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Assessment of nitrous oxide emission from mariculture of marine fish and crustaceans in China, 2003–2022

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Abstract

Aquaculture, as the fastest-growing food production sector in the world, is becoming an increasingly nonnegligible source of greenhouse gas emissions. Despite this, there has been limited research on nitrous oxide (N_2O) emission from marine aquaculture in China, where more marine aquaculture occurs than anywhere else, globally. We estimated N_2O emissions (E) from marine mariculture of 10 fish and 6 crustacean species in China from 2003 to 2022 using production data from the *China Fishery Statistical Yearbook* (2004–2023), and data for feed conversion rates and types from the literature. From 2003, marine aquaculture production, the annual N_2O emissions (E_A), and the annual N_2O emissions per unit of aquaculture area (EI_A) trend upward. The E_A of fish culture was lower than that of crustaceans, but the EI_A of fish culture was generally higher. Sea bass (0.308 Tg/a, in terms of N) and white shrimp (0.945 Tg/a, in terms of N) had the highest average E_A among fish and crustacean cultures, respectively. The highest average E_A from fish and crustacean were both Guangdong Province (fish: 0.248 Tg, crustacean: 0.547 Tg), and the highest sea area were both the South China Sea (fish: 0.316 Tg, crustacean: 1.082 Tg); the highest average EI_A for fish and crustacean were Tianjin City [35.40 t/(hm^2·a)] and Guangxi Zhuang Autonomous Region [19.83 t/(hm^2·a)], respectively, and the highest sea areas were both the South China Sea (fish: 0.316 Tg, crustacean: 1.082 Tg). These analyses provide baseline data for a greenhouse gas emissions inventory for China, based on an interpretation of them, we provide recommendations for reducing N_2O emissions in marine fish and crustacean culture.

Key words: marine aquaculture, fish, crustacean, nitrous oxide emission

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1 Introduction

Sustainable economic development in the 21st century is becoming increasingly difficult because of climate change, especially atmospheric warming caused by greenhouse effects. Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are the main greenhouse gases (Crippa et al., 2021). N_2O has a global warming potential over a 100-year period exceeding 310 times that of CO_2, and agriculture is a main source of anthropogenic N_2O emission (Houghton, 1996). Annual N_2O emissions (E_A) from agriculture account for more than 70% of the total N_2O emissions ($\sum E_A$) generated by agriculture, industry, human consumption, and waste management (Luo et al., 2019). The decrease in wild fish populations due to overfishing has produced an increased demand for protein sourced from cultured products, resulting in the aquaculture industry becoming the fastest-growing agricultural sector (FAO, 2016; Pauly et al., 2002). However, most research on N_2O emissions has focused on natural or fertilized soils rather than on N_2O emissions from aquaculture, especially mariculture.

The *State of World Fisheries and Aquaculture Report (2022)* reported global aquaculture production to have reached a historic high of 8.75 × 10^7 t in 2020, and projected this to reach 1.06 × 10^8 t by 2030 (FAO, 2022). With an aquaculture production of 5.22 × 10^7 t in 2020 (~60% of the total global aquaculture production), China is the largest global aquaculture producer (The Bureau Fisheries and Fishery Administration, the Ministry of Agriculture, 2004–2023). With the fast-paced development of China's aquaculture industry, mariculture has become an important component of the country's marine economy, and its scale is steadily rising. From 2003 to 2022, the area used for mariculture in China increased from 1.53 × 10^6 hm^2 to 2.07 × 10^6 hm^2. Because of a lack of research on N_2O emissions from aquaculture,

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the N_2O emissions factor of influent nitrogen (EF_N = 1.80%) in wastewater treatment plants was used to estimate its N_2O emissions (Ahn et al., 2010). The global N_2O emissions (E) from aquaculture increased from 1.58 Tg in 2020 to 1.91 Tg in 2030, exceeding 5.72% of global anthropogenic N_2O emissions (Hu et al., 2012). However, the lack of research data for aquaculture means that this result is likely to be inaccurate. With increased demand for fish and marine products, more accurate estimates of N_2O emissions from aquaculture are required.

We extract data for 10 marine fish and 6 marine crustacean species cultured in China from The Bureau of Fisheries and Fishery Administration, the Ministry of Agriculture (2004–2023), and feed conversion rate and emission factors from existing literature. We quantify the E from mariculture from 2003–2022, and the E_A and annual N_2O emissions per unit of aquaculture area (EI_A) for mariculture in coastal area (excluding Taiwan, Hong Kong SAR, and Macau SAR), according to province, and marine areas in the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. Factors that influence N_2O emissions were discussed. These baseline data could be used to establish and populate a global N_2O emissions inventory for aquaculture water bodies, and a basis for greener and more sustainable development of the aquaculture industry.

2 Methods

2.1 *Data sources*

Mariculture in China mainly involves fishes, crustaceans (shrimp, crab), shellfish, algae, and other species (sea cucumber, sea urchin, seawater pearl, and jellyfish) (The Bureau of Fisheries and Fishery Administration, the Ministry of Agriculture, 2004–2023). We extract data of annual marine aquaculture production and mariculture areas for 10 fish [sea bass, Bothidae (flounders), large yellow croaker, black kingfish, Japanese amberjack, snapper, red drum, pufferfish, grouper, and European plaice] and 6 crustacean (white shrimp, giant tiger prawn, Chinese white shrimp, kuruma prawn, swimming crab, and mud crab) species from The Bureau of Fisheries and Fishery Administration, the Ministry of Agriculture (2004–2023). Our estimate of E from mariculture excludes the significant contributions of shellfish and algae (~40% of the total aquaculture production), and other species (sea cucumber, sea urchin, seawater pearl, and jellyfish).

The aquaculture production and area data of coastal area (excluding Taiwan, Hong Kong SAR, and Macau SAR), according to province, was obtained from The Bureau of Fisheries and Fishery Administration, the Ministry of Agriculture (2004–2023). The aquaculture production and area data of sea areas (the Bohai Sea, Yellow Sea, East China Sea, and South China Sea) were calculated from provincial data. Among various provinces, Shandong and Liaoning provinces cross the Yellow Sea and Bohai Sea. According to the Wang and Wu (2022), in Shandong Province, the main contributing cities for marine aquaculture are Qingdao, Dongying, Yantai, Weifang, Weihai, and Rizhao. Qingdao, Rizhao, and Weihai are located on the coast of the Yellow Sea, with a total aquaculture production of over 56%. Meanwhile, Huludao and Dalian were the main contributing cities to mariculture in Liaoning Province, and Huludao and Dalian are located near the Bohai Sea and adjacent to the Bohai Sea. Therefore, Shandong Province is designated as the Yellow Sea, and Liaoning Province is designated as the Bohai Sea.

2.2 *Estimation method*

The E of aquaculture species can be estimated according to the formula (Zhou et al., 2021):

$$M = EF \times P, \tag{1}$$

where M is the E from species, EF is the emission factor from species, and P is production (kg). Our EF values refer to values studied by Zhou et al. (2021), and were estimated by calculating dissolved nitrogen using feed conversion rate, and the protein contents of animals and feeds, and multiplying the former by the ratio (animal protein content to feed) of the latter. Data used to calculate EFs were based on research by Zhou et al. (2021) (Table 1), with the following inclusion criteria: (1) a field study is superior to a laboratory experiment; (2) research conducted in China was prioritized; (3) selection of any laboratory experiment required a control group that was free of any supplementation; and (4) we preferentially took studies conducted from 2003–2019 into consideration. Average EF for the 10 fish and 6 crustacean species in culture were selected (Table 1), which ranged 0.86–2.34 g/kg (N_2O/animal weight) animal weight. On the basis of these values we estimated the E of each of the 16 species in marine culture in China from 2003 to 2022.

The formula for calculating EI_A is

$$F = M/S, \tag{2}$$

where, F is the EI_A from species; S is the production area (hm^2).

Table 1. Average emission factors of the marine fish and crustacean culture [g/kg (N_2O/animal weight)] (Zhou et al., 2021)

Fish		Crustacean	
Species	Average emission factors	Species	Average emission factors
Sea bass (*Perca fluviatilis*)	1.41	South American white shrimp (*Penaeus vannamei*)	1.19
Bothidae (*Bothidae*)	0.86	Giant tiger prawn (*Penaeus monodon*)	1.59
Large yellow croaker (*Larimichthys crocea*)	0.89	Chinese white shrimp (*Fenneropenaeus chinensis*)	2.34
Black King Fish (*Rachycentron canadum*)	0.14	Kuruma Prawn (*Marsupenaeus japonicus*)	1.29
Japanese amberjack (*Seriola quinqueradiata*)	1.17	Swimming crab (*Portunus trituberculatus*)	1.25
Snapper (*Pagrcrs auratus*)	1.27	Mud crab (*Scylla*)	1.74
Red drum (*Sciaenops ocellatus*)	0.84		
Pufferfish (Tetraodontidae)	0.79		
Grouper (*Epinephelus spp.*)	0.94		
European plaice (*Pleuronectes platessa*)	1.06		

The *S* values of coastal provinces were provided by yearbook, and the *S* values of each sea areas were the sum of the production area of corresponding coastal provinces data.

3 Results and discussion

3.1 N_2O emissions from marine fish and crustacean culture

For both fish and crustaceans, E_A and annual N_2O emissions per unit of total aquaculture area ($\sum EI_A$) generally trend upward from 2003 to 2022. The E_A from fish increases from 0.36 Tg/a N in 2003 to 1.13 Tg/a N in 2022 (average 0.82 Tg/a N), and that of crustaceans increases from 0.89 Tg/a N in 2003 to 2.32 Tg/a N (average 1.58 Tg/a N)—1.9 times higher than that for fish. Thus, the cumulative *E* values for marine fish and crustacean culture from 2003 to 2022 were 0.77 Tg N and 1.43 Tg N, respectively. While E_A values for crustacean culture significantly exceed those for fish, EI_A values for fish significantly exceed those for crustaceans ($P < 0.05$) (Fig. 1). According to the results, the E_A in fish mariculture was lower than that in crustaceans, but the EI_A of fish culture was generally higher than that of crustaceans. The reason might be that the N_2O emission coefficient and aquaculture production of crustaceans are higher than those of fish mariculture. The crustaceans are more likely to disturb the sediment than fishes, and they are more likely to affect the structure of nitrogen-related microbial communities and promote N_2O production and release from sediments, therefore, the N_2O emission coefficient of crustaceans was nearly 1.5 times that of fish mariculture. Meanwhile, the aquaculture production of crustaceans (1 952 476 t in 2022) was slightly higher than that fish mariculture (1 925 574 t in 2022). So, the E_A in fish mariculture was lower than that in crustaceans. But the aquaculture area of crustacean mariculture was much larger than that of fish mariculture, for example, in 2022, the aquaculture area of crustaceans (300 166 hm^2) was four times that of fish (74 617 hm^2). Therefore, the EI_A of the fish mariculture was higher than that of crustaceans.

From highest to lowest, average E_A values of the 10 fish species were 0.308 Tg/a N for sea bass, 0.117 Tg/a N for large yellow croaker, 0.088 Tg/a N for snapper, 0.086 Tg/a N for grouper, 0.083 Tg/a N for Bothidae, 0.050 Tg/a N for black kingfish, 0.048 Tg/a N for red drum, 0.036 Tg/a N for Japanese amberjack, 0.014 Tg/a N for pufferfish, and 0.010 Tg/a N for European plaice (Fig. 2a). The E_A was influenced by aquaculture production and emission factors for these species. The sea bass has an average E_A of 0.308 Tg/a N, and an annual emission proportion of 23%–31% (average 27%). From 2003 to 2022, production of large yellow croaker increases 7%–20% annually, causing a gradual increase in E_A. Although the average annual production of large yellow croaker was 10 300 t higher than that of sea bass, the average E_A of sea bass was 0.191 Tg/a N higher than that of large yellow croaker, mainly because of the latter's relatively small emission factor (Table 1).

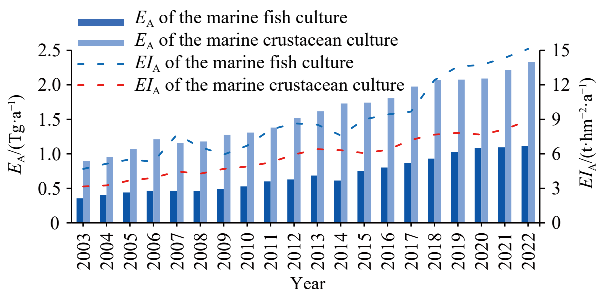

Fig. 1. E_A and EI_A values for marine fish and crustacean culture in China (2003–2022).

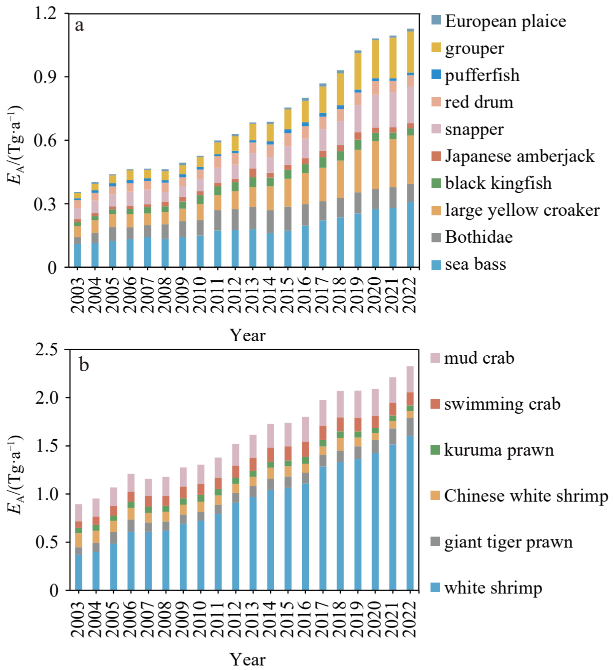

Fig. 2. The E_A from cultured in China, 2003–2022: a. ten species of marine fish, b. six species of marine crustacean.

Average E_A values for the six marine crustaceans, from highest to lowest, were 0.945 Tg/a N for white shrimp, 0.229 Tg/a N for mud crab, 0.124 Tg/a N for swimming crab, 0.116 Tg/a N for giant tiger prawn, 0.102 Tg/a N for Chinese white shrimp, and 0.063 Tg/a N for kuruma prawn (Fig. 2b). The white shrimp had the lowest emission factor and the highest aquaculture production among crustacean mariculture species, and the E_A of the white shrimp mariculture was higher than that of other crustacean species. Yang et al. (2021b) estimated that the Chinese white shrimp ponds in China released ~1.2 Gg/a N_2O into the atmosphere, but in the present study, the estimate average E_A was two to three orders of magnitude higher (0.91 Tg). Yang et al. (2021b) used *E* data from three white shrimp ponds in southeastern China (Minjiang River Estuary) to estimate shrimp pond E_A throughout China, but the *E* of a species may vary latitudinally. Of course, although various estimation methods may have varying degrees of error, they can reflect the overall trend of N_2O emissions from marine culture.

The above results indicated that: (1) The *E* values of crustaceans were higher than that of fish mariculture, accounting for 70% of the total annual N_2O emissions ($\sum E$). The *E* value might vary among different aquaculture species. Based on the data in the present study, the average emission factor of marine crustaceans was 1.5 times higher than that of marine fish, which indicated that N_2O emission per marine crustacean unit of production is 1.5 times higher than that of marine fish. Fang et al. (2022) reported that the direct N_2O emissions factors in fish ponds and crab ponds were 0.36% and 0.77% of total N input by feed, respectively. The N_2O emissions in crab ponds were more than twice as high as those in fish ponds, and the average emission factor of crustaceans used in this study was also 1.5 times higher than that of fish, showing a similar trend to the present study. (2) Differences in emission factors may also exist between species of fish and crustaceans. For example, the average emission factors of sea bass and pufferfish differ by 0.62 g/kg (N_2/animal weight), while the average emission factors of Chinese white shrimp and white shrimp differ by 1.15 g/kg (N_2/animal weight) (Table 1). White shrimp was the main marine crustacean species cultured in China, with a total production that exceeds 1/3 of that of all 16 cultured marine species (The Bureau of Fisheries and Fishery Administration, the Ministry of Agriculture, 2004–2023). White shrimp was one of the highest aquaculture shrimp species in the world, and had high aquaculture profitable. Meanwhile, they were the largest source of N_2O emissions in mariculture, and the high N_2O emissions were closely related to the higher aquaculture production. The higher N_2O emissions rate reported for culture of this shrimp is one to two orders of magnitude higher than that for any other aquatic invertebrate (Heisterkamp et al., 2016).

Since 2003, there has been a general upward trend in the EI_A of cultured marine fish and crustaceans in China. Moreover, the EI_A of cultured marine fish exceeds those of crustaceans. Average marine crustacean EI_A values, from highest to lowest, were mud crab [8.56 t/(hm²·a)], giant tiger prawn [7.54 t/(hm²·a)], white shrimp [6.41 t/(hm²·a)], swimming crab [4.50 t/(hm²·a)], Chinese white shrimp [4.13 t/(hm²·a)], and kuruma prawn [2.27 t/(hm²·a)], and values increase annually (by 182% from 2003 to 2022). The EI_A of giant tiger prawn increases consistently over time, from 2013 exceeds that of white shrimp, and in 2022 was 1.93 t/(hm²·a) higher than that of mud crab (Fig. 3). Because yearbooks only provide data on the total area of marine fish culture (not separately for species), the *EI* of specific species cannot be calculated.

3.2 N_2O emissions from marine fish and crustacean culture in coastal provinces

From 2003 to 2022, E_A values for marine fish and crustacean culture in 11 coastal provinces of China (excluding Taiwan, Hong Kong SAR, and Macau SAR) ranged 1.252–3.643 Tg N (average 2.399 Tg N) (Fig. 4). From highest to lowest by province, average marine fish culture E_A values were 0.248 Tg/a N in Guangdong, 0.209 Tg/a N in Fujian, 0.084 Tg/a N in Shandong, 0.044 Tg/a N in Hainan, 0.037 Tg/a N in Liaoning, 0.032 Tg/a N in Zhejiang, 0.024 Tg/a N in Guangxi, 0.008 Tg/a N in Hebei, 0.006 Tg/a N in Jiangsu, 0.001 Tg/a N in Tianjin, and 0 Tg/a N in Shanghai. For crustaceans, average E_A values were highest in Guangdong (0.547 Tg/a N), followed by Guangxi (0.397 Tg/a N), Fujian (0.176 Tg/a N), Shandong (0.157 Tg/a N), Hainan (0.138 Tg/a N), Zhejiang (0.107 Tg/a N), Jiangsu (0.075 Tg/a N), Liaoning (0.048 Tg/a N), Hebei (0.035 Tg/a N), Tianjin (0.030 Tg/a N), and Shanghai (0.003 Tg/a N). There was a significant difference between the north and south of the marine aquaculture, and

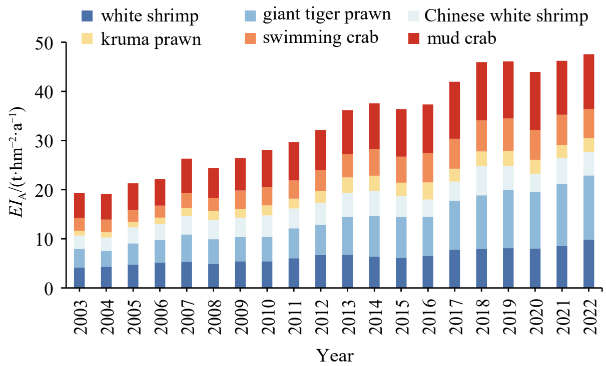

Fig. 3. EI_A values for six species of marine crustacean cultured in China (2003–2022).

most marine fish and crustacean culture occurred in the coastal provinces of South China. Average E_A values of cultured marine fish and crustaceans were relatively high in Guangdong, Guangxi, and Fujian provinces, which may be related to the species being cultured and the area that culture covers. The significant variations in proportions of *E* of marine fish and crustacean culture among the 11 provinces between 2003 and 2022 may reflect provincial differences in the species being cultured. For instance, the main fish species cultured in Fujian Province was large yellow croaker, but in Guangxi Province it is sea bass; the main crustacean species cultured in Guangdong Province is white shrimp, but in Liaoning Province it was Chinese white shrimp. Fang et al. (2022) reported that different aquaculture species also affect N_2O emission.

Except for Tianjin, Shanghai, and Guangxi provinces, $\sum EI_A$ generally trends upward from 2003 (Fig. 5). From highest to lowest, the average E_A for the total area of marine fish and crustacean aquaculture in these 11 provinces was 40.64 t/(hm²·a) in Tianjin, 38.02 t/(hm²·a) in Guangxi, 28.58 t/(hm²·a) in Hainan, 23.83 t/(hm²·a) in Fujian, 18.86 t/(hm²·a) in Shandong, 16.96 t/(hm²·a) in Guangdong, 13.52 t/(hm²·a) in Zhejiang, 10.04 t/(hm²·a) in Hebei, 9.00 t/(hm²·a) in Liaoning, 5.59 t/(hm²·a) in Jiangsu, and 1.86 t/(hm²·a) in Shanghai. In some years, the *EI* of a few provinces was very high. For example, the highest *EI* values for Guangxi occur in 2011 and 2013, primarily because of mud crab culture.

There were differences in EI_A of crustacean aquaculture among provinces, $\sum EI_A$ values in southern coastal provinces was stronger than those in northern coastal provinces. The reason for this phenomenon might be as follows. (1) Caused by temperature differences between the north and south. The temperature in southern coastal provinces is significantly higher than that in northern coastal provinces. Yang et al. (2021a) reported a significant positive correlation between N_2O emission factors and temperature. Temperature can affect nitrification and denitrification processes to affect the N_2O emissions. Both nitrification and denitrification processes are inhibited at temperatures ≤10℃ (Holtan-Hartwig et al., 2002). Taking the *EI* of white shrimp as an example, estimated average EI_A for white shrimp in the southernmost province, Hainan, was highest [14.38 t/(hm²·a)], consistent with Yang et al. (2021a), indicating that provinces with higher temperatures have greater *EI*. (2) Affected by differences in salinity between the north and south. Salinity can control the mineralization rate of N by affecting microbial activity and enzymatic reactions, thereby regulating rates of N_2O production, consumption, and atmospheric emission (Francis et al., 2003; Li et al., 2020; Moin et al., 2009). Studies have revealed negative correlations between dissolved N_2O concentrations and salinity (Fang et al., 2022; Barnes and Owens, 1999; Hashimoto et al., 1999; Welti et al., 2017). Normally, the salinity in southern coastal provinces was higher than those in northern coastal province. In this study, the E_A of white shrimp culture in the north were generally lower than those in the south, consistent with previous research findings. Therefore, salinity can also be an important factor affecting the EI_A in various provinces.

3.3 N_2O emissions from marine fish and crustacean culture in different sea areas

The four sea areas are the Bohai Sea, Yellow Sea, East China Sea, and South China Sea. Among the 11 coastal provinces, Liaoning and Shandong traverse two sea areas. According to the Wang and Wu (2022), the main contributing cities to marine culture in Shandong are Qingdao, Dongying, Yantai, Weifang, Weihai, and Rizhao. Qingdao, Rizhao, and Weihai are located on the

Fig. 4. E_A and $\sum EI_A$ values of 16 marine species (10 fish and 6 crustacean) cultured in 11 coastal provinces in China (2003–2022).

Yellow Sea coast, with the total production of marine culture accounting for more than 56%. Huludao and Dalian, the main contributing cities to marine culture in Liaoning Province, are located near the Bohai Bay and adjacent to the Bohai Sea. Therefore, we allocate Shandong Province to the Yellow Sea, and Liaoning Province to the Bohai Sea. From highest to lowest, the average E_A for marine fish aquaculture areas in the four seas was 0.316 Tg/a N in the South China Sea, 0.251 Tg/a N in the East China Sea, 0.090 Tg/a N in the Yellow Sea, and 0.046 Tg/a N in the Bohai Sea. For marine crustaceans, the average E_A was highest in the South China Sea (1.082 Tg/a N), followed by the East China Sea (0.293 Tg/a N), Yellow Sea (0.232 Tg/a N), and Bohai Sea (0.094 Tg/a N). The E_A values for marine crustacean culture in China were generally higher than those of marine fish culture (Figs 1, 4 and 6), as reported by Fang et al. (2022). Because crustaceans are more likely to disturb the sediment than fishes, they are more likely to affect the structure of nitrogen-related microbial communities and promote N_2O production and release from sediments (An et al., 2021). The South China Sea was the primary aquaculture area in China, where E values for marine crustacean culture peak in 2011 and 2013 (Fig. 6), mainly because significant increases in production of swimming and mud crabs in Guangxi Province in the preceding 2 years caused sharp increases in $\sum E$. However, white shrimp remains the main contributor to E_A in the South China Sea, particularly in Guangdong Province, further indicating that this species was the main source of E in this sea.

The $\sum EI_A$ in the four sea areas generally increases (Fig. 6). From highest to lowest, average $\sum EI_A$ values for marine fish and crustacean culture in the four sea areas were 20.51 t/(hm²·a) in the South China Sea, 20.40 t/(hm²·a) in the East China Sea, 8.58 t/(hm²·a) in the Yellow Sea, and 7.82 t/(hm²·a) in the Bohai Sea. Our estimates indicated that $\sum EI_A$ values in the South China

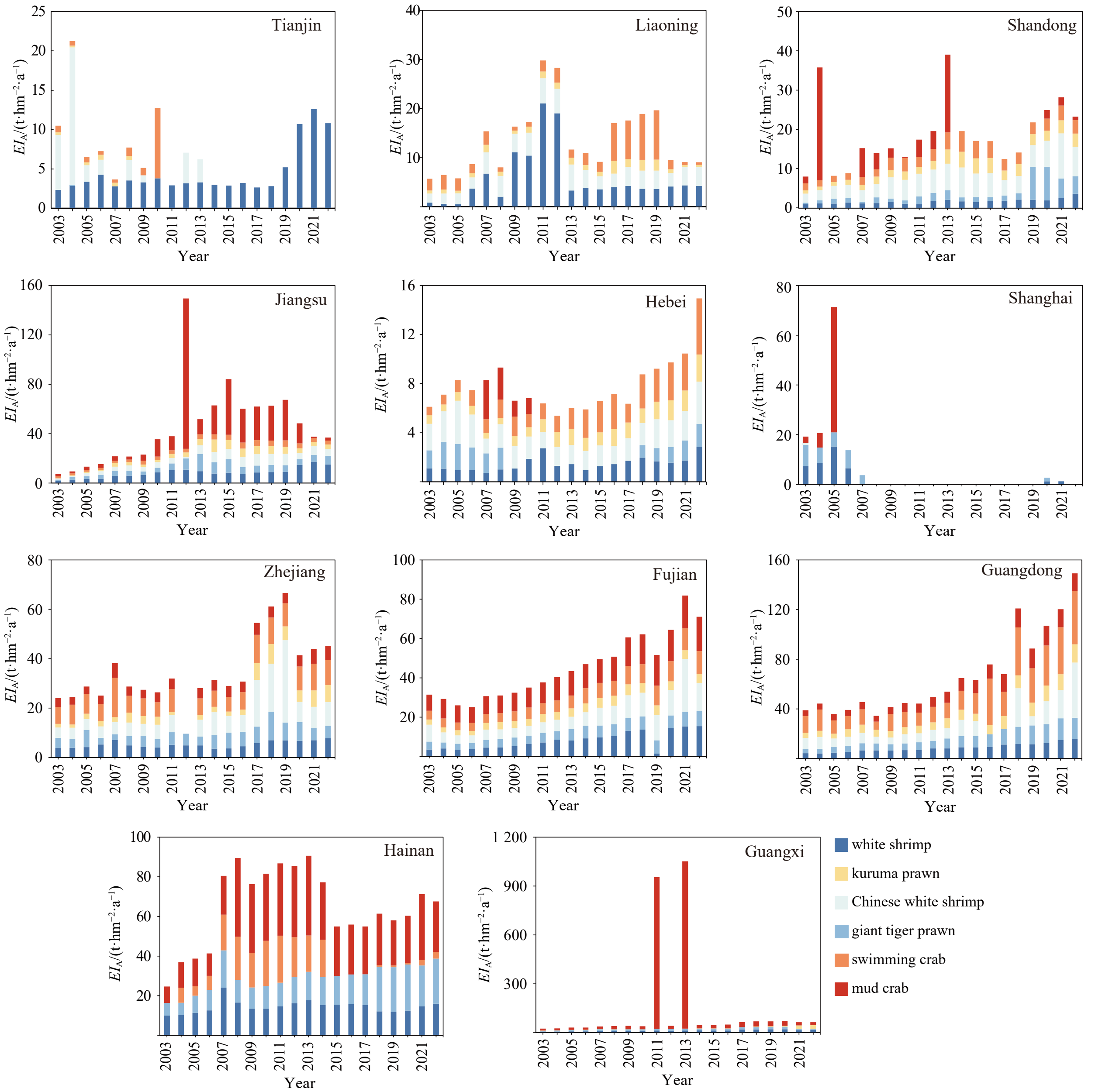

Fig. 5. EI_A values for culture of six marine crustaceans in 11 coastal provinces in China (2003–2022).

Sea were higher than those in the Bohai Sea, possibly because of combined effects, for example, temperature, salinity, aquaculture species, and feed. As mentioned earlier, in relevant studies, there have revealed negative correlations between dissolved N_2O concentrations and salinity. State Oceanic Administration (1997) cites differences in average surface salinities between the South China Sea and Bohai Sea were relatively small (summer: 0.72; winter: 2.44). Estimated $\sum EI_A$ values for the South China Sea exceed those of the Bohai Sea, possibly because the differences in salinity between these two seas are relatively small and have little influence on microbial activity (Yang et al., 2021a). The temperature in the South China Sea is significantly higher than that in the Bohai Sea. From the analysis of two environmental parameters, temperature and salinity, the trend of temperature changes is consistent with the estimated results of this study. Therefore, in the sea areas of this study, we report the influence of temperature to be higher than that of salinity, but the specific mechanism is unknown.

The EI_A values for the four sea areas were inconsistent (Fig. 7). For example, the EI_A values for the mud crab culture area in the Bohai Sea were for the 2007–2010 period only, because mud crab culture commenced in Tianjin during this period. The EI_A values in the Yellow Sea vary significantly, with the highest *EI* in 2012 [90.92 t/(hm²·a)] influenced by mud crab production in Jiangsu Province increasing by 1 214% during this year. The EI_A values in the East China Sea were relatively stable, averaging 6.19 t/(hm²·a). In 2011 and 2013, the *EI* values in the South China Sea were relatively high, mainly because of contributions from Guangxi Province. Because data limitations preclude calculation of *EI* for individual fish species in the sea area, we focus on the *EI* of crustacean mariculture.

3.4 *Study limitations and recommendations for future research*

Because production data for different species before 2003 are

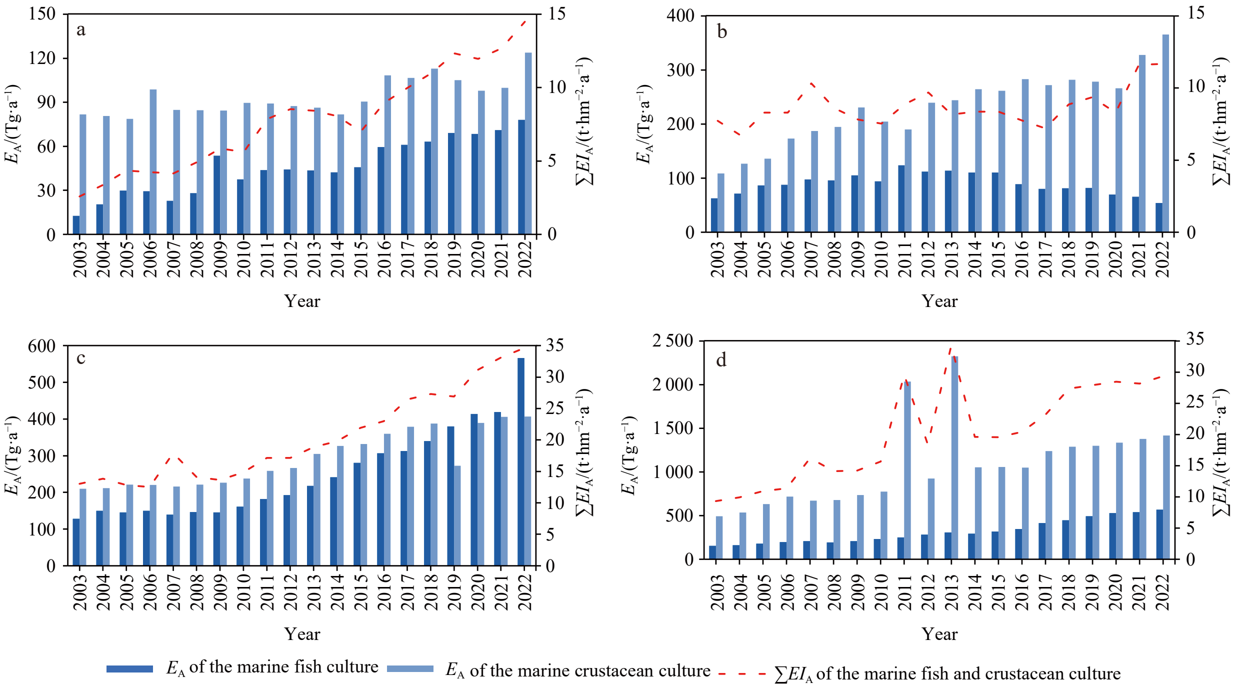

Fig. 6. E_A and $\sum EI_A$ values of 16 marine species (10 fish and 6 crustacean) in China (2003–2022): a. the Bohai Sea, b. the East China Sea, c. the Yellow Sea, d. the South China Sea.

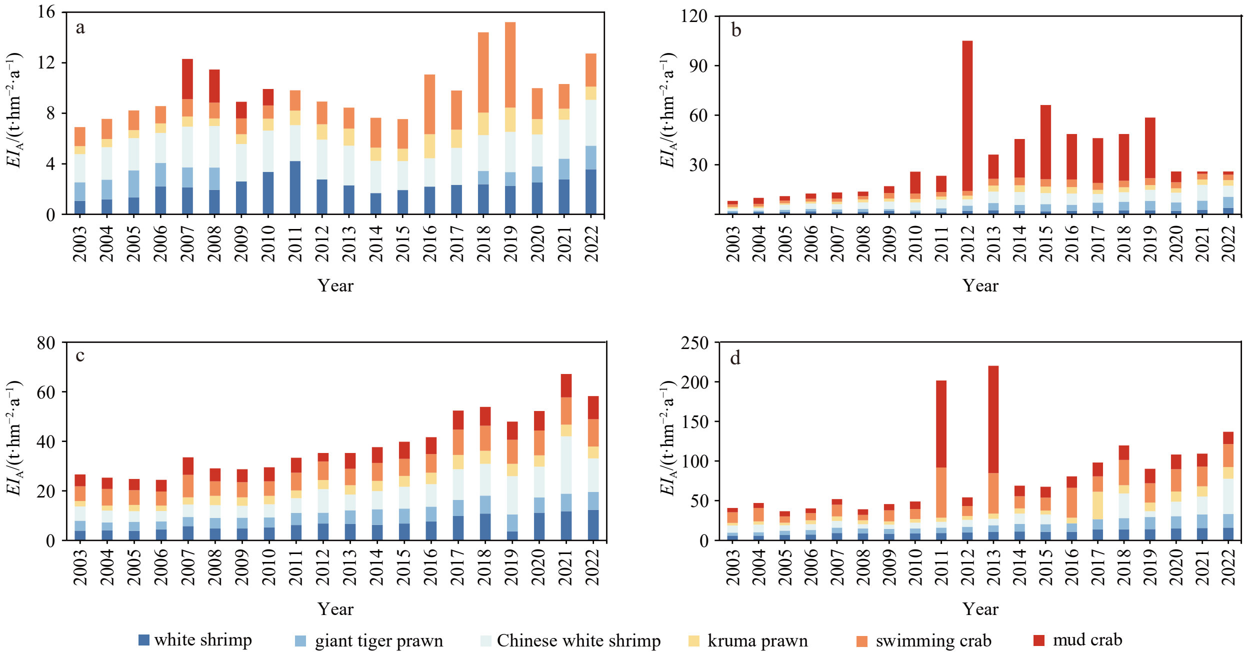

Fig. 7. EI_A values of six cultured marine crustacean species in China (2003–2022): a. the Bohai Sea, b. the East China Sea, c. the Yellow Sea, d. the South China Sea.

unavailable, we had to limit our analysis to data for commonly cultivated marine species (10 fish and 6 crustacean) included in the fishing industry from The Bureau of Fisheries and Fishery Administration, the Ministry of Agriculture (2004–2023). Based on formerly calculated average emission factors, we also estimate *E* and *EI* values for these 16 species in culture from 2003. Accordingly, our estimates of *E* for marine fish and crustacean culture are likely to be lower than actual levels. For instance, in 2022, these 16 species account for 55% (fish) and 92% (crustacean) of cultured marine species in China. Furthermore, emission factor data for different aquaculture species were sourced from the literature. Although we endeavored to select representative data, some deviations from actual field N_2O emissions may exist, with different aquaculture conditions and regions differing in emission factors, potentially affecting our estimates of *E* and *EI*. Finally, yearbooks do not differentiate specific areas of individual fish aquaculture, and the total area of marine fish culture is based on the combined area of only our 10 marine fish species. Therefore, our results will underestimate the actual *EI* for marine fish.

We considered only 16 marine species, which may be an incomplete account of marine data for each province, sea area, and the entirety of China. More reliable estimates require further field measurements encompassing a wide range of species, regions, and species types, and the emission factors of different mariculture species in different coastal areas are measured simultaneously.

4 Conclusions

Greenhouse (N_2O) gas emissions generated by mariculture remain largely unknown for the global N_2O budget. We identify patterns in *E* and *EI* for cultures of marine fish and crustaceans in China, in different coastal provinces and sea areas from 2003 to 2022. Species, feed, temperature, and salinity all significantly affect N_2O emissions. Additionally, our estimated *E* from culture of these 16 species may be an underestimate, because limited data were available for N_2O emissions from aquaculture practices. Given continued growth of the aquaculture industry and increasing production, efforts to minimize the adverse effects of this industry on the environment, including nutrients and greenhouse gases, should be made. Feasible reducing N_2O emission strategies, such as optimizing feed formulas, selecting appropriate aquaculture species, optimizing aquaculture environment, and promoting ecological aquaculture models, are among possible solutions to help coordinate development of economic and environmental benefits.

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