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Article — Published Version

Exploring the emergence and changing dynamics of a new integrated rice-crawfish farming system in China

Environmental Research Letters

Provided in Cooperation with:

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Suggested Citation: Wei, Yanbing et al. (2023) : Exploring the emergence and changing dynamics of a new integrated rice-crawfish farming system in China, Environmental Research Letters, ISSN 1748-9326, IOP Publishing, Bristol, Vol. 18, Iss. 6, pp. 1-13, <https://doi.org/10.1088/1748-9326/acd8d2> , <https://iopscience.iop.org/article/10.1088/1748-9326/acd8d2>

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ENVIRONMENTAL RESEARCH
LETTERS

LETTER

Exploring the emergence and changing dynamics of a new integrated rice-crawfish farming system in China

OPEN ACCESS

RECEIVED

14 March 2023

REVISED

3 May 2023

ACCEPTED FOR PUBLICATION

25 May 2023

PUBLISHED

6 June 2023

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Yanbing Wei^{1,2} , Daniel Müller^{2,3,4} , Zhanli Sun² , Miao Lu¹, Huajun Tang¹ and Wenbin Wu^{1,*}

¹ State Key Laboratory of Efficient Utilization of Arid and Semi-arid Arable Land in Northern China/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, People's Republic of China

² Leibniz Institute of Agricultural Development in Transition Economies (IAMO), Halle (Saale) 06120, Germany

³ Geography Department, Humboldt-Universität zu Berlin, Berlin 10099, Germany

⁴ Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt Universität zu Berlin, Berlin 10099, Germany

* Author to whom any correspondence should be addressed.

E-mail: wuwenbin@caas.cn

Keywords: crop-aquaculture system, crawfish, paddy rice, spatio-temporal dynamics

Supplementary material for this article is available [online](#)

Abstract

Crop-aquaculture systems are widely adopted around the world as they can provide high protein and energy outputs per unit of land and raise farm incomes, particularly for smallholder farmers. Recently, a new crop-aquaculture system, which combines rice production with crawfish breeding (integrated rice-crawfish farming), has emerged and rapidly expanded in China. However, the spatial extent and temporal dynamics of this integrated farming system largely remain unclear, which prohibits rigorous impact assessments to support its sustainable development. Here we use time series of Landsat satellite data, for the first time, to explore the emergence and the changing dynamics of this rice-crawfish farming system for the period of 2013–2021 in five provinces (805 600 km²) of China, where 90% of the global crawfish are produced. Our analysis reveals that the total area of rice-crawfish farming in these five provinces increased steadily from 0.11 Mha in 2013 to 0.70 Mha in 2019, then sharply contracted by a third in 2020 and rebounded in 2021. Spatially, rice-crawfish system is located primarily in low-elevation plain areas with abundant water resources, where paddy rice cultivation has traditionally dominated agriculture. More concentrated rice-crawfish distribution is observed in Jiangnan Plain, and regions around Dongting Lake and Poyang Lake. The spatial distribution of rice-crawfish cultivation experienced considerable expansion towards the east and north from 2013 to 2021, with the largest expansion found in Jiangsu and Anhui after 2018. At the county level, over 6% of counties experienced notable area increases of more than 60 km² from 2017 and 2019, but 20% of counties have decreased from 2019 to 2021. Among the converted land use types, irrigated cropland is the largest contributor to rice-crawfish expansion with a contribution of 56%, followed by water bodies (25%) and rainfed cropland (13%). The spatial and temporal information provided in this study helps to understand the evolution of rice-crawfish cultivation in China and facilitates more efficient management of land resources under the rapid development of this farming system.

1. Introduction

We are entering a stage which requires producing more diverse foods with less resource and environment effects (Devi *et al* 2017, Siddiqui *et al* 2021). In this regard, integrated food production systems such as crop-aquaculture systems are highly encouraged as

they can provide high protein and energy outputs per unit of land and raise farm incomes (Nhan *et al* 2007, Singh and Singh 2017, Costello *et al* 2020, Bernhardt and O'Connor 2021). Aquaculture, the production of aquatic animals under controlled conditions, has reduced pressure on capture fisheries and is expected to surpass the volume of seafood from stagnant

capture fisheries by 2030 (FAO 2020a, Cottrell *et al* 2021). Efforts are being made to maximize the efficiency of aquaculture as a food production system by increasing total yield and density (Stevens *et al* 2018, Naylor *et al* 2021, Thilsted 2021). One such promising resource recycling strategy is the integration of aquaculture and crop production, which has been practiced for thousands of years, particularly in East and South Asia (Xie *et al* 2011, Islam *et al* 2015).

China is the global largest supplier of both rice and aquaculture products, accounting for 30% and 58% of global production, respectively (FAO 2019, 2020a). Considering the limited cropland resources in China, how to guarantee sufficient protein and caloric output on limited available land is a pivotal issue both for the government, to ensure domestic food security, and for farmers, who aim to generate competitive incomes. Co-cultivation of crops and aquaculture farming systems are well-developed practices in China and can make more efficient use of resources relative to traditional cropping patterns (Ahmed and Garnett 2011). Red swamp crawfish (*Procambarus clarkii*), native to northeastern Mexico and the southern USA, have recently become a flourishing commodity in China due to skyrocketing demand for crawfish as a popular street and snack food (Zhang *et al* 2021). Crawfish become one among the most popular freshwater species for aquaculture in China (Jin *et al* 2019). In 2019, domestic production of crawfish reached two million tons, accounting for 96% of global production (FAO 2020b). Approximately 86% of all crawfish in China are bred in paddy fields (National Bureau of Statistics of China (NBSC) 2020a). Rice-crawfish farming system has a much higher pure profit comparing with traditional rice cultivation, with 23×10^3 Yuan ha^{-1} compared to 6×10^3 Yuan ha^{-1} (Hou *et al* 2020). Under the drivers of high demands and high profits, rice-crawfish farming system has recently become increasingly popular among paddy farmers in subtropical China.

In the integrated rice-crawfish farming system, resources are well recycled by transferring outputs of a subsystem as inputs of the other system, which generates important co-benefits for nutrient accumulation, productivity, and profitability (Hu *et al* 2013, Bashir *et al* 2020, Dong *et al* 2021, Xu *et al* 2022). Crawfish in the paddy field provide an immediate source of organic fertilization for crops, and the digging and foraging activities loosen the top soil which facilitates air circulation under the water table (Hou *et al* 2020, Hu *et al* 2021). The rice straw and multiple organisms in the farmland also provide shade and food for the crawfish. Most studies used site data from field experiments to investigate the effects on the environment: these predominantly highlighted positive effects on the decrease of greenhouse gas

emissions and improvement of nutrients in the soil (Si *et al* 2017, Xu *et al* 2021, Gao *et al* 2022). Our results underscore that the growing importance of rice-crawfish farming calls for accurate spatial and temporal data about the footprint of rice-crawfish farming to characterize its evolution and help understand regional implications. Even though there are rough statistical data about the total area of rice-crawfish cultivation at a regional level, spatial information and change dynamics of this novel agricultural system from emergence to current situation are still lacking (Yu *et al* 2022). It is therefore urgent to provide distribution data for understanding the spatial knowledge of rice-crawfish farming in China and supporting relative studies on ecological effects.

Recent advances in satellite data and computational resources have enabled the mapping of the growing extent of rice-crawfish farming at high spatial and temporal resolutions (Gorelick *et al* 2017, Weiss *et al* 2020). Studies on remote-sensed mapping of rice-crawfish system focused on effective identifying methods which are mostly in small regional scales and short time series, nevertheless, spatio-temporal information at a large scale is currently absent which hinders understanding the holistic characteristics of development across China (Wei *et al* 2019, 2022, Xia *et al* 2021). We here used Landsat imagery to map, for the first time, rice-crawfish production every year from 2013 to 2021 in the middle-lower Yangtze Plain in China, the epicenter of global crawfish production. We then analyzed the characterization of change dynamics and further investigated the effects of rice-crawfish expansion on past land systems. This analysis sheds much-needed light on the development knowledge of a promising and highly efficient integrated crop-aquaculture system that is currently increasing in popularity across China and that may also enrich the product portfolio of small farmers in other regions of the world.

2. Study area

We focused on the five provinces in China that produce most crawfish, namely, Anhui, Hubei, Hunan, Jiangsu, and Jiangxi. These provinces are located between 24°N and 36°N and 108°E and 122°E , and cover $805\,600\text{ km}^2$ (figure 1). The region has a subtropical climate with hot and humid summers and mild winters and paddy rice cultivation is the dominant farming system. The annual average precipitation is approximately 800–1500 mm; the average temperature ranges between 26°C and 30°C in summer and between -1°C and 5°C in winter. The Yangtze River, the longest river in Asia, runs through the region. Thousands of smaller lakes are scattered throughout the study area, including the two largest

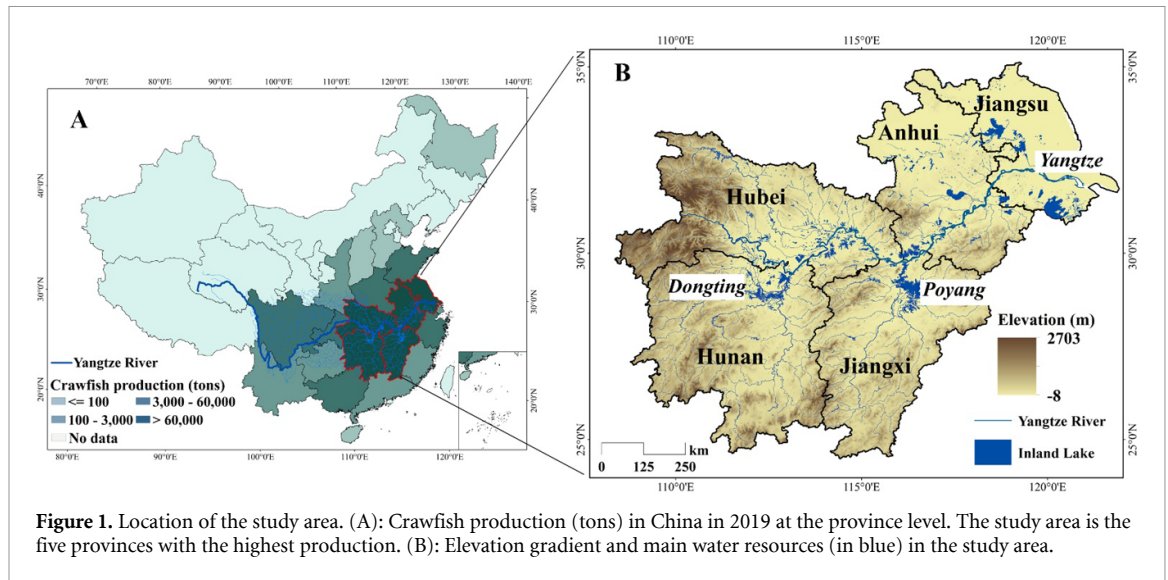


Figure 1. Location of the study area. (A): Crawfish production (tons) in China in 2019 at the province level. The study area is the five provinces with the highest production. (B): Elevation gradient and main water resources (in blue) in the study area.

freshwater lakes in China, Poyang Lake in Jiangxi and Dongting Lake in Hunan.

In 2019, approximately two million tons of crawfish, 92% of China's domestic production and 88% of global production, were produced in the study area (National Bureau of Statistics of China (NBSC) 2020a). Paddy rice planted in these five provinces occupies 14 million hectares accounting for 48% of China's total rice cultivation area (National Bureau of Statistics of China (NBSC) 2020b). The river floodplains and lakeshores with widespread paddy fields, sufficient water resource, and suitable climate conditions provide favorable conditions for rice-crawfish cultivation. As the center of crawfish production where rice-crawfish expansion considerably took place, this study area is highly appropriate to understand its development characteristics at a spatial level and comprehensively analyze its change dynamics and effects.

Integrated rice-crawfish farming system was developed by local farmers in Hubei Province and the standard technology was initially approved by the China Fisheries Association in 2013 (Cao *et al* 2017). The production process typically includes two periods per year (figure 2): the rice planting period (from June to October) and the rice fallow period (from November to May of the following year). The field layout of the integrated rice-crawfish cultivation system is characterized by rearing trenches that surround the paddy fields. The trenches are excavated to provide refuge for crawfish when the paddy fields run dry. The crawfish re-enter the fields after the fields are inundated again in June and the young rice stems have grown strong enough to withstand the crawfish. Farmers generally add crawfish two times per year: juvenile crawfish around March, and adult crawfish before the rice harvest. Overall, the typical annual

production cycle yields one harvest of rice and at least two harvests of crawfish.

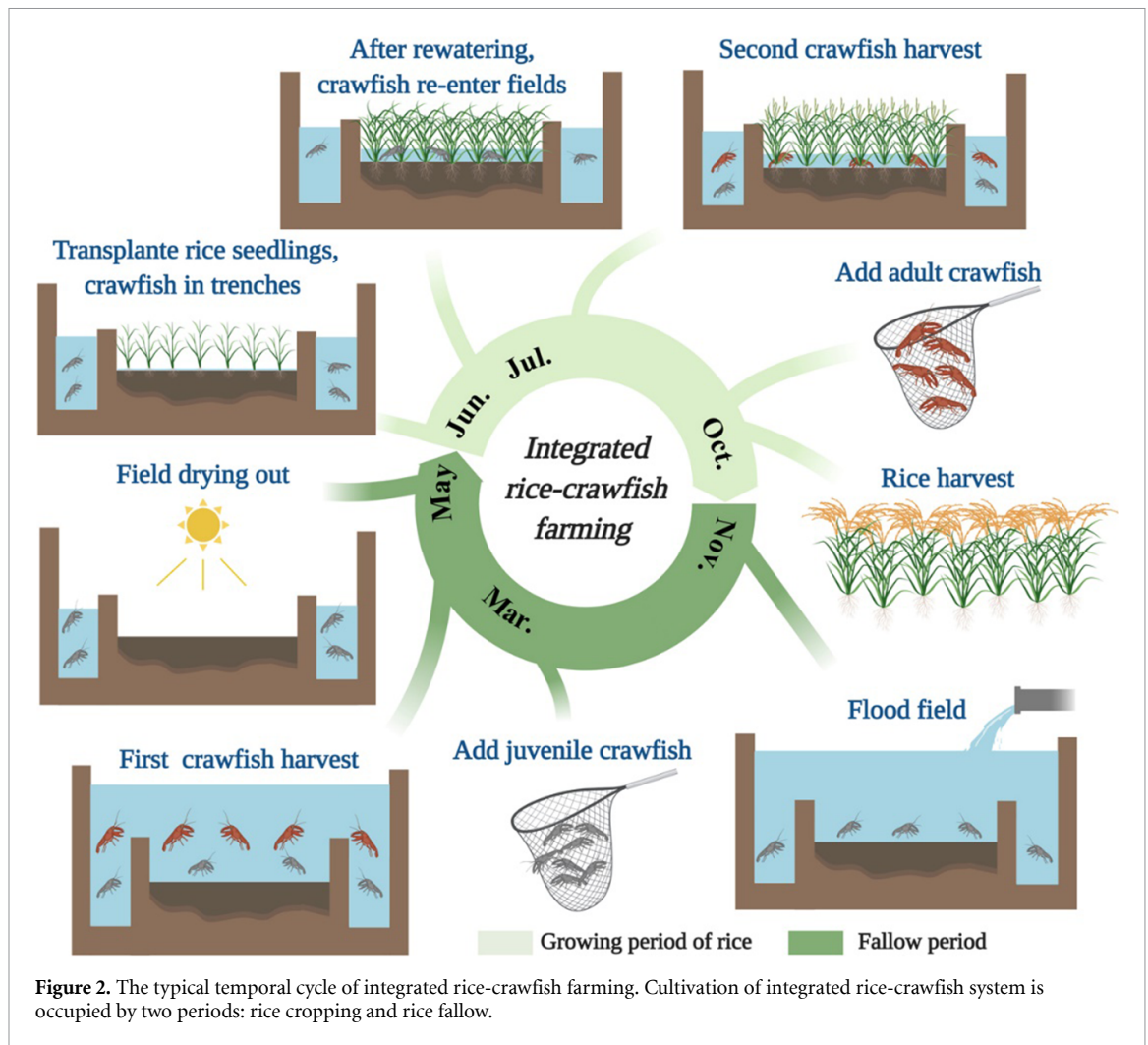
3. Data and methods

3.1. Data sources

We used data from the Landsat 8 Operational Land Imager and Landsat 7 enhanced thematic mapper plus (ETM+). Landsat 8 images with high cloud cover were supplemented by Landsat 7 images. We produced composite images from all available imagery for the study area from 2013 to 2021 for the two key farming periods, from July to October and from November to March of the following year. All images have been preprocessed in the Google Earth engine (GEE).

We used 1300 points of integrated rice-crawfish farming and 1138 points of other land use types to validate the accuracies of mapping (figure S1). We collected the crawfish sample points through visual interpretation of the available high-resolution images from 2013 to 2021 on Google Earth. The unique spatial pattern of crawfish cultivation, that is, the water trenches surrounding the rice fields, is visible in very-high spatial resolution data (figure S2). When high-resolution imagery was not available from Google Earth for a point, we labeled those points using Landsat surface reflectance data extracted from the GEE Timeseries Explorer plugin in QGIS (Rufin *et al* 2021).

To investigate the effects of expansion for rice-crawfish system on original land-use systems, we use a high-quality land-use dataset in 2010 derived by Resource and Environment Science and Data Center (www.resdc.cn). This dataset is at 30 m spatial resolution and was generated by Landsat TM/ETM+ images, which includes a three-level classification



scheme and a sum of 33 classes. We reclassified and focused on five first-level classes and two second-level classes, which are irrigated cropland, rainfed cropland, water bodies, woodlands, built-up land, grasslands, and bareland. Detailed description of data sources is provided in the supplementary material.

3.2. Mapping of rice-crawfish cultivation

The changes in water bodies between two cultivation periods are essential information for mapping rice-crawfish farming (Wei *et al* 2021). Based on the object-based water difference method that integrates pixel-based identification with object-based segmentation, we introduced classification and regression tree (CART) decision-tree algorithm and simple non-iterative clustering algorithm (SNIC) in this study (figure S3).

We first mapped the distribution of water bodies by using automated water extraction index (AWEI_{sh}) (Feyisa *et al* 2014). CART decision tree algorithm was used to determine the thresholds of AWEI_{sh} by inputting water samples. We then extracted the integrated rice-crawfish area at the pixel level based on changes in the presence of water between the fallow and rice planting periods. To identify rice-crawfish pixels on

land parcels, we used the SNIC algorithm to segment Landsat images for every year on GEE. SNIC clusters are based on the connectivity of pixels and have been tested with fast-running procedures with good performance (Achanta and Susstrunk 2017).

We intersected the segmentation results with the rice-crawfish pixels. The percentage of crawfish pixels within each parcel object was calculated and used 50% as the threshold for rice-crawfish detection. We mapped rice-crawfish farming only when there was a change in the presence of water between the fallow and planting periods. By using this method, we generated the spatial distribution of rice-crawfish farming from 2013 to 2021. We assessed the accuracies from 2013 to 2021 by using error matrix and described the overall accuracy, producers' accuracy and user's accuracy in each year, and showed good performance with overall accuracies higher than 90%. Details of rice-crawfish mapping method are described in the supplementary material.

3.3. Characterizing of spatio-temporal dynamics

Because of the small sizes and scattered distribution of rice-crawfish fields, it was difficult to visualize regional patterns of change dynamics at a 30 m spatial

resolution in a large study area. We used hexagons instead of squares to highlight the change tendency as visualization with hexagons is more natural and visually appealing besides other benefits (Birch *et al* 2007, Senf and Seidl 2021). We subdivided the entire study region into a ca. 1000 km² hexagon grid, with a total number of 901 hexagons. Within each hexagon, we counted the number of rice-crawfish pixels per year and calculated the total area of rice-crawfish farming for each hexagon by multiplying by 900 m².

To reveal the characteristics of rice-crawfish distribution from a spatial statistical perspective, we calculated standard deviational ellipse (SDE). SDE is a statistical method to reveal the spatial distribution characteristics of geographic elements from a spatial statistical perspective (Yuill 1971). The azimuth, center coordinates and ellipse area reveal the directionality, center of gravity and concentration and divergence of geographic elements distribution in the research region (Zhang *et al* 2020). We mapped SDE for the year of 2013, 2015, 2017, 2019, and 2021. The coordinates of the centroids were calculated as follows:

$$\bar{X} = \frac{\sum_{i=1}^n x_i}{n} \quad \bar{Y} = \frac{\sum_{i=1}^n y_i}{n} \quad (1)$$

where \bar{X} and \bar{Y} represent the coordinates of the centers; n is the number of rice-crawfish fields; x_i and y_i represent the x coordinate and y coordinate of each rice-crawfish cultivation field unit, respectively.

We quantified the area of rice-crawfish cultivation at a provincial level and calculated the area change rates of the entire region from year to year as follows:

$$\text{Area change rate} = \frac{(\text{Area}_n - \text{Area}_{n-1})}{\text{Area}_{n-1}} \times 100\% \quad (2)$$

where $\text{Area}_{n,n-1}$ indicates the area of rice-crawfish farming of the total study region; n represents the year from 2014 to 2021. $\text{Area}_{a,b}$ Aiming for quantification of rice-crawfish change dynamics within a fine scale, we calculated the total area amount at a county level and mapped area changes at a two-year interval from 2013 to 2021. Proportions of counties within different ranges of change area were counted to reveal the divergence of change dynamics among years and regions.

3.4. Transformation between rice-crawfish cultivation and other land uses

To investigate the effects of rice-crawfish expansion on past land systems, we conducted a transition matrix at a pixel level by using land use and land cover distribution in 2010 and the current rice-crawfish distribution. To analyze the full extent of the impact on rice-crawfish expansion, we chose 2019, the year with the highest area and largest extent of rice-crawfish

farming. The classes of land use and land cover systems in 2010 were categorized into seven classes: irrigated cropland, rainfed cropland, water bodies, built-up land, grasslands, woodlands, and bareland. Class of water bodies includes lakes, rivers, and other artificial water areas, such as aquaculture ponds. By calculating the proportion of transformed area amount for different classes at a regional level, we investigated the spatial effects of rice-crawfish farming expansion on land use patterns. To highlight the contribution from main land use types, we selected the top three land use and land cover classes with a high area amount of transformation and subsequently used a hexagon grid to map the spatial characteristics.

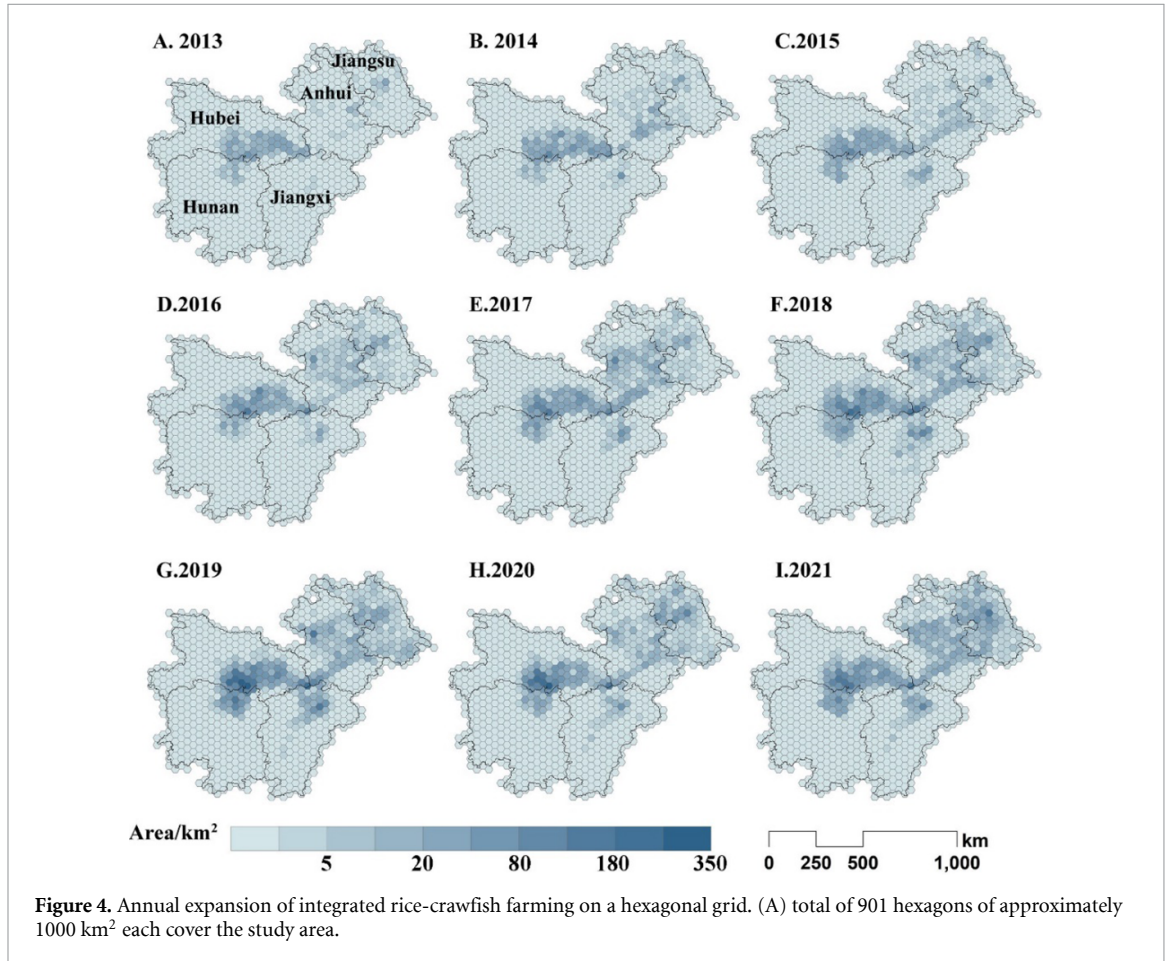
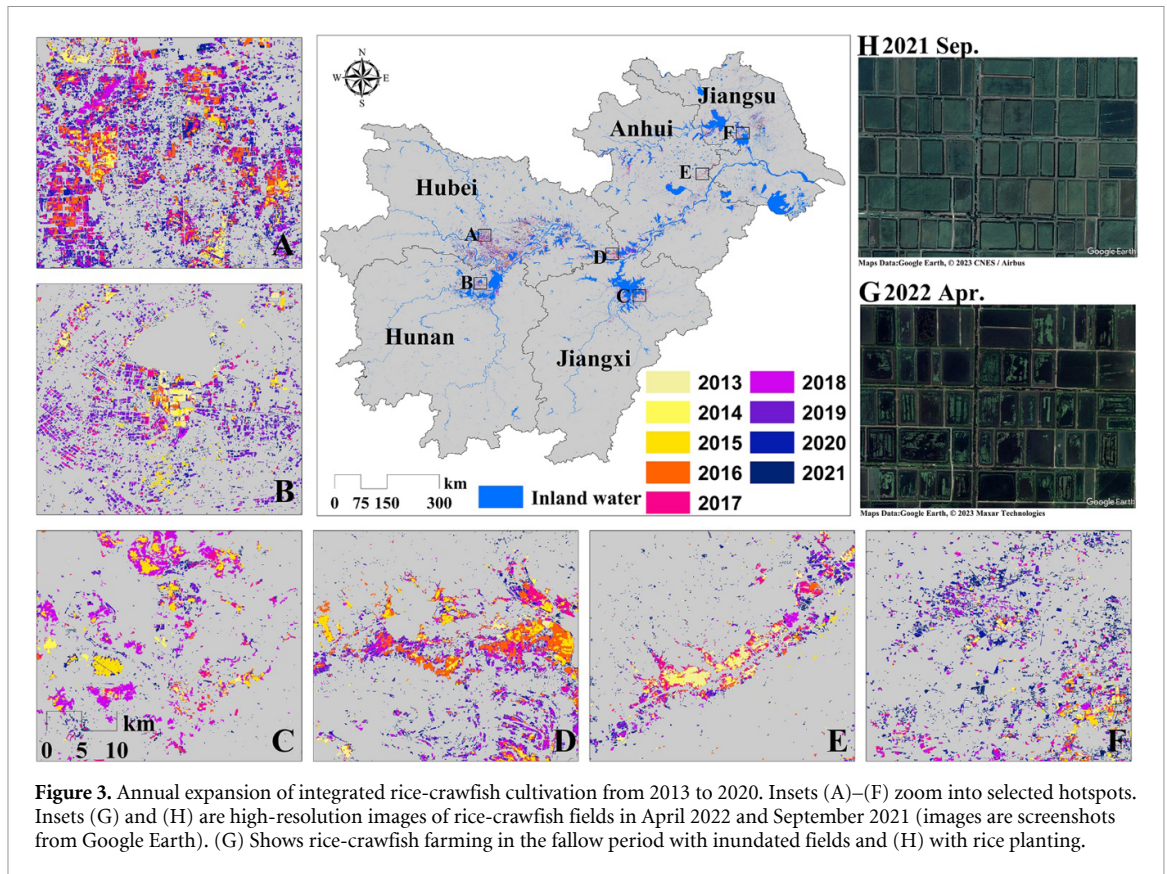
4. Results

4.1. Distribution of rice-crawfish farming system

In Hubei, Rice-crawfish production has clustered in a few core zones with intensive density in the south of Hubei which is the original region of this system and has experienced a long-term experiment of rice-crawfish farming before 2013 (figure 3(A)). In Hunan and Jiangxi provinces, rice-crawfish cultivation surrounds the largest freshwater lakes in China, the Dongting and Poyang Lakes (figures 4(B) and (C)). The spatial patterns of rice-crawfish cultivation are more scattered in Anhui and Jiangsu and concentrate along the Yangtze River and its branches. Regions with significant increasing trends in rice-crawfish production in 2021 include the west of Anhui and Jiangsu.

Rice-crawfish systems are located primarily in low-elevation plain areas with abundant water resources, where paddy rice cultivation has traditionally dominated agriculture (figure 4). At the initial stage when rice-crawfish farming technology was first officially released, rice-crawfish farming was concentrated in the southwestern part of Hubei Province, which is mainly in the Jiangnan Plain. With the gradual spread of technology, the influence of rice-crawfish farming become stronger, as shown by the spread of distribution in the north of Hunan and Jiangxi. The extent of rice-crawfish in Anhui and Jiangsu started to enlarge in 2017, however, the area of rice-crawfish in each hexagon is much lower than in other provinces, indicating a scattered distribution and low density.

The spatial distribution of SDEs experienced considerable enlargement towards the direction of eastern and northern, especially from 2013 to 2017 (figure 5). Under the large expansion of rice-crawfish cultivation in Jiangsu and Anhui, the distribution of SDE gradually across the boundary of Jiangsu Province in 2019 and 2021. The centers movement route of rice-crawfish was consistently within the boundary of Hubei Province, which has the highest area of rice-crawfish cultivation across the study period. The centers of rice-crawfish distribution moved towards the northeastern direction with



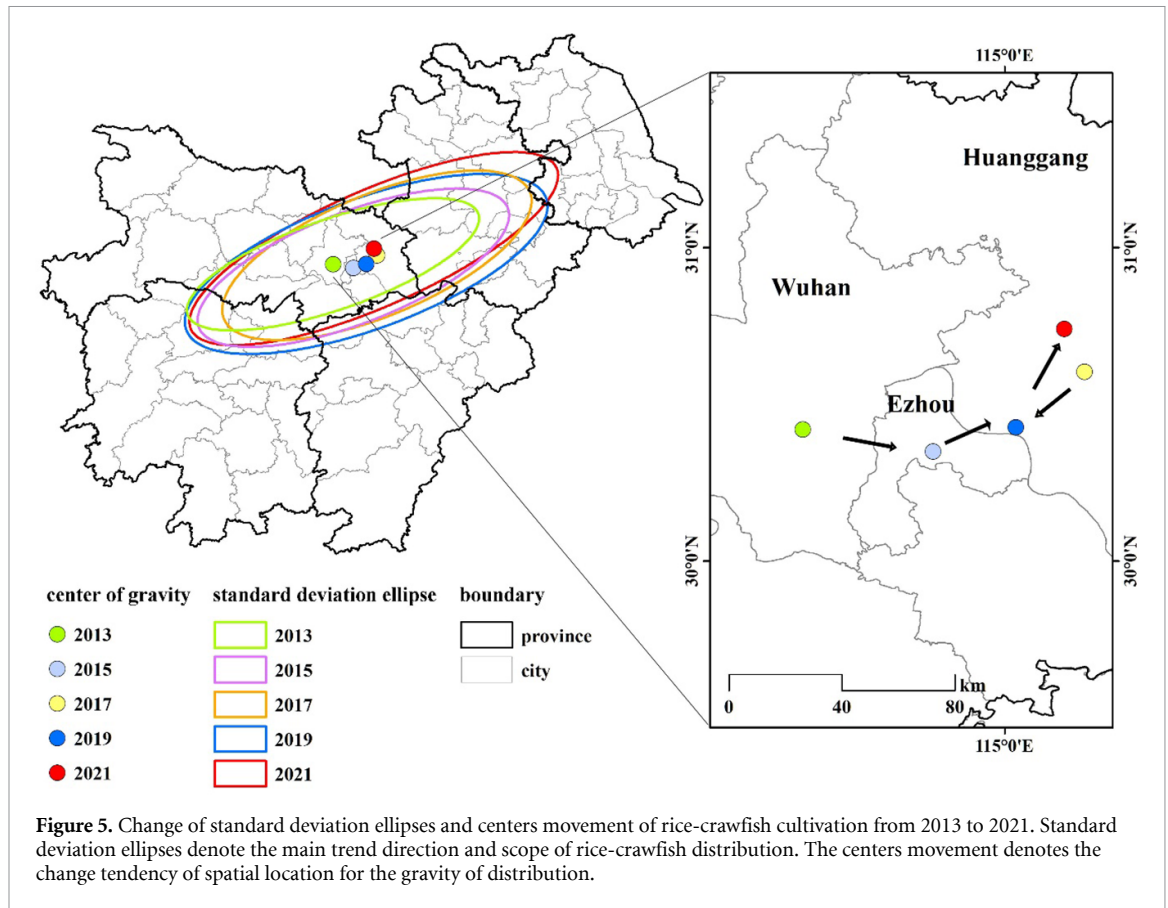


Figure 5. Change of standard deviation ellipses and centers movement of rice-crawfish cultivation from 2013 to 2021. Standard deviation ellipses denote the main trend direction and scope of rice-crawfish distribution. The centers movement denotes the change tendency of spatial location for the gravity of distribution.

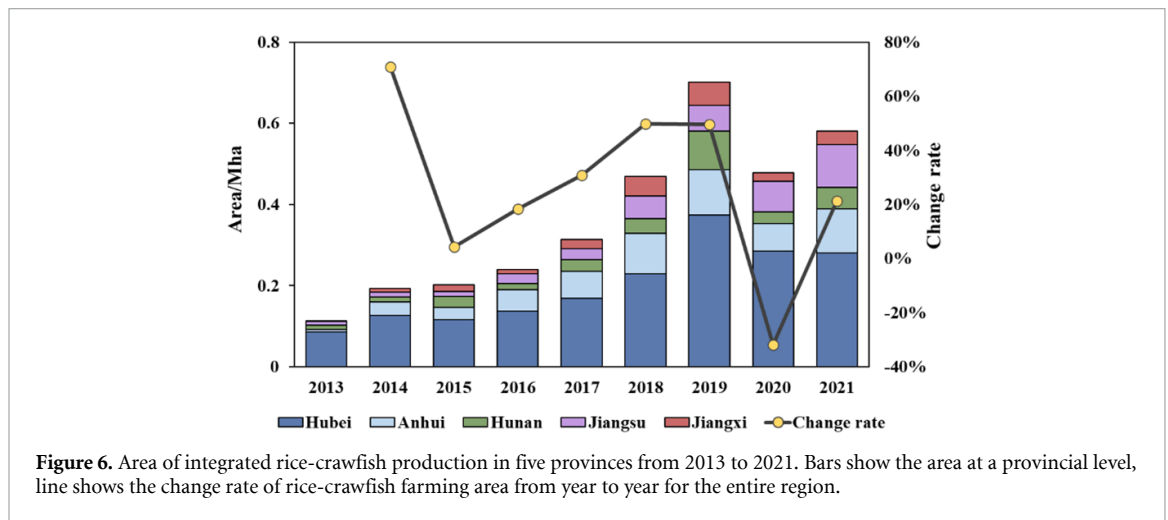


Figure 6. Area of integrated rice-crawfish production in five provinces from 2013 to 2021. Bars show the area at a provincial level, line shows the change rate of rice-crawfish farming area from year to year for the entire region.

a total of accumulated 88 km from 2013 to 2021, at an average rate of 11 km per year.

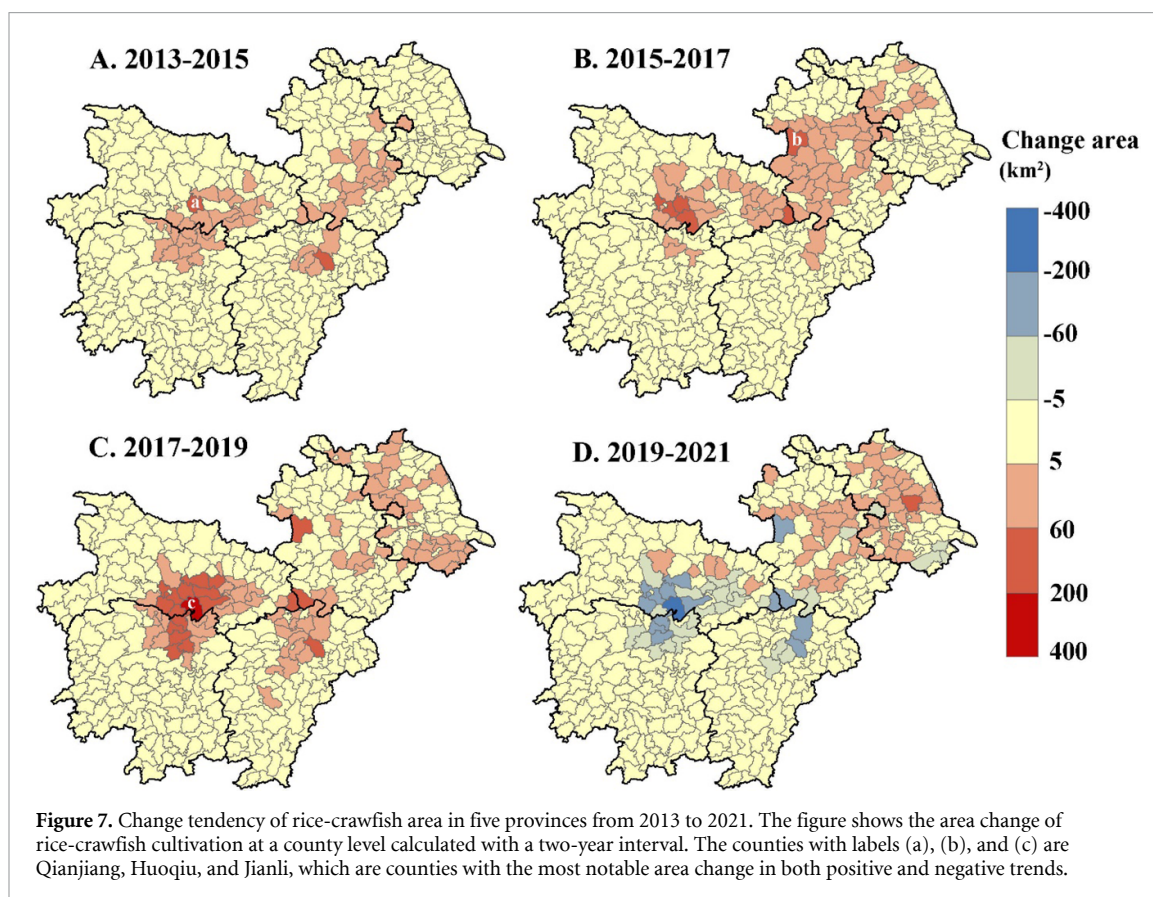
4.2. Spatial-temporal dynamics

The total area of rice-crawfish farming in the five provinces increased steadily from 0.11 Mha in 2013 to 0.70 Mha in 2019 (figure 6). Hubei was the largest contributor to rice-crawfish farming in the study region and the area occupied about 60% of the total. Rapid increases in area in five provinces happened

since 2017. The area amount reached its peak in 2019, and the largest contribution is from Hubei province (nearly 0.4 Mha), followed by Anhui and Hunan. The change rate consistently increased from 2015 to 2019 and showed a sharp drop in 2020 when a considerable area contraction of 0.22 Mha suddenly happened. The contraction was particularly stark in Hubei Province, with a decrease of 0.09 Mha, followed by Hunan Province and Jiangxi Province. In 2021, the areal extent of rice-crawfish farming partially rebounded to

Table 1. Distribution of the trends in change area at a county level from 2013 to 2021.

Range	Proportion of the change area at a county level across five provinces (%)			
	2013–2015	2015–2017	2017–2019	2019–2021
≤ -200	0.00	0.00	0.00	0.35
$-200 \leq -60$	0.00	0.00	0.00	4.55
$-60 \leq -5$	0.00	0.00	0.00	13.99
$-5 \leq 5$	78.17	70.69	65.20	61.54
$5 \leq 60$	21.40	28.02	28.21	19.23
$60 \leq 200$	0.44	2.16	6.23	0.35
>200	0.00	0.00	0.37	0.00



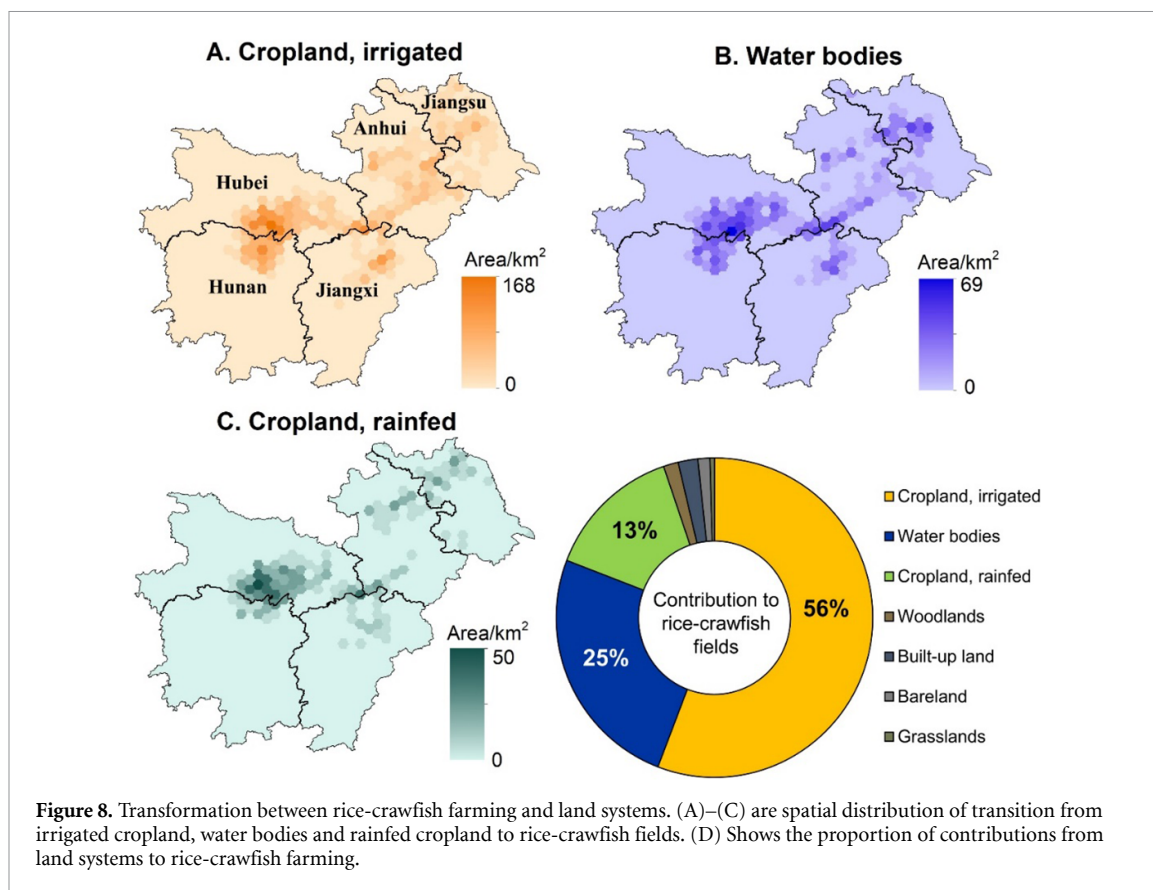
0.60 Mha. Anhui province has the largest increase in the rice-crawfish area in 2021 with over 0.04 Mha.

Statistically, change area of most counties in five provinces was stable and within an interval between -5 km^2 and 5 km^2 , shown by an average occupation of 68.9% (table 1). Besides, increase trends in area from 2013 to 2019 happened within a range of $5\text{--}60 \text{ km}^2$, with proportions around 30%. Only several counties had increases over 60 km^2 , including Qianjiang, Jianli, and Huoqiu (figure 7). From 2017 to 2019, many counties experienced notable increases between 60 km^2 to 200 km^2 , as shown by the occupation raised to 6.23%. Different from increase trends dominated until 2019, ca. 20% of counties with negative trends in area amount were found from 2019 to 2021. Most counties with large area decreased from 2019 to 2021 were the same as the counties with a

high increase area in 2019, especially Jianli has the strongest negative trend.

4.3. Effects of rice-crawfish expansion on land systems

The expansion of rice-crawfish farming underwent a considerable transformation from the original land systems since 2010 (figure 8). Overall, 69% of the rice-crawfish farming fields are transferred from cropland, and the rest are transitioned from other land systems. Within the cropland class, irrigated cropland, which is dominated by paddy rice cultivation, is the largest contributor with a proportion of 56%. Paddy rice fields are generally waterlogged fields with abundant water resources and advanced irrigation facilities systems nearby. Rainfed cropland with no irrigation equipment has a much higher cost to reconstruct



the field and build irrigation facilities, thus only contributing 13% of rice-crawfish fields. For other land classes, water bodies have a high proportion of contribution (25%), which is primarily the transformation from aquaculture ponds. The rice-crawfish fields sourced from irrigated cropland are primarily distributed in the south of Hubei and the northern part of Dongting Lake in Hunan. Rice-crawfish farms from water bodies and rainfed cropland are mainly distributed in the south of the Jiangnan Plain; scattered distribution exists in the middle of Jiangsu.

5. Discussion

5.1. Divergences of rice-crawfish expansion in five provinces

Hubei Province is the biggest contributor to rice-crawfish production in five provinces from 2013 to 2021, occupying about 60% of the total. Rice-crawfish farming in Hubei is characterized by the highest density of distribution in the south of Hubei, with area in most hexagon grids over 100 km² (figure 4). Southern Hubei as the original region of rice-crawfish farming technology, contains major crawfish trade centers and fully efficient supply chains (Cao *et al* 2017, Chen *et al* 2020). Hubei crawfish is now a renowned national brand with an excellent reputation throughout China, which remarkably promotes the demand for crawfish production in Hubei (Wang *et al* 2022). The combination of well-developed supply chains, high and

rising demand from consumers and excellent transport connections have provided perfect conditions for rice-crawfish production in Hubei (Cheng *et al* 2022, Guo *et al* 2022). Anhui Province is the second largest contributor to rice-crawfish area from 2013 to 2020. Counties in Anhui experienced notable enlargement in 2017 and 2021, with a higher increase area amount and extensive distribution. Jiangsu Province had notable increases in 2018 and 2021, especially in 2021. Rice-crawfish production in Hunan and Jiangxi is concentrated around Dongting and Poyang Lakes, and the area amount majorly increased at the late stage (2018 and 2019). However, under the considerable reduction in 2020, although a slight return of area happened in 2021, Hunan and Jiangsu are dominated by counties with area decrease (figure 8).

Political support, including millions of dollars in subsidies and targeted extension services, has stimulated the expansion of rice-crawfish farming in China (Cao *et al* 2017). Government investments have played a crucial role in developing functional supply chains to support crawfish and rice marketing. Additional subsidies have been provided to promote technology adoption and encourage farmers to switch to integrated rice-crawfish aquaculture. Technical assistance through farm visits and demonstration events introduced farmers to the novel rice-crawfish farming production process (Yang *et al* 2021). Technology adoption has been reinforced by the high profits that farmers expect to receive from

crawfish sales, as rice-crawfish aquaculture is four times as profitable per unit area as traditional rice cropping (Liu *et al* 2019, Hou *et al* 2020).

5.2. Drivers of sharp contraction in 2020

The COVID-19 pandemic, as the key driver, interrupted the consistent increase trend and triggered the sharp contraction of rice-crawfish, by breaking the crawfish value chains and dampening demand. Spring is a critical season for crawfish rearing and feeding, and juvenile crawfish are added to the trenches in February to ensure the production of the first harvest in April (figure 2). However, Hubei observed the first COVID-19 outbreak and implemented strict lockdown measurements in early 2020 to curb the spread of the virus (HBPPG, Hubei Provincial People's Government 2020a, 2020b). The lockdown measures restricted people's movements, which compromised field management and access to essential production inputs during the peak period of crawfish rearing (Pu and Zhong 2020, Li *et al* 2022). Compared to traditional agriculture production, crawfish production strongly rely on functioning supply chains, which aggravated the negative effects of the lockdown measure. Crawfish sales also plummeted because the restrictions on movement complicated traditional offline sales, and the closure of market logistics prevented the sale of crawfish to end consumers.

Yet, the sharp contraction was only a temporary shock and rice-crawfish production quickly rebounded in 2021, with government support to farmers and efforts to re-establish crawfish value chains (Pu and Zhong 2020, Xie *et al* 2021). The Ministry of Transportation has opened 'green channels' that prioritize the transportation of agricultural products (Zhan and Chen 2021). Local governments and private entrepreneurs have established e-commerce platforms to increase online crawfish sales and online input purchases (JPCMSC, Joint Prevention and Control Mechanism of the State Council 2020, FAO 2020c). As a result, the supply chain for crawfish production is recovering and the price of crawfish rebounded to the pre-pandemic level in spring 2021.

5.3. Socioecological tradeoffs of the integrated rice-crawfish system

Changes in farming practices, such as the shift from traditional cropland to integrated rice-crawfish systems, can lead to profound ecological implications. Since paddy rice fields are the major source of rice-crawfish farming system, we summarized a series of studies that focused on investigating the trade-offs between rice-crawfish production and traditional rice cropping, including rice monoculture and rotation of rice and winter wheat.

For inputs, due to the harm of the fertilizers and pesticides on crawfish, 17% fewer pesticides, and

fertilizers are used in the rice-crawfish system than in rice monocultures (Hou *et al* 2020, Hu *et al* 2021). However, rice-crawfish systems have additional nutrient inputs into the water, including feed, medication and disinfectants (Boyd and Massaut 1999, Henriksson *et al* 2018, Cai *et al* 2021). Moreover, lime is used to disinfect the water and mitigate the acidity at the bottom of the trenches to keep the water pH at approximately 8 (Hou *et al* 2021). The nutrient loads in the water of rice-crawfish system are 101% higher than those in the paddy fields for N and 208% higher for P (He *et al* 2019, Liu *et al* 2019, Si *et al* 2019). As the water is exchanged approximately every ten days during the rearing period, nutrients in the wastewater dissipate into natural water bodies, which contributes to the potential for eutrophication. Given the large extent of rice-crawfish production and the prospect of its further expansion, the high nutrient loadings in water bodies need to be carefully monitored. Measures to treat nutrient waste before it is released are critical for limiting water pollution; such measures include improving nutrient recirculation, and feeding crawfish soybean meal (Wan *et al* 2017, Dauda *et al* 2019).

For outputs, rice-crawfish system produces substantially higher monetary benefits and high-value nutrition than traditional paddy rice cultures. Crawfish provide high-quality animal protein that is rich in omega-3 fatty acids, which are essential components of human diets (Mozaffarian and Rimm 2006). A dietary intake amount of 28 g of seafood per day is recommended, as it has been shown to reduce the risk of cardiovascular disease (Zheng *et al* 2012, Willett *et al* 2019). Promoting integrated aquaculture production systems, such as rice-crawfish, in other regions can help to improve dietary patterns where seafood intake is low; it could be particularly beneficial in Africa and Latin America, where the average seafood intake is only half the recommended level (Willett *et al* 2019).

5.4. Implication on sustainable rice-crawfish development

Crop-aquaculture co-cultivation has been expanding rapidly in China in the past few decades. The rice-crawfish farming system, an emerging new crop-aquaculture system, in particular takes the lion's share. Mapping the expansion of rice-crawfish system over time—pinpointing where and when rice-crawfish farming develops—is an essential step to inform land-use policy makers to better manage natural resource utilization and regulate environmental effects. In terms of resource utilization, rice-crawfish has a much higher demand for water compared with traditional cropping systems, especially in rainfed crop cultivation due to the frequent water exchange of trenches in summer and the long-term flooding period in winter. With the data of transformation between rice-crawfish and other cropland types,

effects on water utilization can be further quantified at a large spatial level. Moreover, environmental footprints have been widely applied to understand how rice-crawfish activities exert pressures on environment, including aspects of carbon emission and nutrients residual. Although previous studies evaluated these impacts, most such studies are on micro-levels, i.e. field or plot scale. The effects at macro-levels or regional levels, which is essential for supporting policy design, were still lacking. The spatial-temporal characteristics of rice-crawfish farming revealed in this study will surely contribute to a more comprehensive assessment at a regional scale and help steer rice-crawfish farming in sustainable development pathways.

6. Conclusion

Integrating aquaculture with crop production can achieve synergies with nutrient cycling, balance labor demands, raise land productivity, and provide higher incomes to farmers and is thus a promising way to improve nutritional quality and quantity with a small land footprint. Here, we revealed, for the first time, the development of the integrated rice-crawfish system since 2013. The rice-crawfish system emerged in southern Hubei in 2013 and spread across the middle Yangtze Plain to Hunan and to the three downstream provinces, Jiangxi, Anhui, and Jiangsu, where natural conditions for crawfish and paddy rice production are ideal. The effects of rice-crawfish expansion on land systems show that considerable enlargement of rice-crawfish system since 2013 was mainly from cropland and aquaculture ponds. The rice-crawfish system generates a key staple crop and valuable seafood protein on the same land, exploits synergies in nutrient cycling, and raises the incomes of smallholder farmers. The high monetary profits from the system will, in the absence of regulatory intervention, lead to its continuing expansion, which was only temporarily interrupted by COVID-19. To take advantage of the benefits of the rice-crawfish farming system at minimal environmental costs, advancements in waste management and effective regulatory policies will be needed. With such measures, the integrated rice-crawfish system can become a sustainable farming system that achieves high land productivity and nutritional benefits at comparatively low ecological costs.

Data availability statement


The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This research is supported by the National Key Research and Development Program of China (2019YFA0607400), and by the National Natural Science Foundation of China (41921001, 41871356 and 42071419)

ORCID iDs

Yanbing Wei  <https://orcid.org/0000-0002-5802-5361>

Daniel Müller  <https://orcid.org/0000-0001-8988-0718>

Zhanli Sun  <https://orcid.org/0000-0001-6204-4533>

References

- Achanta R and Susstrunk S 2017 Superpixels and polygons using simple non-iterative clustering *Proc. IEEE Conf. on Computer Vision and Pattern Recognition* pp 4651–60
- Ahmed N and Garnett S T 2011 Integrated rice-fish farming in Bangladesh: meeting the challenges of food security *Food Secur.* **3** 81–92
- Bashir M A, Liu J, Geng Y, Wang H, Pan J, Zhang D, Rehim A, Aon M and Liu H 2020 Co-culture of rice and aquatic animals: an integrated system to achieve production and environmental sustainability *J. Clean. Prod.* **249** 119310
- Bernhardt J R and O'Connor M I 2021 Aquatic biodiversity enhances multiple nutritional benefits to humans *Proc. Natl Acad. Sci.* **118** e1917487118
- Birch C P, Oom S P and Beecham J A 2007 Rectangular and hexagonal grids used for observation, experiment and simulation in ecology *Ecol. Modelling* **206** 347–59
- Boyd C E and Massaut L 1999 Risks associated with the use of chemicals in pond aquaculture *Aquac. Eng.* **20** 113–32
- Cai M, Zhang Y, Zhu J, Li H, Tian H, Chu W, Hu Y, Liu B and Wang A 2021 Intervention of re-feeding on growth performance, fatty acid composition and oxidative stress in the muscle of red swamp crayfish (*Procambarus clarkii*) subjected to short-term starvation *Aquaculture* **545** 737110
- Cao C, Jiang Y, Wang J, Yuan P and Chen S 2017 Dual character of rice-crayfish culture and strategies for its sustainable development *Chin. J. Eco-Agric.* **25** 1245–53
- Chen S, Jiang Y, Wang J and Cao C 2020 Situation and countermeasures of integrated rice-crayfish farming in Hubei province *J. Anhui Agric. Univ.* **39** 1–7
- Cheng H, Huang F and Nie N 2022 A measurement method for the regional public brand value: a case study based on Qianjiang Crayfish *J. Macro-Qual. Res.* **10** 1–21
- Costello C, Cao L, Gelcich S, Cisneros-Mata M Á, Free C M, Froehlich H E, Golden C D, Ishimura G, Maier J and Macadam-Somer I 2020 The future of food from the sea *Nature* **588** 95–100
- Cottrell R S, Ferraro D M, Blasco G D, Halpern B S and Froehlich H E 2021 The search for blue transitions in aquaculture-dominant countries *Fish Fish.* **22** 1006–23
- Dauda A B, Ajadi A, Tola-Fabunmi A S and Akinwale A O 2019 Waste production in aquaculture: sources, components and managements in different culture systems *Aquac. Fish.* **4** 81–88
- Devi S, Gupta C, Jat S L and Parmar M 2017 Crop residue recycling for economic and environmental sustainability: the case of India *Open Agric.* **2** 486–94
- Dong S, Gao Y, Gao Y, He M, Liu F, Yan F and Wang F 2021 Evaluation of the trophic structure and energy flow of a rice-crayfish integrated farming ecosystem based on the ecopath model *Aquaculture* **539** 736626

- FAO 2019 FAOSTAT-FAO Statistical Databases (available at: <http://faostat.fao.org/>)
- FAO 2020a FAO Yearbook. *Fishery and Aquaculture Statistics 2018* (Rome: FAO)
- FAO 2020b *FishStatJ* (Rome: FAO) (available at: www.fao.org/fishery/en/statistics/software/fishstatj/en)
- FAO 2020c *Local Food Systems and COVID-19: A Look into China's Responses* (Rome) (available at: www.fao.org/in-action/food-for-cities-programme/news/detail/en/c/1270350/) (Accessed 8 April 2020)
- Feyisa G, Meilby H, Fensholt R and Proud S 2014 Automated water extraction index: a new technique for surface water mapping using Landsat imagery *Remote Sens. Environ.* **140** 23–35
- Gao H, Peng X, Dai L, Li J, Yang Q, Dou Z and Xu Q 2022 Determination of soil cadmium safety thresholds for food production in a rice-crayfish coculture system *Foods* **11** 3828
- Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D and Moore R 2017 Google Earth engine: planetary-scale geospatial analysis for everyone *Remote Sens. Environ.* **202** 18–27
- Guo W, Zhao W and Min M 2022 Operation scale, transfer experience, and farmers' willingness toward farmland transfer-in: a case study of rice-crayfish cultivating regions in China *Sustainability* **14** 4081
- HBPPG, Hubei Provincial People's Government 2020a *Notice of the People's Government of Hubei Province on Strengthening the Prevention and Control of Novel Coronavirus Infections* (available at: www.hubei.gov.cn/zfwj/ezf/202002/t20200220_2142431.shtml)
- HBPPG, Hubei Provincial People's Government 2022b *Enterprises in Hubei Will Resume Work No Earlier Than February 20* (available at: www.gov.cn/xinwen/2020-02/13/content_5478259.htm)
- He J et al 2019 Effect of rice-crawfish system on water environment *Jiangsu Agric. Sci.* **47** 213–5
- Henriksson P J G, Belton B, Murshed-e-Jahan K and Rico A 2018 Measuring the potential for sustainable intensification of aquaculture in Bangladesh using life cycle assessment *Proc. Natl Acad. Sci.* **115** 2958–63
- Hou J, Styles D, Cao Y and Ye X 2020 The sustainability of rice-crayfish coculture systems: a mini review of evidence from Jiangnan plain in China *J. Sci. Food Agric.* **101** 3843–53
- Hou J, Zhang D and Zhu J 2021 Nutrient accumulation from excessive nutrient surplus caused by shifting from rice monoculture to rice-crayfish rotation *Environ. Pollut.* **271** 116367
- Hu L, Ren W, Tang J, Li N, Zhang J and Chen X 2013 The productivity of traditional rice-fish co-culture can be increased without increasing nitrogen loss to the environment *Agric. Ecosyst. Environ.* **177** 28–34
- Hu N, Liu C, Chen Q and Zhu L 2021 Life cycle environmental impact assessment of rice-crayfish integrated system: a case study *J. Clean. Prod.* **280** 124440
- Islam A H M S, Barman B K and Murshed-e-Jahan K 2015 Adoption and impact of integrated rice-fish farming system in Bangladesh *Aquaculture* **447** 76–85
- Jin S, Jacquin L, Xiong M, Li R, Lek S, Li W and Zhang T 2019 Reproductive pattern and population dynamics of commercial red swamp crayfish (*Procambarus clarkii*) from China: implications for sustainable aquaculture management *PeerJ.* **7** e6214
- JPCMSC, Joint Prevention and Control Mechanism of the State Council 2020 *Press Conference of the Joint Prevention and Control Mechanism of the State Council* (available at: www.gov.cn/xinwen/gwylflkjz65/index.htm) (Accessed 22 March 2020)
- Li S, Kallas Z and Rahmani D 2022 Did the COVID-19 lockdown affect consumers' sustainable behaviour in food purchasing and consumption in China? *Food Control* **132** 108352
- Liu C, Hu N, Song W, Chen Q and Zhu L 2019 Aquaculture feeds can be outlaws for eutrophication when hidden in rice fields? A case study in Qianjiang, China *Int. J. Environ. Res. Public Health* **16** 4471
- Mozaffarian D and Rimm E B 2006 Fish intake, contaminants, and human health: evaluating the risks and the benefits *Jama* **296** 1885–99
- National Bureau of Statistics of China (NBSC) 2020a *China Report of Development of Crayfish Industry*
- National Bureau of Statistics of China (NBSC) 2020b *China Statistical Yearbook*
- Naylor R L, Hardy R W, Buschmann A H, Bush S R, Cao L, Klinger D H, Little D C, Lubchenco J, Shumway S E and Troell M 2021 A 20-year retrospective review of global aquaculture *Nature* **591** 551–63
- Nhan D K, Phong L T, Verdegem M J, Duong L T, Bosma R H and Little D C 2007 Integrated freshwater aquaculture, crop and livestock production in the Mekong delta, Vietnam: determinants and the role of the pond *Agric. Syst.* **94** 445–58
- Pu M and Zhong Y 2020 Rising concerns over agricultural production as COVID-19 spreads: lessons from China *Glob. Food Sec.* **26** 100409
- Rufin P, Rabe A, Nill L and Hostert P 2021 GEE timeseries explorer for qgis—instant access to petabytes of earth observation data *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **46** 155–8
- Senf C and Seidl R 2021 Mapping the forest disturbance regimes of Europe *Nat. Sustain.* **4** 63–U102
- Si G et al 2019 Effect of crayfish farming on water quality under rice-crayfish coculture *Jiangsu Agric. Sci.* **47** 299–303
- Si G, Peng C, Yuan J, Xu X, Zhao S, Xu D and Wu J 2017 Changes in soil microbial community composition and organic carbon fractions in an integrated rice-crayfish farming system in subtropical China *Sci. Rep.* **7** 1–10
- Siddiqui Z, Hagare D, Jayasena V, Swick R, Rahman M M, Boyle N and Ghodrat M 2021 Recycling of food waste to produce chicken feed and liquid fertiliser *Waste Manage.* **131** 386–93
- Singh R and Singh G 2017 Traditional agriculture: a climate-smart approach for sustainable food production *Energy Ecol. Environ.* **2** 296–316
- Stevens J R, Newton R W, Tlusty M and Little D C 2018 The rise of aquaculture by-products: increasing food production, value, and sustainability through strategic utilisation *Mar. Policy* **90** 115–24
- Thilsted S H 2021 Diversifying aquaculture systems to nourish nations *Nat. Food* **2** 450–1
- Wan J, Shen M, Tang J, Lin H, Yan W, Li J and Zhu L 2017 Effects of soybean meal processing treatments on growth performance, nutrient digestibility, nitrogen and phosphorus excretion in red swamp crayfish, *Procambarus clarkii* *Aquac. Int.* **25** 543–54
- Wang X, Qi Z, Yang C and Liu Z 2022 Influence of capital endowment on farmers' adoption scale of rice and shrimp co-culture technology: mediating effects based on technology cognition *J. Sichuan Agric. Univ.* **40** 130–6
- Wei H, Yang J, Cai Z, Chen Y, Zhang X, Xu B and Hu Q 2022 Phenology windows and multi-source medium-/high-resolution image extraction for rice-crayfish paddy fields mapping *Natl Remote Sens. Bull.* **26** 1423–36
- Wei Y, Lu M and Wu W 2019 Study on extraction method of rice-crayfish based on seasonal difference of water *Chin. J. Agric. Res. Reg. Plan.* **40** 14–20
- Wei Y, Lu M, Yu Q, Xie A, Hu Q and Wu W 2021 Understanding the dynamics of integrated rice-crawfish farming in Qianjiang county, China using Landsat time series images *Agric. Syst.* **191** 103167
- Weiss M, Jacob F and Duveiller G 2020 Remote sensing for agricultural applications: a meta-review *Remote Sens. Environ.* **236** 111402
- Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F and Wood A 2019 Food in the anthropocene: the EAT–Lancet commission on healthy diets from sustainable food systems *The Lancet* **393** 447–92

- Xia T, Ji W, Li W, Zhang C and Wu W 2021 Phenology-based decision tree classification of rice–crayfish fields from Sentinel-2 imagery in Qianjiang, China *Int. J. Remote Sens.* **42** 8124–44
- Xie J, Hu L, Tang J, Wu X, Li N, Yuan Y, Yang H, Zhang J, Luo S and Chen X 2011 Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system *Proc. Natl Acad. Sci.* **108** E1381–7
- Xie Y, Sarkar A, Hossain M, Hasan A K and Xia X 2021 Determinants of farmers' confidence in agricultural production recovery during the early phases of the COVID-19 pandemic in China *Agriculture* **11** 1075
- Xu Q, Liu T, Guo H, Dou Z, Gao H and Zhang H 2021 Conversion from rice–wheat rotation to rice–crayfish coculture increases net ecosystem service values in Hung-tse Lake area, East China *J. Clean. Prod.* **319** 128883
- Xu Q, Peng X, Guo H, Che Y, Dou Z, Xing Z, Hou J, Styles D, Gao H and Zhang H 2022 Rice–crayfish coculture delivers more nutrition at a lower environmental cost *Sustain. Prod. Consum.* **29** 14–24
- Yang X, Qi Z, Chen X and Yang C 2021 Government training technology cognition and farmer eco-agricultural technology adoption behavior *Chin. J. Agric. Res. Reg. Plan.* **42** 198–208
- Yu X, Hao X, Dang Z, Yang L, Wang X, Zhang Y, Cai J and Zhang Y 2022 China report of development of crayfish industry *China Fish.* **559** 47–54 (In Chinese)
- Yuill R S 1971 The standard deviational ellipse; an updated tool for spatial description *Geogr. Ann. B* **53** 28–39
- Zhan Y and Chen K Z 2021 Building resilient food system amidst COVID-19: responses and lessons from China *Agric. Syst.* **190** 103102
- Zhang D, Fraser M A, Huang W, Ge C, Wang Y, Zhang C and Guo P 2021 Microplastic pollution in water, sediment, and specific tissues of crayfish (*Procambarus clarkii*) within two different breeding modes in Jianli, Hubei province, China *Environ. Pollut.* **272** 115939
- Zhang P Y, Yang D, Qin M Z and Jing W L 2020 Spatial heterogeneity analysis and driving forces exploring of built-up land development intensity in Chinese prefecture-level cities and implications for future Urban Land intensive use *Land Use Policy* **99** 104958
- Zheng J, Huang T, Yu Y, Hu X, Yang B and Li D 2012 Fish consumption and CHD mortality: an updated meta-analysis of seventeen cohort studies *Public Health Nutr.* **15** 725–37