Jiang *et al. Ecological Processes* (2023) 12:40
https://doi.org/10.1186/s13717-023-00452-x

Ecological Processes

RESEARCH

Open Access

Process analysis and mitigation strategies for wetland degradation caused by increasing agricultural water demand: an ecology–economy nexus perspective

Lin Jiang[1], Hui Wang[1], Saige Wang[2] and Wen Zhang[1*]

Abstract

Background Farmland expansion has played a major role in wetland degradation in Heilongjiang Province, China in recent decades. Farmland expansion increases the demands for water, thereby affecting wetland water cycles, and promoting the shrinkage of wetland areas and degradation of ecosystem functions. As an open system, agricultural production is limited by both ecological and socioeconomic conditions. However, our understanding of wetland degradation caused by farmland expansion from the perspective of the ecology–economy nexus is limited.

Methods A correlation between farmland expansion and agricultural economic activities was established, and wetland degradation driven by agroeconomic activities was inversely derived using a multi-regional input–output (MRIO) analysis. We developed an ecology–economy nexus framework to explore the ecological process of the area and water demand tradeoffs between wetland degradation and farmland expansion, the economic process of wetland degradation driven by food consumption, and the nexus between the two processes. We finally explored strategies to mitigate wetland degradation due to increased agricultural water demand.

Results Farmland expansion contributed to 93.76% of the total degraded wetland area. There was a significant negative correlation between wetland area and the water consumption for crop production, but no significant correlation between wetland area and the ecological footprint of croplands. The direct wetland degradation caused by local final demand accounted for 63.02%, while the indirect degradation caused by non-local final demand accounted for 36.98%. Hebei, Shandong, Liaoning, Inner Mongolia, and Shanghai were the top five provinces contributing to indirect wetland degradation in Heilongjiang. Our findings indicated that a mixed scenario combining water footprint reduction per unit yield with food export reduction could maximize wetland restoration while reducing local farmland–wetland competition for water.

Conclusions Our research highlights the effects of economic processes in the agricultural sector on wetland degradation, and showed that the adjustment of food trade patterns can effectively promote wetland restoration.

Keywords Agricultural economic activities, Farmland expansion, Water footprint, Wetland degradation, Wetland restoration

*Correspondence:
Wen Zhang
zhangwen0421@sdnu.edu.cn
[1] Institute of Environment and Ecology, Shandong Normal University, No. 1 Daxue Road, Ji'nan 250358, Shandong, China
[2] School of Environment, Beijing Normal University, Beijing 100875, China

Introduction

Large-scale farmland development has had a major effect on local land-use patterns in Northeast China due to the national regulations on food production goals established in the 1950s, resulting in farmland expansion and wetland shrinking (Niu et al. 2012; Chen et al. 2018). The increase in water consumption for crop production has greatly reduced the availability of water resources for wetlands (Siebert et al. 2010; Rodell et al. 2018; Zou et al. 2018), resulting in wetland degradation mainly manifested in the reduction of wetland area and loss of ecological function (Zhang et al. 2010; Niu et al. 2012), which has already caused considerable ecological and economic damage (An et al. 2007). At the regional scale, more than 85% of wetland degradation has been caused by agricultural activities (Wang et al. 2011; Mao et al. 2018). Achieving sustainable crop production at a regional scale while reducing wetland degradation or even restoring wetland ecology remains challenging.

The conflict between farmland and wetland water demand is widely recognized (Han et al. 2012; Niu et al. 2012). The conflict was mainly manifested as the difference between agricultural water consumption and wetland ecological water demand in the previous studies (Zou et al. 2018), while the specific relationship between wetland area degradation and the water consumption for crop production was not quantified. Furthermore, studies on the impact of agricultural activities on wetland degradation have focused on physical water resource consumption during crop production (Zhang et al. 2010; Zou et al. 2018), and have paid little attention to the role of water resource embedded in grain consumption in wetland degradation. With the rise of the virtual water strategy and the strengthening of inter-regional trade, increasing amounts of virtual water (referring to the water invested in commodities) are transferred between regions (Allan 1998; Ma et al. 2006; Han et al. 2018). The risk of water shortages in commodity-importing regions spills over to commodity-exporting regions, aggravating the risk of resource shortages in export regions (Feng et al. 2014; Liu and Chen 2020). It is believed that the risk of wetland degradation can be transferred from food-importing regions to food-exporting regions through trade. Therefore, in addition to direct competition for water resources, the threat to wetland degradation of indirectly diverting water resources through food trade should also be considered (Dalin et al. 2017, 2019; Deng et al. 2020). The impact assessment of water resources embedded in food trade on wetland degradation would further enrich the socioeconomic impact of wetland degradation, while more general economic indicators, such as GDP, were considered in previous analysis (Cui et al. 2013; Ricaurte et al. 2017; Chen et al. 2018).

In this study, based on the ecological process of wetland degradation with the economic process of food trade, an ecology–economy nexus framework was constructed to comprehensively track wetland degradation caused by agricultural activities and explored potential measures for wetland restoration that also consider food security. We chose Heilongjiang as our study locality because of the prominent contradiction between wetlands and farmlands in this region. Based on a land use transfer matrix, we first analyzed the proportion of different land use types, main contribution of farmland expansion, and main driver of wetland degradation. Based on the ecology–economy nexus, we determined the contributions of Heilongjiang and other regions in China on local wetland degradation. Based on our findings, we explored a variety of scenarios for mitigating the wetland–farmland water conflict and promoting wetland restoration. We concluded that a mixed scenario combining a lower water footprint for crop production and reduced food export could promote wetland restoration to the maximum extent and reduce the conflict between farmland and wetland water usage.

Methods

Study area

Heilongjiang Province, which is located in Northeast China (121°11′–135°05′E, 43°26′–53°33′N), is rich in natural wetlands and has one of the most extensive areas of marsh wetlands in China (Niu et al. 2012; Mao et al. 2020). In the early 1950s, the total area of marsh wetlands in Heilongjiang was 791.4×10^4 hm^2, accounting for 17.48% of the total area of the province, which was characterized by high levels of biodiversity and high ecosystem value (Ning et al. 2008). The region is rich in water resources and fertile soil, and the climate is conducive to agricultural production (Chen et al. 2018). In 2015, the planting area of rice, wheat, corn, and soybean accounted for 95.70% of the total crop-planted area, and the crop output accounted for 57.72% of the province's total primary industrial output. Farmland expansion has caused large-scale degradation of wetlands in Heilongjiang: by 2015, the wetland area had decreased to 299.1×10^4 hm^2. The conflict between wetland protection and farmland development was prominent and mainly concentrated to the Sanjiang Plain and Songnen Plain (Chen et al. 2018; Zou et al. 2018) (Fig. 1).

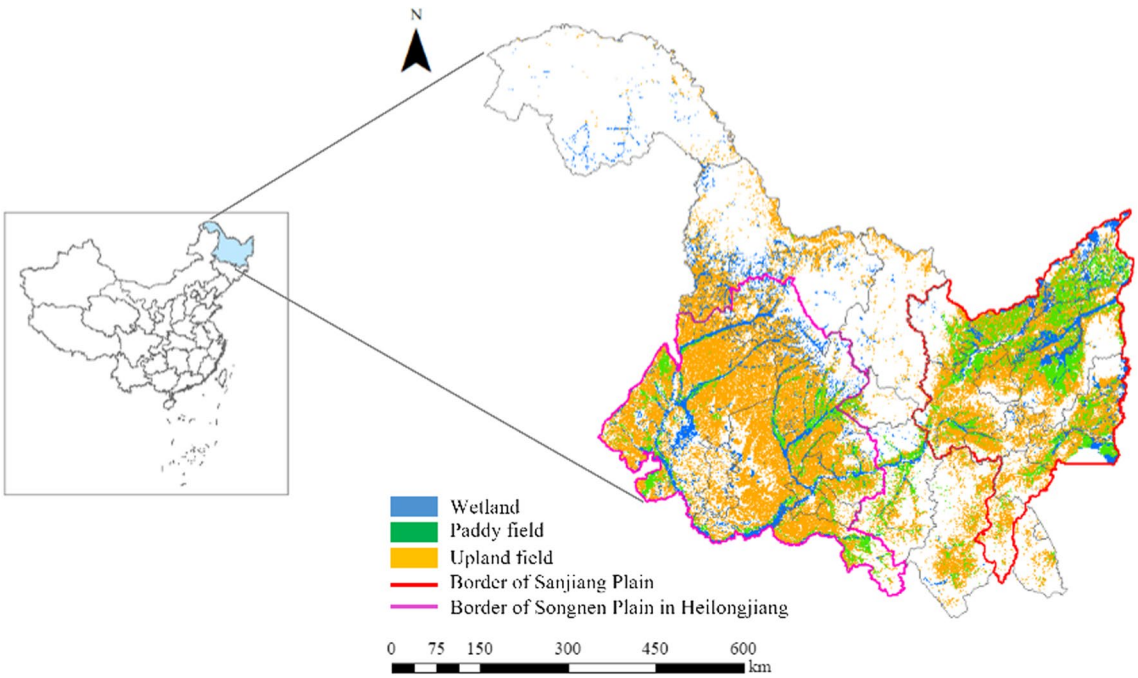

Fig. 1 Geographical location and distribution of wetland and farmland of Heilongjiang Province

Research framework and analysis of ecological and economic processes

To construct an ecology–economy nexus framework and analyze the area tradeoffs between wetlands and farmlands, we assumed that the sum of wetland and farmland area in Heilongjiang Province did not change during 1980–2015 (Fig. 2 and Additional file 1: Fig. S1). The framework mainly included the ecological process of area and water demand tradeoff between wetland degradation and farmland expansion, economic process of wetland degradation driven by food consumption, and nexus between the two processes. Research on ecological processes has focused on wetland degradation caused by land-use change and agricultural water consumption (Chen et al. 2018; Zou et al. 2018). The economic process quantifies the food trade driven by local and non-local food consumption and the wetland degradation embedded in the trade process based on multi-regional input–output (MRIO) analysis. Based on the ecology–economy nexus framework, the process of wetland degradation and the key influencing factors were analyzed comprehensively.

Land use changes analysis

The land use data of Heilongjiang Province covering a period of 35 years were extracted from the China multi-period land use and land cover remote monitoring datasets (CNLUCC, http://www.resdc.cn/DOI), which was developed based on the Landsat TM digital images using human–computer interactive interpretation method (Xu et al. 2018). The extracted land use data are a series of typical raster images with a spatial resolution of 1 km×1 km and a temporal resolution of year. For convenience of analysis, according to land use properties, the 21 subgroups of land use were reclassified into 8 types, including paddy

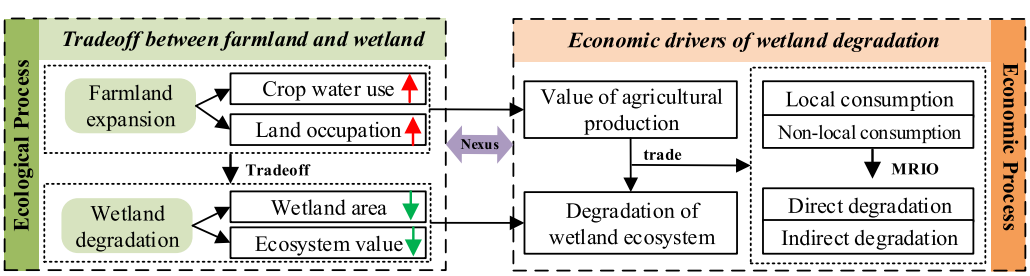

Fig. 2 Framework of ecology–economy nexus in context of area and water demand tradeoff between farmland and wetland

field, upland filed, wetland, forest land, grassland, waterbody, urban and rural land, and other unused land.

The change of specific land use type in the study region was calculated as:

$$\Delta A_{ij} = A_{ij} - A_{ji} \tag{1}$$

where ΔA_{ij} is the net change areas of land use type i to j in a certain period; A_{ij} is the area of land use type i transformed into j and A_{ji} is the area of land use type j transformed into i. A_{ij} and A_{ji} were obtained from the transfer matrix of two sets of land use data with the help of ArcGIS platform (Additional file 1: Table S1).

Water use and land occupancy

Water use for crop production Although irrigated agriculture occupies a dominant position in agricultural production, the proportion of rain-fed agriculture in Heilongjiang cannot be ignored. In the Sanjiang Plain, except that rice was an irrigated crop, other crops such as wheat, corn and soybean were all rain-fed. According to Portmann et al. (2010) and Hoekstra (2019), about 67% of the world's production came from rain-fed agriculture, and the efficient use of rainwater was as important as irrigation water. Therefore, both of green water and blue water related to crop production were considered in this study (Ma et al. 2021b). The green water refers to the amount of water resources stored in the soil for the evaporation of rainwater during the growth process of crops, while the blue water refers to the amount of water resources consumed in freshwater bodies, mainly including the evaporation of farmland irrigation water (Chapagain and Hoekstra 2011; Hoekstra 2019).

Theoretically, the water use of crop production (WU) is the amount of water resources consumed in the growth process of four crops (rice, wheat, corn and soybean), i.e., the sum of green water (WU_{green}) and blue water (WU_{blue}), represented as:

$$WU = WU_{green} + WU_{blue} \tag{2}$$

$$WU_{green} = WF_{green} * Y \tag{3}$$

$$WU_{blue} = WF_{blue} * Y + WL, \tag{4}$$

where WF_{green} and WF_{blue} was the green water footprint and blue water footprint, respectively; Y was crop yield per unit area; and WL was the water loss during irrigation:

$$WL = \alpha * WF_{blue} * Y * \frac{1-\eta}{\eta} \tag{5}$$

where α was the proportion of water surface evaporation to water loss for distribution; η was the effective utilization coefficient of farmland irrigation water (Shi et al. 2015).

Referred to the practice of Wu et al. (2019) and Zhuo et al. (2020), the study adopted the "fast track" to quantify the green and blue water use for crop production. Based on the principle that the water footprint per unit of crop is linearly negatively correlated with the yield level per unit of crop, "fast track" is a fast method to calculate the water footprint of crop production based on the water footprint database of crop production in a specific year (Zhuo et al. 2020; Ma et al. 2021a). The expression formula was as follows:

$$WF_t = \frac{WF_T * Y_T}{Y_t} \tag{6}$$

where WF_t and WF_T is the water footprint per unit of crop production for a given crop in year t and T. Y_t and Y_T is the yield of the crop in year t and T. Because of its low cost and high reliability, this method has been widely used in the world (Tuninetti et al. 2017; Ma et al. 2021a).

Land occupancy According to the definition and calculation method of ecological footprint (Rees 1992; Rashid et al. 2018), ecological footprint of cropland refers to the area of cropland resources needed to absorb the consumed resources and the generated wastes. The ecological footprint of cropland is a measure of human consumption of cropland from the perspective of human demand, highlighting the impact of social indicators on regional cropland resources (Rees 1992). The ecological footprint of cropland calculated in this study is one of the six productive land types, and the calculation formula was as follows:

$$EF = N \times ef \tag{7}$$

$$ef = \sum_{1}^{q} \gamma \left(\frac{c_q}{p_q} \right) \tag{8}$$

where the EF is the total ecological footprint of the regional cropland; N refers to the regional population; ef is the ecological footprint of cropland per capita; q is the crop type; γ is cropland balance factor; according to the existing researches and the actual situation of the research area, $\gamma = 1.71$ was used in this study (Liu and Li 2009); c_q is the qth crop area per capita annual output; P_q is the average productivity of the qth crop. Subject to the constraints of relevant statistical data, we used the total

grain yield and the average yield per unit area instead of the index of crops in the quantification.

Valuation of ecosystem services

The ecosystem services include supply services (e.g., food production), regulation services (climate regulation, hydrology regulation, etc.), support services (soil conservation) and cultural services (providing esthetic landscapes) (Costanza et al. 1997; Xie et al. 2008; Yan and Zhang 2019). In this study, the degradation of wetland structure and function was characterized by the decline of wetland ecosystem services. At the same time, we also estimated the ecosystem services of cropland to analyze the changes in total value of ecosystem services in the regional wetland–cropland complex system.

Different land use types have different services value per unit area. For example, wetland can provide more regulation, support and cultural services, while farmland is more prominent in provisioning services (Song et al. 2021). According to Chen (2018), paddy field and upland field also provide different services value. Paddy field, as one of the constructed wetlands, has better regulation service than dry field, while dry field has better soil conservation service. Some studies have quantified the services value of different ecosystems through questionnaire survey, data collection and expert scoring method (Ouyang et al. 1999; Xie et al. 2008; Yan and Zhang 2019). In this study, the value of ecosystem services per unit area (Additional file 1: Table S2) was used for further study. The data were obtained by combining the correlation coefficient proposed by Xie et al. (2008) and Chen (2018). According to Song et al. (2010), the value of ecosystem services per unit area of Heilongjiang Province changed by about 5% during 1999–2007, with a small range. Therefore, for the convenience of accounting, we assumed that the value of ecosystem services did not change at the time frame of this study.

The calculation formula of Costanza et al. (1997) was used to determine the ecosystem services of the study region:

$$ESV = \sum_{1}^{m} (S_m VC_{mn}) \tag{9}$$

where ESV is the total value of ecosystem services (yuan), m is land use type, n is ecosystem services function type, S_{m} is the area (hm^2) of the mth land use type, and VC_{mn} is the coefficient (yuan hm^{-2} yr^{-1}) corresponding to the nth ecosystem services value of the mth land use type.

Direct and indirect wetland degradation analysis

Water is essential to wetland structure, and thus water balance determines the change in wetland area (Zou et al. 2018). Therefore, wetland degradation can be simply understood as a reduction in wetland water storage. By consuming agricultural products from Heilongjiang, local and non-local economic sectors indirectly consume virtual water, thus indirectly competing with wetland water resources in Heilongjiang. Based on the virtual water concept (Allan 1998), it is assumed that the higher the unit economic output value, the larger the area of wetland being degraded, though this hypothesis has some limitations (Zhang et al. 2020).

Multi-regional input–output (MRIO) analysis is a useful tool for providing comprehensive interwoven economic linkages of inter-regional trade and intersectoral allocation, facilitating to track resources to their origin or to where they are utilized in a complex economic network (Wang and Chen 2016). Given its strengths to investigate the interdependencies, MRIO has been widely used in different scales and fields to explain the embedded resource flows caused by intersectoral trade activities (Liu and Chen 2020; Zhang et al. 2020). As a top-down method, the MRIO model cannot describe the specific relationship between economic value and wetland degradation. Nevertheless, it is possible to track wetland degradation caused by competition between economic activities for water resources among sectors and even regions. Here, wetland degradation driven by local consumption was defined as direct wetland degradation, whereas wetland degradation caused by the trade of agricultural products or services from Heilongjiang was defined as indirect wetland degradation. Considering the relationship between water resources and wetlands, the MRIO was used to quantify the proportion of wetland degradation in Heilongjiang caused by local consumption and inter-regional trade. Compared with a bottom-up approach, which only considers the wetland degradation caused by direct water consumption in the production process, the direct and indirect estimates using the MRIO model can more effectively track wetland degradation caused throughout the supply chain.

The basic MRIO model can be described as:

$$X = Z + Y \tag{10}$$

where X was the total output column matrix; Z was the intermediate flow matrix, and Y was the final demand matrix. A_{ij}^{rs} was the direct input coefficient matrix:

$$A_{ij}^{rs} = \left(a_{ij}^{rs}\right) = \left(\frac{Z_{ij}^{rs}}{x_j^s}\right) \tag{11}$$

where Z_{ij}^{rs} was the cross-sectoral monetary flow that from sector i in region r to sector j in region s, and x_j^s was the total input of sector j in region s. Therefore,

$$X = AX + Y \tag{12}$$

Further, then

$$X = (I - A)^{-1}Y \tag{13}$$

where $(I - A)^{-1}$ was the Leontief inverse matrix, representing the total increased input in the supply chain required to meet the final demand of a unit, including direct input and indirect input. I was the identity matrix with the same dimension as A. Therefore, the environmental extended MRIO model related to water resource consumption can be expressed as follows:

$$F = (I - A)^{-1} \times K \times Y \tag{14}$$

where F represented the total amount of water resource consumed in the whole supply chain driven by final demand, and K was the coefficient matrix of direct water consumption.

Scenario analysis for wetland restoration

Based on the area tradeoff between wetlands and farmlands, five scenarios were established to explore the potential for wetland restoration by 2030. According to the Fourteenth Five-Year Plan (2021–2025) of Heilongjiang Province and the 2035 Vision Goals Suggestion, the grain output of Heilongjiang will be stable at more than 75×10^9 kg. Therefore, in the baseline scenario, we assumed that the total output of the four major crops in 2030 will increase by 1.18 times that in 2015, so as to ensure that the total grain output from Heilongjiang can reach the target output. At the same time, the water footprint of crop production per unit yield and crop planting structure remained unchanged. Scenario 1, reduced water footprint: we assumed that the water footprint of crop production per unit yield was reduced by 10% based on the baseline scenario. Scenario 2, adjusted crop planting structure: we assumed that the acreage of crops with higher and lower water footprints per unit yield decreased and increased by ~ 20%, respectively (water footprint of crop production data from Zhuo et al. (2016)). Scenario 3, reduced food exports: we assumed that the total food transfer from Heilongjiang was reduced by 20%. Scenario 4: this scenario combined Scenarios 1 and 2. Scenario 5: this scenario combined Scenarios 1 and 3.

For convenience of calculation, in Scenario 2, we adjusted the crop planting structure on the basis of yield because yield and area were assumed to be proportional. In addition, the equation used to calculate the potential of wetland restoration considered the relationship between the water consumption for crop production and wetland area. Based on the observed wetland area and simulated wetland area, the R^2, normalized root mean square error (*nRMSE*) and mean absolute error (*MAE*) were used to verify the restoration potential of wetland. The *nRMSE*, *MAE* and R^2 of simulated wetland area and observed wetland area were 7.60%, 7.38% and 0.67, respectively. The simulated values agreed with the observed values within the acceptable range, and it was believed that the simulated wetland restoration potential was reliable.

Data sources

Land use data for Heilongjiang were obtained from the Resource and Environment Science and Data Center, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences (https://www.resdc.cn/). The blue and green water footprints of crops per unit yield in different years required by the "fast track" to quantify the water footprint of crop production were obtained from the International Water Footprint Network database (WaterStat) (http://waterfootprint.org/en/resources/waterstat). The database includes water footprints of both crop production (1961–2009) and consumption (1978–2009) in Chinese mainland at the provincial level for 22 crops (Zhuo et al. 2016). The basic data used to account for the ecological footprint of cropland, such as regional population, crop-planted area, total yield, and yield per unit area, were obtained from the China Statistical Yearbook. Coefficients for the calculation of ecosystem services were obtained through literature research. Direct and indirect wetland degradation were accounted for based on China's MRIO table. The land use transfer matrix and GIS map were completed using ArcGIS, and the correlation analysis between resources consumption and wetland degradation was conducted using Origin software.

Results

Wetland degradation driven by farmland expansion

In the land use change analysis, we first analyzed the ecological process of wetland degradation driven by farmland expansion. The shrinking area of wetlands and the total wetland area showed a decreasing trend from 1980 to 2010 (Fig. 3a, b). During this period, the shrinking wetland area caused by farmland expansion was 10716.02 km^2, accounting for 93.76% of the total shrinking wetland area, of which the expansion of paddy fields accounted for 50.90%, being higher than that of upland fields (43.86%). The proportion of shrinking wetland areas caused by upland field expansion decreased annually, while that caused by the expansion of paddy fields increased. During 1980–1990, the shrinking wetland area was the largest throughout the study period, accounting for 4961.99 km^2. Among them, the shrinking area driven

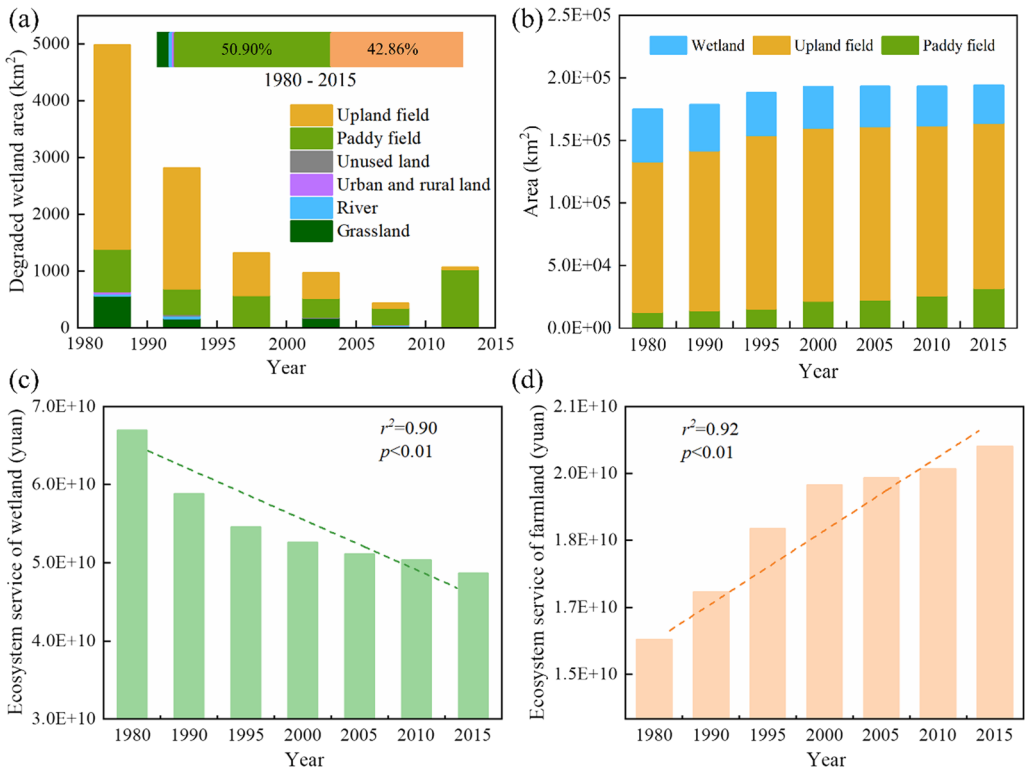

Fig. 3 Area and ecosystem services changes of wetland and farmland during 1980–2015. **a** composition of wetland area shrinking caused by different land use types; **b** area changes of wetland and farmland; **c** ecosystem service changes of wetland; **d** ecosystem service changes of farmland

by upland field expansion accounted for 71.87%, while that driven by paddy fields accounted for 15.01%. During 1990–2005, wetland area shrinking driven by upland field expansion remained dominant. Since then, the proportion of paddy field expansion had increased, resulting in an 80% and 98.37% shrinkage of wetland area from 2005 to 2010 and 2010 to 2015, respectively. During 2010–2015, the shrinking wetland area was 1060.99 km^2, with farmland expansion accounting for 98.60%.

In addition to wetland area shrinkage, we also quantified the degradation of wetland structure and function by accounting for changes in wetland ecosystem services. Since 1980, the ecosystem services of wetlands had decreased ($P<0.01$, Fig. 3c), indicating that the structure and function of wetlands had been degraded. Simultaneously, the ecosystem services of farmland increased ($P<0.01$, Fig. 3d), which was mainly related to the expansion of farmland and the high economic value per unit of agricultural products. Therefore, Heilongjiang lost the ecological benefits of wetlands and gained the economic benefits of farmland. However, the ecosystem services of the wetland–farmland complex showed a significant downward trend, indicating that the economic benefits related to the agricultural economy did not compensate for the sacrificed wetland ecosystem services.

In the ecological process analysis of wetland degradation driven by farmland expansion, the correlation between wetland area and water consumption for crop production and ecological footprint of cropland was further analyzed to explore the cause of wetland degradation (Fig. 4). We observed a negative correlation between wetland area and the water consumption for crop production ($P<0.05$), indicating that increasing water consumption by regional crop production made the wetland unable to maintain the ecological water demand, and thus increased the risk of wetland degradation. A negative correlation between wetland area and the ecological footprint of cropland was observed, though this was not significant ($P>0.05$). This indicated that the main cause of regional wetland degradation was the increase in the water consumption for crop production, rather than the expansion of crop acreage.

Wetland degradation driven by agricultural economic activities

Based on the ecology–economy nexus framework, we analyzed the economic process of direct and indirect

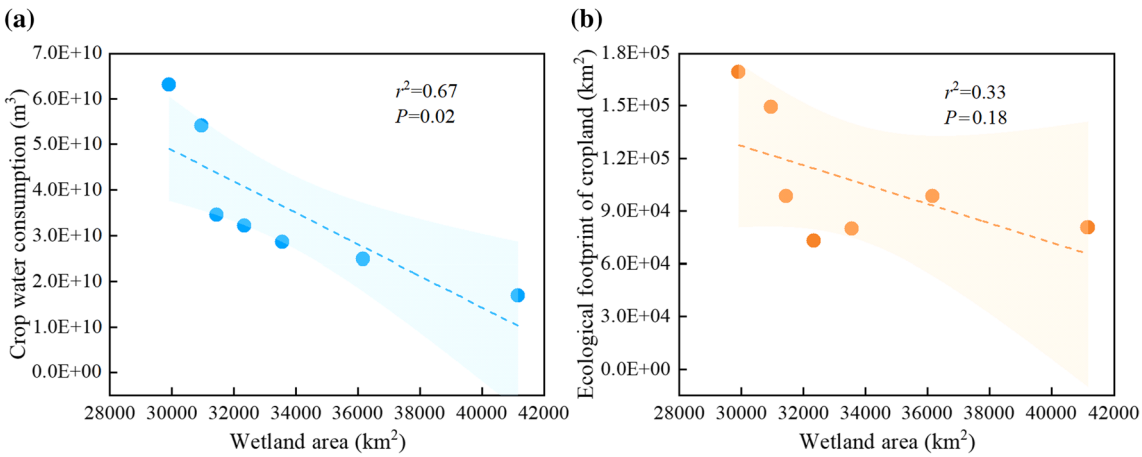

Fig. 4 Correlation analysis between wetland area and water consumption for crop production and ecological footprint of cropland. **a** Correlation between wetland area and water consumption for crop production; **b** correlation between wetland area and ecological footprint of cropland

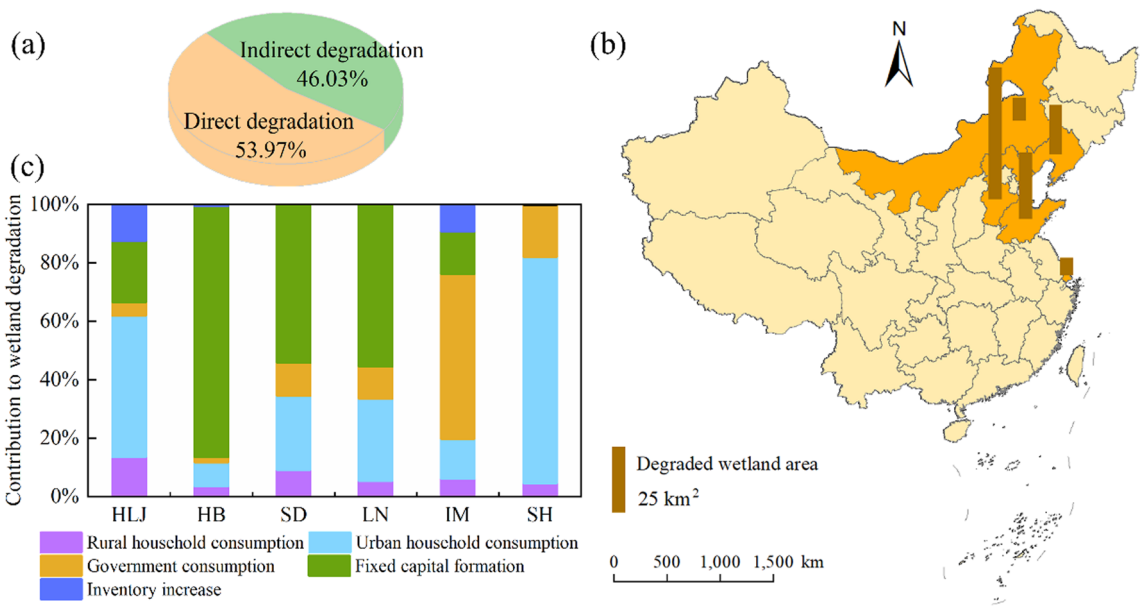

Fig. 5 Wetland degradation driven by agricultural economic activities. **a** proportion of direct and indirect wetland degradation driven by local and non-local final demand; **b** the top five provinces contributing to the annual average indirect wetland degradation in Heilongjiang; **c** contribution of final demand types to wetland degradation. HLJ, Heilongjiang; HB, Hebei; SD, Shandong; LN, Liaoning; IM, Inner Mongolia; SH, Shanghai

wetland degradation. The net degraded (shrinking) wetland area caused by farmland expansion was 306.17 km^2 per year from 1980 to 2015, of which the direct wetland degradation reached 53.97%, while the indirect wetland degradation accounted for 46.03% (Fig. 5a). Therefore, the main burden of wetland degradation caused by farmland expansion was in Heilongjiang, though the amount of wetland degradation driven by economic activities in other regions should not be underestimated. Hebei and Shandong made the greatest contributions to indirect wetland degradation, corresponding to areas of 50.44 km^2 and 25.57 km^2, respectively, followed by Liaoning (18.88 km^2), Inner Mongolia (8.88 km^2), and Shanghai (6.96 km^2) (Fig. 5b). The wetland degradation caused by these five provinces accounted for 78.57% of indirect wetland degradation, followed by Tianjin, Zhejiang, Guangdong, Yunnan, and Henan. The ten provinces collectively

accounted for more than 90% of the indirect degradation of wetlands in Heilongjiang.

Regarding local factors of final water demand, the direct wetland degradation caused by urban household consumption accounted for the largest proportion (48.41%), followed by fixed capital formation (21.05%) and rural household consumption (13.54%) (Fig. 5c). Regarding indirect factors of wetland degradation driven by economic activities in Hebei, fixed capital formation accounted for the largest proportion (85.98%), followed by urban and rural household consumption. The proportion of indirect degradation caused by different types of consumption in Shandong and Liaoning was similar, with fixed capital formation, urban household consumption, and government consumption accounting for the largest proportion. In Shanghai, indirect wetland degradation driven by urban consumption accounted for 77.48%, followed by government consumption (17.80%) and rural household consumption (4.69%). Policy formation should specifically consider the major consumers when formulating the economic compensation required for wetland restoration.

Scenario analysis of wetland restoration

Compared to 2015 in the baseline scenario, farmlands will continue to compete with wetlands for water due to increased crop yields and total water consumption for crop production, leading to further degradation of wetland area (loss of ~ 3412 km^2) (Fig. 6). Scenarios 1 and 2 also showed potential for degradation by 1241 km^2 and 1869 km^2, respectively, though this degree of degradation is much lower than that in the baseline scenario. Scenarios 3, 4, and 5 all showed wetland restoration potential, among which Scenario 5 had the largest wetland restoration area (2668 km^2), followed by Scenario 3 (931 km^2) and Scenario 4 (148 km^2). Compared with the baseline scenario, the wetland ecosystem services under all scenarios increased to varying degrees: Scenario 5 showed the best improvement, followed by Scenarios 3, 4, 1, and 2. There was little difference in farmland ecosystem services under the different scenarios.

Discussion

Under the framework of ecology–economy nexus, we analyzed the ecological process of area and water demand tradeoff between wetland degradation and farmland expansion and the economic process of wetland degradation driven by food consumptions, and explored the strategies of wetland restoration. It was highlighted that the increase in crop water consumption caused by farmland expansion was considered to be the main cause of wetland degradation and the virtual water embedded in exported agricultural products also increased the considerable risk of wetland degradation. By reducing water consumption in crop production with improving food trade patterns, wetland restoration can be effectively promoted.

Drivers of wetland degradation

Several studies have shown that agricultural development was the main cause of wetland degradation, without elucidating the main factor of wetland degradation among agricultural activities and the specific correlation between wetland degradation and agricultural expansion (Li et al. 2020). In the present study, a more significant correlation between water consumption for crop production and wetland degradation than between the land use change and wetland degradation was found (Fig. 4 and Additional file 1: Fig. S2). The findings emphasize the risk posed by farmland water conflict on wetland degradation. In addition, it is important to note that the

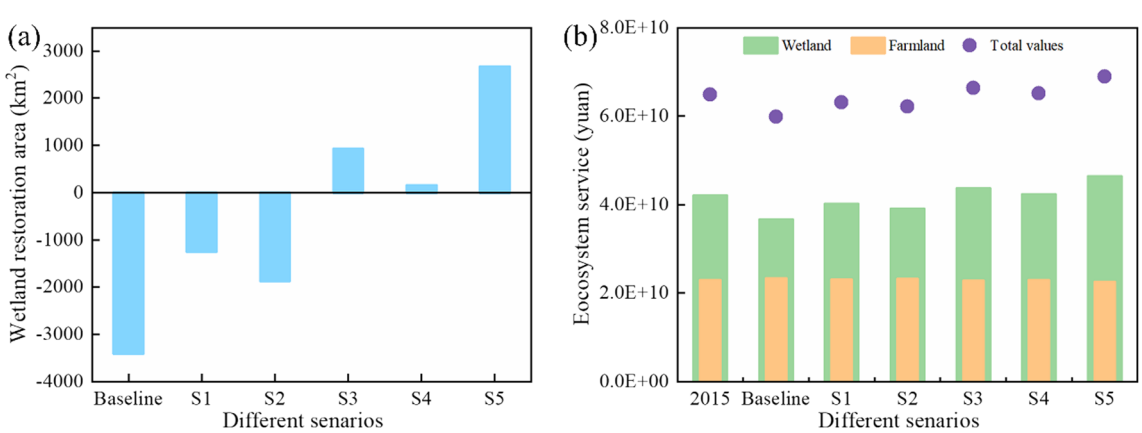

Fig. 6 Wetland restoration potential (**a**) and ecosystem services of wetland and farmland (**b**) under different scenarios in 2030

green water consumption of crops and the development of rain-fed agriculture could have a profound impact on wetland condition: green water can supplement surface water sources through surface runoff, but also infiltrate the soil to replenish groundwater sources, which will impact the local water cycle (Hoekstra 2019). Zou et al. (2018) also showed that green water can supplement groundwater or wetlands, and maintain the ecological water demand of wetlands. From 1980 to 2015, the green water of crop production in Heilongjiang was much higher than the blue water, and the increase in the green water use of crop production (73.26%) was comparable to that of the blue water (73.61%) (Additional file 1: Fig. S3), indicating that the role of green water in agricultural production was as important as the role of blue water. Therefore, future research should especially consider the roles of green water in regional wetland protection and sustainable agricultural development.

The export of agricultural products from Heilongjiang was a major external driver of wetland degradation. Under current economic activities, the local final demand of Heilongjiang contributed 53.97% of the annual average wetland degradation; and the combined contribution of the final demand of Hebei, Shandong, and other regions was 46.03% (Fig. 5), implying that increased trade from Heilongjiang to other would accelerate the degradation of local wetlands. Similar resource risk transfers and spillovers have been investigated in other studies. For example, Dalin et al. (2019) showed that the transfer of virtual water from export regions to import regions through food trade increased the use of non-renewable groundwater and aggravated the risk of water shortages in export regions. The study suggested that reducing virtual water exports in the food trade would contribute to the sustainability of local water resources. Therefore, reducing the export of water-intensive primary and processed products from Heilongjiang may promote wetland protection. However, reducing food exports from Heilongjiang would be challenging. In the current market, considering the dominant force of resource allocation and technical conditions of food production, Heilongjiang has a considerable comparative advantage over other regions in crop production (Xu et al. 2001). As one of China's major grain producers, Heilongjiang accounts for half of the total agricultural output and is therefore especially vulnerable to environmental degradation through trade. Therefore, driven by current economic regulations and market forces, the degradation of wetlands in Heilongjiang is strongly influenced by the final water demand of other provinces.

Strategies for wetland restoration based on the ecology–economy nexus

On balance, the scenarios suggest that the most effective way to restore wetland ecology is to change the domestic food trade pattern, that is, to reduce the food export volume from Heilongjiang (Fig. 6). Changes in food trade patterns can be facilitated by national policy instruments, though this remains difficult. Meanwhile, the decrease in grain production and exports from Heilongjiang would lead to increased food production in other regions to meet the national food demand for food, which simply shifts the burden of wetland degradation. The change in the footprint of the national production chain would result either in resource saving or more severe environmental effects at the national scale. For example, Harris et al. (2020) found that among Indian states, 41% and 21% of the grains traded within India came from states with excessive exploitation and severe depletion of groundwater, respectively, which suggests that the food trade added to the pressure on some of the most water-stressed regions. Therefore, we hypothesize that the environmental and economic value of national trade may decrease if the negative environmental impact of new food producers becomes too high.

Reducing the water footprint of crop production per unit yield is fundamental for restoring wetland ecology. However, the improvement in water resource utilization efficiency is affected by irrigation habits and technology, though its effect on wetland change is particularly slow. For example, Cao et al. (2020) showed that the production water footprint efficiency of crops has increased by 0.122 over the past 20 years. Further improvements to the water footprint efficiency of crops can be made by increasing irrigation efficiency and limiting the irrigation area. Deng et al. (2006) also reported that the improvement and promotion of advanced surface irrigation technology were relatively slow and difficult to implement. Therefore, there is an urgent need to improve the design and efficiency of irrigation systems in order to improve the utilization of water resources.

In this study, the potential for wetland restoration by adjusting crop planting patterns was limited, which may be related to the small degree of adjustment. Keeping the total planting area unchanged, the planting area of different crops increased or decreased in the same proportion, so that the change in the total water consumption for crop production did not change much. For wetland restoration with greater crop planting pattern adjustment than in the baseline scenario, the effect remained non-significant. According to Dai et al. (2021), optimizing crop planting patterns can significantly reduce the blue and grey water

footprints of the Hai River Basin and achieve more efficient economic water productivity. Therefore, to simultaneously maintain national food security, the optimization of crop planting structure may achieve better results.

Limitations and topics for future research

In this study, the quantification of wetland degradation mainly considered the shrinking of wetland area, which is one of the most important indicators of wetland degradation (O'Connell 2003; Zhang and Li 2004). However, we quantified the degradation of wetland structure and function by the reduction of wetland ecosystem services without considering the specific degradation process. Second, for the convenience of calculation, we simplified the quantification of the ecology–economy nexus between wetlands and farmland, and considered the relationship between wetland degradation and farmland expansion instead as a relationship between wetland degradation and agricultural economic value. The MRIO itself may affect the accuracy of wetland degradation estimates for interprovincial agricultural economic activities to some extent, but this would not affect our main conclusions. Finally, the regional water cycle of wetlands, including their formation, decay, and disappearance, plays an important role in correlating the water consumption for crop production and wetland degradation (Han et al. 2012). However, based on the scope of the current study, we did not consider the various water movement mechanisms between wetlands and farmland, especially the influence on wetland degradation by the interaction of surface and groundwater, which should be considered in future studies.

Conclusions

This study explored the ecological process of the area and water demand tradeoffs between wetlands and farmlands, the economic process of wetland degradation driven by food consumption, and the nexus between the two processes in Heilongjiang. Our study extends the current paradigm on the relationship between wetland degradation, agricultural production, and interprovincial food trade. We showed that the main driver of wetland degradation was the increase in the water consumption caused by farmland expansion, and the major external driver was the indirect consumption through trade to other regions in China. Agricultural development in Heilongjiang in recent decades has come at the expense of wetland ecosystems, and the economic gain was far outweighed by the ecological loss related to wetland degradation. To reduce the impact of agricultural production on wetland degradation, the ecology–economy nexus framework should be incorporated into policy formation, and advanced water resource-use technology should be combined with the adjustment of regional planting structure and improvement of domestic food trade patterns, so as to promote the sustainable synergistic benefits of regional agricultural production and wetland protection.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13717-023-00452-x.

Additional file 1: Table S1. Transfer matrix of land use. **Table S2.** Ecosystem services value per unit area of wetland and farmland (yuan hm^{-2} yr^{-1}). **Fig. S1.** Total area of wetland and farmland during 1980–2015. **Fig. S2.** Correlation between blue water/green water consumption and wetland area. **Fig. S3.** Blue and green water consumption for crop production in 1980–2015.

Acknowledgements
We thank the land use data support provided by Resource and Environment Science and Data Center, Chinese Academy of Sciences. We appreciate the constructive comments provided by the editor and anonymous reviewers to this paper.

Author contributions
LJ and WZ designed and supervised the research; LJ, HW, and SW collected, analyzed, and visualized the data; LJ wrote the first draft; WZ edited the paper. All authors reviewed the paper critically. All authors read and approved the final manuscript.

Funding
This work was supported by the National Natural Science Foundation of China (No. 72004126) and China Postdoctoral Science Foundation (2019M662430).

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no conflicts of interest to disclose.

Received: 21 February 2023 Accepted: 14 August 2023
Published online: 04 September 2023

References

Allan JA (1998) Virtual water: a strategic resource global solutions to regional deficits. Groundwater 36:545–546
An S, Li H, Guan B, Zhou C, Wang Z, Deng Z, Zhi Y, Liu Y (2007) China's natural wetlands: past problems, current status, and future challenges. Ambio 36:551–558
Cao X, Shu R, Ren J, Wu M, Huang X, Guo X (2020) Variation and driving mechanism analysis of water footprint efficiency in crop cultivation in China. Sci Total Environ 725:138537

Chapagain AK, Hoekstra AY (2011) The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol Econ 70:749–758
Chen D (2018) Analysis of marsh wetland change and ecosystem service value in the Sanjiang Plain. Jilin University, Changchun
Chen H, Zhang W, Gao H, Nie N (2018) Climate change and anthropogenic impacts on wetland and agriculture in the Songnen and Sanjiang Plain, Northeast China. Remote Sens 10:356
Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M (1997) The value of the world's ecosystem services and natural capital. Nature 387:252–260
Cui L, Gao C, Zhou D, Mu L (2013) Quantitative analysis of the driving forces causing declines in marsh wetland landscapes in the Honghe region, northeast China, from 1975 to 2006. Environ Earth Sci 71:1357–1367
Dai C, Qin XS, Lu WT (2021) A fuzzy fractional programming model for optimizing water footprint of crop planting and trading in the Hai River Basin, China. J Clean Prod 278:123196
Dalin C, Wada Y, Kastner T, Puma MJ (2017) Groundwater depletion embedded in international food trade. Nature 543:700–704
Dalin C, Taniguchi M, Green TR (2019) Unsustainable groundwater use for global food production and related international trade. Glob Sustain 2:e12
Deng X, Shan L, Zhang H, Turner NC (2006) Improving agricultural water use efficiency in arid and semiarid areas of China. Agric Water Manag 80:23–40
Deng C, Zhang G, Li Z, Li K (2020) Interprovincial food trade and water resources conservation in China. Sci Total Environ 737:139651
Feng K, Hubacek K, Pfister S, Yu Y, Sun L (2014) Virtual scarce water in China. Environ Sci Technol 48:7704–7713
Han D, Yang Y, Yang Y, Li K (2012) Recent advances in wetland degradation research. Acta Ecol Sin 32:1293–1307
Han MY, Chen GQ, Li YL (2018) Global water transfers embodied in international trade: tracking imbalanced and inefficient flows. J Clean Prod 184:50–64
Harris F, Dalin C, Cuevas S, Lakshmikantha NR, Adhya T, Joy EJM, Scheelbeek PFD, Kayatz B, Nicholas O, Shankar B, Dangour AD, Green R (2020) Trading water: virtual water flows through interstate cereal trade in India. Environ Res Lett 15:125005
Hoekstra AY (2019) Green-blue water accounting in a soil water balance. Adv Water Resour 129:112–117
Li Z, Liu M, Hu Y, Xue Z, Sui J (2020) The spatiotemporal changes of marshland and the driving forces in the Sanjiang Plain, Northeast China from 1980 to 2016. Ecol Process 9:24
Liu Y, Chen B (2020) Water-energy scarcity nexus risk in the national trade system based on multiregional input-output and network environ analyses. Appl Energ 268:114974
Liu M, Li W (2009) The calculation of China's equivalence factor under ecological footprint model based on net primary production. J Nat Resour 9:1551–1559
Ma J, Hoekstra AY, Wang H, Chapagain AK, Wang D (2006) Virtual versus real water transfers within China. Philos Trans R Soc B Biol Sci 361:835–842
Ma C, Yang Z, Xia R, Song J, Liu C, Mao R, Li M, Qin X, Hao C, Jia R (2021a) Rising water pressure from global crop production—a 26-yr multiscale analysis. Resour Conserv Recy 172:105665
Ma W, Meng L, Wei F, Opp C, Yang D (2021b) Spatiotemporal variations of agricultural water footprint and socioeconomic matching evaluation from the perspective of ecological function zone. Agric Water Manag 249:106803
Mao D, Luo L, Wang Z, Wilson MC, Zeng Y, Wu B, Wu J (2018) Conversions between natural wetlands and farmland in China: a multiscale geospatial analysis. Sci Total Environ 634:550–560
Mao D, Wang Z, Du B, Li L, Tian Y, Jia M, Zeng Y, Song K, Jiang M, Wang Y (2020) National wetland mapping in China: a new product resulting from object-based and hierarchical classification of Landsat 8 OLI images. J Photogramm Remote Sens 164:11–25
Ning J, Zhang S, Li Y, Wang L (2008) Analysis on wetland shrinking characteristics and its cause in Heilongjiang province for the last 50 years. J Nat Resour 23:79–86
Niu Z, Zhang H, Wang X, Yao W, Zhou D, Zhao K, Zhao H, Li N, Huang H, Li C, Yang J, Liu C, Liu S, Wang L, Li Z, Yang Z, Qiao F, Zheng Y, Chen Y, Sheng Y, Gao X, Zhu W, Wang W, Wang H, Weng Y, Zhuang D, Liu J, Luo Z, Cheng X, Guo Z, Gong P (2012) Mapping wetland changes in China between 1978 and 2008. Chin Sci Bull 57:2813–2823
O'Connell MJ (2003) Detecting, measuring and reversing changes to wetlands. Wetl Ecol Manag 11:397–401
Ouyang Z, Wang X, Miao H (1999) A primary study on Chinese terrestrial ecosystem services and their ecological-economic values. Acta Ecol Sin 19:607–613
Portmann FT, 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. Global Biogeochem Cy 24:GB1011
Rashid A, Irum A, Malik IA, Ashraf A, Rongqiong L, Liu G, Ullah H, Ali MU, Yousaf B (2018) Ecological footprint of Rawalpindi; Pakistan's first footprint analysis from urbanization perspective. J Clean Prod 170:362–368
Rees WE (1992) Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ Urban 4:121–130
Ricaurte LF, Olaya-Rodríguez MH, Cepeda-Valencia J, Lara D, Arroyave-Suárez J, Max Finlayson C, Palomo I (2017) Future impacts of drivers of change on wetland ecosystem services in Colombia. Global Environ Chang 44:158–169
Rodell M, Famiglietti JS, Wiese DN, Reager JT, Beaudoing HK, Landerer FW, Lo MH (2018) Emerging trends in global freshwater availability. Nature 557:651–659
Shi L, Wu P, Wang Y, Sun S, Liu J (2015) Assessment of water stress in Shaanxi Province based on crop water footprint. Chin J Eco-Agric 23(5):650–658
Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Döll P, Portmann FT (2010) Groundwater use for irrigation—a global inventory. Hydrol Earth Syst Sci 14:1863–1880
Song G, Dong F, Sun L, Lei G (2010) The impact of land use change on regional ecosystem service value based on RS/GIS: take Heilongjiang Province as an example. International Conference on Construction & Real Estate Management
Song F, Su F, Mi C, Sun D (2021) Analysis of driving forces on wetland ecosystem services value change: a case in Northeast China. Sci Total Environ 751:141778
Tuninetti M, Tamea S, Laio F, Ridolfi L (2017) A Fast Track approach to deal with the temporal dimension of crop water footprint. Environ Res Lett 12:074010
Wang S, Chen B (2016) Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: a case study of the Beijing–Tianjin–Hebei region. Appl Energy 178:773–783
Wang Z, Song K, Ma W, Ren C, Zhang B, Liu D, Chen JM, Song C (2011) Loss and fragmentation of marshes in the Sanjiang Plain, Northeast China, 1954–2005. Wetlands 31:945–954
Wu P, Zhuo L, Liu Y, Gao X, Wang Y, Zhao X, Sun S (2019) Assessment of regional crop-related physical-virtual water coupling flows. Chin Sci Bull 64:1953–1966
Xie G, Zhen L, Lu C, Xiao Y, Chen C (2008) Expert knowledge based valuation method of ecosystem services in China. J Nat Resour 23:911–919
Xu Z, Fu L, Zhong F (2001) Analysis on the regional comparative advantage of grain production in China. J China Agric Resour Reg Plan 22:45–48
Xu X, Liu J, Zhang S, Li R, Yan C, Wu S (2018) Multi-period land use and land cover remote monitoring datasets (CNLUCC). Res Environ Sci Data Registr Publ Syst. https://doi.org/10.12078/2018070201
Yan F, Zhang S (2019) Ecosystem service decline in response to wetland loss in the Sanjiang Plain, Northeast China. Ecol Eng 130:117–121
Zhang X, Li P (2004) Discussion on standard of wetland degradation. Wetland Science 2:36–41
Zhang J, Ma K, Fu B (2010) Wetland loss under the impact of agricultural development in the Sanjiang Plain, NE China. Environ Monit Assess 166:139–148
Zhang W, Fan X, Liu Y, Wang S, Chen B (2020) Spillover risk analysis of virtual water trade based on multi-regional input-output model—a case study. J Environ Manag 275:111242

Zhuo L, Mekonnen MM, Hoekstra AY (2016) The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: a study for China (1978–2008). Water Res 94:73–85
Zhuo L, Li M, Wu P, Huang H, Liu Y (2020) Assessment of crop related physical-virtual water coupling flows and driving forces in Yellow River Basin. J Hydraul Eng 9:1–11
Zou Y, Duan X, Xue Z, Sun M, Lu X, Jiang M, Yu X (2018) Water use conflict between wetland and agriculture. J Environ Manag 224:140–146

Publisher's Note