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Comparative assessment of Chinese mitten crab aquaculture in China: spatiotemporal changes and trade-offs

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Abstract

The increasing human demand for high-quality animal protein has provided impetus for the development of aquaculture. Chinese mitten crab (*Eriocheir sinensis*) is a catadromous species rapidly being cultured in China but scientific literature documenting its life cycle environmental and economic consequences remains scarce. This study aims to address this gap by examining the spatio-temporal evolution of crab aquaculture in China since the 2000s and evaluating the environmental and economic characteristics along its life-cycle stages: megalopa, juvenile crab, and adult crab cultivation. The geostatistical analysis shows a more dispersed pattern of crab aquaculture nationally as crab grows, with coastal provinces that have brackish water for megalopa cultivation but wider spatial coverage for juvenile and adult crab cultivation. Our findings reveal that the production of 1 ton of live-weight crab results in 7.65 ton of CO_2 equivalent of greenhouse gas emissions, surpassing previous estimates for finfish fish production by approximately 50%. Most environmental pressures occur during the adult crab cultivation stage, with significant contributions from upstream processes such as electricity and feed production. By comparing between different production systems, our study shows that crab aquaculture in lake systems performs better than pond systems in terms of most global environmental impact categories and economic considerations. This work contributes to the existing literature by elucidating the spatio-temporal changes of crab aquaculture boom in China and constructing a representative life cycle data pool that broadens the benchmark knowledge on its environmental and economic characteristics. We highlight the trade-offs between environmental and economic performance as well as the balance between global and local environmental impacts to promote sustainable growth in the aquaculture industry.

Keywords

crab, spatiotemporal evolution, life cycle assessment, environmental impacts, economic cost, tradeoffs

1. Introduction

The increasing global demand for high-quality animal protein has spurred the development of aquaculture, especially for countries like China (Subasinghe et al., 2009; Tilman and Clark, 2014). China represents the world's leading producer, exporter and consumer of farmed fish products (FAO, 2022). In 2022, aquaculture production in China contributed 81% of the national aquatic food supplies, a notable rise from the approximately 30% share seen in the 1990s. Of the 56 million tons of aquaculture production, 59% were practiced in the freshwater environment (MARA, 2001-2023). However, the aquaculture boom in part relies on the use of additional feeds, chemicals and energy to improve productivity (Gui et al., 2018). This results in negative environmental effects, including but not limited to greenhouse gas emissions (Yuan et al., 2019), excess nutrient release (Huang et al., 2020; Wang et al., 2019) and dependence on wild fish resources (Cao et al., 2015). As the demand continues to expand, it has become exceedingly pressing to find solutions to overcome these environmental challenges and achieve a sustainable food production system.

Since the early 2000s, life cycle assessment (LCA) studies have been conducted to comprehensively quantify the environmental impacts of different aquaculture commodities. However, most research within the field has focused on finfish, particularly diadromous fish production in Europe (Bohnes et al., 2018; Bohnes and Laurent, 2019; Gephart et al., 2021; Ray et al., 2019). In 2018, the global reference life cycle inventory (LCI) database Ecoinvent (version 3.5) first introduced the fishery and aquaculture sector, covering only pond and lake-based systems for tilapia and trout (Avadí et al., 2020). Previous research has shown that the use of feed plays a key role in driving most environmental concerns, although the specific impacts may vary significantly by fish species, aquaculture systems and technologies used. Compared with finfish and mollusk species, a few of crustacean species, primarily shrimps and prawns, have been studied regarding their life cycle environmental performance (Cao et al., 2011; Henriksson et al., 2015; Medeiros et al., 2017; Santos et al., 2015). In general, crustacean aquaculture requires less land, but can be a significant source of greenhouse gas emissions, eutrophication, and acidification within major food products (Poore and Nemecek, 2018).

Chinese mitten crab (*Eriocheir sinensis*), a brownish crustacean that is normally regarded as one of the world's most notorious aquatic invasive species (GISD), is the third most produced crustacean species at the global level (FAO, 2022). As a catadromous species, Chinese mitten crab spends most of its life in freshwater environment but requires saline/brackish water to mate and reproduce (Fig. S1) (Gui et al., 2018). Also, being a crustacean species, it must undergo periodic exoskeleton of shedding, known as molting, as a necessary process for its growth. The aquaculture of Chinese mitten crab has been rapidly developed in China because of its high economic value and growing demand. The production has increased from 232 thousand tons in 2000 to over 815 thousand tons in 2022, representing nearly all global mitten crab production (FAO, 2023; MARA, 2001-2023). The main aquaculture system for Chinese mitten crab involves pond, alongside alternative methods such as lake stocking or net enclosures, and, to a lesser extent, rice field co-culture (Gui et al., 2018). Despite being an excellent source of minerals and high-quality protein, the final yield of edible portion is only about 33% of the live weight (Chen et al., 2007). Given its rapid expansion over time, it is essential to analyze the spatiotemporal distribution of Chinese mitten crab aquaculture to gain insights into the industry's evolution trajectory. In addition, to our best knowledge, there is sparse evidence regarding the environmental impacts of Chinese mitten crab aquaculture. This significant knowledge gap not only prevents aquaculture producers to determine and alleviate potential pollution hotspots, but also hinders the understanding of the environmental importance of aquatic food in comparison to other nutritionally equivalent food products.

Therefore, to address these challenges and fulfill knowledge gaps, this study aims to examine the spatio-temporal evolution of crab aquaculture in China from the 2000s onward, and evaluate the environmental impacts of the entire production cycle of Chinese mitten crab, from cradle to farm-gate. The comparative analysis of environmental performance of the two main aquaculture systems, pond and lake, will focus on their relative contribution of different growth stages and substance emissions. The environmental profiles of Chinese mitten crab are further benchmarked against other reference protein sources to shed light on the environmental importance of aquatic food in a sustainable diet. Additionally, a preliminary estimate of the life cycle economic cost associated with crab aquaculture is made to identify any potential trade-offs between economic considerations and environmental aspects. This study makes a valuable contribution to the existing literature in a few of ways. First, a comprehensive life cycle data pool for Chinese mitten crab has been constructed that can be used for analyzing different issues. Second, this study enhances our understanding on the evolution of this species boom by examining its spatio-temporal dynamics in China, and further broadens the benchmark knowledge on the environmental and economic characteristics of crab aquaculture. Third, it highlights the trade-offs between environmental and economic performance as well as the balance between global and local environmental impacts to promote effective management measures and/or programs to enable sustainable aquaculture growth.

2. Materials and Methods

2.1 Life history of crab aquaculture

The life history of crab aquaculture has been well documented by Gui et al. (2018) in the book *Aquaculture in China: Success Stories and Modern Trends*. In every November, sexually mature male and female crabs are selected and placed together in saline water for mating with a female: male ratio of 3-5:1. After mating is completed, male crabs are removed while berried females are reared under intensive care until ready to spawn eggs in next April. These fertilized eggs would hatch into microscopic zoea larvae and develop through four further zoeal stages until undertake metamorphosis to megalopa (about 6-7 milligrams each). Then, a gradual reduction in salinity is used to acclimate the megalopa for stocking in freshwater environment. During their growth, the megalopa undergo five molting stages over the course of a month. This transformative process leads them to evolve into crab-like forms known as stage V juveniles. Subsequently they continue to experience multiple molts until reaching a size of about 5-10 grams per juvenile crab, which is suitable for stocking in grow-out ponds or other rearing units. It should be noted that the intermoult period gradually lengthens as the crab grows larger. During the grow-out stage, the body weight of the crabs would increase significantly after each molt. When these adult crabs reach maturity with fully developed gonads, they are deemed ready for harvesting. To sum up and facilitate the subsequent analysis, the life cycle of Chinese mitten crab was conveniently divided into three distinct stages: megalopa cultivation (S1), juvenile crab cultivation (S2), and adult crab cultivation (S3).

2.2 Spatiotemporal analysis of crab aquaculture

We collected the annual production data of Chinese mitten crab in all Chinese provinces during 2000-2019, excluding pandemic years, from China Fishery Statistical Yearbook (MARA, 2001-2023). To fill in some missing datasets during the period, we had to make some estimations. For example, the adult crab production in 2005, were added by interpolating between preceding and subsequent years' production. In addition, the juvenile crab production in 2000-2002 were not available in the statistics. Therefore, we assumed the average of the ratios of megalopa and juvenile crab production during 2003-2004 would apply to these preceding years and estimated the national juvenile crab production in 2000-2002 by multiplying the national megalopa production for the same period with the average of the ratios (1.6%). For each province, the juvenile crab production in 2000-2002 was further calculated by extrapolating the respective proportions of juvenile crab production in 2003-2004. The contribution of each province to the national totals were categorized into the following five ranges: 0, 0.05%, 0.5%, 5%, 50% and 100%. Finally, we conducted standard deviational ellipse analysis using ArcGIS, whose center corresponds to the center of gravity, to investigate the change of spatial distribution of Chinese mitten crab along the life cycle and over time.

2.3 Life cycle assessment (LCA)

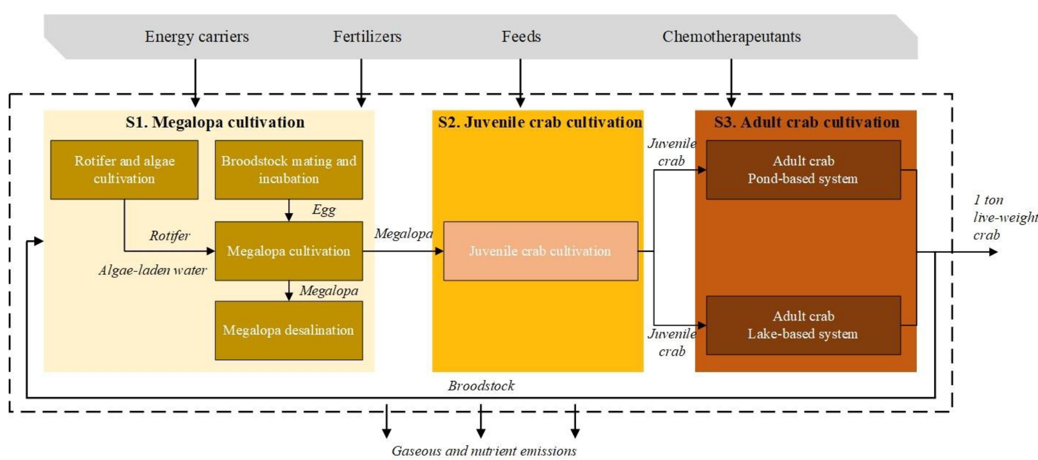

Figure 1 System boundary for LCA of Chinese mitten crab aquaculture in China

We employed ISO-compliant LCA (ISO, 2006) to estimate the cradle-to-farm-gate environmental impacts associated with crab aquaculture. The system boundary (Fig. 1) embraces the three distinct cultivation stages of megalopa (S1), juvenile crabs (S2), and adult crabs (S3). In addition, adult crab cultivation is further divided into pond-based and lake-based systems to explore their difference in environmental performance. The functional unit is one ton of live-weight Chinese mitten crab produced in China in 2019. Pond systems made up 78% of the total production while lake systems contributed to the remaining 22% in 2019 (MARA, 2020). Since Jiangsu Province accounted for 89% of megalopa, 23% of juvenile and 46% of adult crab production in 2022 (MARA, 2023), a total of 18 farming systems in Jiangsu Province, involving major actors from megalopa to adult crab production (Fig. S2-S3), were investigated to compile the LCI for Chinese mitten crab. Such primary information includes, but is not limited to, the usage of fertilizer, feed, chemicals, water, and electricity. Note that transportation and equipment maintenance were not included in the system boundary due to limited contribution (Ayer and Tyedmers, 2009; Mungkung et al., 2013; Pelletier and Tyedmers, 2010) and lack of data and information. Secondary data such as production and processing of raw materials, electricity production, and transportation were obtained from Ecoinvent (v3.5) and modified appropriately to represent Chinese conditions whenever possible. More information about the material input and output of each life cycle stage was compiled and can be found in Supplementary Material (Supplementary Text, Table S1-S10). In this study, global warming potential (GWP), acidification potential (AP), freshwater eutrophication potential (EP) were selected because they are the most considered environmental impact categories for aquaculture in previous studies (Bohnes and Laurent, 2019; Henriksson et al., 2012). In addition, we also included freshwater ecological toxicity potential (FAETP) to evaluate the impact of chemicals and the cumulative energy demand (CED) for energy use. Among them, GWP, AP, EP and FAETP adopted the CML-IA baseline method (v4.7) as it is the most commonly used life cycle impact assessment (LCIA) methods for aquaculture (Henriksson et al., 2012; Philis et al., 2019) while CED used the cumulative energy demand method (v1.11) in openLCA software (v1.10.2).

3. Results

3.1 Spatiotemporal evolution of crab aquaculture

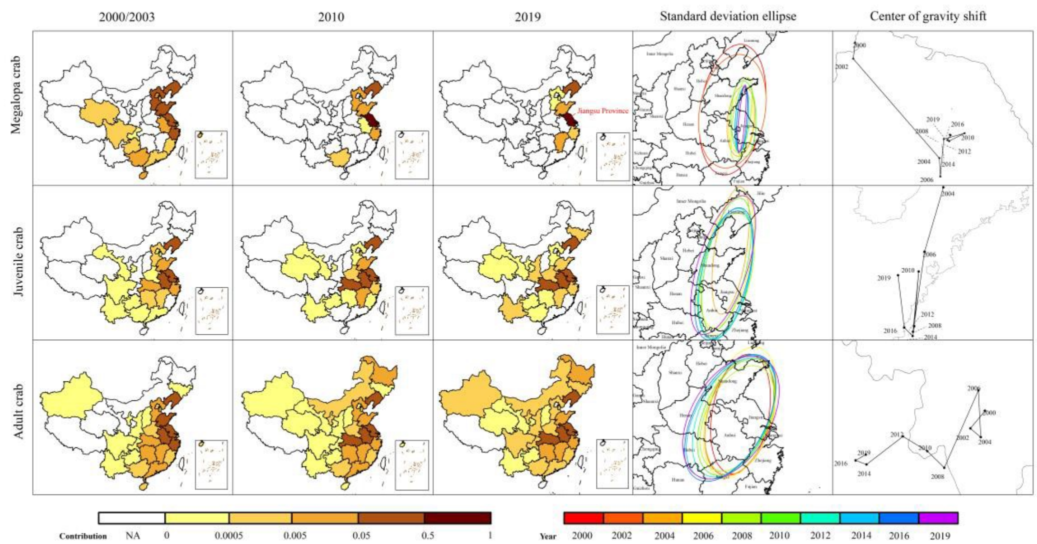

Figure 2 Spatiotemporal pattern of crab production during 2000-2019. Note: production statistics for juvenile crab started from 2003 due to data unavailability in 2000-2002 and may be underestimated for Jiangsu Province due to possible data bias or errors.

The geostatistical analysis shows a more dispersed pattern of crab aquaculture nationally as crab grows (Fig. 2). Coastal provinces that have brackish water, like Liaoning in the north, Jiangsu in the middle, and Guangdong in the south, dominate the megalopa cultivation. However, larger spatial coverages have been found for juvenile and adult crab cultivation, with an increasing number of inland provinces taking part in the practice. Notably, adult crab cultivation has been practiced nearly all over the country except a few provinces, such as Tibet. It is mainly because that post-larval crabs have stronger tolerance to changes in the surrounding environment and can survive in a broader range of freshwater conditions.

Temporally, the annual crab production has shown variations across life cycle stages, especially for the megalopa cultivation. In 2000, megalopa cultivation was undertaken in more than half of the provinces, with Jiangsu Province producing 44.9% of the total, followed by Liaoning (15.2%), Hebei (11.4%) and Shandong (11.0%). Over the years, the national total megalopa production increased from 312 tons in 2000 to 937 tons in 2019. However, the distribution pattern exhibited towards increased spatial concentration, as evidently shown by the continuously decreasing area of standard deviational ellipses (Fig. 2). In parallel, the center of gravity for megalopa cultivation moved towards the south during the early 2000s and eventually stabilized in Jiangsu Province. Benefiting from its geographical advantage of mild temperature, abundant saline water, and social support, Jiangsu Province has developed an industrial cluster for megalopa cultivation along its coast, and contributed to over 90% of the national total megalopa production in 2019.

The combined evidence of broader spatial coverage and larger standard deviational ellipses indicate that juvenile and adult crab cultivation have undergone spatial expansion over time (Fig. 2). Liaoning, Jiangsu, Anhui, and Hubei have emerged as the main producers of juvenile and adult crabs over the past two decades. Among them, Hubei Province grew its share in juvenile and adult crab cultivation from 1.6% and 4.4% in 2000 to 13.3% and 20.4% in 2019, respectively. Consequently, over these years the center of gravity for juvenile crab cultivation has remained in the eastern regions while that for adult crab cultivation has shifted toward more inland areas.

3.2 Environmental impacts of crab aquaculture

Overall, the national aggregated LCI closer to that of the pond system, which is attributed to the dominant contribution of pond system in the total crab production. In terms of resource use, lake system has higher fish use, land occupancy and energy consumption than pond system, as evident by its higher feed conversion rate (FCR), that is, the amount of feed used to raise one ton of product, and lower yield per unit area. Water consumption in the pond system is slightly higher owing to manual water addition to compensate losses from evaporation and leakage. In addition, pond system incurs higher electricity consumption due to aeration and pumping, consequently leading to greater coal consumption. Regarding environmental emissions, the lake system exhibits lower level of pollutants compared to the pond system. This difference can be contributed to the absence of electricity and chemicals in adult crab cultivation stage within the late system, resulting in reduced emissions. The main life cycle resource use and emissions associated with producing 1 ton of live-weight crab in China, along with data specific to lake and pond systems, are available in the Supplementary Material (Table S12).

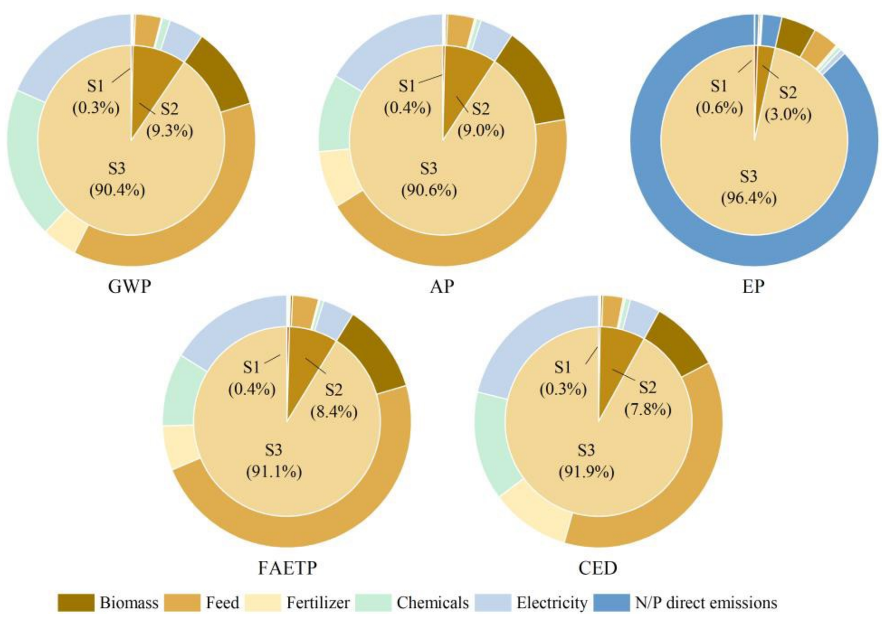

Figure 3 Life cycle contribution across multiple environmental impact categories

Based on the compiled LCI, we evaluated the life cycle environmental impacts of crab aquaculture in China to identify the key contributors for each impact category (Fig. 3). It is found that producing 1 ton of crab would lead to 7.65 tons of CO_2 equivalent for GWP, 30.9 kg of SO_2 equivalent for AP, 229 kg of PO_4^{3-} equivalent for EP, 1.82 tons of 1,4-DB equivalent for FAETP, and 116 GJ for CED. Breaking down the results by contributing processes reveal that feed use during the adult crab cultivation stage is the primary driver across all impact categories, accounting for 37.2-48.3%, with the exception of eutrophication. Commercial feed usually includes animal-based raw materials such as fish oil and fish meal as well as plant-based raw materials such as maize and soybean. Its upstream electricity production and soybean production are the main sources of energy consumption and greenhouse gas emissions. AP is significantly influenced by NH_3 emissions from soybean production and SO_2 emissions from electricity production. Key contributors of FAETP are cypermethrin released from insecticides use and V, Be and Ni from coal ash and coal slime treatment. As for EP, on-site N and P emissions through drainage and sediment removal are the two main contributors, together contributing 89.4% of EP. It aligns with previous LCA studies, which have also found that N and P emissions from uneaten feed and fish faces during farming process are key factors driving aquatic eutrophication impacts (Bohnes et al., 2018; Cortés et al., 2021).

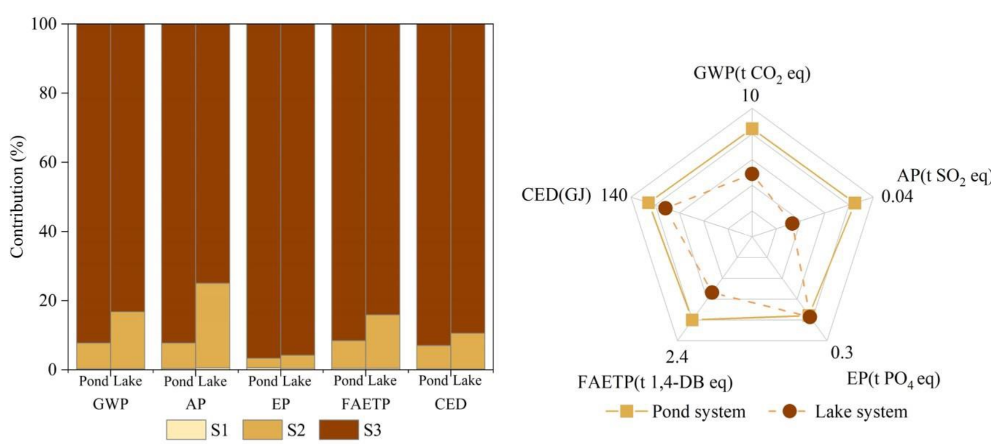

Figure 4 Comparison of life cycle environmental impacts between pond and lake systems

The adult crab cultivation stage shows significantly higher contributions to all impact categories than megalopa and juvenile crab cultivation stages (Fig. 4), accounting for over 91.6% in pond system and 75.0-95.8% in lake system for each impact category. This is mainly due to the increased FCR along the life span, 1.8 for megalopa cultivation, 3.5 for juvenile crab cultivation, and 4.0 for adult crab cultivation. The increasing trend of FCR is primarily for the increase of biomass and is consistent with previous findings about other species (Aubin et al., 2009; Moraes et al., 2015). In general, crabs produced in pond system result in higher life cycle environmental impacts than lake system because pond system relies more heavily on external material inputs than lake system. The production of 1 ton of crab in pond system would lead to a 71.7% increase in GWP, 155.8% increase in AP, 49.2% increase in FAETP and 19.7% increase in CED but 1.8% decrease in EP than lake system.

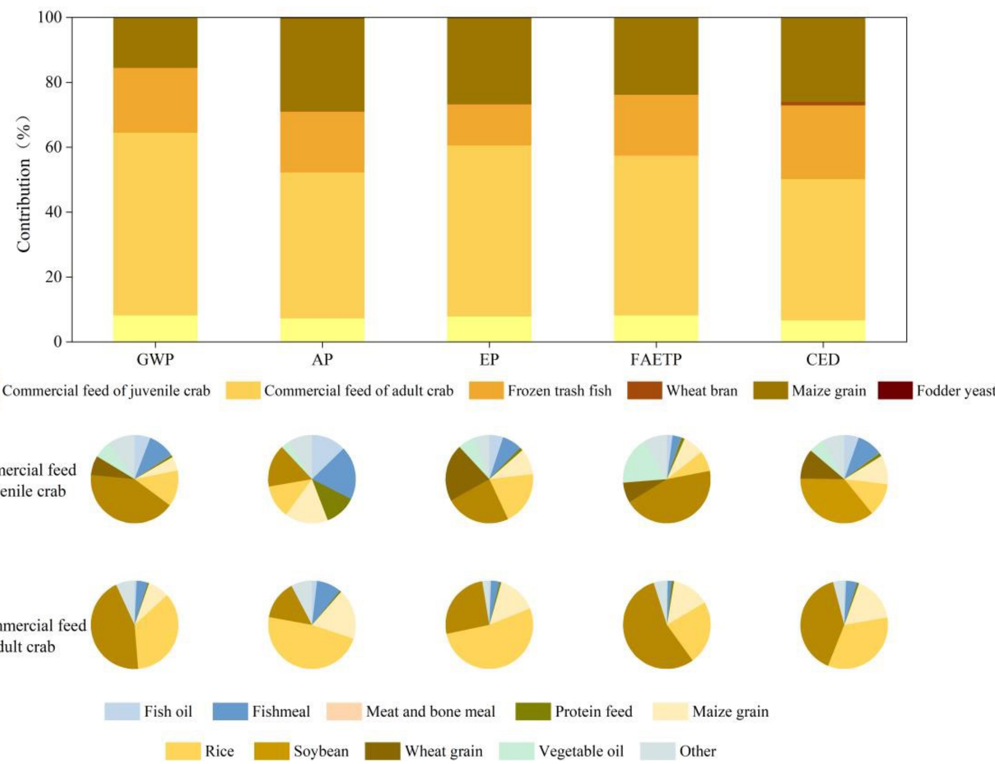

Figure 5 Breakdown of the life cycle environmental impacts by feed type

The results have clearly highlighted the significant influence of feed on the environmental performance of crab aquaculture. Feed production includes upstream processes such as crop cultivation, livestock farming, and capture fishery, which exhibit the highest energy consumption intensity and greenhouse gas emissions intensity throughout the entire life cycle of aquaculture (Pelletier et al., 2009). It is found that, among the various environmental impacts caused by feed production, the highest proportions (69.6-82.5%) are attributed to plant-based feeds and plant-based ingredients in commercial feed (Fig. 5). More specifically, rice, wheat grain, and soybean have significant contributions to the environmental impacts of commercial feed, which may be related to excessive application of fertilizers in field management (Bosma et al., 2011; Henriksson et al., 2017). Animal-based feed inputs, mainly including frozen trash fish, fishmeal and fish oil, are responsible for 15.6-26.1% of the feed-related environmental impacts. Given the trade-offs between ecosystem conservation and food production (Cao et al., 2015; Costello et al., 2020), research is underway to explore possibilities to reduce the proportion of frozen trash fish in feed and replace fishmeal and fish oil in commercial feed with plant- or insect-based ingredients (Bruni et al., 2021; Cottrell et al., 2020), aiming to develop more nutritious and environmentally sustainable feed alternatives.

3.3 Uncertainty analysis

Based on the life cycle analysis, it can be inferred that the key contributing factors of environmental performance are feed input, electricity consumption for crab aquaculture, buildup of sediment, and concentration of on-site N and P emissions. To ensure the robustness of the results, Monte Carlo simulation of 10,000 times were performed by randomly selecting values from the distribution of these key contributing factors to generate ranges of outcomes. A range was provided for each key factor instead of using a single-point estimation. The uncertainty of environmental performance is shown in Fig. S4, which generally indicates a limited influence of input uncertainty on the whole analysis. In comparison, FAETP has the lowest uncertainty of -10% to 12% while CED has the largest range of -32% to 37%. The uncertainty of pond system is higher than that of lake system. It should be noted that the analyses are based on the currently best available data, but future follow-up studies are necessary to substantiate these results further.

4. Discussion

4.1 Comparison with other aquatic products

Making informed comparison of the environmental impacts across different aquatic products can support decision-making towards more environmentally sustainable aquaculture practices. However, due to a wide variety of aquatic products, and the environmental impacts vary among different aquatic products. Further differentiation is thus needed within specific aquatic product categories to accurately assess their environmental footprints. This study represents the first attempt to examine the life cycle environmental impacts of crab aquaculture in China. Moreover, we conducted a comparative analysis of the environmental impacts of aquatic products from existing literature, accounting for differences in species, countries, FCR, GWP and EP (Table S13). Due to difference in methodology regarding eutrophication in LCIA methods, the comparison is restricted to environmental results derived from the CML-IA method. Furthermore, all these studies use a consistent functional unit of 1 ton of live-weight product at farm gate for meaningful comparisons (Fig. 6).

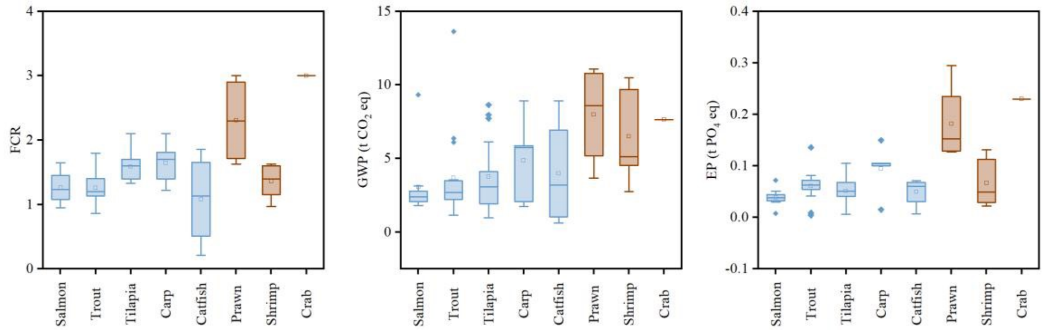

Figure 6 Comparison of FCR, GWP and EP of 1 ton of live-weight fish (blue) and crustacean (brown) products. The box-whisker plots display the median (horizontal line in boxes), 25%-75% quartiles (represented by the boxes), range excluding outliers (represented by the whiskers), and outliers (>1.5 * interquartile range, represented by solid rhombi). Means are represented by solid rectangles.

In total of 8 aquatic product categories are included for comparison, namely salmon, trout, tilapia, carp, catfish, prawn, shrimp and crab. It is important to emphasize that the term crab here represents all categories of crabs, while the LCI of Chinese mitten crab from this study is the only one within this category to our knowledge. The dataset consists of 65 separate cases from 18 countries and 6 continents, and the majority of these cases are sourced from south Asian countries such as Indonesia and for fish products, especially tilapia and trout. Additionally, it is worth noting that most of these LCAs were conducted over ten years ago, yet they continue to be possibly used in recent studies exploring food systems or diets (Gephart et al., 2021; Ivanovich et al., 2023). It, therefore, calls for increased efforts to advance scientific understanding on the environmental performance of freshwater aquaculture, with a specific focus on species intended for local consumption, such as Chinese mitten crab.

By comparison of these cases, it is found that crustacean products tend to show higher values in FCR, GWP and EP compared to fish products (Fig. 6). The average FCR of fish products is 1.4, whereas the FCR for crustaceans is 1.7. This discrepancy may be attributed to their different physiological mechanisms in transforming energy within their bodies through the feed intake. Compared to crustaceans, fish require less energy to sustain their life activities in water, while the burrowing and molting activities of crustaceans significantly increase their energy consumption (NRC, 2011). In addition, their different ingestive behaviors are prone to be important. Fish typically swallow food whole, consuming 90-95% of it, whereas crustaceans tend to nibble on their food, resulting in a consumption rate of only 60-80% (Boyd et al., 2007). The higher feed requirement of crustaceans has resulted in increased energy and resource inputs and the uneaten feed is likely to degrade water quality. Consequently, this translates into higher GWP (8.0 versus 3.7 tons of CO_2 equivalent) and EP (0.1 versus 0.06 tons of PO_4^{3-} equivalent) values in crustaceans compared to fish (Fig. 6).

4.2 Economic costs of crab aquaculture

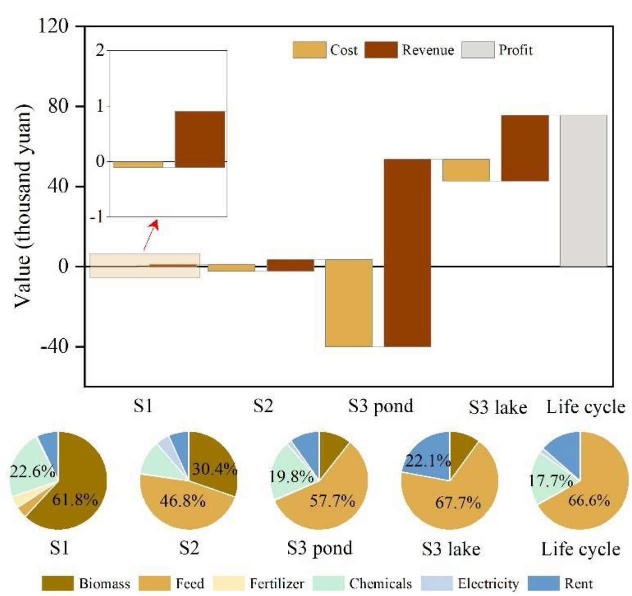

Figure 7 Life cycle cost analysis by stage and input category

In addition to environmental consequences, we further conducted a preliminary life cycle cost analysis of crab aquaculture from an economic standpoint, aiming to assess any possible trade-offs between economic and environmental aspects. The cost components include capital cost, specifically the land rent, and operation cost, which comprises all the expenditures incurred during crab aquaculture, including material inputs and electricity use. The material and electricity costs were mainly collected from representative farmers among above. All the costs were reported in terms of 2019 RMB yuan (1 US dollar ≈7.2 RMB yuan, August 2023). The electricity price was assumed to be the highest selling price of electricity for agricultural production in Jiangsu Province, which has been 0.509 yuan/kWh since 2018. The price of certain materials, of which the billing information was missing or the price fluctuated over time, such as frozen trash fish and tea seed cake, were estimated based on the average price sourced from commercial websites like Taobao.com. The detailed price information is provided in Table S11.

As depicted in Fig. 6, our findings indicate that the life cycle cost and revenue to produce 1 ton of live-weight crab are 51.0 and 126.6 thousand yuan, respectively, yielding a considerable profit rate of 148.4%. The cost is largely dependent on feed cost (66.6%), chemicals cost (17.7%) and rent cost (13.6%), while fertilizer and electricity use play minor roles. Across life cycle stages, adult crab cultivation, especially pond cultivation, contributes substantially to the total cost and revenue. Megalopa cultivation, on the other hand, only contributes less than 1% and can be negligible in comparison. However, as for the profit rates, the megalopa cultivation stage dwarfs all the other stages with a surprisingly high profit rate of 868.8%. This could be due to the highly specialized industrial clusters in Jiangsu Province that secures competitive advantages.

The comparison between pond and lake systems also reveals great difference in economic performance. In lake system, as no fertilizer and chemical inputs are required for adult crab cultivation, the main cost contributor is feed (67.7%), followed by rent (22.1%) and juvenile crab (10.2%). However, in pond system, feed (57.7%) and chemicals (19.8%) are the two most important contributors. The avoidance of chemical use, given relatively high cost, would greatly lower the cost of adult crab cultivation. Furthermore, the average size of adult crabs cultured in lakes (0.175 kg per crab) is larger compared to those in ponds (0.15 kg per crab), requiring fewer juvenile crabs as inputs and resulting in better price. Consequently, the profit rate of adult crab cultivation in lakes surpasses that in ponds (201.8% and 115.1%). We note that these results may be higher than certain cases in practice due to our assumption of a stable crab production status and the exclusion of initial investment on equipment. In practice, failures caused by insufficient farming experience are inevitable, which may lead to unexpected economic losses and bring down the profits.

4.3 Implications for improvement

This study presents quantitative analysis on the spatial and temporal patterns of crab aquaculture in China in the past two decades, primarily driven by rising cravings of consumers and underlying profitability in production. However, due to data limitation, our analysis does not extend beyond the farm gate to explore aspects such as distribution, consumption, and final disposal. Here we briefly discuss the consumption pattern to shed light on the evolution of crab supply chain from a life cycle perspective. The boom of the express delivery sector has expedited the redistribution of live crabs from producing provinces to consuming provinces within 1-2 days (Kang et al., 2021; Zhang et al., 2021). According to JD.com, Beijing, Guangdong and Jiangsu consistently held the top three positions with the highest crab sales between 2016-2018 (JD, 2018), indicating crab consumption activities are primarily concentrated in highly developed urban areas. It is consistent with a previous US study that suggested a positive correlation between the expenditure and the market share for crab (Nguyen et al., 2013). From the footprint perspective, it is essential to acknowledge that consumers should share the responsibility for the life cycle environmental impacts, not only downstream during the treatment and disposal, but also upstream during the production activities (Ivanova et al., 2016). A shift in household behavior shall hold significant potential toward reducing environmental footprints and achieving a balance between economic and environmental sustainability.

Consistent with previous studies (Ayer and Tyedmers, 2009; Ghamkhar et al., 2021; Pelletier and Tyedmers, 2010), our evaluation on crab aquaculture in either pond or lake systems highlights the trade-offs, evidently between global and local environmental impacts (e.g. GWP versus EP), as well as between economic and environmental performance. Currently, due to the pressure to control eutrophication and improve water quality, China is phasing out crab aquaculture in lakes, which has gained positive ecological impacts (Nan et al., 2022). However, our results show that lake system performs better in most global environmental impact categories as well as from the economic perspective. It suggests that this trade-off between environmental and economic considerations should be emphasized in the pursuit towards sustainable development of aquaculture from both producer's and the society's perspectives. It calls for further research and more systematic strategies aiming to mitigate the life cycle environmental impacts and economic costs associated with pond systems, focusing on conventional aspects including feed optimization, reduced use of chemicals, tailwater treatment, etc. In particular, the presence of antimicrobial residues such as enrofloxacin and ciprofloxacin in crabs may cause adverse effects on human health via dietary exposure (Song et al., 2023).

Indeed, there are several other aspects that require careful consideration to ensure benefits from both environmental and economic perspectives. First, the recycling of processed by-products and food wastes into high protein feed ingredients plays a vital role in sustainable aquaculture growth. The growing use of the novel aquafeed, e.g. microalgae, macroalgae, bacteria, yeast and insects, has shown promising results in reducing the demand for forage fish compared to soybean-based diets (Cottrell et al., 2020). Second, the integration of aquaculture with other farming systems, in the forms of aquaponics and rice-fish co-culture, can recover water and nutrient, but on the other hand, such integration may be at the expense of large energy consumption and more greenhouse gas emissions (Boxman et al., 2017; Greenfeld et al., 2021; Yuan et al., 2019). Third, as nutrients in uneaten feed and feces tend to accumulate in pond sediment (Liu et al., 2022), exploring methods to utilize aquaculture waste, for example, back to croplands, could be another solution to achieve aquaculture-agriculture integration. For example, fish pond sediment after composting with selected waste materials can significantly improve the growth of plant roots (Dróżdż et al., 2020).

5. Conclusion

This study investigated the spatiotemporal dynamics of crab aquaculture in China from the 2000s onwards and evaluated the environmental and economic performance along its life-cycle stages: megalopa, juvenile crab, and adult crab cultivation. Our findings reveal that the pattern of crab aquaculture becomes more scattered throughout the country as crabs grows. In addition, contrary to the spatial expansion of juvenile and adult crab cultivation over time, megalopa cultivation became more spatially concentrated, particularly with southward shift, resulting in the formation of prominent cluster in Jiangsu Province. The centroid of juvenile crab cultivation has stayed in the east over these years while that of adult crab cultivation has progressively moved more inland.

Considering environmental impacts, overall, producing Overall, 1 ton of live-weight crab produced in China would lead to 7.65 tons of CO_2 equivalent for GWP, 30.9 kg of SO_2 equivalent for AP, 229 kg of PO_4^{3-} equivalent for EP, 1.82 tons of 1,4-DB equivalent for FAETP, and 116 GJ for CED. Notably, feed use during the adult crab cultivation stage accounts for 37.2-48.3% of all the impact categories, with the exception of eutrophication that is mainly caused by on-site N and P emissions. We also find that the life cycle cost and revenue for producing 1 ton of live-weight crab amount to 51.0 and 126.6 thousand yuan, respectively, with a substantial profit rate of 148.4%. Crab aquaculture in lakes has resulted in lower environmental impacts in terms of global warming, acidification, ecotoxicity impacts, energy use, but higher economic profits. The lake system, nevertheless, entails higher eutrophication impacts than the more intensive pond system, indicating the trade-offs between global and local environmental impacts (e.g. GWP versus EP), as well as between economic and environmental performance. As pond cultivation has emerged as the predominant aquaculture production mode in China, our study suggests that further research and the implementation of systematic strategies are needed to mitigate these trade-offs for pond systems. This endeavor is essential to striking a balance between environmental and economic sustainability in crab aquaculture in China.

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Declaration of Competing Interest

The authors declare that there is no conflict of interest.

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