Assessing carbon greenhouse gas emissions from aquaculture in China based on aquaculture system types, species, environmental conditions and management practices

Yifei Zhang[a,b,c,d], **Kam W. Tang**[e], **Ping Yang**[a,b*], **Hong Yang**[f,g], **Chuan Tong**[a,b], **Changchun Song**[c,h*], **Lishan Tan**[i], **Guanghui Zhao**[i], **Xudong Zhou**[j], **Dongyao Sun**[k]

[a]*School of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China*

[b]*Key Laboratory of Humid Subtropical Eco-geographical Process of Ministry of Education, Fujian Normal University, Fuzhou 350007, China*

[c]*Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China*

[d]*University of Chinese Academy of Sciences, Beijing 100049, China*

[e]*Department of Biosciences, Swansea University, Swansea SA2 8PP, U.K.*

[f]*College of Environmental Science and Engineering, Fujian Normal University, Fuzhou, 350007, China*

[g]*Department of Geography and Environmental Science, University of Reading, Reading, U.K.*

[h]*School of Hydraulic Engineering, Dalian University of Technology, Dalian 116023, China*

[i]*State Key Laboratory of Estuarine and Coastal Research, Institute of Eco-Chongming, East China Normal University, Shanghai 201199, China*

[j]*School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China*

[k]*School of Geography Science and Geomatics Engineering, Suzhou University of Science and Technology, Suzhou 215009, China*

***Corresponding authors**:

Ping Yang (yangping528@sina.cn); Changchun Song (songcc@neigae.ac.cn)

ABSTRACT

Aquaculture is one of the fastest growing food production sectors in China, but many of the small-hold operations are poorly assessed for their climate impact. We analyzed the literature data on CO_2 and CH_4 fluxes from various aquaculture systems in China. The mean fluxes varied from -382.45 to 551.88 g CO_2-C m^{-2} yr^{-1} and -0.03 to 565.09 g CH_4-C m^{-2} yr^{-1}. Aquaculture system reclaimed from mudflat had the highest CH_4 emission (54.92 ± 21.00 g C m^{-2} yr^{-1}) but lowest CO_2 emission. Shrimp aquaculture and semi-intensive farming tended to yield higher CH_4 emission. Small and shallow systems had significantly higher CO_2 and CH_4 emissions, with chlorophyll *a* and dissolved oxygen concentrations among the main environmental drivers. Management practice such as drainage, exposure and desilting during the non-farming period significantly decreased CH_4 emission. We estimated that aquaculture systems in China emitted 181.66 Tg CO_2-eq yr^{-1}, enough to offset ~7% of the national terrestrial carbon sink, with most of the emission concentrated in coastal provinces and along the major rivers in the southeastern quadrant. This study highlights the need to account for carbon greenhouse gas emissions from aquaculture to improve the accuracy of the regional and national carbon budgets.

Keywords: Carbon dioxide (CO_2); Methane (CH_4); Aquaculture systems; management practices; Global warming potential (GWP); Global climate change

1. Introduction

Increasing level of atmospheric greenhouse gases (GHGs) is a global climate challenge (Fang et al., 2018; IPCC, 2021). Carbon dioxide (CO_2) and methane (CH_4) are two important GHGs, accounting for approximately 60% and 20% of the atmospheric radiative forcing, respectively (World Meteorological Organization, 2021). CO_2 and CH_4 emissions from terrestrial aquatic systems such as rivers, lakes, reservoirs and wetlands are estimated at 1.2 – 2.1 Pg C yr^{-1} (Raymond et al., 2013) and 0.65 Pg C yr^{-1} (CO_2-eq) (Bastviken et al., 2011), respectively, enough to offset the majority of the terrestrial carbon sink (Aufdenkampe et al., 2011; Langeveld et al., 2019).

There is increasing evidence that the climate importance of aquatic systems may have been underestimated because the existing GHG budget largely ignores the contribution from small and shallow water bodies (Peacock et al., 2021; Yang et al., 2020a; Zhang et al., 2021), and large variability in GHG emissions due to human disturbances remains poorly resolved (Yuan et al., 2019; Van Bergen et al., 2019). There are estimated 3.2×10^9 small shallow ponds globally, both natural and man-made, covering a total area of approximately 8.0×10^7 ha (Downing, 2010; Holgerson and Raymond, 2016). Assessment of GHG fluxes in shallow ponds, especially aquaculture systems, has attracted much attention in recent years (IPCC, 2021; Liu et al., 2016; Xiao et al., 2017; Yuan et al., 2021) due to their role as potential hotspots for CO_2 and CH_4 emissions (Laurion et al., 2010; Peacock et al.,2019). Compared with natural water bodies, aquaculture systems have much higher biological density and productivity

(Tong et al., 2021) and enrichment from fertilizer and feeds (Kosten et al., 2020; Naskar et al., 2020; Ye et al., 2022). These conditions tend to favor high respiration and methanogenic rates, leading to high CO_2 and CH_4 emissions (Chanda et al., 2019; Kosten et al., 2020; Rutegwa et al., 2019; Yang et al., 2021).

China has the largest land-based aquaculture industry in the world in terms of areal coverage, reaching ~2.57×10^6 ha (Chen et al., 2016; FAO, 2018), equivalent to 7.2% of China's terrestrial water area. Driven by the declining natural fishery resources and strong demand for aquatic products, aquaculture in coastal and inland areas has grown (China Fisheries Yearbook, 2019). China's land-based aquaculture systems can be classified into coastal wetland reclamation system (CWRS), inland pond system (IPS), lake/reservoir system (LRS) and rice-field system (RFS) (Liu et al., 2016; Pu et al., 2022; Yang et al., 2018), with water salinity ranging from fresh to brackish. The primary farmed organisms include fish, shrimp, crab and mixed culture (Hu et al., 2020; Wu et al., 2018; Chen et al., 2016). The aquaculture intensity level ranges from ecological stocking to extensive, semi-intensive and intensive (Ding et al., 2020). Management practices also vary in terms of aeration, frequency of water change, drainage and other aspects (Kauffman et al., 2018; Liu et al., 2016; Maher et al., 2019). These variations will likely affect the biogeochemical conditions that determine CO_2 and CH_4 emissions, but detailed comparisons are limited (Bhattacharyya et al., 2013; Sun et al., 2019).

To fill this knowledge gap, we conducted a comprehensive analysis of data from 132 aquaculture sites in China. The specific objectives of this study were: 1) to quantify the differences in CO_2 and CH_4 emissions across the different land-based aquaculture systems and species; 2) to explore the impact of management methods and key environmental variables in controlling CO_2 and CH_4 emissions; and 3) to assess the combined global warming effect of CO_2 and CH_4 emissions from aquaculture systems in China.

2. Materials and Methods

2.1. Data sources and selection criteria

Data of CO_2 and CH_4 fluxes were collected from peer-reviewed journal articles and dissertations in Web of Science (http://www.webofknowledge.com/), Google Scholar (http://scholar.google.com) and China Knowledge Infrastructure (CNKI, http://www.cnki.net). "GHGs or CO_2 or CH_4 flux", "aquaculture ecosystem or small pond or shallow lake / reservoir or rice field" and "fish or shrimp or crab or mixed aquaculture" were used as search words for the period of 2008 – 2022.

Initial data were filtered according to five criteria: 1) Data were collected in China, including at least one aquaculture system classified as CWRS, IPS, LRS or RFS; 2) Data were from land-based aquaculture systems, excluding marine aquaculture systems such as cage, ranch and bottom seeding; 3) Data covered at least one production cycle, namely the farming period, to minimize short-term noise; 4) Data covered at least one GHG, CO_2 or CH_4; 5) Gas fluxes were either derived from laboratory measurements of water samples (e.g. intensive systems) or directly measured *in situ* (all systems).

2.2. Data extraction

A total of 132 aquaculture sites were identified based on 62 published papers and dissertations for the comprehensive analysis (full list in Supplementary Material Table S1–S4), including 32 CWRS, 53 IPS, 23 LRS and 24 RFS, spanning from tropical to temperate latitudes (Fig. 1). We divided the sites into four farming intensity levels according to Yuan et al. (2019): ecological stocking, extensive, semi-intensive and intensive. CO_2 and CH_4 emission fluxes were measured by floating chamber (*in situ*) or derived from headspace equilibrium and thin boundary layer model, both common methods for determining GHG fluxes across the water-air interface. Numerical values were obtained from the papers or dissertations directly where available; otherwise, they were extracted from digitized graphs using the Image Digitization Tool in OriginPRO 2021.

In addition to CO_2 and CH_4 emission fluxes, we also recorded the geographical coordinates (longitudes and latitudes), aquaculture species, management information and environmental data (Table S5–S8). Management information included the use of aeration, system treatment during non-farming period, plant planting, water salinity and micro topography (water depth and area). Environmental data included mean annual air temperature, mean annual precipitation, water temperature, water pH, dissolved oxygen (DO), Chlorophyll-*a* (Chl-*a*), dissolved organic carbon (DOC), total dissolved nitrogen (TDN), ammonium nitrogen (NH_4^+-N), and nitrate nitrogen concentrations (NO_3^--N). When necessary, missing values for air temperature and precipitation were filled in with data from WorldClim (http://www.worldclim.org/) for the corresponding locations.

Since CH_4 has a stronger warming effect (~45 times of CO_2 over a 100-year time horizon; Neubauer and Megonigal, 2015) than CO_2, we calculated the combined annual

CO_2-equivalent emission (t CO_2-eq ha^{-1} yr^{-1}) from the aquaculture systems with the following equation:

$$\text{CO}_2\text{-equivalent emission} = \frac{1}{100}\times\left(\frac{44}{12}F\text{CO}_2+45\times\frac{16}{12}F\text{CH}_4\right) \quad (1)$$

where FCO_2 and FCH_4 are the carbon fluxes for the respective gases (g C m^{-2} yr^{-1}; positive values for emission); 44/12 and 16/12 are coefficients to convert carbon masses of CO_2 and CH_4 to the respective gas masses; 45 is the factor to covert CH_4 to CO_2-equivalent emission (100-year time horizon); and 1/100 is the unit conversion factor.

2.3. Calculation of aquaculture-GHG flux in China

Based on the mean fluxes of CO_2 and CH_4 during the farming period for the different aquaculture system types (CWRS, IPS, LRS and RFS), we multiplied them by the system-specific areal coverage in each province (China Fisheries Yearbook, 2019; Tan et al., 2019; Yuan et al., 2019) to calculate the spatial distributions and magnitudes of aquaculture-GHG fluxes across China. Species information was not included in the calculation because it was not always available. Estimates from river-ditch and other aquaculture waters were excluded due to their relatively small area (~3.55% of the national land aquaculture area) and the absence of relevant data for GHG fluxes. In addition, the investigation sites used in this study were basically located in eastern China, the traditionally hot spots for aquaculture, while the data of arid and semi-arid areas in the west were scarce.

2.4. Statistical analysis

All statistics were performed in SPSS 25.0 (Chicago, IL, USA). Data were checked for normality and homogeneity of variance, and Tukey transformation was applied when necessary. Non-parametric test (Kruskal-Wallis) was used for data that failed to meet the requirements after conversion. Effects of aquaculture systems, species and management methods on CO_2 and CH_4 fluxes were examined by analysis of variance (ANOVA). Linear and logarithmic regression analysis were conducted to explore the relationship between CO_2 and CH_4 fluxes and environmental variable. Statistical significance was tested at the level of 0.05. Boosted regression tree model (BRT) was used to evaluate the relative importance of different variables in determining CO_2 and CH_4 fluxes, using the package "gbm" in the Rstudio version 1.0.143 (http://www.rstudio.com/). More details of BRT model operation and prediction are included in the Supplementary Material. Aquaculture site map was generated using ArcGIS 10.2 (ESRI, Redlands, CA). The statistical results were plotted using Origin 2022 (Origin Lab Corporation, Northampton, MA, USA). Data are presented as mean ± SE.

3. Results

3.1. Variations in GHGs fluxes among aquaculture systems and species

CO_2 flux value ranged from -382.45 to 551.88 g C m^{-2} yr^{-1}, with 23% of the sites showing a net uptake, whereas CH_4 flux value ranged from -0.03 to 565.09 g C m^{-2} yr^{-1}.

There were significant variations in CO_2 flux among the different aquaculture systems ($P < 0.01$; Table S9), being highest in RFS (509.13 g C m^{-2} yr^{-1}), followed by

IPS (107.14 ± 23.67) and LRS (107.67 ± 28.75) (Fig. 2a–d). CO_2 flux in CWRS was relatively low, ranging from -119.59 to 167.96 g C m^{-2} yr^{-1}, with over 40% of the data showing a net CO_2 uptake especially for mixed species culture. Nevertheless, there was no overall significance difference among farmed species ($P > 0.05$; Table S9).

Large variations in CH_4 fluxes were observed among the different aquaculture systems ($P < 0.001$) and species ($P = 0.003$; Table S9). Mean CH_4 flux (g C m^{-2} yr^{-1}) was 57.92 ± 21.00 in CWRS, 40.48 ± 14.47 in IPS and 29.60 ± 4.45 in RFS (Fig. 2e–h), and it was much lower in LRS (6.32 ± 3.55). Among the different farmed species, CH_4 flux (g C m^{-2} yr^{-1}) was highest for shrimp (80.43 ± 25.23), followed by fish (30.75 ± 8.63), crab (22.05 ± 6.24) and mixed species (6.98 ± 2.71).

The combined GHG emissions of CWRS, IPS, and RFS differed slightly, averaging 35.26, 28.21 and 36.43 t CO_2-eq ha^{-1} yr^{-1}, respectively, with CH_4 as a substantial or the dominant component (Fig 2i, j, l). In comparison, LRS emitted less than 8 t CO_2-eq ha^{-1} yr^{-1} (Fig 2k).

3.2. Influence of aquaculture management on GHG emissions

Farming intensity. CO_2 flux (g C m^{-2} yr^{-1}) decreased in the order of intensive (294.37 ± 110.08) > ecological stocking (105.33 ± 80.74) > extensive (96.96 ± 20.44) > semi-intensive (45.68 ± 19.24) (Fig. 3). CH_4 flux (g C m^{-2} yr^{-1}) decreased in the order of semi-intensive (57.28 ± 15.33) > extensive (24.78 ± 6.53) > intensive (3.47 ± 1.65) > ecological stocking (2.25 ± 0.73) (Fig. 3). Overall, intensive aquaculture had a significantly higher CO_2 emission flux but lower CH_4 emission flux than semi-intensive and extensive aquaculture ($P < 0.05$).

Aeration. The average CH_4 flux was 15.80 ± 5.02 g C m^{-2} yr^{-1} in systems with aeration, and significantly higher in systems without aeration, at 60.78 ± 12.35 g C m^{-2} yr^{-1} ($P < 0.05$; Table 1). In contrast, CO_2 flux showed negligible difference between aerated systems (44.36 ± 24.49 g C m^{-2} yr^{-1}) and non-aerated systems (45.91 ± 19.02 g C m^{-2} yr^{-1}) ($P > 0.05$; Table 1).

Aquatic plants. Although the effects were not statistically significant, the presence of aquatic plants tended to result in 42.7% lower CO_2 and 28.5% lower CH_4 emissions on average (Table 1).

Area and depth. Systems smaller than 1 hectare in size had significantly higher CO_2 flux (78.19 ± 43.73 g C m^{-2} yr^{-1}) and CH_4 flux (87.65 ± 28.86 g C m^{-2} yr^{-1}) than those of larger size (33.62 ± 19.53 g C m^{-2} yr^{-1} as CO_2 and 26.91 ± 7.98 g C m^{-2} yr^{-1} as CH_4) ($P < 0.05$; Table 1). Shallower system (< 1.2 m) had significantly higher CH_4 flux (57.40 ± 13.93 g C m^{-2} yr^{-1}) than deeper system (> 2.0 m; 16.41 ± 14.52 g C m^{-2} yr^{-1}) ($P < 0.05$; Table 1). CO_2 flux also tended to increase with shallower depth, although the difference was not significant ($P > 0.05$; Table 1).

Water salinity. Significant differences in CO_2 and CH_4 fluxes were observed across the salinity spectrum (Table 1). CH_4 flux in high-salt systems (> 5‰) was only 9.17 ± 5.87 g C m^{-2} yr^{-1}, equivalent to 8.6% and 23.1% of that in low-salt and freshwater systems, respectively ($P < 0.05$). CO_2 flux decreased with increasing salinity and became negative in high-salt systems, indicating a net CO_2 uptake (Table 1).

Management practice in non-farming period. The different ways farmers treated their aquaculture systems during the non-farming period significantly affected CH_4 flux but not CO_2 flux (Table 1). In particularly, draining, exposing and desilting the systems (practice III) led to ~97% less CH_4 emission ($P < 0.05$).

3.3. Relationship between GHGs and environmental factors

Linear and logarithmic regressions between CO_2 or CH_4 fluxes and environmental variables are shown in Fig. 4. CO_2 flux was positively correlated with inorganic nitrogen concentrations (NH_4^+-N and NO_3^--N), and negatively with pH and Chl-*a* concentration ($P < 0.001$, Fig. 4a–d). CH_4 flux was positively correlated with water temperature, Chl-*a* and DOC concentrations, and negatively with DO ($P \leq 0.001$, Fig. 4e–h).

BRT model was used to rank the environmental variables in influencing GHG fluxes. Chl-*a* had the largest influence (54%) on CO_2 flux, followed by pH (19.9%), DO (10.7%) and inorganic nitrogen (NH_4^+ and NO_3^- combined 13.1%) (Fig. 5a). For CH_4 flux, Chl-*a* (38.9%), DOC (22.8%) and DO (18.5%) were the most important factors (Fig. 5b).

3.4. Spatial distribution of aquaculture-GHG emissions in China

Based on government statistics on the areas of CWRS, IPS, LRS, and RFS across China, the total annual CO_2 and CH_4 emissions from land-based aquaculture were estimated to be 14.98 and 2.20 Tg C yr^{-1}, respectively (Fig. 6a and 6b). This is equivalent to 0.94% and 5.50% of the national anthropogenic CO_2 and CH_4 emissions, respectively. The combined emission was 181.66 Tg CO_2-eq yr^{-1} (Fig. 6c). Among the different types of aquaculture systems, IPS and RFS made the largest contributions based on their geographical coverage, at 74.61 and 69.35 Tg CO_2-eq yr^{-1}, respectively.

4. Discussion

4.1. CO_2 flux in different aquaculture systems

Our study showed that the biogeochemical conditions within the aquaculture systems had significant effects on CO_2 flux (Fig. 4). In addition to the farmed animals, many of the systems contained high abundances of algae. Photosynthesis by algae would draw down CO_2, resulting in a negative correction between CO_2 flux and Chl-*a* concentration (Fig. 4b). Indeed, photosynthetic draw-down due to the high Chl-*a* concentration in CWRS (Fig. S1d) was strong enough to cause a negative CO_2 flux (net absorption) (Fig. 2a). Water pH can influence CO_2 flux by shifting the chemical equilibrium within the carbonate system (Soumis et al., 2004). Higher pH favors the conversion of CO_2 and HCO_3^- to CO_3^{2-}, thereby decreases $p\mathrm{CO_2}$ and promotes the dissolution of atmospheric CO_2 into the water (Aimé et al., 2018; Olsson et al., 2015; Pacheco et al., 2015; Zhang et al., 2019), which is consistent with the significant negative correlation between CO_2 flux and pH we observed (Fig. 4a). Interestingly, RFS had a high pH (Fig. S1b) and the highest CO_2 emission among all systems (Fig. 2d). Compared to other aquaculture systems, the usually higher biomass (rice and aquatic animals) in RFS would lead to higher respiration rate and CO_2 emission flux. CO_2 flux was positively related to inorganic nitrogen (NH_4^+-N and NO_3^--N; Fig. 4d), reflecting the results of microbial remineralization of organic nitrogen in the system.

Farmed animals are an important source of CO_2 emission (Ma et al., 2018; Mermillod-Blondin and Rosenberg, 2006; Sejr et al., 2014; Liu et al., 2016) based on their respiration capacity and trophic characteristics (Scofield et al., 2016; Sidik and Lovelock, 2013). Larger animals tend to have a greater contribution to CO_2 emission per individual (Chanda et al., 2019; Yang et al., 2018; Zhang et al., 2019), while filter feeders such as *Hypophthalmichthys molitrix* and *Aristichthys nobilis*, both popular farmed fish species in China, consume microalgae in the water and decrease photosynthetic draw-down of CO_2 (Chen et al., 2016). Nevertheless, we found no significant differences in CO_2 flux among fish, crab, shrimp and mixed species cultures (Table S9). While shrimp is considerably smaller in size than fish and crab, shrimp and mixed aquaculture often has a higher stocking density that results in an overall high respiratory CO_2 emission from the system.

4.2. CH_4 flux in different aquaculture systems

All of the aquaculture systems we examined were a stronger source of atmospheric CH_4 than lakes, reservoirs and rivers (Chen et al., 2021; Delsontro et al., 2016; Ding et al., 2005; Li et al., 2018). Aquaculture systems have high organic loading from feeds and animal wastes that would fuel methanogenesis (Tong et al., 2021; Yuan et al., 2021), as evidenced by the positive correlation between CH_4 flux and DOC (Fig. 4h). Also, the high respiration rates from microbes and farmed animals would create a low-oxygen environment that favors CH_4 production and transport (Sun et al., 2019; Yang et al., 2019), consistent with the observed negative correlation between CH_4 flux and DO (Fig. 4f). There was also a significant difference in CH_4 flux among the different aquaculture systems (Table S9). LRS located in the open water of lakes and reservoirs would have more water movement leading to a higher DO (Fig. S1c). In contrast, the more enclosed and stagnant nature of CWRS, IPS, and FRS would allow the accumulation of DOC and nutrients (Fig. S1e–i) and depletion of DO (Fig. S1c), which would favor methanogenesis (Fang et al., 2022; Holgerson et al., 2016; Zhu et al., 2016). Consequently, CH_4 fluxes in CWRS, IPS and FRS were all an order of magnitude higher than LRS (Fig. 2e–h).

Across all data, CH_4 flux was positively correlated with water temperature over a 17 °C range (Fig. 4e). Higher temperature would not only increase microbial activity in CH_4 production, but also decrease gas solubility and increase its transport through ebullition and diffusion across the water-air interface. Nevertheless, the low r-square value (0.13) of the regression means that water temperature was a minor factor. Another interesting observation was the positive correlation between CH_4 flux and Chl-*a* (Fig. 4g). In addition to contributing organic substrates for anaerobic methanogenesis, recent research has shown that some phytoplankton may produce CH_4 directly (Bižić et al., 2020; Günthel et al., 2020; Klintzsch et al., 2019), a phenomenon known as 'oxic methane production' that is widespread in aquatic habitats (Bogard et al., 2014; Günthel et al., 2019; Tang et al., 2016). It is worth noting that some of the high CH_4 flux values were observed in well-oxygenated water (>6 mg DO L^{-1}) and that clearly deviated from the main trend (Fig. 4f), suggesting a possible role of oxic methane production in the systems (Tang et al., 2014).

In terms of farmed species, shrimp aquaculture had a much higher CH_4 flux than fish and crab aquaculture (Fig. 2e–h; Table S9). The higher stocking density and larger amounts of feeds used in shrimp aquaculture compared to the other species would deplete DO (Holgerson, 2015; Van Bergen et al., 2019) and increase CH_4 production (Chen et al., 2016; Chatvijitkul et al., 2017; Yang et al., 2015). Consistent with others' observations (Fang et al., 2022; Yang et al., 2015), mixed species aquaculture had lower CH_4 flux than monoculture (Fig. 2e, f), likely because of the higher efficiency for mixed species to utilize organic matters within the water column and decrease organic input into the sediment for methanogenesis (Hu et al., 2016; Zhang et al., 2022). For example, large fish use feed directly, while their feces and detritus can be utilized by filter-feeders, omnivorous shrimp or crabs.

4.3. Effects of aquaculture management on GHG fluxes

Our results showed that CO_2 and CH_4 fluxes were affected by management measures (Table 1). While high farming intensity increased CO_2 flux due to the higher biological activities, it decreased CH_4 flux likely because of the use of aeration and more precise feeding and water quality regulation (Fig. 3).

Aeration had no significant effect on CO_2 flux, but it decreased CH_4 flux by 75% (Table 1). Most of the aerating devices used by farmers were impeller machines. Aeration would not only increase the DO level to inhibit anaerobic methanogenesis, but the physical mechanism of the impellers would break CH_4 bubbles, thereby decreasing the effectiveness of ebullition as the main CH_4 emission pathway (Tong et al., 2021; Yang et al., 2020b). Other type of aerator, such as bottom micropore oxygenation equipment, have even stronger oxygenation effect near the sediments (Ding et al., 2020; Hu et al., 2016) and may further decrease CH_4 production in the systems.

Planting aquatic plants was necessary to provide habitat and natural feed for some aquaculture species like *Eriocheir sinensis* and *Ctenopharyngodon idella*. Several scholars have observed that aquatic vegetation increased CH_4 emissions by 14 to 128 % (Ding et al., 2020; Liu et al., 2016; Ma et al., 2018), while others found a reduction in GHG emissions (Lin et al., 2013). Our data showed that the presence of aquatic plants decreased CO_2 and CH_4 emissions, albeit not significantly (Table 1). The effects of aquatic vegetation on GHG dynamics can be variable: Aquatic plants not only provide organic substrates for CO_2 / CH_4 production and vascular tissues for transport (Sorrell and Boon, 1994; van der Nat and Middelburg, 1998), but they photosynthetically absorb CO_2 and release O_2 into the rhizosphere to promote oxidation (Calhoun and King, 1997; Fritz et al., 2011; Laanbroek et al., 2010). The effects of aquatic plants can be complex and variable, which may depend on the plant species and their positions in the systems.

GHG emissions varied significantly based on the size (depth and area) of the aquaculture system (Table 1). Smaller systems meant higher concentrations of organic and nutrients (Holgerson and Raymond, 2016; Natchimuthu et al., 2017) and higher biological density, leading to higher respiratory CO_2 output per unit area. Furthermore, a smaller surface area also limited oxygen dissolution from air. At the same time, a shallower depth helps to reduce the oxidation probability as sedimentary CH_4 travels through the water column, thereby increasing its emission to air (Herbeck et al., 2013; Natchimuthu et al., 2014). Under the combined effect of these factors, high levels of CO_2 and CH_4 emissions were observed in small-scale aquaculture systems (Table 1).

Aquaculture systems from reclaimed coastal marshes and mudflats tend to have higher salinity than inland systems. Our data showed that higher salinity significantly decreased CH_4 flux (Table 1) because the presence of SO_4^{2-} from seawater would allow sulfate reducers to outcompete methanogens (Wilson et al., 2015 Poffenbarger et al., 2011; Yang et al., 2018). Another interesting observation is the much lower CO_2 flux (including negative values) at the higher salinity (Table 1). Reclaimed coastal aquaculture systems are usually filled with saltwater drawn from nearby estuaries, which exposes terrestrial microbes to salinity stress and decreases their metabolism (Pivničková et al., 2010). Estuarine water also may contain higher background abundance of algae that could drawdown CO_2 via photosynthesis. As a management strategy to decrease GHG emission, water salinity can be raised artificially for aquatic products (e.g., *Litopenaeus Vannamei*) with a wide salinity tolerance.

Management method during the non-farming period varied among the farmers, from having minimal treatment (practice I), to drainage and exposure (II), to drainage, exposure and dredging (III). Most of the unconsumed feeds and organic wastes tend to accumulate in the sediment (Yang et al., 2022) which, if left untreated, could lead to high CH_4 production in the subsequent farming period. Exposure and desilting after drainage removes the organic deposition, disrupts the sediment methanogen community and reoxygenates the sediment, all leading to a much lower CH_4 emission (Tong et al., 2021), as supported by our findings (Table 1).

4.4. GHG emissions from aquaculture systems in China

The rapid increase in global aquaculture has raised concerns about its GHG emissions (MacLeod et al., 2020). The total aquaculture area in China has doubled while aquaculture production has increased by 41 times in the past four decades (Wang et al., 2019), showing the rapid expansion and intensification of the sector. However, China's aquaculture sector is dominated by small-hold operations in rural areas without proper monitoring, creating a glaring data gap in assessing their environmental impacts. A very recent paper used conversion factors to estimate China's aquaculture GHG emissions from the operation (e.g., use of feeds, fertilizer and energy) and biomass harvest (Xu et al., 2022). Such an approach relies on questionable conversion factors and ignores the *in situ* biogeochemical conditions that regulate the conversion of excess carbon to CO_2 vs. CH_4 (Yang et al., 2020a). More importantly, that approach will not reveal negative CO_2 flux (indicating net absorption), such as what we found in CWRS (Fig. 2a) but which is important for proper auditing of the climate impact of aquaculture. In our study, we compiled GHG emission data that were measured directly or derived from empirical measurements, which showed large differences across the different aquaculture systems (Fig. 2; Table S9). The 25-fold variation in mean CO_2 flux and 9-fold variation in mean CH_4 flux highlight the importance to consider system-specific differences when assessing aquaculture-related GHG emissions.

Our calculations showed that aquaculture systems contributed a non-trivial portion of China's CH_4 emission. The combined emission, 181.66 Tg CO_2-eq yr^{-1}, was equivalent to approximately 7.51% of the 2010-2016 national terrestrial biosphere carbon sink (-2418.78 ± 1906.67 Tg CO_2-eq yr^{-1}) (Wang et al., 2020). Based on our estimation, while aquaculture systems in China accounted for only 0.22–0.56 % of the area of global terrestrial aquatic ecosystems (12.81×10^6–32.91×10^6 km^2) (e.g., lakes, reservoirs, rivers, ponds and wetlands) (Deemer et al., 2016; Holgerson and

Raymond 2016; Melton et al. 2013; Raymond et al. 2013), they contributed 2.84% of the total CH_4 emission (Bastviken et al., 2011). This highlights the disproportionate significance of China's growing aquaculture sector in driving climate warming.

We also found large geographical variations in aquaculture-GHG emissions across China. Perhaps not surprisingly the most intense emissions came from provinces in the middle and lower reaches along the Yangtze River (Fig. 6). The spatial distribution of combined emission we obtained largely agreed with the finding by Xu et al. (2022), in that GHG emissions were concentrated in the coastal provinces and southeastern region, whereas the far north and northwestern regions had negligible emissions because the local climate was not favorable for aquaculture, with the caveat that data for those regions remain very scarce. There are also subtle differences between the two studies. For example, GHG contributions of the land-locked provinces of Sichuan and Hunan ranked more highly in our estimates than in their study. This difference can be partly attributed to the different approach we used to estimate the emissions (empirical, in situ measurements) and our considering system-specific differences in emissions (cf. Xu et al., 2022).

5. Conclusions

By analyzing the literature data, we showed that aquaculture systems in China were a net source of CO_2 and CH_4. There were substantial variations in GHG emissions based on aquaculture system type, environmental conditions, farmed species and management practices. The combined carbon emission was enough to offset ~7% of the national terrestrial carbon burial, and the aquaculture systems had disproportionate significance in terms of CH_4 emission. We further estimated that across China, most of the aquaculture-GHG emissions were concentrated along the major rivers and the coastal region, although data for the north and northwestern regions remain very limited. With the continuous expansion and increasing intensification of the aquaculture sector in China, the study highlights its potential climate impact and the need for more rigorous monitoring and mitigation strategy for the sector.

Declaration of interest

None

Acknowledgment

This research was financially supported by the National Natural Science Foundation of China (Grant No. 41801070, 41671088, and 41730643), the Natural Science Foundation of Fujian Province, China (Grant No. 2020J01136, and 2018J01737), and Minjiang Scholar Programme.

References

Aimé, J., Allenbach M., Bourgeois C., Léopold, A., Jacotot, A., Vinh, T.V., Nho, N.T., Patrona, L.D., Marchand, C., 2018. Variability of CO_2 emissions during the rearing cycle of a semi-intensive shrimp farm in a mangrove coastal zone (New Caledonia). Mar. Polluti. Bull. 129, 194. https://doi.org/10.1016/j.marpolbul.2018.02.025.

Aufdenkampe, A.K., Mayorga, E., Raymond, P.A., Melack, J.M., Doney, S.C., Alin, S.R., Aalto, R.E., Yoo, K., 2011. Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. Front. Ecol. Environ. 9, 53−60.

https://doi.org/10.1890/100014.

Bastviken, D., Tranvik, L.J., Downing, J.A., Crill, P.M., Enrich-Prast, A., 2011. Freshwater methane emissions offset the continental carbon sink. Science 331, 50. https://doi.org/10.1126/science.1196808.

Bhattacharyya, P., Sinhababu, D.P., Roy, K.S., Dash, P.K., Sahu, P.K., Dandapat, R., Neogi, S., Mohanty, S., 2013. Effect of fish species on methane and nitrous oxide emission in relation to soil C, N pools and enzymatic activities in rainfed shallow lowland rice-fish farming system. Agr. Ecosyst. Environ. 176, 53–62. http://dx.doi.org/10.1016/j.agee.2013.05.015.

Bižić, M., Klintzsch, T., Ionescu, D., Hindiyeh, M.Y., Günthel, M., Muro-Pastor, A.M., Eckert, W., Urich, T., Keppler, F., Grossart, H-P., 2020. Aquatic and terrestrial cyanobacteria produce methane. Sci. Adv. 6, eaax5343. https://doi.org/10.1126/sciadv.aax5343.

Bogard, M.J., del Giorgio, P.A., Boutet, L., Chaves, M.C.G., Prairie, Y.T., Merante, A., Derry, A.M., 2014. Oxic water column methanogenesis as a major component of aquatic CH_4 fluxes. Nat. Commun. 5, 5350. https://doi.org/10.1038/ncomms6350.

Calhoun, A., King, G.M., 1997. Regulation of root-associated methanotrophy by oxygen availability in the rhizosphere of two aquatic macrophytes. Appl. Environ. Microb. 63, 3051−3058. https://doi.org/10.1089/oli.1.1997.7.439.

Chanda, A., Das, S., Bhattacharyya, S., Das, I., Giri, S., Mukhopadhyay, A., Samanta, S., Dutta, D., Akhand, A., Choudhury, S.B., Hazra, S., 2019. CO_2 fluxes from aquaculture ponds of a tropical wetland: Potential of multiple lime treatment in reduction of CO_2 emission. Sci. Total Environ. 655, 1321–1333. https://doi.org/10.1016/j.scitotenv.2018.11.332.

Chatvijitkul, S., Boyd, C.E., Davis, D.A., McNevin, A.A., 2017. Pollution potential indicators for feed-based fish and shrimp culture. Aquaculture 477, 43–49. https://doi.org/10.1016/j.aquaculture.2017.04.034.

China Fisheries Yearbook 2019 (Chinese Agriculture Press, 2020).

Chen, Y., Dong, S.L., Wang, F., Gao, Q.F., Tian, X.L., 2016. Carbon dioxide and methane fluxes from feeding and no-feeding mariculture ponds. Environ. Pollut. 212, 489–497. https://doi.org/10.1016/j.envpol.2016.02.039.

Chen, S., Wang, D. Q., Ding, Y., Yu, Z. J., Chen, Z. L., 2021. Ebullition controls on CH_4 emissions in an urban, eutrophic river: a potential time-scale bias in determining the aquatic CH_4 flux. Environ. Sci. Technol. 55, 7287–7298. https://doi.org/10.1021/acs.est.1c00114.

Deemer, B.R., Harrison, J.A., Li, S.Y., Beaulieu, J.J., Delsontro, T., Barros, N., Bezerra-neto, J.F., Powers, S.M., Santos, M.A.D., Vonk, J.A., 2016. Greenhouse gas emissions from reservoir water surfaces: a new global synthesis. Bioscience 66, 949–964. http://dx.doi.org/10.1093/biosci/biw117.

Delsontro, T., Boutet, L., St-Pierre, A., del Giorgio, P.A., Prairie, Y.T., 2016. Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity. Limnol. Oceanogr. 61, S62–S77. https://doi.org/10.1002/lno.10335.

Ding, W.X., Cai, Z.C., Tsurata, H., 2005. Plant species effects on methane emissions from freshwater marshes. Atmos. Environ. 39, 3199–3207. https://doi.org/10.1016/j.atmosenv.2005.02.022.

Ding, W.X., Yuan, J.J., Liu, D.Y., Chen, Z.M., 2020. CH_4 and N_2O emissions from freshwater aquaculture. J. Agro-Environ. Sci. 2020, 39, 749–761 (in Chinese). https://doi.org/10.11654/jaes.2019-1388.

Downing, J.A., 2010. Emerging global role of small lakes and ponds: little things mean a lot. Limnetica 29, 9–23. https://doi.org/10.1899/09-028.1.

FAO. 2018. The State of World Fisheries and Aquaculture. Food and Agricultural Organization of the United Nations, Rome, Italy.

Fang, J.Y., Yu, G.R., Liu, L.L., Hu, S.J., Chapin, F.S., 2018. Climate change, human impacts, and carbon sequestration in China INTRODUCTION. P. Natl. Acad. Sci. USA. 115, 4015–4020. https://doi.org/10.1073/pnas.1700304115.

Fang, X.T., Wu, C., Zhang, T.R., Zheng, F.W., Zhao, J.T., Wu, S., Barthel, M., Six, J., Zou, J.W., Liu, S.W., 2022. Ebullitive CH_4 flux and its mitigation potential by aeration in freshwater aquaculture: Measurements and global data synthesis. Agr. Ecosyst. Environ. 335, 108016. https://doi.org/10.1016/j.agee.2022.108016.

Fritz, C., Pancotto, V.A., Elzenga, J.T.M., Visser, E.J.W., Grootjans, A.P., Pol, A., Iturraspe, R., Roelofs, J.G.M., Smolders, A.J.P., 2011. Zero methane emission bogs: Extreme rhizosphere oxygenation by cushion plants in Patagonia. New Phytol. 190, 398–408. https://doi.org/10.1111/j.1469‐8137.2010.03604.x.

Günthel, M., Donis, D., Kirillin, G., Ionescu, D., Bizic, M., McGinnis, D.F., Grossart, H.-P., Tang, K.W., 2019. Contribution of oxic methane production to surface methane emission in lakes and its global importance. Nat. commun. 10, 1–10. https://doi.org/ 10.1038/s41467-019-13320-0.

Günthel, M., Klawonn, I., Woodhouse, J., Bižić, M., Ionescu, D., Ganzert, L., Kümmel, S., Nijenhuis, I., Zoccarato, L., Grossart, H.-P., Tang, K.W., 2020. Photosynthesis-driven methane production in oxic lake water as an important contributor to methane emission. Limnol. Oceanogr. 65, 2853–2865. https://doi.org/10.1002/lno.11557.

Herbeck, L.S., Unger, D., Wu, Y., Jennerjahn, T.C., 2013. Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China. Cont. Shelf Res. 57, 92–104. https://doi.org/10.1016/j.csr.2012.05.006.

Holgerson, M.A., 2015. Drivers of carbon dioxide and methane supersaturation in small, temporary ponds. Biogeochemistry 124, 305–318. https://doi.org/ 10.1007/s10533-015-0099-y.

Holgerson, M.A., Raymond, P.A., 2016. Large contribution to inland water CO_2 and CH_4 emissions from very small ponds. Nat. Geosci. 9, 222–U150. https://doi.org/10.1038/ngeo2654.

Hu, B.B., Xu, X.F., Zhang, J.F., Wang, T.L., Meng, W.Q., Wang, D.Q., 2020. Diurnal variations of greenhouse gases emissions from reclamation mariculture ponds. Estuar. Coast. Shelf S. 237, 106677. https://doi.org/10.1016/j.ecss.2020.106677.

Hu, Z.Q., Wu, S., Ji, C., Zou, J.W., Zhou, Q.S., Liu, S.W., 2016. A comparison of methane emissions following rice paddies conversion to crab-fish farming wetlands in southeast China. Environ. Sci. Pollut. Res. 23, 1505–1515. https://doi.org/10.1007/s11356-015-5383-9.

IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. In Press.

Kauffman, J.B., Bernardino, A.F., Ferreira, T.O., Bolton, N.W., Gomes, L.E.D., Nobrega, G.N., 2018. Shrimp ponds lead to massive loss of soil carbon and greenhouse gas emissions in northeastern Brazilian mangroves. Ecol. Evol. 8, 5530–5540. https://doi.org/10.1002/ece3.4079.

Kosten, S., Almeida, R.M., Barbosa, I., Mendona, R., Barros, N., 2020. Better assessments of greenhouse gas emissions from global fish ponds needed to adequately evaluate aquaculture footprint. Sci. Total Environ. 748, 141247. https://doi.org/10.1016/j.scitotenv.2020.141247.

Klintzsch, T., Langer, G., Nehrke, G., Wieland, A., Lenhart, K., Keppler, F., 2019. Methane production by three widespread marine phytoplankton species: Release rates, precursor compounds, and relevance for the environment. Biogeosciences. 16, 4129–4144. https://doi.org/10.5194/bg-16-4129-2019-245.

Laanbroek, H.J., 2010. Methane emission from natural wetlands: interplay between emergent macrophytes and soil microbial processes. A mini-review. Annals of Botany, 105, 141–153. https://doi.org/10.1093/aob/mcp2010.

Langeveld, J., Bouwman, A.F., Van Hoek, W.J., Vilmin, L., Beusen, A.H., Mogollón, J.M., Middelburg, J. J., 2019. Global data-base and model on dissolved carbon in soil solution. Biogeosci. Discuss. 1–35. https://doi.org/10.5194/bg-2019-238.

Laurion, I., Vincent, W.F., MacIntyre, S., Retamal, L., Dupont, C., Francus, P., Pienitz, R., 2010. Variability in greenhouse gas emissions from permafrost thaw ponds. Limnol. Oceanogr. 55, 115–133. https://doi.org/10.4319/lo.2010.55.1.0115.

Li, S., Bush, R.T., Santos, I.R., Zhang, Q.F., Song, K.S., Mao, R., Wen, Z.D., Lu, X.X., 2018. Large greenhouse gases emissions from China’s lakes and reservoirs. Water Res. 147, 13−24. https://doi.org/10.1016/j.watres.2018.09.053.

Lin, H., Zhou, G., Li, X.G., Zhou, J., Zhang, T.Q., Wang, G.M., 2013. Greenhouse gases emissions from pond culture ecosystem of Chinese mitten crab and their comprehensive global warming potentials in summer. Journal of Fisheries of China, 37, 417–424. (in Chinese) https://doi.org/10.3724/SP.J.1231.2013.38282.

Liu, S.W., Hu, Z.Q., Wu, S., Li, S.Q., Li, Z.F., Zou, J.W., 2016. Methane and nitrous oxide emissions reduced following conversion of rice paddies to inland crab-fish aquaculture in Southeast China. Environ. Sci. Technol. 50, 633–642. https://doi.org/10.1021/acs.est.5b04343.

Ma, Y.C., Sun, L.Y., Liu, C.Y., Yang, X.Y., Zhou, W., Yang, B, Schwenke, G., Liu, D.L., 2018. A comparison of methane and nitrous oxide emissions from inland mixed-fish and crab aquaculture ponds. Sci. Total Environ. 637–638, 517–523. https://doi.org/10.1016/j.scitotenv.2018.05.040.

MacLeod, M.J., Hasan, M.R., Robb, D.H.F., Mamun-Ur-Rashid, M., 2020. Quantifying greenhouse gas emissions from global aquaculture. Sci. Rep. 10, 11679. https://doi.org/10.1038/s41598-020-68231-8.

Maher, D.T., Drexl, M., Tait, D.R., Johnston, S.G., Jeffrey, L.C., 2019. IAMES: an inexpensive, automated methane ebullition sensor. Environ. Sci. Technol 53, 6420 – 6426. https://doi.org/10.1021/acs.est.9b01881.

Mermillod-Blondin, F., Rosenberg, R., 2006. Ecosystem engineering: the impact of bioturbation on biogeochemical processes in marine and freshwater benthic habitats. Aquat. Sci. 68, 434 – 442. https://doi.org/10.1007/s00027-006-0858-x.

Melton, J.R., Wania, R., Hodson, E.L., Poulter, B., Ringeval, B., Spahni, R., Bohn, T., Avis, C.A., Beerling, D.J., Chen, G., 2013. Present state of global wetland extent and wetland methane modelling: Conclusions from a model inter-comparison project (WETCHIMP). Biogeosciences 10, 753–788. https://doi.org/10.5194/bg-10-753-2013.

Naskar, S., Pailan, G.H., Datta, S., Sawant, P.B., Bharti, V.S., 2020. Effect of different organic manures and salinity levels on greenhouse gas emission and growth of common carp in aquaculture systems. Aquac. Res. 52, 1–10. http://dx.doi.org/10.1111/are.15041.

Natchimuthu, S., Sundgren, I., Gålfalk, M., Klemedtsson, L., Bastviken, D., 2017. Spatiotem-poral variability of lake $p\mathrm{CO}_2$ and CO_2 fluxes in a hemiboreal catchment. J. Geophys. Res. Biogeosci. 122, 30–49. https://doi.org/10.1002/2016JG003449.

Natchimuthu, S., Selvam, B.P., Bastviken, D., 2014. Influence of weather variables on methane and carbon dioxide flux from a shallow pond. Biogeochemistry 119, 403–413. https://doi.org/10.1007/s10533-014-9976-z.

Neubauer, S. C., Megonigal, J. P., 2015. Moving beyond global warming potentials to quantify the climatic role of ecosystems. Ecosystems 18 1000–1013. https://doi.org/10.1007/s10021-015-9879-4.

Olsson, L., Ye, S., Yu, X., Wei, M., Krauss, K.W., Brix, H., 2015. Factors influencing CO_2 and CH_4 emissions from coastal wetlands in the Liaohe Delta, Northeast China. Biogeosciences 12, 4965–4977. https://doi.org/10.5194/bg-12-4965-2015.

Pacheco, F.S., Soares, M.C.S., Assireu, A.T., Curtarelli, M.P., Roland, F., Abril, G., 2015. The effects of river inflow and retention time on the spatial heterogeneity of chlorophyll and water-air CO_2 fluxes in a tropical hydropower reservoir. Biogeosciences 12, 147–162. https://doi.org/10.5194/bg-12-147-2015.

Peacock, M., Audet, J., Bastviken, D., Cook, S., Futter, M.N., 2021. Small artificial waterbodies are widespread and persistent emitters of methane and carbon dioxide. Glob. Change Biol. 27, 5109–5123. https://doi.org/10.1111/gcb.15762.

Peacock, M., Audet, J., Jordan, S., Smeds, J., Wallin, M.B., 2019. Greenhouse gas emissions from urban ponds are driven by nutrient status and hydrology. Ecosphere 10, e02643. https://doi.org/10.1002/ecs2.2643.

Pivničková, B., Rejmánková, E., Snyder, J. M., Šantrůčková, H., 2010. Heterotrophic microbial activities and nutritional status of microbial communities in tropical marsh sediments of different salinities: the effects of phosphorus addition and plant species. Plant Soil 336, 49–63. https://doi.org/10.1007/s11104-010-0439-6.

Poffenbarger, H.J., Needelman, B.A., Megonigal, J.P., 2011. Salinity influence on methane emissions from tidal marshes. Wetlands 31, 831–842. https://doi.org/10.1007/s13157-011-0197-0.

Pu, Y.N., Zhang, M., Jia, L., Zhang, Z., Xiao, W., Liu, S.D., Zhao, J.Y., Xie, Y.H., Lee, X.H., 2022. Methane emission of a lake aquaculture farm and its response to ecological restoration. Agr. Ecosyst. Environ. 330, 107883. https://doi.org/10.1016/j.agee.2022.107883.

Raymond, P.A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Dürr, H., Meybeck, M., Ciais, P., Guth, P., 2013. Global carbon dioxide emissions from inland waters. Nature 503, 355–359. https://doi.org/10.1038/nature12760.

Rutegwa, M., Gebauer, R., Veselý, L., Regenda, J., Strunecký, O., Hejzlar, J., Drozd, B., 2019. Diffusive methane emissions from temperate semi-intensive carp ponds. Aquacult. Env. Interac. 11, 19–30. https://doi.org/10.3354/aei00296.

Scofield, V., Melack, J.M., Barbosa, P.M., Amaral, J.H.F., Forsberg, B.R., Farjalla, V.F., 2016. Carbon dioxide outgassing from amazonian aquatic ecosystems in the negro river basin. Biogeochemistry 129, 77–91. https://doi.org/10.1007/s10533-016-0220-x.

Sejr, M.K., Krause-Jensen, D., Dalsgaard, T., Ruiz-Halpern, S., Duarte, C.M., Middelboe, M., Rysgaard, S., 2014. Seasonal dynamics of autotrophic and heterotrophic plankton metabolism and pCO_2 in a subarctic Greenland fjord. Limnol. Oceanogr. 59, 1764–1778. https://doi.org/10.4319/lo.2014.59.5.1764.

Sidik, F., Lovelock, C.E., 2013. CO_2 Efflux from Shrimp Ponds in Indonesia. Plos One 8, e66329. https://doi.org/10.1371/journal.pone.0066329.

Sorrell, B.K., Boon P.I., 1994. Convective gas flow in Eleocharis sphacelata R. Br.:

Methane transport and release from wetlands. Aquat. Bot. 47, 197–212. https://doi.org/10.1016/0304-3770(94)90053-1.

Soumis, N., Duchemin, E., Canuel, R., Lucotte, M., 2004. Greenhouse gas emissions from reservoirs of the western United States. Glob. Biogeochem. Cycles 18, 1–11. https://doi.org/10.1029/2003GB002197.

Sun, Z.C., Guo, Y., Li, C.F., Cao, C.G., Yuan, P.L., Zou, F.L., Wang, J.H., Jia, P.G., Wang, J.P., 2019. Effects of straw returning and feeding on greenhouse gas emissions from integrated rice-crayfish farming in Jianghan Plain, China. Environ. Sci. Pollut. R. 26, 11710–11718. https://doi.org/10.1007/s11356-019-04572-w.

Tan, L.S., Ge, Z.M., Zhou, X.H., Li, S.H., Li, X.Z., Tang, J.W., 2019. Conversion of coastal wetlands, riparian wetlands, and peatlands increases greenhouse gas emissions: A global meta-analysis. Glob. Change Biol. 26, 1638–1653. https://doi.org/10.1111/gcb.14933.

Tang, K.W., McGinnis, D.F., Frindte, K., Bruchert, V., Grossart, H.P., 2014. Paradox reconsidered: Methane oversaturation in well-oxygenated lake waters. Limnol. Oceanogr. 59, 275–284. https://doi.org/10.4319/lo.2014.59.1.0275.

Tang, K.W., McGinnis, D.F., Ionescu, D., Grossart, H.P., 2016. Methane production in oxic lake waters potentially increases aquatic methane flux to air. Environ. Sci. Tech. Let. 3, 227–233. https://doi.org/10.1021/acs.estlett.6b00150.

Tong, C., Bastviken, D., Tang, K.W., Yang, P., Yang, H., Zhang, Y.F., Guo, Q.Q., Lai, D.Y.F., 2021. Annual CO_2 and CH_4 fluxes in coastal earthen ponds with *Litopenaeus vannamei* in southeastern China. Aquaculture 545, 737229. https://doi.org/10.1016/j.aquaculture.2021.737229.

Van Bergen, T., Barros, N., Mendonca, R., Aben, R., 2019. Seasonal and diel variation in greenhouse gas emissions from an urban pond and its major drivers. Limnol. Oceanogr. 64, 2129–2139. https://doi.org/10.1002/lno.11173.

van der Nat, F.J.W.A., Middelburg, J.J., 1998. Seasonal variation in methane oxidation by the rhizosphere of Phragmites australis and Scirpus lacustris. Aquat. Bot. 61, 95–110. https://doi.org/10.1016/S0304-3770(98)00072-2.

Wang, J., Feng, L., Palmer, P.I., Liu, Y., Fang, S., Bsch, H., O'Dell, C.W., Tang, X.P., Yang, D.X., Liu, L.X., Xia, C.Z., 2020. Large Chinese land carbon sink estimated from atmospheric carbon dioxide data. Nature 586, 720–723. https://doi.org/10.1038/s41586-020-2849-9.

Wang, P.P., Ji, J.Y., Zhang, Y., 2019. Aquaculture extension system in China: Development, challenges, and prospects. Aquacult. Rep. 17, 100339. https://doi.org/10.1016/j.aqrep.2020.100339.

Wilson, B.J., Mortazavi, B., Kiene, R.P., 2015. Spatial and temporal variability in carbon dioxide and methane exchange at three coastal marshes along a salinity gradient in a northern Gulf of Mexico estuary. Biogeochemistry 123, 329–347. https://doi.org/10.1007/s10533-015-0085-4.

World Meteorlogical Organization, 2021. WMO Greenhouse Gas Bulletin No.17: The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2020. https://library.wmo.int/doc_num.php?explnum_id=10931.pdf.

Wu, S., Hu, Z.Q., Hu, T., Chen, J., Yu, K., Zou, J.W., Liu, S.W., 2018. Annual methane and nitrous oxide emissions from rice paddies and inland fish aquaculture wetlands in southeast China. Atmos. Environ. 175, 135–144. https://doi.org/10.1016/j.atmosenv.2017.12.008.

Xiao, Q.T., Zhang, M., Hu, Z.H., Gao, Y.Q., Hu, C., Liu, C., Zhang, Z., Zhao, J., Xiao, W., 2017. Spatial variations of methane emission in a large shallow eutrophic lake in subtropical climate. J. Geophys. Res.-Biogeo. 122, 1597–1614. https://doi.org/10.1002/2017JG003805.

Xu, X.Y., Zhang, M.M., Peng, C.L., Si, G.H., Zhou, J.X., Xie, Y.Y., Yuan, J.F., 2017. Effect of rice-crayfish co-culture on greenhouse gases emission in straw-puddled paddy fields. Chinese Journal of Eco-Agriculture 25, 1591–1603 (In Chinese). https://doi.org/10.13930/j.cnki.cjea.170280.

Xu, G.J., Su, G.H., Zhao, K.H., Xu, X.Q., Li, X.Q., H, Q., Xue, Y., Xu, J., 2022. Current status of greenhouse gas emissions from aquaculture in China. Water Biol. Secur. 10, 100041. https://doi.org/10.1016/j.watbs.2022.100041.

Yang, H., Andersen, T., Dörsch, P., Tominaga, K., Thrane, J.E., Hessen, D.O. 2015, Greenhouse gas metabolism in Nordic boreal lakes. Biogeochemistry 126, 211–225. https://doi.org/10.1007/s10533-015-0154-8.

Yang, P., Zhang, Y.F., Lai, D.Y.F., Tan, L.S., Jin, B.S., Tong, C., 2018. Fluxes of carbon dioxide and methane across the water-atmosphere interface of aquaculture shrimp ponds in two subtropical estuaries: the effect of temperature, substrate, salinity and nitrate. Sci. Total Environ. 635, 1025–1035. https://doi.org/10.1016/j.scitotenv.2018.04.102.

Yang, P., Zhang, Y.F., Yang, H., Guo, Q.Q., Lai, D.Y.F., Zhao, G.H., Li, L., Tong, C., 2020a. Ebullition was a major pathway of methane emissions from the aquaculture ponds in southeast China. Water Res. 184, 116176. https://doi.org/10.1016/j.watres.2020.116176.

Yang, P., Yang, H., Lai, D. Y. F., Guo, Q.Q., Zhang, Y.F., Tong, C., Xu, C.B., Li, X.F., 2020b. Large contribution of non-aquaculture period fluxes to the annual N_2O emissions from aquaculture ponds in Southeast China. J. Hydrol. 582, 124550. https://doi.org/10.1016/j.jhydrol.2020.124550.

Yang, P., Zhang, Y., Yang, H., Zhang, Y.F., Xu, J., Tan, L.S., Tong, C., Lai, D.Y.F., 2019. Large fine-scale spatiotemporal variations of CH_4 diffusive fluxes from shrimp aquaculture ponds affected by organic matter supply and aeration in Southeast China. J. Geophys. Res. - Biogeo. 124, 1290–1307. https://doi.org/10.1029/2019JG005025.

Yang, P., Zhao, G.H., Tong, C., Tang, K.W., Lai, D.Y.F., Li, L., Tang, C., 2021. Assessing nutrient budgets and environmental impacts of coastal land-based aquaculture system in southeastern China. Agr. Ecosyst. Environ. 322, 107662. https://doi.org/10.1016/j.agee.2021.107662.

Yang, P., Tang, K.W., Yang, H., Tong, C., Yang, N., Lai, D.Y.F., Hong, Y., Ruan, M.J., Tan, Y.Y., Zhao, G.H., Li, L., Tang, C., 2022. Insights into the farming-season carbon budget of coastal earthen aquaculture ponds in southeastern China. Agr. Ecosyst. Environ. 335, 107995. https://doi.org/10.1016/j.agee.2022.107995.

Ye, W., Sun, H., Li, Y., Zhang, J., Zhang, M., Gao, Z., Yan, J., Liu, J., Wen, J., Yang, H., Shi, J., Zhao, S., Wu, M., Xu, S., Xu, C., Zhan, L., 2022. Greenhouse gas emissions from fed mollusk mariculture: A case study of a *Sinonovacula constricta* farming system. Agr. Ecosyst. Environ. 336, 108029. https://doi.org/10.1016/j.agee.2022.108029.

Yuan, J.J., Xiang, J., Liu, D.Y., Kang, H.J., He, T.H., Kim, S.H., Lin, Y.X., Freeman, C., Ding, W.X., 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. Nat. Clim. Change 9, 318–322. https://doi.org/10.1038/s41558-019-0425-9.

Yuan, J.J., Liu, D.Y., Xiang, J., He, T.H., Kang, H.J., Ding, W.X., 2021. Methane and nitrous oxide have separated production zones and distinct emission pathways in freshwater aquaculture ponds. Water Res. 190, 116739. https://doi.org/10.1016/j.watres.2020.116739.

Zhang, D.X., Xu, W.J., Wang, F., He, J., Cai, X.R., 2022. Carbon dioxide fluxes from mariculture ponds with swimming crabs and shrimps in eastern China: The effect of adding razor clams. Aquacult. Rep. 22, 100917. https://doi.org/10.1016/j.aqrep.2021.100917.

Zhang, Y.F., Lyu, M., Yang, P., Lai, D.Y.F., Tong, C., Zhao, G.H., Li, L., Zhang, Y.H., Yang, H., 2021. Spatial variations in CO_2 fluxes in a subtropical coastal reservoir of Southeast China were related to urbanization and land-use types. J. Environ. Sci. 109, 206−218. https://doi.org/10.1016/j.jes.2021.04.003.

Zhang, Y.F., Yang, P., Yang, H., Tan, L.S., Guo, Q.Q., Zhao, G.H., Li, L., Gao, Y., Tong, C., 2019. Plot-scale spatiotemporal variations of CO_2 concentration and flux across water-air interfaces at aquaculture shrimp ponds in a subtropical estuary. Environ. Sci. Pollut. R. 26, 5623–5637. https://doi.org/10.1007/s11356-018-3929-3.

Zhu, D., Wu, Y., Chen, H., He, Y., Wu, N., 2016. Intense methane ebullition from open water area of a shallow peatland lake on the eastern Tibetan Plateau. Sci. Total Environ. 542, 57–64. https://doi.org/10.1016/j.scitotenv.2015.10.087.

Table 1

CO_2, CH_4 and combined fluxes (mean ± SE) in aquaculture systems under different management conditions. Management practice in non-farming period: I = almost no drainage; II = drainage + exposure; III = drainage + exposure + desilting. Different superscripts indicate significant differences between management conditions in each of the categories ($P < 0.05$). ND means no data.

Management conditions	GHG flux (g C m^{-2} yr^{-1})		Combined flux (t CO_2-eq ha^{-1} yr^{-1})	Sample size
	CO_2	CH_4		
Aeration				
With	44.36 ± 24.49^{a}	15.80 ± 5.02^{b}	11.11 ± 3.91	*n* = 44
Without	45.91 ± 19.02^{a}	60.78 ± 12.35^{a}	38.15 ± 8.11	*n* = 36
Hydrophyte				
With	29.23 ± 11.05^{a}	30.56 ± 4.57^{a}	19.41 ± 3.15	*n* = 34
Without	51.53 ± 16.95^{a}	42.76 ± 10.16^{a}	27.55 ± 6.72	*n* = 59
Water depth				
< 1.2 m	48.35 ± 24.87^{a}	57.40 ± 13.93^{a}	36.21 ± 9.27	*n* = 33
1.2 m – 2.0 m	34.73 ± 26.66^{a}	41.93 ± 16.96^{ab}	26.43 ± 11.15	*n* = 27
> 2.0 m	23.24 ± 51.36^{a}	16.41 ± 14.52^{b}	10.70 ± 10.60	*n* = 7
Area				
< 1 hectare	78.19 ± 43.73^{a}	87.65 ± 28.86^{a}	55.46 ± 18.92	*n* = 25
> 1 hectare	33.62 ± 19.53^{b}	26.91 ± 7.98^{b}	17.38 ± 5.50	*n* = 28
Water salinity				
Freshwater (< 0.5‰)	111.48 ± 25.42^{a}	39.76 ± 8.19^{a}	27.94 ± 5.85	*n* = 75
Low-salt (0.5–5‰)	37.45 ± 19.66^{ab}	106.34 ± 52.71^{a}	65.18 ± 32.35	*n* = 10
High-salt (> 5‰)	-26.56 ± 22.33^{b}	9.17 ± 5.87^{b}	4.53 ± 4.34	*n* = 15
Management practice in non-farming period				
I	42.24 ± 30.37^{a}	90.84 ± 28.38^{a}	56.05 ± 18.14	*n* = 14
II	37.57 ± 22.31^{a}	114.16 ± 36.98^{a}	69.87 ± 23.01	*n* = 16
III	ND	2.52 ± 0.67^{b}	1.51 ± 0.40	*n* = 12

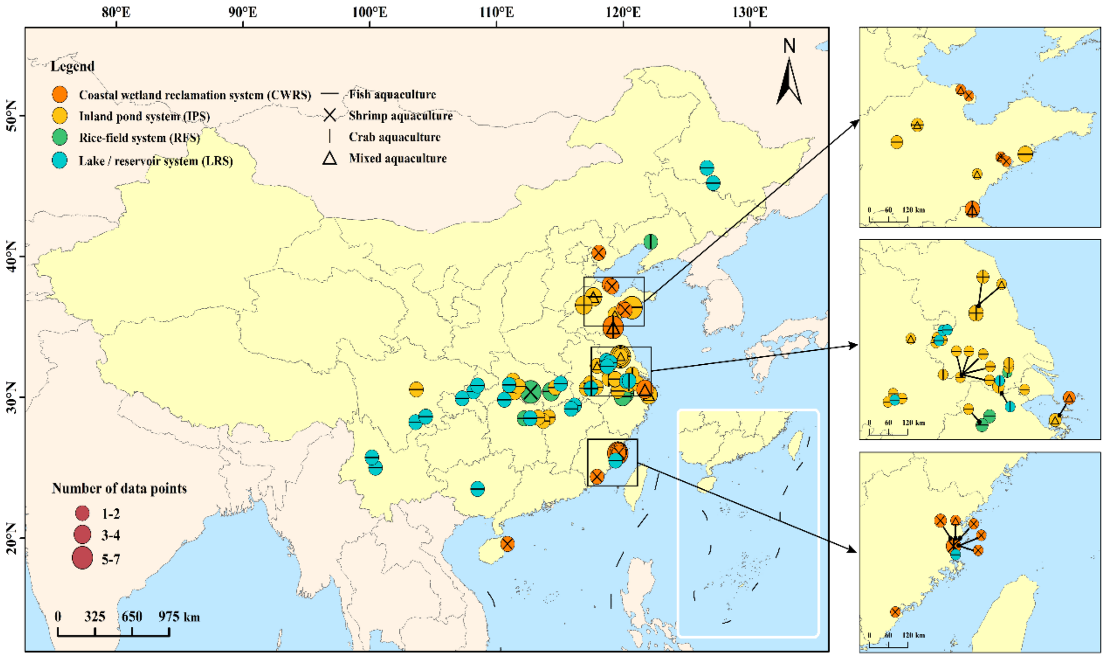

Fig. 1. Distribution of the study sites in China. Coastal wetland reclamation system (CWRS) is created by leveling, embankment and reclamation of the intertidal mudflat along the coast. Inland pond system (IPS) is artificially excavated ponds or natural ponds for extensive or semi-intensive aquaculture. Lake/reservoir system (LRS) is aquaculture operation that includes cage, fence or ecological stocking. Rice-field system (RFS) is artificial ditches in rice paddies. The symbols for aquaculture system are further marked for fish, shrimp, crab or mixed species farming. Details of data source are given in Table S1–S4.

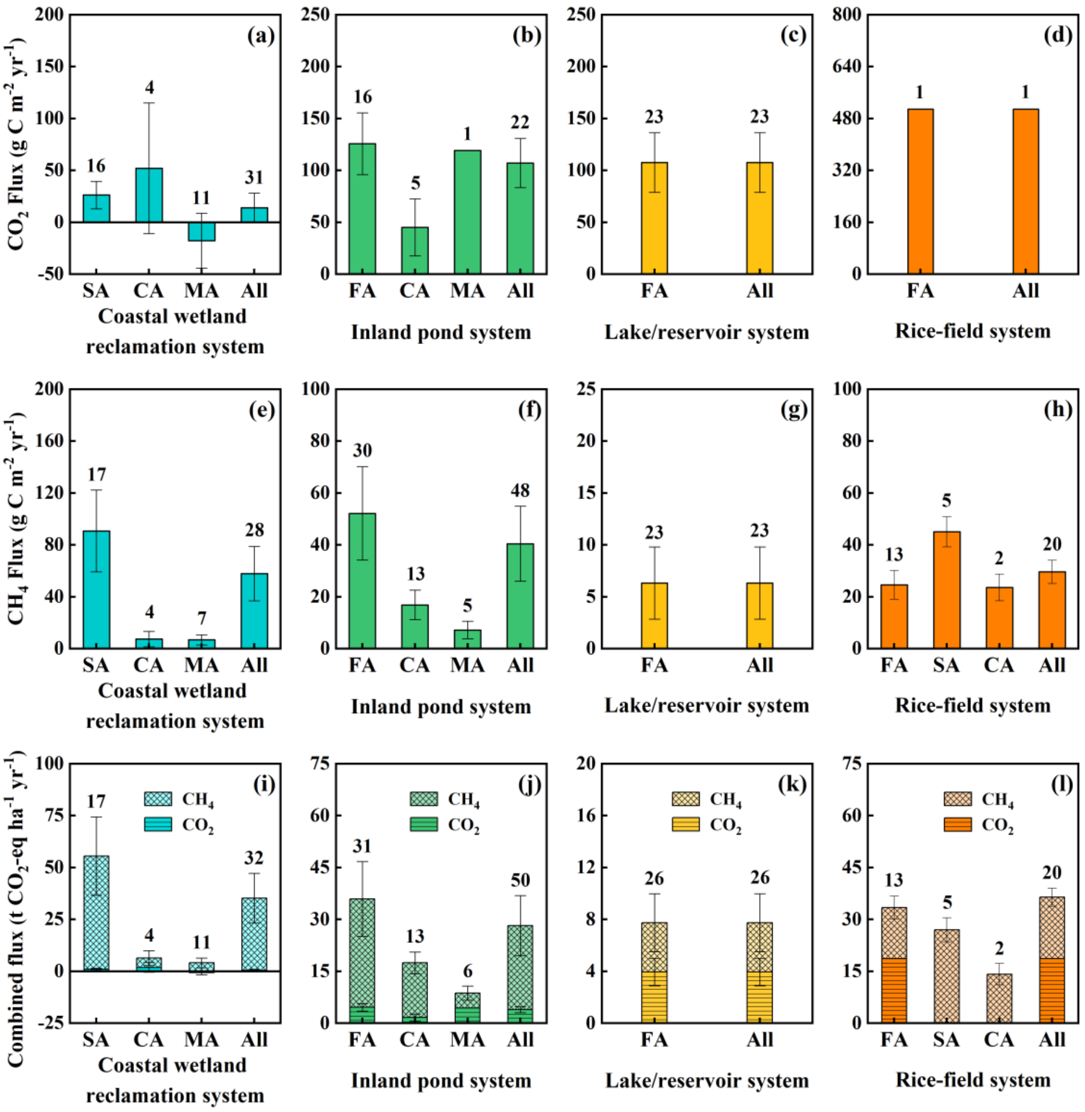

Fig. 2. CO_2, CH_4 and combined fluxes (mean ± SE) in mudflat reclamation system (a, e, i), inland pond system (b, f, j), lake/reservoir system (c, g, k) and rice-field system (d, h, l). Negative values indicate absorption. Numbers above the bars represent sample sizes. SA = shrimp aquaculture; FA = fish aquaculture; CA = crab aquaculture; MA = mixed aquaculture.

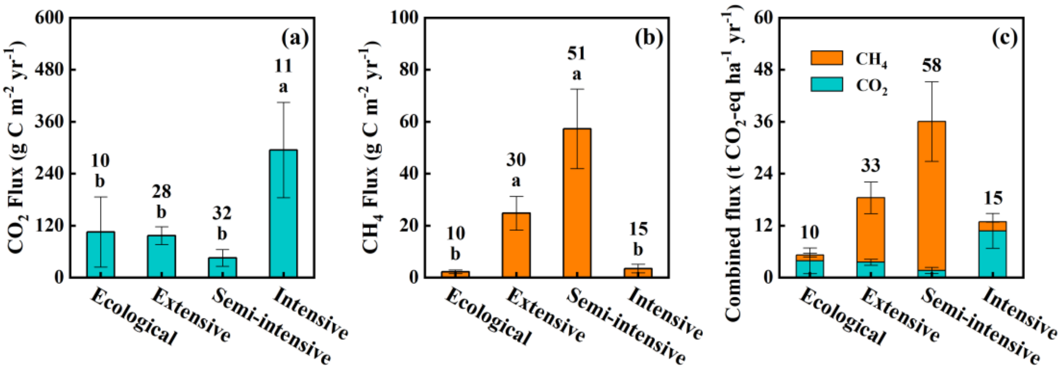

Fig. 3. CO_2, CH_4 and combined fluxes for the different farming intensity levels. Numbers above the bars represent sample sizes. Different letters above the bars indicate significance difference at $P < 0.05$.

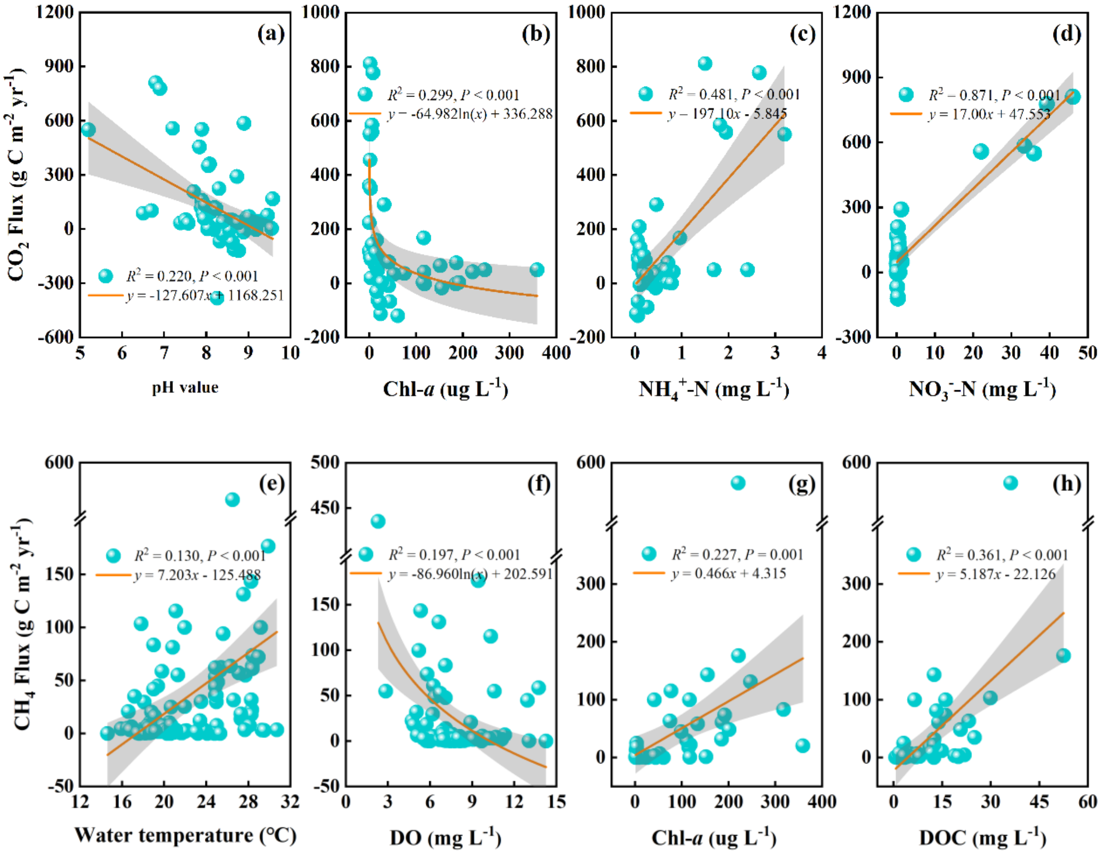

Fig. 4. Relationships between CO2 (a-d) or CH4 flux (e-h) and environmental variables. Red lines represent regressions fitted to the data; gray areas represent 95% confidence intervals.

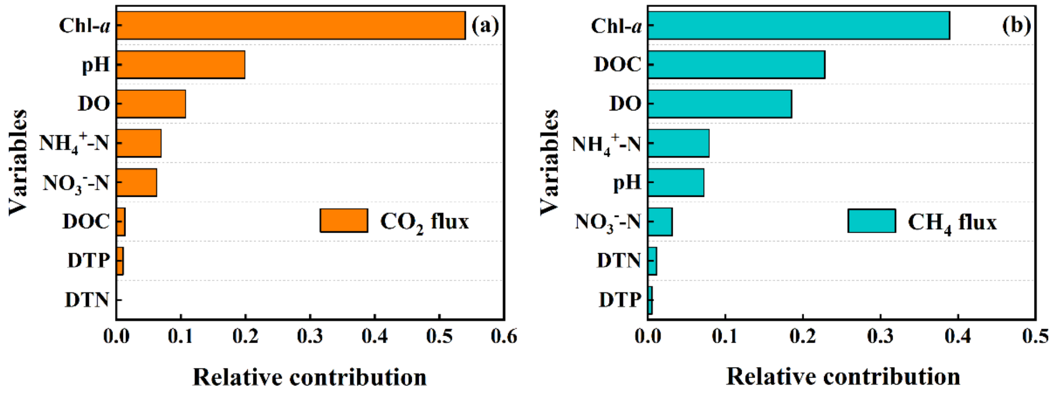

Fig. 5. Relative contributions of environmental variables to variations in (a) CO_2 and (b) CH_4 fluxes in BRT model. Chl-*a* = chlorophyll-*a*; DOC = dissolved organic carbon; DO = dissolved oxygen; NO_3^--N = nitrate nitrogen; NH_4^+-N = ammonium nitrogen; DTP = dissolved total phosphorus; DTN = dissolved total nitrogen.

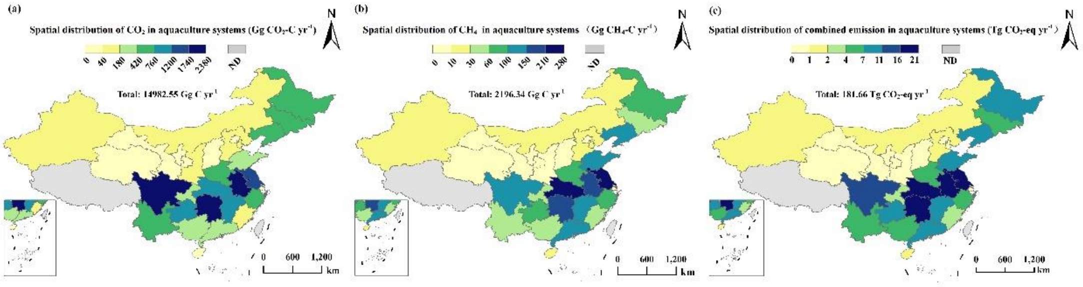

Fig. 6. Spatial distribution of (a) CO_2 emission, (b) CH_4 emission and (c) combined emission in different aquaculture systems across China. ND indicates no data.

Supplementary Material

Assessing carbon greenhouse gas emissions from aquaculture in China based on aquaculture system types, species, environmental conditions and management practices

Yifei Zhang[a,b,c,d], Kam W. Tang[e], Ping Yang[a,b*], Hong Yang[f,g], Chuan Tong[a,b], Changchun Song[c,h*], Lishan Tan[i], Guanghui Zhao[i], Xudong Zhou[j], Dongyao Sun[k]

[a]*School of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China*

[b]*Key Laboratory of Humid Subtropical Eco-geographical Process of Ministry of Education, Fujian Normal University, Fuzhou 350007, China*

[c]*Key Laboratory of Wetland Ecology and Environment, Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences, Changchun 130102, China*

[d]*University of Chinese Academy of Sciences, Beijing 100049, China*

[e]*Department of Biosciences, Swansea University, Swansea SA2 8PP, U.K.*

[f]*College of Environmental Science and Engineering, Fujian Normal University, Fuzhou, 350007, China*

[g]*Department of Geography and Environmental Science, University of Reading, Reading, U.K.*

[h]*School of Hydraulic Engineering, Dalian University of Technology, Dalian 116023, China*

[i]*State Key Laboratory of Estuarine and Coastal Research, Institute of Eco-Chongming, East China Normal University, Shanghai 201199, China*

[j]*School of Hydrology and Water Resources, Nanjing University of Information Science and Technology, Nanjing 210044, China*

[k]*School of Geography Science and Geomatics Engineering, Suzhou University of Science and Technology, Suzhou 215009, China*

***Corresponding authors**:

Ping Yang (yangping528@sina.cn); Changchun Song (songcc@neigae.ac.cn)

Supporting text

The environmental parameters of aquaculture waters were used in the boosted regression tree model (BRT) of CO_2 and CH_4 flux. In this BRT model, learning rate (*lr*) = 0.05, tree complexity (*tc*) = 5, and bag fraction = 0.5 with a Gaussian distribution were set (Elith et al., 2008; Tan et al., 2021). All BRT models were evaluated using percent (%) predictive deviance, where % predictive deviance = (mean total deviance − cross-validated (CV) deviance) / mean total deviance (Kuechle et al., 2019; Wintle et al., 2005).

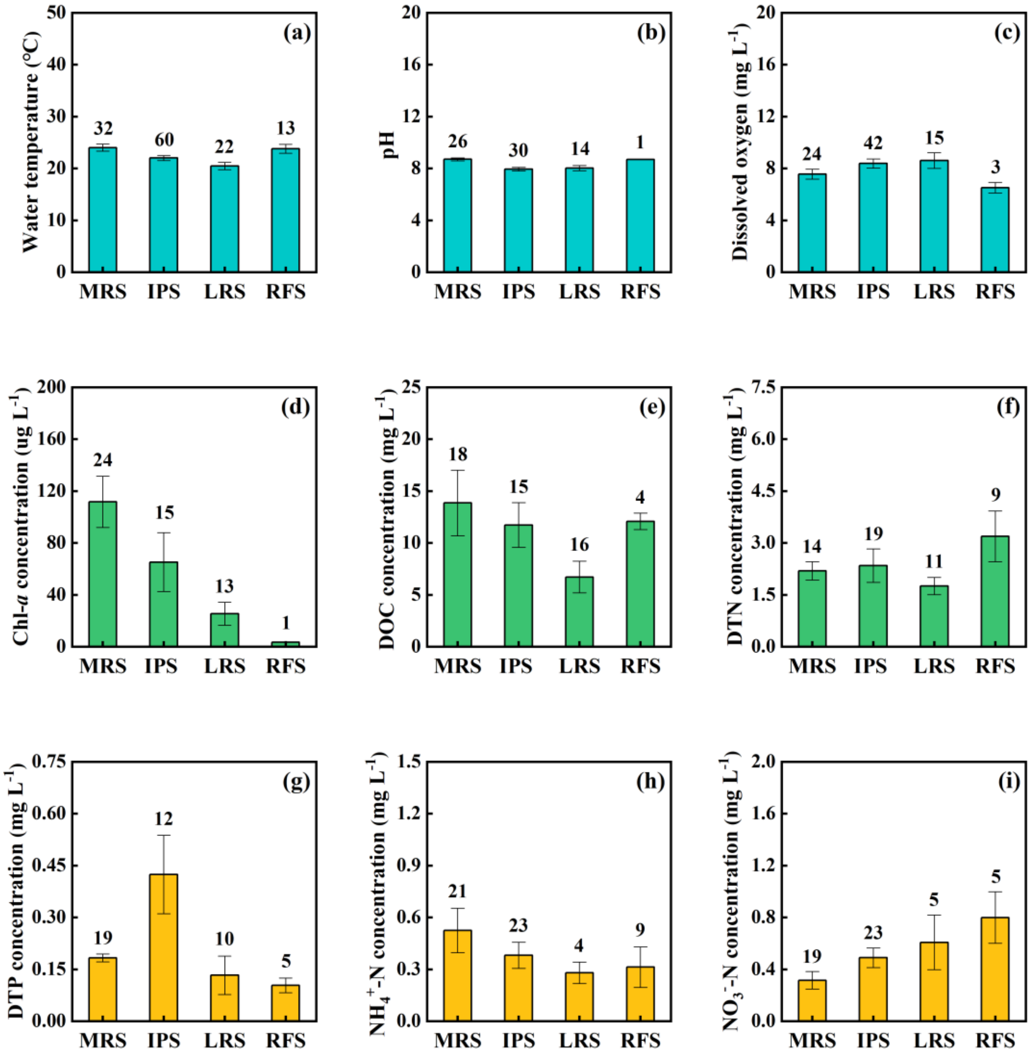

Fig. S1. Environmental variables (mean ± SE) including water temperature, pH, dissolved oxygen, Chlorophyll a (Chl-*a*), dissolved organic carbon (DOC), dissolved total nitrogen (DTN), dissolved total phosphorus (DTP), ammonia nitrogen (NH_4^+-N), and nitrate nitrogen (NO_3^--N) concentrations among the different aquaculture systems: coastal wetland reclamation system (CWRS), inland pond system (IPS), lake/reservoir system (LRS) and rice-field system (RFS). Numbers above the bars are sample sizes.

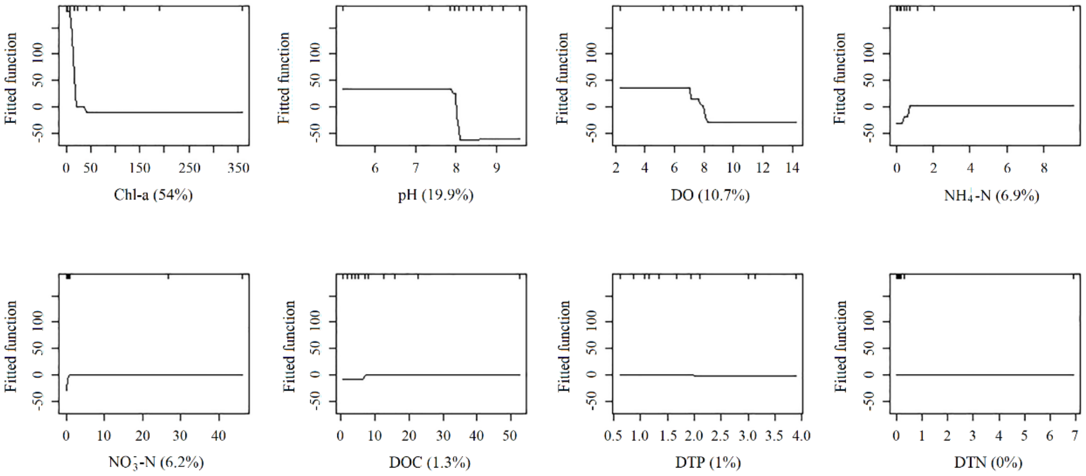

Fig. S2. Fitted functions of BRT model between CO_2 flux and environmental variables.

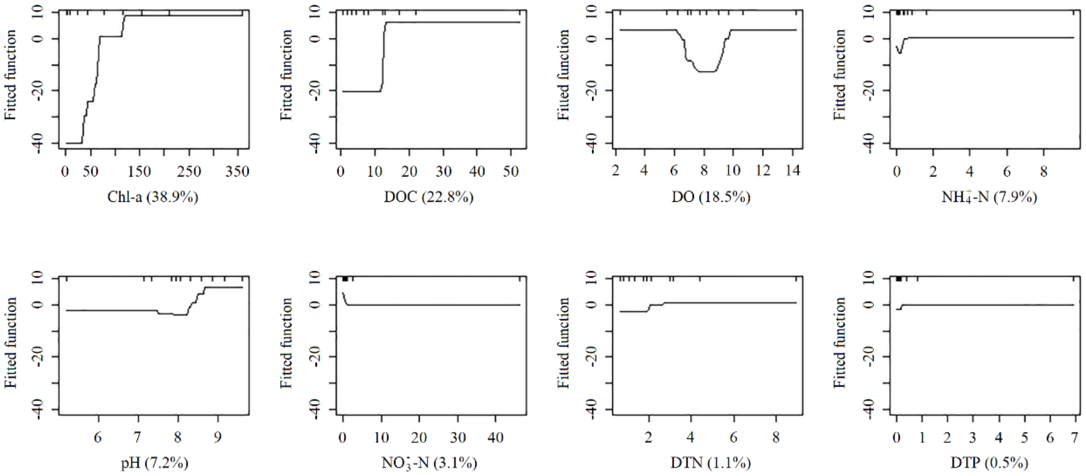

Fig. S3. Fitted functions of BRT model between CH_4 flux and environmental variables.

Table S1

Summary of literature information on CO_2 and CH_4 fluxes (g C m^{-2} yr^{-1}) and characteristics of coastal wetland reclamation system (CWRS). Negative flux values indicate absorption. Y = yes; N = no; salinity level is classified into high salt (> 5‰), low salt (0.5–5‰) and freshwater (< 0.5‰).

CWRS Location	Species	Longitude	Latitude	CO_2	CH_4	Aeration	Aquatic plant	Salinity level	Water depth (m)	Area (ha)	Intensity level	Management practice in non-farming period	Observation year	Reference
30 km north of the Yellow River Estuary	shrimp	119.10	37.85	-87.29	0.04		N	High salt			Semi -intensive		2013-2014	Song, H.L., Liu, X.T., Wen, B.L., 2017. Greenhouse gases fluxes at water-air interface of aquaculture ponds in the Yellow River

														Estuary. Eco. Environ. Sci. 26, 1554–1561 (in Chinese). et al., 2017
Min River Estuary, Fujian Province	shrimp	119.57	26.04	-16.99	143.29	Y	N	Low salt	1.15		Semi -intensive	Drainage, sun exposure	2017	Tong, C., Bastviken, D., Tang, K.W., Yang, P., et al., 2021. Annual CO_2 and CH_4 fluxes in coastal earthen ponds with

															Litopenaeus vannamei in Southeastern China. Aquaculture 545.et al., 2021
Dongying City, Shandong Province	Mixed	118.87	38.00	-97.54	0.02		N	High salt	1.75		Semi-intensive			2013	Song, H.L., Liu, X.T., 2016. Anthropogenic effects on fluxes of ecosystem respiration and methane in the Yellow

														River Estuary, China. Wetlands 36, S113–S123.et al., 2016
Ganyu County, Jiangsu Province	Mixed	119.20	34.97	-67.20 159.05	0.43 0.45	Y	N	High salt	2.30	1.02	Intensive	Drainage, desilting, sun exposure, frequent water change	2014	Zhang, D.X., Tian, X.L., Dong, S.L., Chen, Y., Feng, J., et al., 2020. Carbon budgets of two typical polyculture pond systems in coastal

											China and their potential roles in the global carbon cycle. Aquacult. Env. Interac. 12, 105–115. et al., 2020
Qingdao, Shandong Province	Shrimp	120.00	36.30	-9.53	99.84	N		Semi -intensive	Spring water change	2014	Chen, Y., Dong, S.L., Wang, F., Gao, Q.F., Tian, X.L., 2016. Carbon dioxide and
	Crab			20.18	25.26		High salt				

														methane fluxes from feeding and no-feeding mariculture ponds. Environ. Pollut. 212, 489–497.et al., 2016
Ganyu County, Jiangsu Province	Mixed	119.20	34.97	-119.58 94.23	0.44 0.45	Y	N	High salt	2.30	1.02	Intensive	Drainage, desilting, sun exposure, frequent water changes	2014	Zhang, D.X., Tian, X.L., Dong, S.L., Chen, Y., Feng, J., et al., 2020. Carbon dioxide fluxes from two typical

														mariculture polyculture systems in coastal China. Aquaculture 521. et al., 2020
Min River Estuary, Fujian Province	Shrimp	119.68	26.03	-2.10 -2.27 3.23	22.40 31.80 17.87	Y	N	Low salt	1.30	1.40 1.30 1.25	Semi-intensive	Drainage, sun exposure	2018	Zhao, G.H., 2020. Carbon, nitrogen and phosphorus budgets in reclaimed shrimp ponds of the Min River

														Estuary. Master thesis, Fujian Normal Univ. (in Chinese). et al., 2020
Ganyu County, Jiangsu Province	Crab	119.20	34.97	-112.43	0.41	Y	N	High salt	1.50	1.02	Intensive	Drainage, desilting, sun exposure, frequent water changes	2013	Zhang, D.X., 2015. Studies on CH_4 and CO_2 fluxes at water-air interface and carbon budgets of different culture systems

														with portunus trituberculatus, marsupenaeus japonicas and ruditapes philippinarum. Master thesis, Ocean Univ. China (in Chinese).et al., 2015
Min River Estuary, Fujian Province	Mixed	119.62	26.02	50.27	20.70	N	N		0.90	0.65	Semi-intensive	Drainage, sun exposure	2011	Yang, P., He, Q.H., Huang,
	Shrimp	119.63	26.02	49.65	131.07				1.00					

															J.F., Tong, C., 2015. Fluxes of greenhouse gases at two different aquaculture ponds in the coastal zone of southeastern China. Atmos. Environ. 115, 269–277. et al., 2015
Min River Estuary, Fujian Province	Shrimp	119.57	26.05	41.74	565.09		N	Low salt		0.70	Semi -intensive	Drainage, sun exposure	2015		Yang, P., Zhang,

Jiulong Estuary, Fujian Province	Shrimp	117.93	24.37	36.79	63.33	N	High salt	0.70	Semi -intensive	Drainage, sun exposure	2015	Y.F., Lai, D.Y.F., Tan, L.S., Jin, B.S., Tong, C., 2018. Fluxes of carbon dioxide and methane across the water–atmosphere interface of aquaculture shrimp ponds in two subtropical estuaries:

												the effect of temperature, substrate, salinity and nitrate. Sci. Total. Environ. 635, 1025–1035. et al., 2018
Binhai New Area, Tianjin City	Shrimp	118.07	40.25	65.81 35.68	-0.03 2.53	Y	N	High salt	1.20 1.30	Semi -intensive	2019	Hu, B.B., Xu, X.F., Zhang, J.F., Wang, T.L., Meng, W.Q., Wang, D.Q., 2020.

														Diurnal variations of greenhouse gases emissions from reclamation mariculture ponds. Estuar. Coast. Shelf Sci. 237. et al., 2020
Min River Estuary, Fujian Province	Shrimp	119.67	26.01	42.96	176.40	N	N		0.95	2.14	Semi -intensive	Drainage, sun exposure	2017	Tan, L.S., Yang, P., Xu. K., Chen. K.L.,

Huang. J.F., Tong, C., 2018. Comparison of CH4 emissions following brackish *Cyperus malaccensis* marsh conversion to shrimp pond in the Min River estuary. Acta Sci. Circumstant. 38, 1214–1223 (in

														Chinese). et al., 2018
Min River Estuary, Fujian Province	Shrimp	119.57	26.04	167.96	99.86	Y	N	Low salt	0.80	2.14	Semi-intensive	Drainage, sun exposure	2017	Yang, P., Zhang, Y., Yang, H., Zhang, Y.F., Xu, J., Tan, L.S., et al., 2019. Large fine-scale spatiotemporal variations of CH4 diffusive fluxes from shrimp aquaculture
				76.51	60.97				1.80	1.84				
				3.17	73.58				1.40	1.91				

ponds affected by organic matter supply and aeration in Southeast China. J. Geophys. Res-Biogeo. 124, 1290–1307. et al., 2019

Zhang, Y.F., Yang, P., Yang, H., Tan, L.S., Guo, Q.Q., Zhao, G.H.,

et al., 2019. Plot-scale spatiotemporal variations of CO2 concentration and flux across water–air interfaces at aquaculture shrimp ponds in a subtropical estuary. Environ. Sci. Pollut. Res. 26,

														5623–5637. et al., 2019
Min River Estuary, Fujian Province	Shrimp	119.57	26.04		48.55		N	Low salt	1.10		Semi -intensive	Drainage, sun exposure	2020	Tang et al., 2021
Dagu river, Qingdao city	Shrimp	120.12	36.21	15.50			N	Freshwater			Extensive	Little management	2013	Dong, R.C., 2015. Study on CO_2 flux and source/sink function in Jiaozhou Bay coastal wetland. Master thesis, Qingdao Univ. (in

								Chinese).et al., 2015
Min River Estuary, Fujian Province	Crab	119.57	26.04	186.35	2.30	Extensive	2017	Chen, X.X., Wiesmeier, M., Sardans, J., Van Zwieten, L., Fang, Y.Y., Gargallo-Garriga, A., et al., 2021. Effects of crabs on greenhouse gas emissions, soil
				155.29	1.91			

									nutrients, and stoichiometry in a subtropical estuarine wetland. Biol. Fertil. Soils 57, 131–144.et al., 2021
Bamen Bay, Hainan Province	Shrimp	110.87	19.60	7.48	N	High salt		2008	Han, Y., Zhang, G.L., Zhao, Y.C., 2012. Distribution and fluxes of methane in tropical

										rivers and lagoons of eastern Hainan. Journal of Tropical Oceanography 31, 87–95 (in Chinese). et al., 2012
Changbai Island, Zhejiang Province	Mixed	122.02	30.17	-61.29 -73.71 -68.91 -29.84		N	High salt	Semi-intensive	2020	Zhang, D.X., Xu, W.J., Wang, F., He, J., Chai, X.R., 2022. Carbon dioxide

fluxes from mariculture ponds with swimming crabs and shrimps in eastern China: the effect of adding razor clams. Aquacult. Rep. 22. et al., 2022

Table S2

Summary of literature information on CO_2 and CH_4 fluxes (g C m^{-2} yr^{-1}) and characteristics of inland pond system (IPS). See Table S1 caption for explanation.

IPS Location	Species	Longitude	Latitude	CO_2	CH_4	Aeration	Aquatic plant	Water depth (m)	Area (ha)	Intensity level	Management practice in non-farming period	Observation year	Reference
Chongzhou City, Sichuan Province	Fish	103.67	30.56	243.83	4.41	Y	N			Extensive		2014-2015	Wu, M., 2016. The characteristics and influencing factors of green gas emissions in different water bodys in Chongzhou. Master thesis,

											Sichuan Agric. Univ. (in Chinese). et al., 2016
Changshu City, Jiangsu Province	Fish	120.71	31.55	6.39	N	N	2.10	0.70	Semi-intensive	2016	Ma, Y.C., Sun, L.Y., Liu, C.Y., Yang, X.Y., Zhou, W., Yang, B., Schwenke, G., Liu, D.L., 2018. A comparison of methane and nitrous oxide emissions
	Crab			5.34	N	Y	1.40	0.50			
	Crab			4.73	N	N	1.40	0.50			

											from inland mixed-fish and crab aquaculture ponds. Sci. Total. Environ. 637, 517–523.et al., 2018
Chinese Academy of Fishery Sciences Research Center, Shanghai City	Fish	121.16	30.95	308.08	72.18	N	2.00	0.50	Semi-intensive	2014	Zhu, L., Che, X., Liu, H., Liu, X.G., Liu, C., Chen, X.L., Shi, X., 2016. Greenhouse gas emissions

and comprehensive greenhouse effect potential of *Megalobrama amblycephala* culture pond ecosystems in a 3-month growing season. Aquacult. Int. 24, 893–902.et al., 2016

Xinghua City, Jiangsu province	Mixed	119.33	35.86		3.57	Y	Y	1.00	0.20	Semi-intensive	Drainage, desilting, sun exposure	2013-2014	Liu, S.W., Hu, Z.Q., Wu, S., Li, S.Q., Li, Z.F., Zou, J.W., 2016. Methane and nitrous oxide emissions reduced following conversion of rice paddies to inland crab fish aquaculture in southeast China.
					1.57	Y	N						

									Environ. Sci. Technol. 50, 633–642.et al., 2016
Gaoqing Country, Shandong Province	Fish	117.55	37.06	223.69	Y	N	Semi-intensive	2013	Chen, X.X., Wiesmeier, M., Sardans, J., Van Zwieten, L., Fang, Y.Y., Gargallo-Garriga, A., et al., 2021. Effects of crabs on greenhouse gas
	Mixed			119.16	Y	N			
	Fish			360.46	Y	N			

													emissions, soil nutrients, and stoichiometry in a subtropical estuarine wetland. Biol. Fertil. Soils 57, 131–144.et al., 2015
Wuhan City, Hubei Province	Fish	114.33	30.50	0.81	2.73×10^{-3}	Y	N	2.00	1.13	Intensive		2014	Lan. J., 2015. Greenhouse gases concentration, emission and

													influence factors in farming waters. Master thesis, Huazhong Agri. Univ. (in Chinese). et al., 2015
Yichang City, Hubei Province	Fish	111.33	30.76		29.53	N	N	0.60	0.05	Extensive	Rarely change water	2014-2015	Zhang, C., 2018. On the process and mechamism of methane emission from eutrophic
		111.34	30.75		83.45	N	N	1.00	0.02	Extensive	little management		
		111.34	30.75		44.85	N	N	1.10	0.08	Extensive	Rarely change water		
		111.35	30.75		58.60	N	N	1.60	0.03	Semi-intensive	little management		
		111.34	30.74		115.37	N	N	1.20	0.04	Extensive	little management		

												ponds. Doctoral thesis, China Univ. Geosci. (in Chinese). et al., 2018
Chizhou City, Anhui Province	Fish	117.50	30.66	51.91	34.97	N	Y	1.50	1.80	Semi-intensive	2015-2016	Yue, Q., 2018. Quantifying greenhouse gas emissions and the mitigation potential in agriculture with literature statistics
		117.58	30.73	33.57	4.79	N	Y	1.00	2.00	Extensive	2015-2017	
		117.46	30.64	49.71	103.35	N	Y	3.00	53	Semi-intensive	2015-2018	

											method and case study. Doctoral thesis, Nanjing Agri. Univ. (in Chinese).et al., 2018
Suzhou City, Jiangsu Province	Crab	120.71	31.44	3.24 13.74	Y	Y	1.50	0.01	Semi-intensive	2018	Liu, Y.M., Fu, W.G., Jin, M.J., Shi, L.L., Shen, M.X., Zhang, J.Q., 2020. Effects of different aquatic plants on

											water purification and greenhouse gas emission in crab pond in high temperature season. J. Eco. Rural Environ. 36, 1072–1079 (in Chinese).et al., 2020
Chuzhou City, Anhui Province	Fish	118.25	31.97	10.42 41.90	N	N	0.72 0.75	Semi-intensive	Drainage, sun exposure	2017 2018	Wang, J., Xiao, W., Zhang, X.F.,

Zhang, M., Zhang, W.Q., Liu, Q., et al., 2019. Methane emission characteristics and its influencing factors over aquaculture ponds. Environ. Sci. 40, 5503–5514 (in Chinese).et al., 2019

Chuzhou City, Anhui Province	Fish	118.69	32.24	347.68	N	1.80	0.77	Semi-intensive	Drainage, sun exposure	2019	Jia. L., Zhang, M., Pu, Y.N., Zhao, J.Y., Wang, J., Xie, Y.H., et al., 2021. Temporal and spatial characteristics of methane flux and its influencing factors in a typical aquaculture pond. China Environ. Sci. 41,

													2910–2922 (in Chinese).et al., 2021
Changsha County,	Fish	113.36	28.52	-113.83	54.77	N	N	0.40	0.07	Semi-intensive	Little management	2019-2021	Shen, Y.L., Zhou, J.G., Peng, P.Q., Wu, J.S., 2020. Spatio-temporal variation of nitrogen and phosphorus contents in cascade ponds in subtropical headstream
Hunan Province		113.33	28.55	190.05	435.37			1.40	0.23				
		113.35	28.56	62.79	54.96			1.00	0.07				

													watershed and its influencing factors. J. Agro-Environ. Sci. 39, 2420–2428 (in Chinese).et al., 2020
Xinghua City, Jiangsu Province	Crab	119.83	32.86		3.29	Y	Y	0.70~ 1.20	0.67	Semi-intensive	Drainage, desilting, sun exposure	2017-2018	Hu, T., 2019. Measurements of mathane and nitrous oxide fluxes from freshwater crab/fish
	Fish				5.50	Y	N	1.50~2.50	1.33				

											farming wetlands. Master thesis, Nanjing Agri. Univ. (in Chinese).et al., 2019
Chuzhou City, Anhui Province	Mixed	118.25	31.96	20.10	Y	0.90	0.70	Semi-intensive	Drainage, sun exposure	2017-2018	Zhao. J.Y., 2020. Dynamic of methane emission from water-atmosphere interface in freshwater aquaculture ponds in the

													Yangtze River Delta. Doctoral thesis, Nanjing Univ. Inform. Sci. Technol. (in Chinese). et al., 2020
Gaochun City,	Crab	118.85	31.33	69.40	31.54	N	Y	2.00	2.01	Extensive	Little management	2012	Lin, H., Zhou, G., Li, X.G., Zhou, J., Zhang, T.Q., Wang, G.M., 2013. Greenhouse gases
Jiangsu Province				156.22	57.09		N						

													emissions from pond culture ecosystem of Chinese mitten crab and their comprehensive global warming potentials in summer. J. Fish. China 37, 417–424 (in Chinese).et al., 2013
Xinghua City, Jiangsu Province	Mixed	119.83	32.86		7.54 3.29	Y	Y N	1.20	1.95	Semi-intensive	Drainage, desilting, sun exposure	2013	Hu, Z.Q., Wu, S., Ji, C., Zou,

J.W., Zhou, Q.S., Liu, S.W., 2015. A comparison of methane emissions following rice paddies conversion to crab-fish farming wetlands in southeast China. Environ. Sci. Pollut. Res. 23, 1505–1515.et al.,

													2015
Xinghua City, Jiangsu Province	Fish	119.83	32.86		3.35	Y	N	2.10	3.42	Semi-intensive	Drainage, desilting, sun exposure	2014-2015	Wu, S., Hu, Z.Q., Hu, T., Chen, J., Yu, K., Zou, J.W., Liu, S.W., 2017. Annual methane and nitrous oxide emissions from rice paddies and inland fish aquaculture wetlands in southeast China.

											Atmos. Environ. 175, 135–144.et al., 2017
Nanjing City, Jiangsu Province	Fish	119.03	32.25	65.42	1.60	Y	N	1.10	Semi-intensive	2020-2021	Chen, Y.B., 2021. Study on variation law and influencing factors of greenhouse gas emission flux in different water bodies. Master thesis,

									Nanjing Univ. Inform. Sci. Technol. (in Chinese). et al., 2021
Tianshe River Basin	Fish	119.39	31.22	208.78	7.04	N	Extensive	2018-2020	Wu, W. X., 2020. Characteristics and influencing factors of greenhouse gas emission from water in Zhongtianshe River Basin in
		119.38	31.21	-5.09	2.16				
		119.38	31.20	117.77	4.26				
		119.38	31.20	83.23	3.03				
		119.38	31.20		10.30				
		119.38	31.19	131.89	3.05				

											Tianmu Lake area. Master thesis, Nanjing Normal Univ. (in Chinese).et al., 2020
Xinghua City, Jiangsu Province	Fish	119.83	32.86	1.44	Y	N	1.75	2.7	Semi-intensive	2017-2019	Fang, X.T., Zhao, J.T., Wu, S., Yu, K., Huang, J., Ding, Y., Hu, T., et al., 2021. A two-year measurement of methane
				2.79			1.75	2.7			
				5.17			1.75	2.7			
				2.15			0.95	1.26			
				2.51			0.95	1.26			
				3.02			0.95	1.26			

												and nitrous oxide emissions from freshwater aquaculture ponds: affected by aquaculture species, stocking and water management. Sci. Total. Environ. 813.et al., 2021
Tai Lake basin, East China	Crab	120.41	31.03	-3.02	59.26	N	Y	1.60	Extensive	Little management	2013-2014	Yuan, J.J., Xiang, J., Liu, D.Y.,
				6.71	93.95			1.33				
				4.14	62.15			1.18				

Kang, H., He, T.H., et al., 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. Nat. Clim. Change 9, 318–322.et al., 2019

Table S3

Summary of literature information on CO_2 and CH_4 fluxes (g C m^{-2} yr^{-1}) and characteristics of lake/reservoir system (LRS). See Table S1 caption for explanation.

LRS Location	Species	Longitude	Latitude	CO_2	CH_4	Aquatic plant	Salinity level	Water depth (m)	Intensity level	Observation year	Reference
Nanjing City, Jiangsu Province	Fish	118.84	32.45	42.60	0.83		Freshwater	1.20	Extensive	2020-2021	Chen, Y.B., 2021. Study on variation law and influencing factors of greenhouse gas emission flux in different water bodies. Master thesis, Nanjing Univ. Inform. Sci. Technol. (in Chinese).et al.,

											2021
Wuhan City, Hubei Province	Fish	114.38	30.55	33.69	6.98		Freshwater	2.50	Extensive	2003-2004	Xing, Y.P., Xie, P., Yang, H., Ni, L.Y., Wang, Y.S., Rong, K.W., 2005. Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical Lake in China. Atmos. Environ. 39, 5532–5540. et al., 2005
Duchang County, Jiangxi Province	Fish	116.05	29.34	87.04	1.67		Freshwater	1.90	Extensive	2010	Liu, L.X., Xu, M., Lin, M., Zhang, X., 2013. Spatial variability of greenhouse gas effluxes

											and their controlling factors in the Poyang Lake in China. Pol. J. Environ. Stud. 22, 749–758.et al., 2013
Xingzi County, Jiangxi Province	Fish	116.12	29.44	102.18	0.98		Freshwater	1.90	Extensive	2010	Liu, L.X., Xu, M., Lin, M., Zhang, X., 2013. Spatial variability of greenhouse gas effluxes and their controlling factors in the Poyang Lake in China. Pol. J. Environ. Stud. 22, 749–758.et al., 2013
Harbin City, Heilongjiang Province	Fish	126.60	46.28	48.18			Freshwater	1.73	Extensive	2008	
											Lv, D.K., 2013. Study on CO_2 fluxes across water-air interface peatland

											reservoirs around Harbin. Doctoral thesis, Northeast Forestry Univ. (in Chinese).et al., 2013
Harbin City, Heilongjiang Province	Fish	127.10	45.20	68.73						2008	Lv, D.K., 2013. Study on CO_2 fluxes across water-air interface peatland reservoirs around Harbin. Doctoral thesis, Northeast Forestry Univ. (in Chinese).et al., 2013
Chizhou City, Anhui Province	Fish	117.52	30.67	32.39	3.09		Freshwater	5.00	Extensive	2016	

										Yue, Q., 2018. Quantifying greenhouse gas emissions and the mitigation potential in agriculture with literature statistics method and case study. Doctoral thesis, Nanjing Agri. Univ. (in Chinese).et al., 2018
Dali City, Yunnan Province	Fish	100.15	25.86	-1.65	0.30		Freshwater	Ecological stocking	2016	Li, D., 2017. Study on greenhouse gas fluxes at the

											water-air interface in Erhai Lake. Master thesis, Yunnan Univ. (in Chinese).et al., 2017
Dali City, Yunnan Province	Fish	100.16	25.73	-382.45	0.15	Y	Freshwater		Ecological stocking	2016	Li, D., 2017. Study on greenhouse gas fluxes at the water-air interface in Erhai Lake. Master thesis, Yunnan Univ. (in Chinese).et al., 2017
Fuzhou City, Fujian Province	Fish	119.63	25.82	291.18	1.64		Low salt	1.50	Extensive	2018-2019	Zhang, Y.F., Lyu, M., Yang, P., Lai, D.Y.F., Tong, C., Zhao, G.H., et

											al., 2021. Spatial variations in CO2 fluxes in a subtropical coastal reservoir of Southeast China were related to urbanization and land-use types. J. Environ. Sci. 109, 206–218.et al., 2021
Changsha County, Hunan Province	Fish	113.32	28.52	111.18	2.82		Freshwater	10.00	Extensive	2019-2020	Shen, Y.L., Zhou, J.G., Peng, P.Q., Wu, J.S., 2020. Spatio-

										temporal variation of nitrogen and phosphorus contents in cascade ponds in subtropical headstream watershed and its influencing factors. J. Agro-Environ. Sci. 39, 2420–2428 (in Chinese). et al., 2020
Nanjing City, Jiangsu Province	Fish	118.97	32.47	4.28	0.39		Freshwater	Ecological stocking	2012-2013	Han, Y., 2013. Greenhouse gases emission characteristics

											of rivers in Nanjing and influencing factors. Master thesis, Nanjing Univ. Infor. Sci.Technol. (in Chinese). et al., 2013
Nanjing City, Jiangsu Province	Fish	118.73	32.20	58.46	16.36		Freshwater		Extensive	2012-2014	Han, Y., 2013. Greenhouse gases emission characteristics of rivers in Nanjing and influencing factors. Master thesis, Nanjing Univ. Infor. Sci.Technol.
Suzhou City, Jiangsu Province	Crab	120.42	31.03	96.84	81.08		Freshwater	1.20	Extensive	2013-2014	

											(in Chinese). et al., 2013
											Xiang, J., 2015. Greenhouse gases emissions from the lakeside wetland and crab pond in Riparian zone of Taihu lake. Doctoral thesis, Univ. Chinese Academy Sci. (in Chinese).et al., 2015
Suzhou City, Jiangsu Province	Crab	120.45	31.1	1.61	5.23		Freshwater	1.62	Extensive	2013-2014	Xiang, J., 2015. Greenhouse gases emissions from
Yongshan County, Yunnan Province	Fish	103.61	28.24	98.25	1.64				Extensive	2019	

the lakeside wetland and crab pond in Riparian zone of Taihu lake. Doctoral thesis, Univ. Chinese Academy Sci. (in Chinese).et al., 2015

Tan, W., 2020. A comparative study of carbon flux changes at the water-air interface of typical reservoirs in the Yangtze River Basin.

								Master thesis, Chongqing Jiaotong Univ. (in Chinese). et al., 2020
Zhaotong City, Yunnan Province	Fish	104.41	28.63	89.38	1.83	Ecological stocking	2019	Tan, W., 2020. A comparative study of carbon flux changes at the water-air interface of typical reservoirs in the Yangtze River Basin. Master thesis, Chongqing Jiaotong Univ. (in Chinese). et al., 2020
Yichang City, Hubei Province	Fish	108.18	30.41	144.22	7.48	Ecological stocking	2014	
Changshou Lake, Chongqing City	Fish	107.29	29.93	78.50	3.35	Ecological stocking		
Nanning City, Guangxi Autonomous Region	Fish	108.50	23.50	350.84	3.29	Ecological stocking		

Li J.H., Pu, J.B., Sun, P.A., Yuan, D.X., Liu, W., Zhang, T., Mo, X., 2015. Summer greenhouse gases exchange flux across water-air interface in three water reservoirs located in different geologic setting in Guangxi, China.

								Environ. Sci. 36, 4032–4042 (in Chinese).et al., 2015
Xiangxi River, Hubei Province	Fish	110.77	30.97	113.60	2.50	Ecological stocking	2010	Zhao, Y., Wu, B.F., Zeng, Y., 2013. Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China. Biogeosciences 10, 1219–1230.et al., 2013
Zigui City, Hubei Province	Fish	10.98	30.87	551.88	1.01	Ecological stocking	2010	Zhao, Y., Wu,

Wanzhou City, Chongqing City	Fish	108.49	30.84	455.52	1.84		Extensive	B.F., Zeng, Y., 2013. Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China. Biogeosciences 10, 1219–1230.et al., 2013

Table S4

Summary of literature information on CO_2 and CH_4 fluxes (g C m^{-2} yr^{-1}) and characteristics of rice-field system (RFS). See Table S1 caption for explanation.

FRS Location	Species	Longitude	Latitude	CO_2	CH_4	Aeration	Aquatic plant	Salinity level	Water depth (m)	Intensity level	Observation year	Reference
Qianjiang City, Hubei Province	Shrimp	112.70	30.38		53.43	N	Y	Freshwater	0.10	Intensive	2016-2017	Sun, Z.C., Guo, Y., Li, C.F., Cao, C.G., Yuan, P.L., Zou, F.L., Wang, J.H., Jia, P.A., Wang, J.P., 2019. Effects of straw returning and feeding on

												greenhouse gas emissions from integrated rice-crayfish farming in Jianghan Plain, China. Environ. Sci. Pollut. Res. 26, 11710–11718. et al., 2019
Qianjiang City, Hubei Province	Shrimp	112.70	30.38		35.86	N	Y	Freshwater	0.10	Intensive	2016-2017	Sun, Z.C.,
Wuhan City, Hubei Province	Fish	114.36	30.48		61.95	N	Y	Freshwater	0.80		2006-2007	Guo, Y., Li,

44.14	C.F., Cao, C.G., Yuan, P.L., Zou, F.L., Wang, J.H., Jia, P.A., Wang, J.P., 2019. Effects of straw returning and feeding on greenhouse gas emissions from integrated rice-crayfish farming in
47.70	

Jianghan Plain, China. Environ. Sci. Pollut. Res. 26, 11710–11718. et al., 2019

Yuan, W.L., Cao, C.G., Li, C.F., Zhan, M., Cai, M.L., Wang, J.P., 2009. Methane and nitrous oxide emissions

												from rice-duck and rice-fish complex ecosystems and the evaluation of their economic significance. Agri. Sci. China 8, 1246–1255.et al., 2009
Wuhan City, Hubei Province	Fish	114.36	30.48		52.49	N	Y	Freshwater	0.80		2006-2007	Yuan, W.L., Cao, C.G., Li, C.F., Zhan, M., Cai, M.L.,
China National Rice Research Institute, Hangzhou, Zhejiang Province	Fish	120.16	30.27		3.42		Y	Freshwater			2017	

Wang, J.P., 2009. Methane and nitrous oxide emissions from rice-duck and rice-fish complex ecosystems and the evaluation of their economic significance. Agri. Sci. China 8, 1246–1255.et al., 2009

Feng, J.F., Liu, Y.B., Li, F.B., Zhou, X.Y., Xu, C.C., Fang, F.P., 2021. Effect of phosphorus and potassium addition on greenhouse gas emissions and nutrient utilization of a rice-fish co-

									culture system. Environ. Sci. Pollut. Res. 28, 38034–38042. et al., 2021
China National Rice Research Institute, Hangzhou, Zhejiang Province	Fish	120.16	30.27	4.27		Y	Freshwater	2017	Feng, J.F., Liu, Y.B., Li, F.B., Zhou, X.Y., Xu, C.C., Fang, F.P., 2021. Effect of phosphorus and potassium addition on
Suzhou City, Jiangsu Province	Crab	120.71	31.44	8.08		Y	Freshwater	2018	
				24.70					
				18.43	N				

greenhouse gas emissions and nutrient utilization of a rice-fish co-culture system. Environ. Sci. Pollut. Res. 28, 38034–38042. et al., 2021

Liu, Y.M., Fu, W.G., Jin, M.J., Shi, L.L., Shen, M.X., Zhang, J.Q., 2020. Effects of different aquatic plants on water purification and greenhouse gas emission in crab pond in high temperature season. J. Eco. Rural Environ. 36, 1072–1079 (in

												Chinese). et al., 2020
Qianjiang City, Hubei Province	Shrimp	112.70	30.38		29.89	N	Y	Freshwater	0.50-1.00		2015-2016	Xu, X.Y., Zhang, M.M., Peng, C.L., Si, G.H., et al., 2017. Effect of rice-crayfish co-culture on greenhouse gases emission in straw-puddled paddy fields. Chinese J.

												Eco-Agri. 25, 1591–1603 (in Chinese). et al., 2017
Taojiang County, Hunan Province	Fish	112.17	28.51		29.76	N	Y	Freshwater	0.80		2005	Liu, X.Y., Huang, H., Yang, Z.P., Yu, J.B., Dai, Z.Y., Wang, D.J., Tan, S.Q., 2006. Methane emission from rice-duck-fish complex ecosystem. Eco.

												Environ. 02, 265–269 (in Chinese).et al., 2006
Taojiang County, Hunan Province	Fish	112.17	28.51		35.94	N	Y	Freshwater	0.80		2005	Liu, X.Y., Huang, H., Yang, Z.P., Yu, J.B., Dai, Z.Y., Wang, D.J., Tan, S.Q., 2006. Methane emission from rice-duck-fish complex ecosystem. Eco. Environ. 02,
Wuhan City, Hubei Province	Fish	114.36	30.48	509.13	63.39		Y	Freshwater	0.30		2006	

265–269 (in Chinese).et al., 2006

Zhan, M., Cao, C.G., Wang, J.P., Cai, M.L., Yuan, W.L., 2008. Greenhouse gases exchange of integrated paddy field and their comprehensive global warming potentials. Acta

									Ecologica Sin. 11, 5461–5468 (in Chinese). et al., 2008
Hangzhou City,	Fish	119.95	30.05	12.11	Y	Y	Freshwater	2019	References
Zhejiang Province									et al., 2021
Hangzhou City,	Fish	119.95	30.05	21.86				2019	References
Zhejiang Province	Crab	122.16	41.03	6.87					et al., 2021
Liaohe estuary, Panjin City,				9.04					Zhang, Y.B.,
Liaoning Province				28.71	N	Y	Freshwater		Xu, Y., Wang, H.Y., Wang, S.P., Zhai, L.M., Liu, H.B., 2022. Greenhouse

gas emission characteristics and influencing factors of rice-crab symbiosis system. J. Agric. Res. Environ. 1–11 (in Chinese). et al., 2021

Table S5

Summary of literature information on environment variables in coastal wetland reclamation system (CWRS). DO = dissolved oxygen; DOC = dissolved organic carbon; DTN = dissolved total nitrogen; DTP = dissolved total phosphorus; NH_4^+-N = ammonia nitrogen; NO_3^--N = nitrate nitrogen.

CWRS Location	Air temperature (°C)	Precipitation (mm)	Water temperature (°C)	pH	DO (mg L^{-1})	Chl-*a* (μg L^{-1})	DOC (mg L^{-1})	DTN (mg L^{-1})	DTP (mg L^{-1})	NH_4^+-N (mg L^{-1})	NO_3^--N (mg L^{-1})	Reference
30 km north of the Yellow River Estuary	12.10	551.60	14.61							0.26		Song, H.L., Liu, X.T., Wen, B.L., 2017. Greenhouse gases fluxes at water-air interface of aquaculture ponds in the Yellow River Estuary. Eco. Environ. Sci.

											26, 1554–1561 (in Chinese). et al., 2017
Min River Estuary, Fujian Province	19.60	1350	28.26	8.88	5.33	155.01	12.56	1.15	0.16	0.44	Tong, C., Bastviken, D., Tang, K.W., Yang, P., et al., 2021. Annual CO_2 and CH_4 fluxes in coastal earthen ponds with Litopenaeus vannamei in Southeastern China. Aquaculture

												545.et al., 2021
Dongying City, Shandong Province	12.10	551.60	17.65									Song, H.L., Liu, X.T., 2016. Anthropogenic effects on fluxes of ecosystem respiration and methane in the Yellow River Estuary, China. Wetlands 36, S113–S123.et al., 2016
Ganyu County, Jiangsu Province	13.80	976.40	21.70	8.32	8.42	44.11	3.38	3.66	0.22	0.06	0.21	Zhang, D.X., Tian, X.L., Dong, S.L., Chen, Y.,
			21.60	7.90	7.35	15.61	1.76	3.13	0.14	0.05	0.47	

									Feng, J., et al., 2020. Carbon budgets of two typical polyculture pond systems in coastal China and their potential roles in the global carbon cycle. Aquacult. Env. Interac. 12, 105–115. et al., 2020
Qingdao, Shandong Province	12.30	662.10	21.95	8.30	41.7	6.47	3.89	0.31	Chen, Y., Dong, S.L., Wang, F., Gao, Q.F., Tian, X.L.,
				8.05	3.88	3.13	3.03	0.19	

											2016. Carbon dioxide and methane fluxes from feeding and no-feeding mariculture ponds. Environ. Pollut. 212, 489–497.et al., 2016
Ganyu County, Jiangsu Province	19.60	1350	24.20	8.77	7.66	60.8	3.26	3.13	0.21	0.06	0.31	Zhang, D.X., Tian, X.L., Dong, S.L., Chen, Y., Feng, J., et al., 2020. Carbon dioxide fluxes from two
				8.10	5.75	17.60	0.61	1.95	0.10	0.06	0.48	

												typical mariculture polyculture systems in coastal China. Aquaculture 521. et al., 2020
Min River Estuary, Fujian Province	19.60	1350	28.32	9.19	4.71	118.60	11.94	1.06	0.20	0.37	0.07	Zhao, G.H., 2020. Carbon, nitrogen and phosphorus budgets in reclaimed shrimp ponds of the Min River Estuary. Master thesis, Fujian Normal Univ. (in
				9.18	5.03	185.29	12.53	1.05	0.23	0.35	0.17	
				9.17	4.84	114.81	11.15	1.31	0.20	0.25	0.08	

												Chinese). et al., 2020
Ganyu County, Jiangsu Province	13.80	976.40	24.60	8.66	7.13	24.25	1.06	1.97	0.10	0.033	0.33	Zhang, D.X., 2015. Studies on CH_4 and CO_2 fluxes at water-air interface and carbon budgets of different culture systems with portunus trituberculatus, marsupenaeus japonicas and ruditapes philippinarum

									. Master thesis, Ocean Univ. China (in Chinese).et al., 2015
Min River Estuary, Fujian Province, China	19.60	1350	16.60	8.62	8.89	359.02	1.69	0.43	Yang, P., He, Q.H., Huang, J.F., Tong, C., 2015. Fluxes of greenhouse gases at two different aquaculture ponds in the coastal zone of southeastern China. Atmos. Environ. 115, 269–277. et al.,
			27.53	8.52	6.64	246.73	2.41	0.15	

												2015
Min River Estuary, Fujian Province	19.90	1346	26.50	9.24	10.5	220.71	36.16	1.71	0.14	0.44	0.06	Yang, P., He, Q.H., Huang, J.F., Tong, C., 2015. Fluxes of greenhouse gases at two different aquaculture ponds in the coastal zone of southeastern China. Atmos. Environ. 115, 269–277. et al., 2015
Jiulong Estuary, Fujian Province	21.00	1371	28.37	9.16	9.3	75.16	23.18	1.78	0.13	0.76	0.13	Yang, P., Zhang, Y.F., Lai, D.Y.F., Tan,

L.S., Jin, B.S., Tong, C., 2018. Fluxes of carbon dioxide and methane across the water–atmosphere interface of aquaculture shrimp ponds in two subtropical estuaries: the effect of temperature, substrate, salinity and nitrate. Sci.

								Total. Environ. 635, 1025–1035. et al., 2018
Binhai New Area, Tianjin City	13.68	550.31	20.61	8.97	9.68	0.08	0.78	Hu, B.B., Xu, X.F., Zhang, J.F., Wang, T.L., Meng, W.Q., Wang, D.Q., 2020. Diurnal variations of greenhouse gases emissions from reclamation mariculture ponds. Estuar. Coast. Shelf
			22.12	8.76	8.76	0.17	0.70	

												Sci. 237. et al., 2020
Min River Estuary, Fujian Province	19.90	1342	29.90	8.42	9.44	221.60	52.46		0.18	0.82	0.24	Tan, L.S., Yang, P., Xu. K., Chen. K.L., Huang. J.F., Tong, C., 2018. Comparison of CH4 emissions following brackish *Cyperus malaccensis* marsh conversion to shrimp pond in the Min River estuary.

												Acta Sci. Circumstant. 38, 1214–1223 (in Chinese). et al., 2018
Min River Estuary, Fujian Province	19.90	1342	29.17	9.58	5.20	116.44	16.08			0.96	0.13	Yang, P., Zhang, Y., Yang, H., Zhang, Y.F., Xu, J., Tan, L.S., et al., 2019. Large fine-scale spatiotemporal variations of CH4 diffusive fluxes from shrimp aquaculture ponds affected
			28.39	9.45	6.25	186.19	13.89			0.70	0.05	
			28.41	9.55	5.80	191.95	15.95			0.69	0.06	

by organic matter supply and aeration in Southeast China. J. Geophys. Res-Biogeo. 124, 1290–1307. et al., 2019

Zhang, Y.F., Yang, P., Yang, H., Tan, L.S., Guo, Q.Q., Zhao, G.H., et al., 2019. Plot-scale spatiotemporal variations of CO2

												concentration and flux across water–air interfaces at aquaculture shrimp ponds in a subtropical estuary. Environ. Sci. Pollut. Res. 26, 5623–5637. et al., 2019
Min River Estuary, Fujian Province	19.9	1342	25.10	7.26	6.34	201.22	20.68	1.88	0.19	0.34	1.15	Tang et al., 2021
Dagu river, Qingdao city, Shandong Province	12.00	900	20.30									Dong, R.C., 2015. Study on CO_2 flux and source/sink

				function in Jiaozhou Bay coastal wetland. Master thesis, Qingdao Univ. (in Chinese).et al., 2015
Min River Estuary, Fujian Province	19.90	1341	22.00	Chen, X.X., Wiesmeier, M., Sardans, J., Van Zwieten, L., Fang, Y.Y., Gargallo-Garriga, A., et al., 2021. Effects of crabs on

				greenhouse gas emissions, soil nutrients, and stoichiometry in a subtropical estuarine wetland. Biol. Fertil. Soils 57, 131–144.et al., 2021
Bamen Bay, Hainan Province	24.10	2062	25.00	Han, Y., Zhang, G.L., Zhao, Y.C., 2012. Distribution and fluxes of methane in tropical rivers and lagoons of

									eastern Hainan. Journal of Tropical Oceanography 31, 87–95 (in Chinese). et al., 2012
Changbai Island, Zhejiang Province	16.00	1360	22.70	8.57	9.48	18.86		0.21	Zhang, D.X., Xu, W.J., Wang, F., He, J., Chai, X.R., 2022. Carbon dioxide fluxes from mariculture ponds with swimming crabs and shrimps in
				8.62	9.68	22.39		0.20	
				8.60	9.69	22.74		0.19	
				8.38	9.59	15.70		0.17	

eastern China: the effect of adding razor clams. Aquacult. Rep. 22. et al., 2022

Table S6

Summary of literature information on environment variables in inland pond system (IPS). See Table S5 caption for explanation.

IPS Location	Air temperature (°C)	Precipitation (mm)	Water temperature (°C)	pH	DO (mg L^{-1})	Chl-*a* (μg L^{-1})	DOC (mg L^{-1})	DTN (mg L^{-1})	DTP (mg L^{-1})	NH_4^+-N (mg L^{-1})	NO_3^--N (mg L^{-1})	Reference
Chongzhou City, Sichuan Province	15.90	1012.40	15.90									Wu, M., 2016. The characteristics and influencing factors of green gas emissions in different water bodys in Chongzhou. Master thesis, Sichuan Agric. Univ.

					(in Chinese). et al., 2016
Changshu City, Jiangsu Province	16.90	1135.60	16.90	5.10 6.20 6.90	Ma, Y.C., Sun, L.Y., Liu, C.Y., Yang, X.Y., Zhou, W., Yang, B., Schwenke, G., Liu, D.L., 2018. A comparison of methane and nitrous oxide emissions from inland mixed-fish and crab aquaculture ponds. Sci.

				Total. Environ. 637, 517–523.et al., 2018
Chinese Academy of Fishery Sciences Research Center, Shanghai City	17.60	1173.40	28.95	Zhu, L., Che, X., Liu, H., Liu, X.G., Liu, C., Chen, X.L., Shi, X., 2016. Greenhouse gas emissions and comprehensive greenhouse effect potential of *Megalobrama amblycephala*

							culture pond ecosystems in a 3-month growing season. Aquacult. Int. 24, 893–902.et al., 2016
Xinghua City, Jiangsu province	17.80	1090	17.90	8.80	0.16	0.12	Liu, S.W., Hu, Z.Q., Wu, S., Li, S.Q., Li, Z.F., Zou, J.W., 2016. Methane and nitrous oxide emissions reduced following conversion of
	17.90	1090	17.60	8.66			

							rice paddies to inland crab fish aquaculture in southeast China. Environ. Sci. Technol. 50, 633–642.et al., 2016
Gaoqing Country, Shandong Province	13.10	539.40	26.50	8.30	0.34	7.94	Chen, X.X., Wiesmeier, M., Sardans, J., Van Zwieten, L., Fang, Y.Y., Gargallo-Garriga, A., et al., 2021. Effects of
			26.10	8.20	0.30	6.48	
			26.90	8.08	0.16	9.37	

										crabs on greenhouse gas emissions, soil nutrients, and stoichiometry in a subtropical estuarine wetland. Biol. Fertil. Soils 57, 131–144.et al., 2015
Wuhan City, Hubei Province	16.20	1207	20.29	8.03	8.13	12.42	3.46	0.78	0.71	Lan. J., 2015. Greenhouse gases concentration, emission and influence

												factors in farming waters. Master thesis, Huazhong Agri. Univ. (in Chinese). et al., 2015
Yichang City, Hubei Province	16.90	1215.60	18.10	7.14	6.19	110.80		3.68	0.60	0.39	1.54	Zhang, C., 2018. On the process and mechamism of methane emission from eutrophic ponds. Doctoral thesis, China Univ. Geosci. (in Chinese). et
			19.00		7.10	317.60		8.96	1.07	0.36	3.52	
			19.40		12.95	99.00		3.02	0.74	0.61	1.29	
			19.80		13.75	133.70		6.00	1.19	0.85	2.02	
			21.10		10.32	77.10		2.93	0.46	0.29	1.29	

												al., 2018.
Chizhou City, Anhui Province	16.50	1800	17.20	7.52			24.99	1.93		0.60	0.57	Yue, Q., 2018. Quantifying greenhouse gas emissions and the mitigation potential in agriculture with literature statistics method and case study. Doctoral thesis, Nanjing Agri. Univ. (in Chinese).et al., 2018
			16.50	7.39			21.83	1.30		0.46	0.36	
			17.80	7.50			29.93	2.07		0.66	1.36	

Suzhou City, Jiangsu Province	15.70	1100	29.30 27.30	9.62 9.27	10.68 7.11	4.56 2.49		0.80 0.66	0.05 0.04	0.10 0.07	0.05 0.04	Liu, Y.M., Fu, W.G., Jin, M.J., Shi, L.L., Shen, M.X., Zhang, J.Q., 2020. Effects of different aquatic plants on water purification and greenhouse gas emission in crab pond in high temperature season. J. Eco. Rural Environ. 36,

				1072–1079 (in Chinese).et al., 2020
Chuzhou City, Anhui Province	15.40	1090	18.68 19.00	Wang, J., Xiao, W., Zhang, X.F., Zhang, M., Zhang, W.Q., Liu, Q., et al., 2019. Methane emission characteristics and its influencing factors over aquaculture ponds. Environ. Sci. 40, 5503–5514 (in

				Chinese).et al., 2019
Chuzhou City, Anhui Province	15.40	1090	26.69	Jia. L., Zhang, M., Pu, Y.N., Zhao, J.Y., Wang, J., Xie, Y.H., et al., 2021. Temporal and spatial characteristics of methane flux and its influencing factors in a typical aquaculture pond. China Environ. Sci. 41, 2910–

					2922 (in Chinese).et al., 2021
Changsha County, Hunan Province	17.20	1442	27.70	2.84	Shen, Y.L., Zhou, J.G., Peng, P.Q., Wu, J.S., 2020. Spatio-temporal variation of nitrogen and phosphorus contents in cascade ponds in subtropical headstream watershed and its influencing factors. J. Agro-
			29.30	2.30	
			21.30	10.58	

						Environ. Sci. 39, 2420–2428 (in Chinese).et al., 2020
Xinghua City, Jiangsu Province	15.00	1024.80	23.80	8.40	8.15	Hu, T., 2019. Measurements of mathane and nitrous oxide fluxes from freshwater crab/fish farming wetlands. Master thesis, Nanjing Agri. Univ. (in Chinese).et al., 2019
			20.30	8.20	9.74	

Chuzhou City, Anhui Province	15.40	1090	18.80	Zhao. J.Y., 2020. Dynamic of methane emission from water-atmosphere interface in freshwater aquaculture ponds in the Yangtze River Delta. Doctoral thesis, Nanjing Univ. Inform. Sci. Technol. (in Chinese). et al., 2020

Gaochun City, Jiangsu Province	15.90	1157	26.60	Lin, H., Zhou, G., Li, X.G., Zhou, J., Zhang, T.Q., Wang, G.M., 2013. Greenhouse gases emissions from pond culture ecosystem of Chinese mitten crab and their comprehensive global warming potentials in summer. J.
			27.10	

							Fish. China 37, 417–424 (in Chinese).et al., 2013
Xinghua City, Jiangsu Province	15.00	1024.80	28.11 27.65	7.58 8.15	1.22	0.94	Hu, Z.Q., Wu, S., Ji, C., Zou, J.W., Zhou, Q.S., Liu, S.W., 2015. A comparison of methane emissions following rice paddies conversion to crab-fish farming wetlands in southeast China.

								Environ. Sci. Pollut. Res. 23, 1505–1515.et al., 2015
Xinghua City, Jiangsu Province	15.00	1024.80	16.76	10.51	18.89	0.16	0.11	Wu, S., Hu, Z.Q., Hu, T., Chen, J., Yu, K., Zou, J.W., Liu, S.W., 2017. Annual methane and nitrous oxide emissions from rice paddies and inland fish aquaculture wetlands in southeast

											China. Atmos. Environ. 175, 135–144.et al., 2017
Nanjing City, Jiangsu Province	15.40	1106.50	19.60	7.97	6.69	151.67		0.62	0.18		Chen, Y.B., 2021. Study on variation law and influencing factors of greenhouse gas emission flux in different water bodies. Master thesis, Nanjing Univ. Inform. Sci. Technol. (in

												Chinese). et al., 2019
Tianshe River Basin, Jiangsu Province	16.00	1146.60	20.52	7.70	11.32		5.21	0.80		0.09	0.33	Wu, W. X., 2020. Characteristics and influencing factors of greenhouse gas emission from water in Zhongtianshe River Basin in Tianmu Lake area. Master thesis, Nanjing Normal Univ. (in Chinese).et al., 2020
			20.78	8.55	11.11		7.17	1.15		0.11	0.40	
			20.01	7.88	10.69		6.24	1.03		0.10	0.59	
			21.12	7.93	9.22		5.21	1.54		0.09	0.92	
			20.48	7.33	6.88		2.76	1.04		0.10	0.52	
			19.89	7.97	9.26		5.09	1.15		0.12	0.60	

Xinghua City, Jiangsu Province	15.00	1024.80	20.03	9.64	Fang, X.T., Zhao, J.T., Wu, S., Yu, K., Huang, J., Ding, Y., Hu, T., et al., 2021. A two-year measurement of methane and nitrous oxide emissions from freshwater aquaculture ponds: affected by aquaculture species,
			20.19	9.17	
			20.53	8.12	
			20.14	8.01	
			20.40	7.85	
			20.50	7.46	

				stocking and water management. Sci. Total. Environ. 813.et al., 2021
Tai Lake basin, East China	16.5	1176	25.3 25.6 25.4	Yuan, J.J., Xiang, J., Liu, D.Y., Kang, H., He, T.H., et al., 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture.

Nat. Clim. Change 9, 318–322.et al., 2019

Table S7

Summary of literature information on environment variables in lake/reservoir system (LRS). See Table S5 caption for explanation.

LRS Location	Air temperature (°C)	Precipitation (mm)	Water temperature (°C)	pH	DO (mg L^{-1})	Chl-*a* (μg L^{-1})	DOC (mg L^{-1})	DTN (mg L^{-1})	DTP (mg L^{-1})	NH_4^+-N (mg L^{-1})	NO_3^--N (mg L^{-1})	Reference
Nanjing City, Jiangsu Province	15.40	1106.50	20.93	8.41	8.10	117.03		1.09	0.07			Chen, Y.B., 2021. Study on variation law and influencing factors of greenhouse gas emission flux in different water bodies. Master thesis, Nanjing Univ. Inform. Sci. Technol. (in Chinese).et

												al., 2021
Wuhan City, Hubei Province	16.90	1320	18.40			52.72	7.33					Xing, Y.P., Xie, P., Yang, H., Ni, L.Y., Wang, Y.S., Rong, K.W., 2005. Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical Lake in China. Atmos. Environ. 39, 5532–5540. et al., 2005
Duchang County, Jiangxi Province	17.10	1500	20.40	6.50			4.10			0.22	0.60	Liu, L.X., Xu, M., Lin, M., Zhang, X., 2013. Spatial variability of greenhouse gas effluxes
Xingzi County, Jiangxi Province	17.10	1500	20.30	6.70			3.80			0.19	0.90	

										and their controlling factors in the Poyang Lake in China. Pol. J. Environ. Stud. 22, 749–758. et al., 2013
Harbin City, Heilongjiang Province	3.30	531.20	17.45	9.09	7.81	18.09	3.26	1.50	0.12	Lv, D.K., 2013. Study on CO$_2$ fluxes across water-air interface peatland reservoirs around Harbin. Doctoral thesis, Northeast Forestry Univ.
Harbin City, Heilongjiang Province	3.40	563.00	19.73	9.02	7.11	12.55	1.73	1.09	0.10	

								(in Chinese).et al., 2013
Chizhou City, Anhui Province	16.50	1800	7.57	20.01	0.66	0.25	0.28	Yue, Q., 2018. Quantifying greenhouse gas emissions and the mitigation potential in agriculture with literature statistics method and case study. Doctoral thesis, Nanjing Agri. Univ. (in Chinese).et al., 2018

Dali City, Yunnan Province	15.10	1000	17.46	8.18	13.05							Li, D., 2017. Study on greenhouse gas fluxes at the water-air interface in Erhai Lake. Master thesis, Yunnan Univ. (in Chinese).et al., 2017
			18.21	8.26	14.25							
Fuzhou City, Fujian Province	19.60	1350	23.02	8.73	7.71	31.81	20.00	1.62	0.17	0.46	1.22	Zhang, Y.F., Lyu, M., Yang, P., Lai, D.Y.F., Tong, C., Zhao, G.H., et al., 2021. Spatial variations in CO2 fluxes in a subtropical coastal reservoir of Southeast

					China were related to urbanization and land-use types. J. Environ. Sci. 109, 206–218.et al., 2021
Changsha County, Hunan Province	17.20	1442	29.50	5.54	Shen, Y.L., Zhou, J.G., Peng, P.Q., Wu, J.S., 2020. Spatio-temporal variation of nitrogen and phosphorus contents in cascade ponds

										in subtropical headstream watershed and its influencing factors. J. Agro-Environ. Sci. 39, 2420–2428 (in Chinese). et al., 2020
Nanjing City, Jiangsu Province	15.87	1106.50	18.66	8.05	26.41	2.05	0.04		0.04	Han, Y., 2013. Greenhouse gases emission characteristics of rivers in Nanjing and influencing factors. Master thesis, Nanjing Univ. Infor.
Nanjing City, Jiangsu Province	15.19	1106.50	19.10	7.95			0.62	9.6		

						Sci.Technol. (in Chinese). et al., 2013
Suzhou City, Jiangsu Province	17.00	1120	20.80		13.28	Xiang, J., 2015. Greenhouse gases emissions from the lakeside wetland and crab pond in Riparian zone of Taihu lake. Doctoral thesis, Univ. Chinese Academy Sci. (in Chinese).et al., 2015
Suzhou City, Jiangsu Province	17.00	1120	18.53		3.05	

Yongshan County, Yunnan Province	17.60	750	19.40		8.39	2.37	1.20	2.48	0.04	Tan, W., 2020. A comparative study of carbon flux changes at the water-air interface of typical reservoirs in the Yangtze River Basin. Master thesis, Chongqing Jiaotong Univ. (in Chinese). et al., 2020
Zhaotong City, Yunnan Province	19.40	1077.70	19.20		9.09	3.39	1.11	2.63	0.03	
Yichang City, Hubei Province	18.00	1493.20	19.90		6.89	6.53	1.75	3.09	0.08	
Changshou Lake, Chongqing City	17.70	1120	20.04		8.02	42.28	4.24	2.97	0.06	
Nanning City, Guangxi Autonomous Region	20.90	1680	30.70	8.05	10.21	3.12	3.17	0.74		Li J.H., Pu, J.B., Sun, P.A., Yuan, D.X., Liu, W.,

Zhang, T., Mo, X., 2015. Summer greenhouse gases exchange flux across water-air interface in three water reservoirs located in different geologic setting in Guangxi, China. Environ. Sci. 36, 4032–4042 (in Chinese).et al., 2015

Xiangxi River, Hubei Province	15.30	1082	20.36	8.23	9.08	14.34	7.54	Zhao, Y., Wu, B.F., Zeng, Y., 2013. Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China. Biogeosciences 10, 1219–1230.et al., 2013
Zigui City, Hubei Province	16.90	1215.60	18.82	7.90	6.99	1.20	6.92	
Wanzhou City, Chongqing City	17.70	1243	19.17	7.84	6.97	1.88	8.02	

Table S8

Summary of literature information on environment variables in rice-field system (FRS). See Table S5 caption for explanation.

FRS Location	Air temperature (°C)	Precipitation (mm)	Water temperature (°C)	pH	DO (mg L^{-1})	Chl-*a* (μg L^{-1})	DOC (mg L^{-1})	DTN (mg L^{-1})	DTP (mg L^{-1})	NH_4^+-N (mg L^{-1})	NO_3^--N (mg L^{-1})	Reference
Qianjiang City, Hubei Province	16.10	1100	24.86									Sun, Z.C., Guo, Y., Li, C.F., Cao, C.G., Yuan, P.L., Zou, F.L., Wang, J.H., Jia, P.A., Wang, J.P., 2019. Effects of straw returning and feeding on greenhouse

				gas emissions from integrated rice-crayfish farming in Jianghan Plain, China. Environ. Sci. Pollut. Res. 26, 11710–11718. et al., 2019
Wuhan City, Hubei Province	16.80	1150	7.09	Yuan, W.L., Cao, C.G., Li, C.F., Zhan, M., Cai, M.L., Wang, J.P., 2009.
	16.80	1150	6.73	

					Methane and nitrous oxide emissions from rice-duck and rice-fish complex ecosystems and the evaluation of their economic significance. Agri. Sci. China 8, 1246–1255.et al., 2009
China National Rice Research Institute, Hangzhou City, Zhejiang Province	20.65	7.13	0.09	0.45	Feng, J.F., Liu, Y.B.,
	20.65	4.39	0.13	0.37	

	20.65		5.19	0.10	1.14	Li, F.B., Zhou, X.Y., Xu, C.C., Fang, F.P., 2021. Effect of phosphorus and potassium addition on greenhouse gas emissions and nutrient utilization of a rice-fish co-culture system. Environ. Sci. Pollut. Res.
	20.65		4.63	0.16	0.42	

												28, 38034–38042. et al., 2021
Suzhou City, Jiangsu Province	16.00	1100	27.30	8.68	5.73	3.56		0.65	0.04	0.03	0.04	Liu, Y.M., Fu, W.G., Jin, M.J., Shi, L.L., Shen, M.X., Zhang, J.Q., 2020. Effects of different aquatic plants on water purification and greenhouse gas emission in crab pond

				in high temperature season. J. Eco. Rural Environ. 36, 1072–1079 (in Chinese). et al., 2020
Qianjiang City, Hubei Province	16.10	1100	23.50	Xu, X.Y., Zhang, M.M., Peng, C.L., Si, G.H., et al., 2017. Effect of rice-crayfish co-culture on greenhouse gases emission in

				straw-puddled paddy fields. Chinese J. Eco-Agri. 25, 1591–1603 (in Chinese). et al., 2017
Taojiang County, Hunan Province	16.60	1566	24.97	Liu, X.Y., Huang, H., Yang, Z.P., Yu, J.B., Dai, Z.Y., Wang, D.J., Tan, S.Q., 2006. Methane emission from rice-

				duck-fish complex ecosystem. Eco. Environ. 02, 265–269 (in Chinese).et al., 2006
Wuhan City, Hubei Province	16.80	1150	26.30	Zhan, M., Cao, C.G., Wang, J.P., Cai, M.L., Yuan, W.L., 2008. Greenhouse gases exchange of integrated paddy field and their comprehensi

									ve global warming potentials. Acta Ecologica Sin. 11, 5461–5468 (in Chinese). et al., 2008
Hangzhou City, Zhejiang Province					14.82	1.71	0.13	1.07	References
					12.44	1.77	0.09	1.15	et al., 2021
					11.72	1.71	0.10	0.90	
					11.64	1.54	0.07	0.83	
Panjin City, Liaoning Province	8.30	645	16.20	7.93					Zhang, Y.B., Xu, Y., Wang, H.Y., Wang, S.P., Zhai, L.M., Liu, H.B.,

2022. Greenhouse gas emission characteristics and influencing factors of rice-crab symbiosis system. J. Agric. Res. Environ. 1–11 (in Chinese). et al., 2021

Table S9

Summary of two-way ANOVA tests for the effects of farmed species, aquaculture system and their interactions on CO_2 and CH_4 fluxes.

	CO_2 flux					**CH_4 flux**				
	Sum of square	***df***	**Mean square**	***F* value**	***P* value**	**Sum of square**	***df***	**Mean square**	***F* value**	***P* value**
Intercept	4.129	1	4.129	5.570	0.021	0.584	1	0.584	0.803	> 0.05
Species	0.346	3	0.115	0.156	> 0.05	10.950	3	3.650	5.017	0.003
Aquaculture system	10.225	3	3.408	4.598	< 0.01	19.581	3	6.527	8.972	< 0.001
Species × Aquaculture system	1.650	2	0.825	1.113	> 0.05	1.125	3	0.375	0.515	> 0.05
Residuals	51.149	69	0.741			78.295	109	0.727		

References

Bao, T., 2021. Impacts of different crop-fish co-culture systems on greenhouse gas emissions from freshwater aquaculture system. Master thesis, Chinese Academy of Agric. Sci. (in Chinese). https://doi.org/10.11654/jaes.2020-1367.

Chen, X.X., Wiesmeier, M., Sardans, J., Van Zwieten, L., Fang, Y.Y., Gargallo-Garriga, A., et al., 2021. Effects of crabs on greenhouse gas emissions, soil nutrients, and stoichiometry in a subtropical estuarine wetland. Biol. Fertil. Soils 57, 131–144. https://doi.org/10.1007/s00374-020-01512-6.

Chen, Y.B., 2021. Study on variation law and influencing factors of greenhouse gas emission flux in different water bodies. Master thesis, Nanjing Univ. Inform. Sci. Technol. (in Chinese). https://doi.org/10.27248/d.cnki.gnjqc.2021.000746.

Chen, Y., Dong, S.L., Wang, F., Gao, Q.F., Tian, X.L., 2016. Carbon dioxide and methane fluxes from feeding and no-feeding mariculture ponds. Environ. Pollut. 212, 489–497. https://doi.org/10.1016/j.envpol.2016.02.039.

Chen, Y., Dong, S.L., Wang, Z.A., Wang, F., Gao, Q.F., Tian, X.L., Xiong, Y.H., 2016. Variations in CO_2 fluxes from grass carp Ctenopharyngodon idella aquaculture polyculture ponds. Aquacult. Env. Interac. 8, 31–40. https://doi.org/10.3354/aei00149.

Dong, R.C., 2015. Study on CO_2 flux and source/sink function in Jiaozhou Bay coastal wetland. Master thesis, Qingdao Univ. (in Chinese).

Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77, 802–813. https://doi.org/10.1111/j.1365-2656. 2008.01390.x.

Fang, X.T., Zhao, J.T., Wu, S., Yu, K., Huang, J., Ding, Y., Hu, T., et al., 2021. A two-year measurement of methane and nitrous oxide emissions from freshwater aquaculture ponds: affected by aquaculture species, stocking and water management. Sci. Total. Environ. 813. https://doi.org/10.1016/j.scitotenv. 2021.151863.

Feng, J.F., Liu, Y.B., Li, F.B., Zhou, X.Y., Xu, C.C., Fang, F.P., 2021. Effect of phosphorus and potassium addition on greenhouse gas emissions and nutrient utilization of a rice-fish co-culture system. Environ. Sci. Pollut. Res. 28, 38034–38042. https://doi.org/10.1007/s11356-020-12064-5.

Gao, H., 2020. Enhanced performance of algal-bacterial-based aquaponics based on optimization of its carbon and nitrogen cycles. Master thesis, Shandong Univ. (in Chinese). https://doi.org/10.27272/d.cnki.gshdu.2020.004570.

Han, Y., 2013. Greenhouse gases emission characteristics of rivers in Nanjing and influencing factors. Master thesis, Nanjing Univ. Infor. Sci.Technol. (in Chinese).

Han, Y., Zhang, G.L., Zhao, Y.C., 2012. Distribution and fluxes of methane in tropical rivers and lagoons of eastern Hainan. Journal of Tropical Oceanography 31, 87–95 (in Chinese). https://doi.org/10.3969/j.issn.1009-5470.2012. 02.012.

Hu, B.B., Xu, X.F., Zhang, J.F., Wang, T.L., Meng, W.Q., Wang, D.Q., 2020. Diurnal variations of greenhouse gases emissions from reclamation mariculture ponds. Estuar. Coast. Shelf Sci. 237. https://doi.org/10.1016/j.ecss.2020.106677.

Hu, Z.Q., Wu, S., Ji, C., Zou, J.W., Zhou, Q.S., Liu, S.W., 2015. A comparison of methane emissions following rice paddies conversion to crab-fish farming wetlands in southeast China. Environ. Sci. Pollut. Res. 23, 1505–1515. https://doi.org/10.1007/s11356-015-5383-9.

Hu, T., 2019. Measurements of mathane and nitrous oxide fluxes from freshwater crab/fish farming wetlands. Master thesis, Nanjing Agri. Univ. (in Chinese). https://doi.org/10.27244/d.cnki.gnjnu.2019.000637.

Jia. L., Zhang, M., Pu, Y.N., Zhao, J.Y., Wang, J., Xie, Y.H., et al., 2021. Temporal and spatial characteristics of methane flux and its influencing factors in a typical aquaculture pond. China Environ. Sci. 41, 2910–2922 (in Chinese). https://doi.org/10.19674/j.cnki.issn1000-6923.2021.0295.

Kuechle, K.J., Webb, E.B., Mengel, Doreen, Main, A.R., 2019. Factors influencing neonicotinoid insecticide concentrations in flood plain wetland sediments across Missouri. Environ. Sci. Technol. 53, 10591–10600. https://doi.org/ 10.1021/acs.est.9b01799.

Lan. J., 2015. Greenhouse gases concentration, emission and influence factors in farming waters. Master thesis, Huazhong Agri. Univ. (in Chinese). https://doi.org/10.7666/d.Y2803380.

Li J.H., Pu, J.B., Sun, P.A., Yuan, D.X., Liu, W., Zhang, T., Mo, X., 2015. Summer greenhouse gases exchange flux across water-air interface in three water reservoirs located in different geologic setting in Guangxi, China. Environ. Sci. 36, 4032–4042 (in Chinese). https://doi.org/10.13227/j.hjkx.2015.11.012.

Li, D., 2017. Study on greenhouse gas fluxes at the water-air interface in Erhai Lake. Master thesis, Yunnan Univ. (in Chinese).

Lin, H., Zhou, G., Li, X.G., Zhou, J., Zhang, T.Q., Wang, G.M., 2013. Greenhouse gases emissions from pond culture ecosystem of Chinese mitten crab and their comprehensive global warming potentials in summer. J. Fish. China 37, 417–424 (in Chinese). https://doi.org/10.3724/SP.J.1231.2013.38282.

Liu, L.X., Xu, M., Lin, M., Zhang, X., 2013. Spatial variability of greenhouse gas effluxes and their controlling factors in the Poyang Lake in China. Pol. J. Environ. Stud. 22, 749–758.

Liu, S.W., Hu, Z.Q., Wu, S., Li, S.Q., Li, Z.F., Zou, J.W., 2016. Methane and nitrous oxide emissions reduced following conversion of rice paddies to inland crab fish aquaculture in southeast China. Environ. Sci. Technol. 50, 633–642. https://doi.org/10.1021/acs.est.5b04343.

Liu, X.Y., Huang, H., Yang, Z.P., Yu, J.B., Dai, Z.Y., Wang, D.J., Tan, S.Q., 2006. Methane emission from rice-duck-fish complex ecosystem. Eco. Environ. 02, 265–269 (in Chinese). https://doi.org/10.16258/j.cnki.1674-5906.2006.02.014.

Liu, Y.M., Fu, W.G., Jin, M.J., Shi, L.L., Shen, M.X., Zhang, J.Q., 2020. Effects of different aquatic plants on water purification and greenhouse gas emission in crab pond in high temperature season. J. Eco. Rural Environ. 36, 1072–1079 (in Chinese). https://doi.org/10.19741/j.issn.1673-4831.2019.0613.

Lv, D.K., 2013. Study on CO_2 fluxes across water-air interface peatland reservoirs around Harbin. Doctoral thesis, Northeast Forestry Univ. (in Chinese).

Ma, Y.C., Sun, L.Y., Liu, C.Y., Yang, X.Y., Zhou, W., Yang, B., Schwenke, G., Liu, D.L., 2018. A comparison of methane and nitrous oxide emissions from inland mixed-fish and crab aquaculture ponds. Sci. Total. Environ. 637, 517–523. https://doi.org/10.1016/j.scitotenv.2018.05.040.

Shen, Y.L., Zhou, J.G., Peng, P.Q., Wu, J.S., 2020. Spatio-temporal variation of nitrogen and phosphorus contents in cascade ponds in subtropical headstream watershed and its influencing factors. J. Agro-Environ. Sci. 39, 2420–2428 (in Chinese). https://doi.org/10.11654/jaes.2019-1257.

Song, H.L., Liu, X.T., 2016. Anthropogenic effects on fluxes of ecosystem respiration and methane in the Yellow River Estuary, China. Wetlands 36, S113–S123. https://doi.org/10.1007/s13157-014-0587-1.

Song, H.L., Liu, X.T., Wen, B.L., 2017. Greenhouse gases fluxes at water-air interface of aquaculture ponds in the Yellow River Estuary. Eco. Environ. Sci. 26, 1554–1561 (in Chinese). https://doi.org/10.16258/j.cnki.1674-5906. 2017.09.014.

Sun, Z.C., Guo, Y., Li, C.F., Cao, C.G., Yuan, P.L., Zou, F.L., Wang, J.H., Jia, P.A., Wang, J.P., 2019. Effects of straw returning and feeding on greenhouse gas emissions from integrated rice-crayfish farming in Jianghan Plain, China. Environ. Sci. Pollut. Res. 26, 11710–11718. https://doi.org/10.1007/ s11356-019-04572-w.

Tan, L.S., Yang, P., Xu. K., Chen. K.L., Huang. J.F., Tong, C., 2018. Comparison of CH4 emissions following brackish *Cyperus malaccensis* marsh conversion to shrimp pond in the Min River estuary. Acta Sci. Circumstant. 38, 1214–1223 (in Chinese). https://doi.org/10.13671/j.hjkxxb.2017.0447.

Tan, L.S., Ge, Z.M., Li, S.H., Li, Y.L., Xie, L.N., Tang, J.W., 2021. Reclamation-induced tidal restriction increases dissolved carbon and greenhouse gases diffusivefluxes in salt marsh creeks. Sci. Total. Environ. 773, 1456844. https://doi.org/10.1016/j.scitotenv.2021.145684.

Tan, W., 2020. A comparative study of carbon flux changes at the water-air interface of typical reservoirs in the Yangtze River Basin. Master thesis, Chongqing Jiaotong Univ. (in Chinese). https://doi.org/10.27671/d.cnki.gcjtc.2020.000089.

Tang, C., 2021. Effects on methane fluxes of the brackish *C. malaccensis* marsh conversion to aquaculture pond in Min River Estuary. Fujian norm. Univ. (in Chinese).

Tong, C., Bastviken, D., Tang, K.W., Yang, P., et al., 2021. Annual CO_2 and CH_4 fluxes in coastal earthen ponds with Litopenaeus vannamei in Southeastern China. Aquaculture 545. https://doi.org/10.1016/j.aquaculture.2021.737229.

Wang, J., Xiao, W., Zhang, X.F., Zhang, M., Zhang, W.Q., Liu, Q., et al., 2019. Methane emission characteristics and its influencing factors over aquaculture ponds. Environ. Sci. 40, 5503–5514 (in Chinese). https://doi.org/10.13227/j.hjkx.201905149.

Wintle, B.A., Elith, J., Potts, J.M., 2005. Fauna habitat modelling and mapping in an urbanising environment; A case study in the Lower Hunter Central Coast region of NSW. Austral Ecol. 30, 719–738. https://doi.org/10.1111/j.1442-9993.2005.01514.x.

Wu, M., 2016. The characteristics and influencing factors of green gas emissions in different water bodys in Chongzhou. Master thesis, Sichuan Agric. Univ. (in Chinese).

Wu, S., Hu, Z.Q., Hu, T., Chen, J., Yu, K., Zou, J.W., Liu, S.W., 2017. Annual methane and nitrous oxide emissions from rice paddies and inland fish aquaculture wetlands in southeast China. Atmos. Environ. 175, 135–144. https://doi.org/10.1016/j.atmosenv.2017.12.008.

Wu, W. X., 2020. Characteristics and influencing factors of greenhouse gas emission from water in Zhongtianshe River Basin in Tianmu Lake area. Master thesis, Nanjing Normal Univ. (in Chinese). https://doi.org/10.27245/d.cnki.gnjsu.2020.001588.

Xiang, J., 2015. Greenhouse gases emissions from the lakeside wetland and crab pond in Riparian zone of Taihu lake. Doctoral thesis, Univ. Chinese Academy Sci. (in Chinese).

Xing, Y.P., Xie, P., Yang, H., Ni, L.Y., Wang, Y.S., Rong, K.W., 2005. Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical Lake in China. Atmos. Environ. 39, 5532–5540. https://doi.org/10.1016/j.atmosenv.2005. 06.010.

Xu, X.Y., Zhang, M.M., Peng, C.L., Si, G.H., et al., 2017. Effect of rice-crayfish co-culture on greenhouse gases emission in straw-puddled paddy fields. Chinese J. Eco-Agri. 25, 1591–1603 (in Chinese). https://doi.org/10.13930/j.cnki.cjea. 170280.

Xu, X.F., 2020. Research on the characteristics and influencing factors of greenhouse gas emissions from marine aquaculture ponds in Tianjin. Master thesis, Tianjin Norm. Univ. (in Chinese). https://doi.org/10.27363/d.cnki.gtsfu.2020.000759.

Yang, P., He, Q.H., Huang, J.F., Tong, C., 2015. Fluxes of greenhouse gases at two different aquaculture ponds in the coastal zone of southeastern China. Atmos. Environ. 115, 269–277. https://doi.org/10.1016/j.atmosenv.2015.05.067.

Yang, P., Zhang, Y.F., Lai, D.Y.F., Tan, L.S., Jin, B.S., Tong, C., 2018. Fluxes of carbon dioxide and methane across the water–atmosphere interface of aquaculture shrimp ponds in two subtropical estuaries: the effect of temperature, substrate, salinity and nitrate. Sci. Total. Environ. 635, 1025–1035. https://doi.org/10.1016/j.scitotenv.2018.04.102.

Yang, P., Zhang, Y., Yang, H., Zhang, Y.F., Xu, J., Tan, L.S., et al., 2019. Large fine-scale spatiotemporal variations of CH4 diffusive fluxes from shrimp aquaculture ponds affected by organic matter supply and aeration in Southeast China. J. Geophys. Res-Biogeo. 124, 1290–1307. https://doi.org/10.1029/ 2019JG005025.

Yuan, J.J., Xiang, J., Liu, D.Y., Kang, H., He, T.H., et al., 2019. Rapid growth in greenhouse gas emissions from the adoption of industrial-scale aquaculture. Nat. Clim. Change 9, 318–322. https://doi.org/10.1038/s41558-019-0425-9.

Yuan, W.L., Cao, C.G., Li, C.F., Zhan, M., Cai, M.L., Wang, J.P., 2009. Methane and nitrous oxide emissions from rice-duck and rice-fish complex ecosystems and the evaluation of their economic significance. Agri. Sci. China 8, 1246–1255. https://doi.org/10.1016/S1671-2927(08)60335-1.

Yue, Q., 2018. Quantifying greenhouse gas emissions and the mitigation potential in agriculture with literature statistics method and case study. Doctoral thesis, Nanjing Agri. Univ. (in Chinese). https://doi.org/10.27244/d.cnki.gnjnu.2018.000246.

Zhan, M., Cao, C.G., Wang, J.P., Cai, M.L., Yuan, W.L., 2008. Greenhouse gases exchange of integrated paddy field and their comprehensive global warming potentials. Acta Ecologica Sin. 11, 5461–5468 (in Chinese). https://doi.org/10.3321/j.issn:1000-0933.2008.11.030.

Zhang, C., 2018. On the process and mechamism of methane emission from eutrophic ponds. Doctoral thesis, China Univ. Geosci. (in Chinese).

Zhang, D.X., 2015. Studies on CH_4 and CO_2 fluxes at water-air interface and carbon budgets of different culture systems with portunus trituberculatus, marsupenaeus japonicas and ruditapes philippinarum. Master thesis, Ocean Univ. China (in Chinese).

Zhang, D.X., Tian, X.L., Dong, S.L., Chen, Y., Feng, J., et al., 2020. Carbon budgets of two typical polyculture pond systems in coastal China and their potential roles in the global carbon cycle. Aquacult. Env. Interac. 12, 105–115. https://doi.org/10.3354/aei00349.

Zhang, D.X., Tian, X.L., Dong, S.L., Chen, Y., Feng, J., et al., 2020. Carbon dioxide fluxes from two typical mariculture polyculture systems in coastal China. Aquaculture 521. https://doi.org/10.1016/j.aquaculture.2020.735041.

Zhang, D.X., Xu, W.J., Wang, F., He, J., Chai, X.R., 2022. Carbon dioxide fluxes from mariculture ponds with swimming crabs and shrimps in eastern China: the effect of adding razor clams. Aquacult. Rep. 22. https://doi.org/ 10.1016/j.aqrep.2021.100917.

Zhang, Y.B., Xu, Y., Wang, H.Y., Wang, S.P., Zhai, L.M., Liu, H.B., 2022. Greenhouse gas emission characteristics and influencing factors of rice-crab symbiosis system. J. Agric. Res. Environ. 1–11 (in Chinese).

Zhang, Y.F., Lyu, M., Yang, P., Lai, D.Y.F., Tong, C., Zhao, G.H., et al., 2021. Spatial variations in CO2 fluxes in a subtropical coastal reservoir of Southeast China were related to urbanization and land-use types. J. Environ. Sci. 109, 206–218. https://doi.org/10.1016/j.jes.2021.04.003.

Zhang, Y.F., Yang, P., Yang, H., Tan, L.S., Guo, Q.Q., Zhao, G.H., et al., 2019. Plot-scale spatiotemporal variations of CO2 concentration and flux across water–air interfaces at aquaculture shrimp ponds in a subtropical estuary. Environ. Sci. Pollut. Res. 26, 5623–5637. https://doi.org/10.1007/s11356-018 -3929-3.

Zhao, G.H., 2020. Carbon, nitrogen and phosphorus budgets in reclaimed shrimp ponds of the Min River Estuary. Master thesis, Fujian Normal Univ. (in Chinese). https://doi.org/10.27019/d.cnki.gfjsu.2020.002282.

Zhao, Y., Wu, B.F., Zeng, Y., 2013. Spatial and temporal patterns of greenhouse gas emissions from Three Gorges Reservoir of China. Biogeosciences 10, 1219–1230. https://doi.org/10.5194/bg-10-1219-2013.

Zhao. J.Y., 2020. Dynamic of methane emission from water-atmosphere interface in freshwater aquaculture ponds in the Yangtze River Delta. Doctoral thesis, Nanjing Univ. Inform. Sci. Technol. (in Chinese). https://doi.org/ 10.27248/d.cnki.gnjqc.2020.000860.

Zhu, L., Che, X., Liu, H., Liu, X.G., Liu, C., Chen, X.L., Shi, X., 2016. Greenhouse gas emissions and comprehensive greenhouse effect potential of *Megalobrama amblycephala* culture pond ecosystems in a 3-month growing season. Aquacult. Int. 24, 893–902. 10.1007/s10499-015-9959-7.