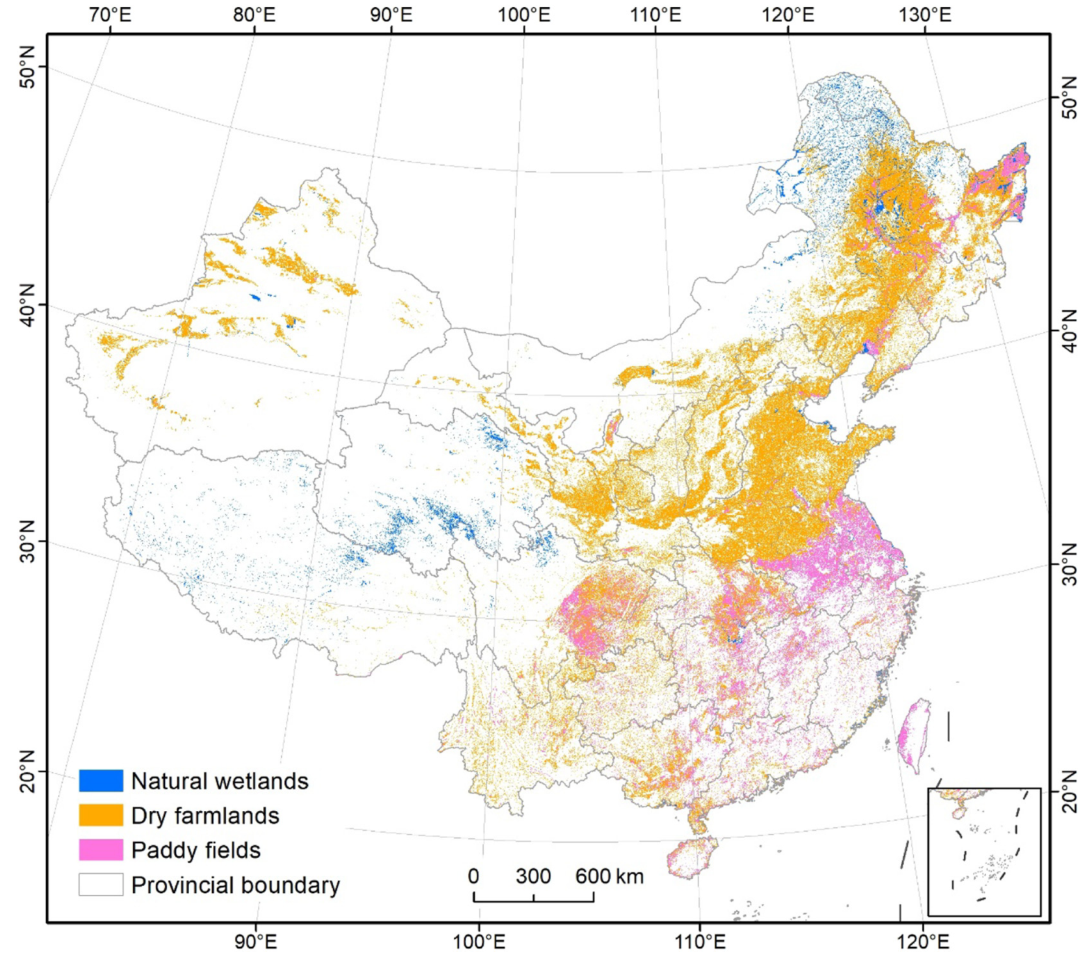

Fig. 2. Spatial distribution of China's natural wetlands and farmland in 2010.

from 1990 to 2010. The loss rate of natural wetlands due to agricultural encroachment was high from 1990 to 2000 (1178 km^2 yr^{-1}), which was approximately 3 times the rate from 2000 to 2010 (399 km^2 yr^{-1}). China exhibited more evident damage to natural wetlands due to the farmland expansion in the first observed decade than in the second.

As shown in Fig. 4, natural wetland declines caused by agricultural encroachment (15,765 km^2) were the highest in Northeast China (13,467 km^2 or 85.4%), followed by Inner Mongolia (1277 km^2 or 8.1%), North China (415 km^2 or 2.6%) and Southeast China (392 km^2 or 2.5%). There was little agricultural encroachment into natural wetlands in the Tibetan Plateau and Southwest China, where the natural wetland loss due to agriculture encroachment was estimated to be less than 1 km^2. Specifically, natural wetlands lost to farmland expansion were primarily reclaimed into dry farmland (11,822 km^2 or 75%), of which 83.6% occurred in Northeast China (9887 km^2) and 10.3% in Inner Mongolia (1223 km^2). Natural wetlands converted into paddy field (3943 km^2) were mainly observed in Northeast China (3580 km^2 or 90.8%) and Southeast China (241 km^2 or 6.1%). In Inner Mongolia and North China, a total of 95 km^2 of natural wetlands were converted into paddy field.

Between the observed two decades, areas of natural wetlands lost to crop cultivation have declined remarkably in Northeast China (by 6848 km^2 or 67.4%), Inner Mongolia (by 666 km^2 or 68.6%), North China (by 273 km^2 or 79.3%) and Central China (by 39 km^2 or 90.7%). However, the area of natural wetlands lost to agricultural encroachment has notably increased by 36 km^2 or 57.1% in Northwest China. In Southeast China, the area of natural wetlands reclaimed to paddy field was observably larger than that reclaimed to dry farmland, whereas the total amount of natural wetlands lost to agricultural encroachment was almost unchanged.

Table 1 shows the areas converted from natural wetland to dry farmland and paddy field in different climatic zones during the periods of 1990–2000 and 2000–2010. There is evident variation in the amount of natural wetlands converted to farmland among different climatic zones. Natural wetlands in the humid zone experienced tremendous agricultural encroachment with an area loss of 10,649 km^2, accounting for 67.5% of the total reclamation-induced natural wetland loss in China. 2125 (13.6%) and 2812 km^2 (17.8%) of natural wetland loss to farmland occurred in the semi-arid and semi-humid zones, respectively. Little conversion of natural wetlands to farmland (18 km^2 or 1.1%) occurred in the arid zone because both wetlands and farmland are rare in these areas. Approximately 25.7% of the natural wetlands converted to farmland in the humid zone were converted into paddy field, compared to 3.4% in arid zone. Additionally, with an exception of an increase of 15 km^2 or 18.3% in the arid zone, natural wetlands reclaimed to farmland in the other three climatic zones were reduced significantly during the study periods. Reductions in the area of natural wetlands encroached by expanded farmland was mostly observed in the humid zone (5727 km^2 or 69.9%) and semi-humid zone (1632 km^2 or 73.4%).

3.2. Spatiotemporal variation in the return of natural wetlands from farmland

The area of natural wetlands restored from farmland in China is mapped in Fig. 5. The restoration of natural wetlands from farmland was primarily implemented in Northeast China and the humid zone.

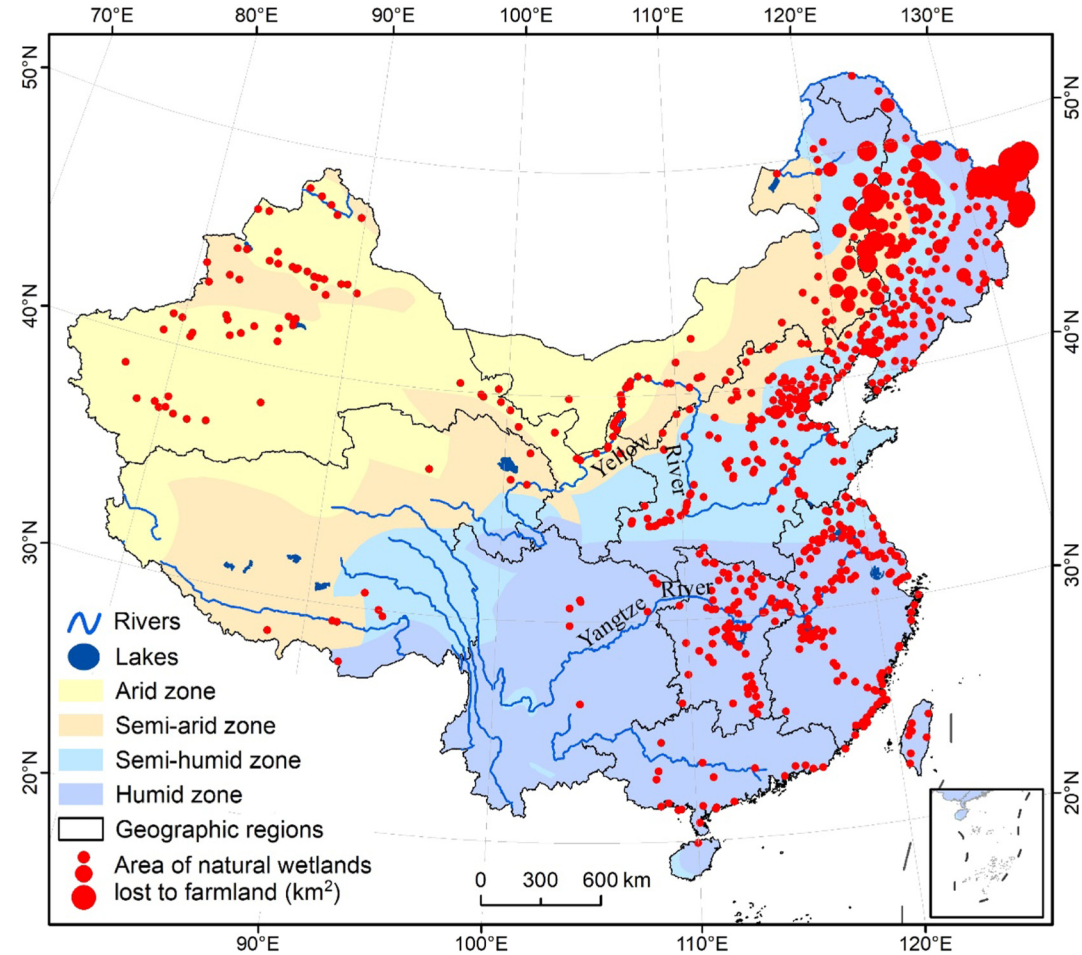

Fig. 3. Spatial pattern of natural wetlands reclaimed to farmland (Bigger points denote larger areas of natural wetlands cultivated to farmland within a county).

Between 1990 and 2010, a total of 1369 km^2 of natural wetlands were recovered from farmland, of which 66.3% occurred in the second decade. Compared to the 461 km^2 of natural wetland restoration from farmland from 1990 to 2000, China made additional efforts to restore natural wetlands from farmland during 2000–2010 (908 km^2). The Sanjiang Plain, located in the northeast corner of China and the humid zone, experienced the most dramatic wetland conversion to farmland and had the most significant natural wetland restoration from farmland.

Natural wetlands restored from farmland were mostly observed in Northeast China (Figs. 5 and 6a). In this region, there were 846 km^2 of natural wetlands restored from farmland accounting for 61.1% of total restoration in China. Natural wetlands restored from farmland in North China, Inner Mongolia, and Southeast China varied from 100 to 150 km^2 or 8.5% to 10.9%. Similar to the little agricultural encroachment in Southwest China and the Tibetan Plateau, little restoration of natural wetlands occurred in these two regions (Fig. 6a). During the observed two decades, significant increases in the area of natural wetlands restored from farmland were documented in five geographic regions, including Northeast China (325 km^2 or 125%), North China (84 km^2 or 253%), Inner Mongolia (67 km^2 or 197%), Northwest China (33 km^2 or 183%), and Central China (13 km^2 or 154%). Declines in the area of natural wetlands restored from farmland were observed in the other four regions, especially in Southeast China (55 km^2). Specifically, the restored natural wetlands were mainly returned from dry farmland (81.4%). Restored areas of natural wetlands from paddy field were larger than from dry farmland only in Southeast China (74.4% from paddy field) and South China (89.7% from paddy field). Meanwhile, the percentage of natural wetland restoration from paddy field increased between the 1990–2000 and 2000–2010 periods (Fig. 6b) in Northeast China, North China, Inner Mongolia and Central China.

At the scale of the climatic zone, natural wetland restoration from farmland documented in Fig. 6c was found primarily in humid (632 km^2 or 46.2%) and semi-humid zones (582 km^2 or 42.5%). The restoration of natural wetlands from farmland was remarkably increased between the observed two decades in all four climatic zones. Although only 155 km^2 or 11.3% of natural wetland restoration was carried out in semi-arid and arid zones, the relative increase (130%) was larger than in other two climatic zones. Moreover, the natural wetlands restored from farmland in the four climatic zones were largely converted from dry farmland (Fig. 6d). The percentage of restoration from paddy field also decreased during the observed periods in each climatic zone.

4. Discussion

4.1. Mapping natural wetlands and farmland based on remote sensing

As shown in Fig. 7, satellite images clearly reveal the patterns of agricultural encroachment into natural wetlands during the study period. Accurate identification of natural wetlands and farmland was an important first step in revealing the notable patterns and processes of conversion. In the process of producing the ChinaCover, an object-oriented image classification method was used to distinguish the different classes of land cover in China (Zhang et al., 2014a). Multiscale segmentations based on three parameters (scale, shape, and compactness) generated optimal boundaries for homogeneous landscape patches. In addition to the traditional classification based on spectral difference,

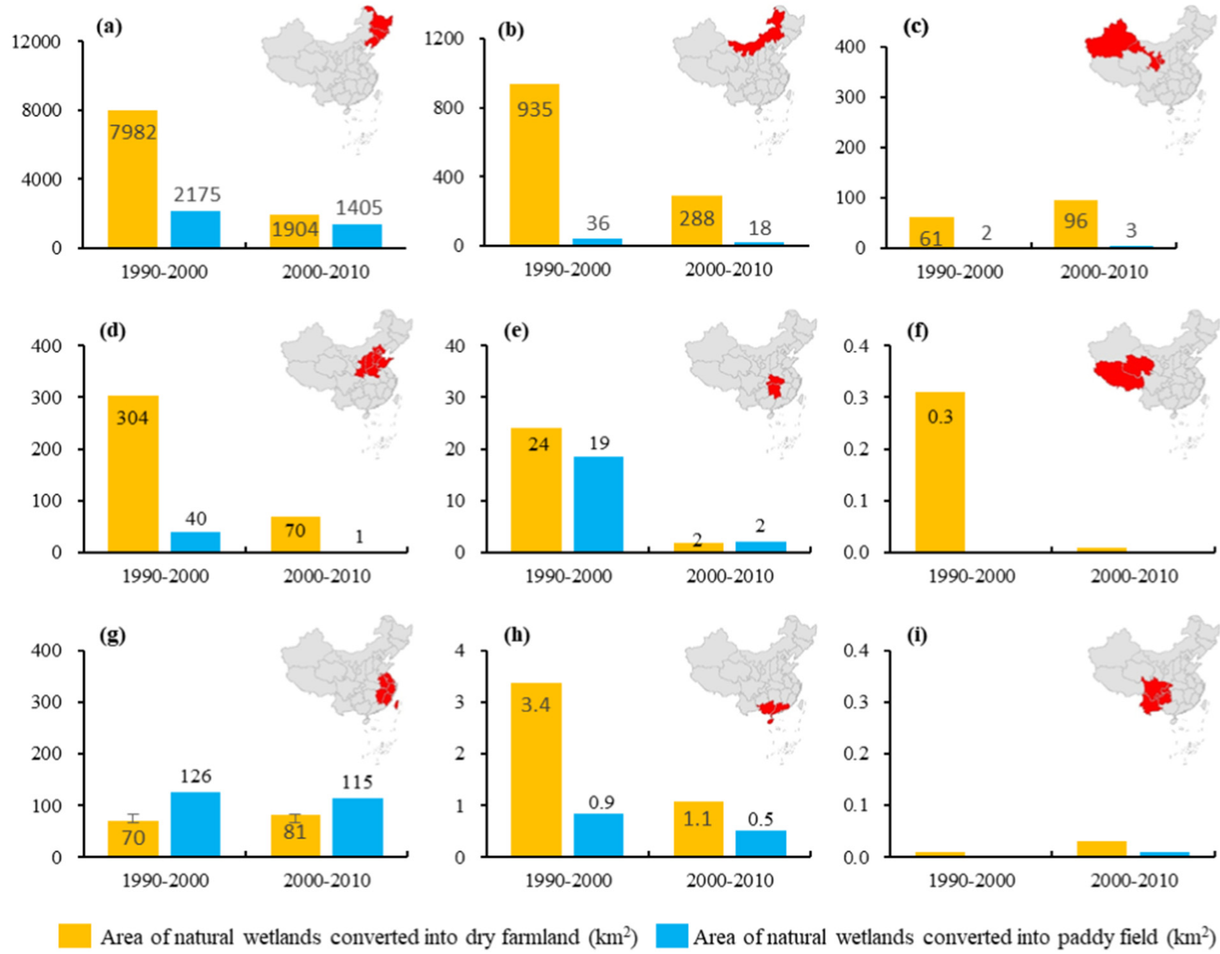

Fig. 4. Spatiotemporal variation in the amount of natural wetland lost to farmland (km^2) among the geographic regions of China: (a) Northeast China, (b) Inner Mongolia, (c) Northwest China, (d) North China, (e) Central China, (f) Tibetan Plateau, (g) Southeast China, (h) South China, and (i) Southwest China.

shape, and texture, phonologic features reflected by multi-seasonal images provided critical information for identifying natural wetlands and farmland (Wang et al., 2015). Because China is vast in territory, there are also phenological differences for the same land cover class located in different geographic regions. Hierarchical and heterogeneous rule sets were thus designed to identify various categories of land cover (Lei et al., 2016). Revisions of the preliminary classification results were carried out based on visual interpretation and a great deal of field survey samples. In total, 13 cycles of checking and modification were performed on these datasets. All these steps contributed substantially to the improvements in the accuracy of ChinaCover. The classification accuracy of the ChinaCover was assessed by 31,658 field samples, achieving the best estimation of China's land cover, and thus ChinaCover has been widely used in ecological and environmental studies (Ouyang et al., 2016). Although a national-scale evaluation of natural wetlands-farmland conversions was attempted, more accurate and detailed assessments at regional and local scales with updated datasets are much needed for sustainable ecosystem management and regional planning.

Table 1
Variation in natural wetlands lost to farmland (km^2) in different climatic zones.

Climatic zones	Natural wetlands loss during 1990–2000		Natural wetlands loss during 2000–2010	
	To dry farmland	To paddy field	To dry farmland	To paddy field
Arid zone	80	2	93	4
Semi-arid zone	890	397	727	111
Semi-humid zone	1693	529	427	163
Humid zone	6717	1471	1196	1265
Total	9380	2398	2444	1543

As our results show, agricultural encroachment caused 60% of the total reduction in natural wetlands in China from 1990 to 2010. Our finding supports previous conclusions that agricultural activities are the most important proximate cause of natural wetland conversion (An et al., 2007; Asselen et al., 2013). In this study, we determined the spatiotemporal variations of these conversions at multiple scales. Though we now know the patterns and processes of the conversion between natural wetlands and farmland, there is further need to understand the underling drivers of these conversions for the sustainable management of China's natural wetland ecosystems.

4.2. Underlying drivers for conversion between natural wetlands and farmland

In China, a series of national policies (Fig. 8a) strongly stimulated agricultural encroachment into natural wetlands for grain production (Wang et al., 2012). Converting natural wetlands to farmland requires a relatively high level of human input, but the introduction of modern agricultural machinery in the late 1980s and the establishment of large farms made agricultural encroachment more feasible (Song et al., 2014). The market economic system was established in 1992, which promoted trade in grains. The household responsibility system, which allows farmland to be leased to families for a 30-year period, promoted crop cultivation. Furthermore, after China joined the World

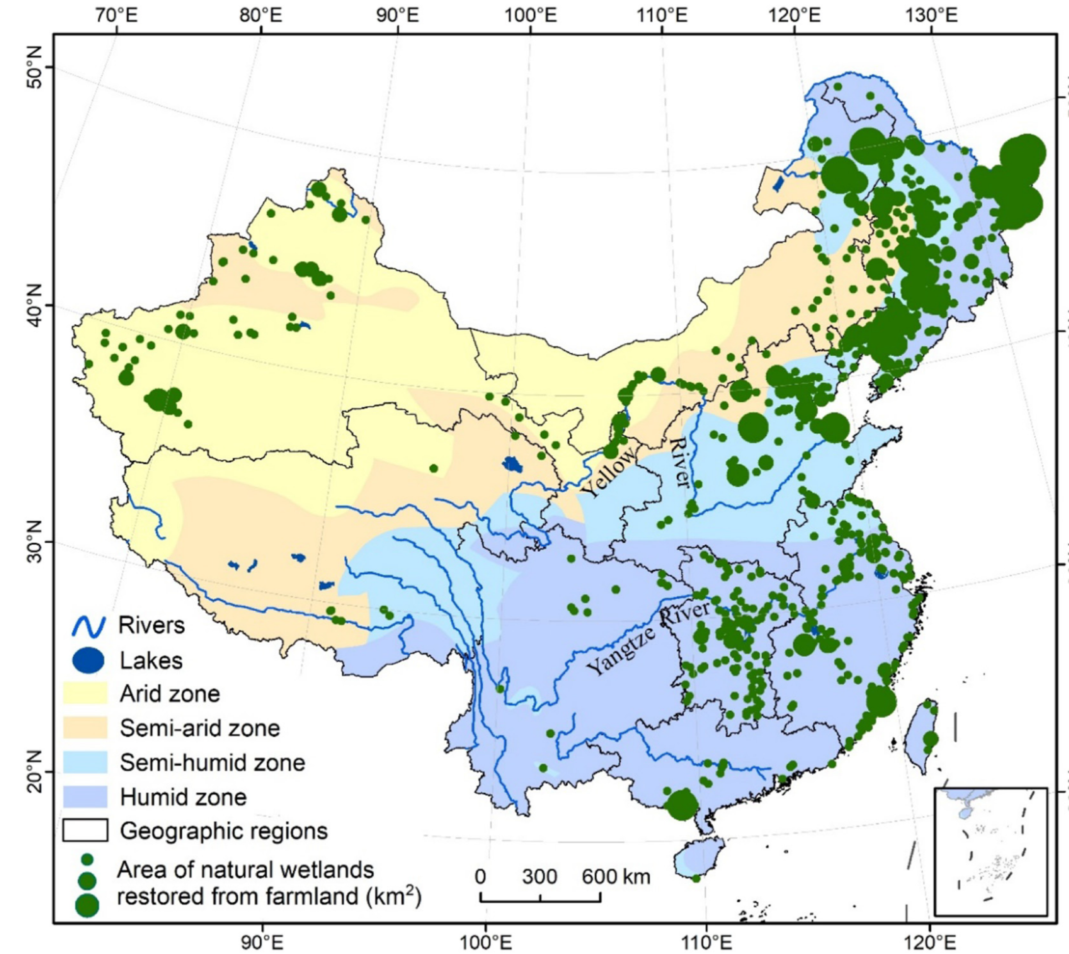

Fig. 5. Spatial pattern of natural wetlands restored from farmland (Bigger points denote larger areas of natural wetlands restored from farmland within a county).

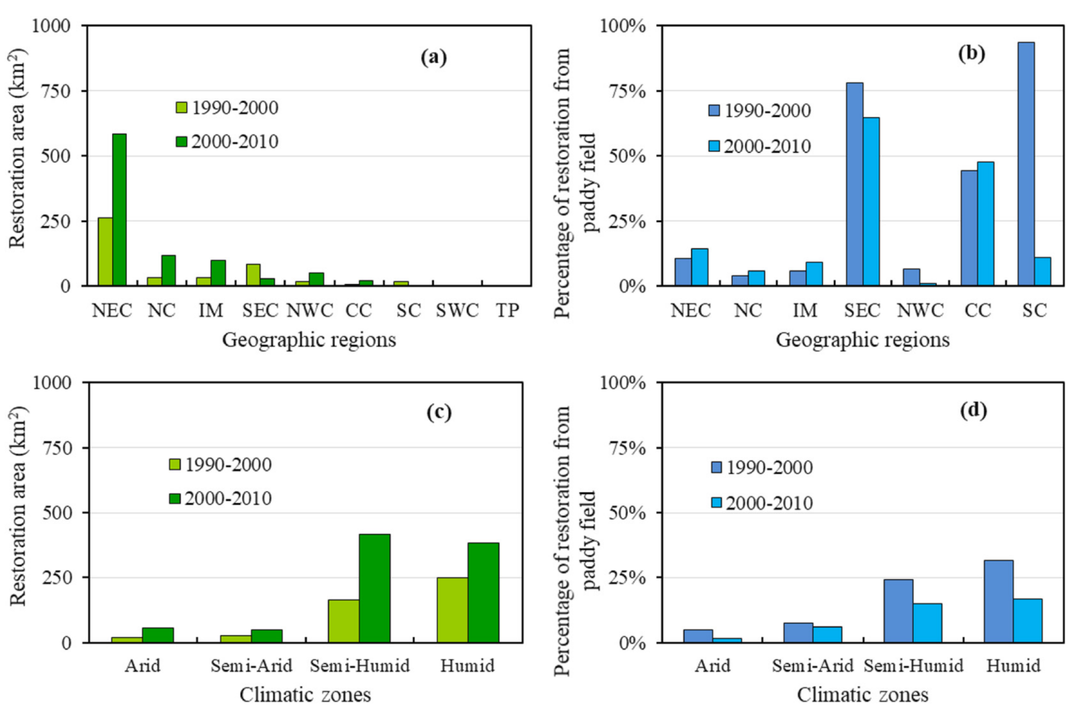

Fig. 6. Spatiotemporal variation in the area of natural wetlands restored from farmland (a) and in the percentage of natural wetlands restored from paddy field among different geographic regions (b); spatiotemporal variation in the area of natural wetland restored from farmland (c) and in percentage of natural wetlands returned from paddy field among different climate zones (d). NEC denotes Northeast China, NC denotes North China, IM denotes Inner Mongolia, SEC denotes Southeast China, NWC denotes Northwest China, CC denotes Central China, SC denotes South China.

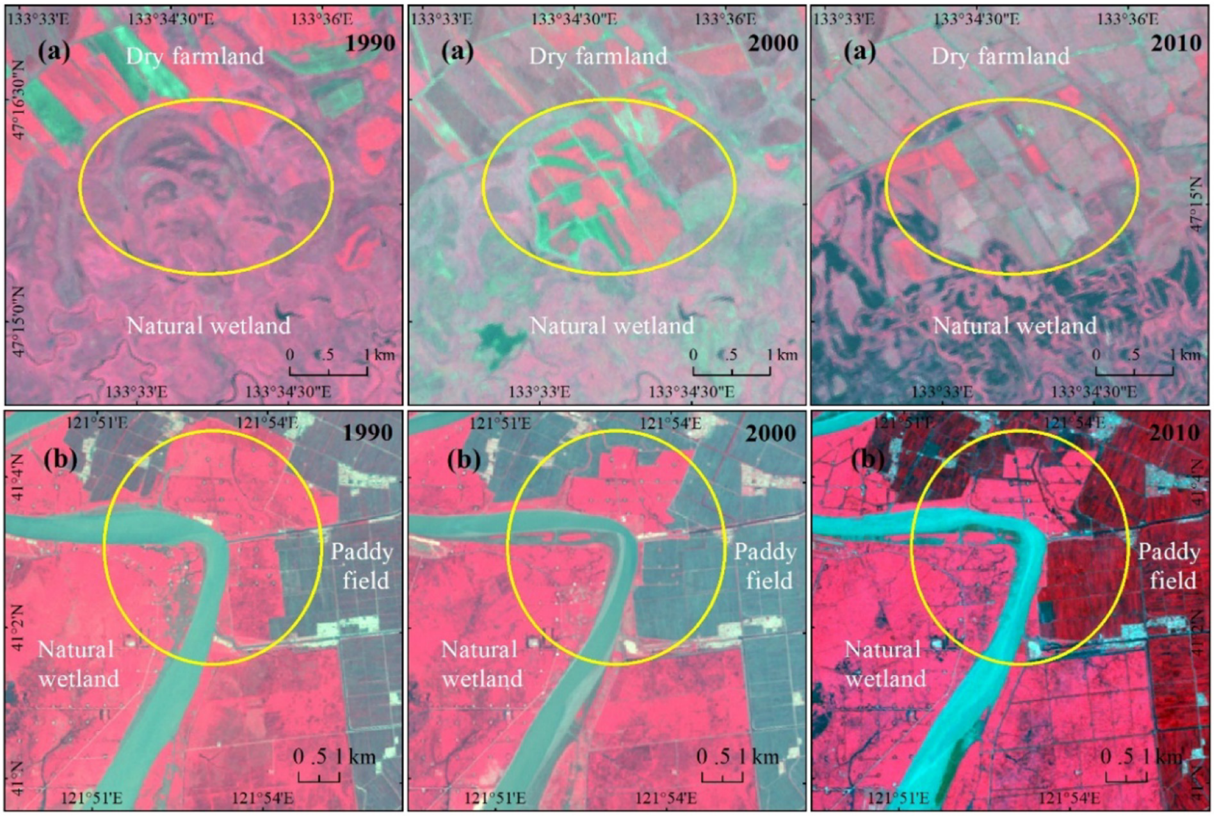

Fig. 7. Landsat image examples for the natural wetland loss to dry farmland (a) and paddy field (b) from 1990 to 2010.

Trade Organization (WTO) in 2001, grain markets were expanded. In 2005, the Chinese government rescinded the agricultural tax. Significant numbers of illegal croplands were thus developed, such as in the Sanjiang Plain (Song et al., 2014), due to the increase of farming profit under the background of these policies. During the most recent decade, China launched a food security project in 2009 aimed at achieving an additional 50 million tons of grain production and implemented a national plan to adjust agricultural plantation structures. These two policies gave rise to the expansion of paddy field (Man et al., 2017). On one hand, large areas of these new paddy field were converted from natural wetlands. On the other hand, converting dry farmland to paddy field consumed massive amounts of groundwater, which affected hydrologic processes in natural wetlands (Chen et al., 2015).

As documented by Asselen et al. (2013), economic and population growth are the most frequent underlying forces for wetland conversion. China had the largest population and high population growth rate in the world during the period of 1990–2010 (Fig. 8b). Significantly increased grain production (22.5%) was also observed over this period (Fig. 8c). Notable increases in the GDP of the agricultural sector (Fig. 8d) from 1990 to 2010 indicate a rapid agricultural development. Demand for grain and increasing commodity prices triggered by the market economic system promoted agricultural development and stimulated the alteration of natural wetlands (Grumbine, 2014). Therefore, the sustainable management of natural wetlands and farmland is urgently needed.

Concerns about changes in China's natural wetlands have been growing due to their dramatic loss and degradation in recent decades (Gong et al., 2010; Bi et al., 2012). From the late 1980s, the ecological functions of natural wetlands were universally recognized (Song et al., 2014). Some ecological projects and wetland inventories were developed to protect and restore natural wetlands in China (Fig. 8a). For example, there are more than 600 wetland nature reserves and 39 Ramsar sites in China to date, which play critical roles in the conservation of natural wetlands. Two national wetland inventories (NWIs, 1995–2003 and 2009–2013) were launched by the central government to quantify wetland area and distribution. Natural wetland conservation was also promoted by legislation in different provinces, such as Heilongjiang and Jilin. A national wetland conservation project was also implemented from 2005 to protect and restore additional natural wetlands (Wang et al., 2012). In addition, China has developed an eco-functional regionalization plan, which delineates the country's land into regions with different dominant designated land uses for the purpose of optimizing the geospatial pattern of ecological security. Three of such regions are covered by extensive natural wetlands. The Sanjiang Plain, the Goize Plateau, and the Three-River Headwater region, were planned as national key eco-functional regions. The State Forestry Administration announced in 2016 that China must have no less than 800 million μ (1 ha = 15 μ) of wetlands by 2020. As we examined, the conversion from natural wetlands to farmland has been reduced markedly between the two decades, with an area decline of 7791 km^2. In addition, the total area of natural wetlands restored from farmland has increased by 447 km^2. This suggests that policies and management measures are continually protecting and restoring natural wetlands in China.

4.3. Implications of natural wetland management

Though the intensity of natural wetland reclamation to farmland has been weakened and restoration of natural wetlands from farmland was enhanced over the study period (Figs. 4 and 6), China urgently needs to promote the sustainable and spatially variable managements of natural wetlands. Over the study period, there were 1369 km^2 of natural wetlands restored from farmland, accounting for only 8.7% of the natural wetland loss due to crop cultivation. Specifically, Northeast China should aim to restore more natural wetlands. More natural wetland restoration projects should be performed in this geographic region because the area proportion (61.8%) of natural wetlands restored from farmland was much smaller than its contribution (85.4%) to the agricultural encroachment of natural wetlands in China. Based on our findings, the

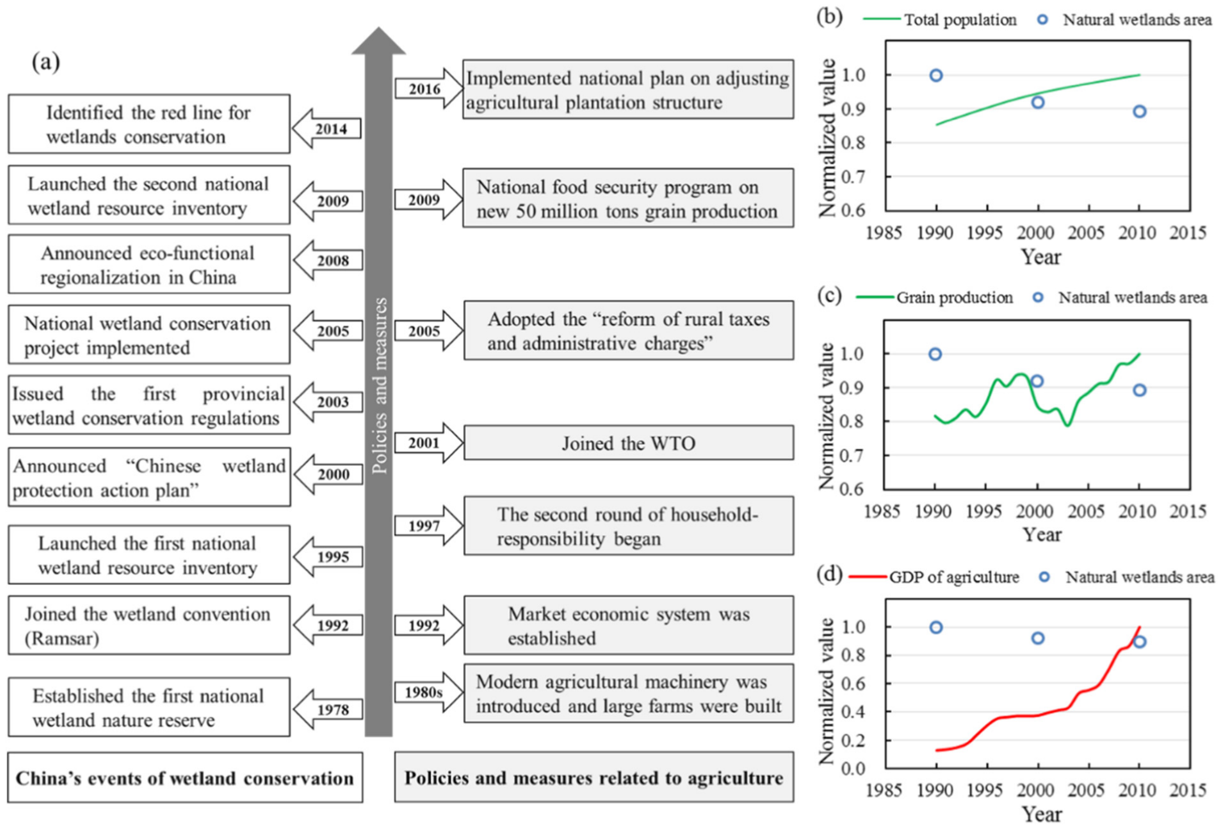

Fig. 8. Summary of the driving forces for the conversion between natural wetlands and farmland: (a), policies and managing measures related to agriculture development and wetland conservation; (b) changes in normalized population and natural wetland areas in China; (c) changes in normalized total grain production and natural wetland areas across the whole country; (d) changes in China's normalized GDP of primary industry and natural wetland areas.

conservation efficiency of natural wetlands in two wetland ecological regions, the Sanjiang and Songnen Plains, located in Northeast China, should also receive significant attention due to extensive distribution, great area loss, and fragmentation of natural wetlands (Fig. 3).

Natural wetlands in Northwest China should receive more attention on account of notable area increases in agricultural encroachment in this region during the observed periods. Likewise, our results indicated that the loss of natural wetlands primarily occurred in the humid and semi-humid zones. Sustainable natural wetland restoration should be enhanced in those two zones because it is easier due to underlying hydrological conditions. The loss of natural wetlands should be reversed in arid and semi-arid zones because natural wetland restoration is quite difficult due to limited water supply. Effective governance of wetlands has achieved successful conservation of global waterbird populations (Amano et al., 2018). However, in China there is still a need to improve the protection of natural wetlands, especially the coastal wetlands, to save endangered migratory birds (Yang et al., 2017). Additionally, consistent monitoring and studies should be performed to quantify the spatiotemporal changes in natural wetlands and further understand their spatially variable underlying drivers.

As introduced by Wang et al. (2012), China's wetlands are jointly controlled by several government departments including the State Forestry Administration, the Ministry of Land and Resources, State Environmental Protection Administration, and others. Although the first provincial wetland conservation regulation was issued in 2003 (Fig. 8a), the protection levels varied across provinces. Therefore, a sound national regulatory law is needed to improve natural wetland conservation. Zheng et al. (2012) reported that a majority of national wetland reserves are in a poor condition for protecting natural wetlands. Continuing to increase protected wetland areas, increasing the effectiveness of protected areas, and enhancing natural wetland restoration are essential measures for achieving China's wetland ecosystem sustainability. Although China has ambitious aims (i.e., the National Wetland Conservation Action Plan) to protect and restore more natural wetlands, the program needs a more scientific and comprehensive restoration strategy across different scales (Zedler, 2003). Multi-source images from satellites or other platforms could be selected to examine different human threats (Nagendra et al., 2013; Tian et al., 2017). The application of remote sensing technology should be increased because of its advantages in addressing the inaccessibility of wetlands for field investigation and its ability to support spatial decision-making.

Achieving food security while ensuring environmental sustainability is a grand challenge (Lu et al., 2015). Other than direct encroachment into natural wetlands, competition between rice production and natural conservation and the pollution from intensive application of fertilizers and pesticides to natural wetlands are the most serious ecological problems that wetlands face (Liu and Diamond, 2005; MA, 2005). The irrigation of paddy field makes great demands on limited water supplies, particularly in northern China (Chen et al., 2015). Additionally, the soil salinization of croplands poses a great threat to the water supply of natural wetlands in arid and semiarid zones (Zhu et al., 2016) as well as in coastal area (Yu et al., 2009). Agricultural pollution also significantly affects the quality of wetland ecosystems and weakens the ability of wetlands to provide ecosystem services (David et al., 2002; Chen et al., 2015). The conservation and rehabilitation of natural wetlands needs consistent attention from both the government and the public. Policies for adjusting crop-planting structure should balance the needs of China's natural wetland conservation and rice production for sustainable ecosystems. Saline agriculture could be considered to expand the food supply and improve ecosystem conditions in areas that provide small amount of ecosystem services (Yan et al., 2013; Zhang et al., 2014b). Organic farming should be promoted in the regions with heavy pollution.

5. Conclusions

The spatiotemporal patterns of the conversion between natural wetlands and farmland in China were revealed in this study based on ChinaCover, a land cover database established by means of satellite images and object-oriented classification approach. Our study reveals that agricultural activity has been the most important cause for the loss of natural wetlands in China. However, during the study period, the wetland-to-farmland conversion began to slow down while natural wetland restoration from farmland started to pick up the pace in China. Although a series of national policies and increasing population have promoted agricultural development and stimulated the alteration of natural wetlands, many policies or management measures protect and restore current natural wetlands in China. Additionally, the conversion between natural wetlands and farmland quantified at the scale of geographic regions and climatic zones indicates that China urgently needs to promote geospatially variable strategies for sustainable management of natural wetlands, especially in the Northeast China and the arid zone. This study provides important scientific information necessary for developing place-based wetland conservation and restoration policies.

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