Article

The ‘Perfect’ Conversion: Dramatic Increase in CO₂ Efflux from Shellfish Ponds and Mangrove Conversion in China

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Abstract: Aquaculture, particularly shellfish ponds, has expanded dramatically and become a major cause of mangrove deforestation and “blue carbon” loss in China. We present the first study to examine CO₂ efflux from marine aquaculture/shellfish ponds and in relation to land-use change from mangrove forests in China. Light and dark sediment CO₂ efflux from shellfish ponds averaged at 0.61 ± 0.07 and 0.90 ± 0.12 kg CO₂ m^{−2} yr^{−1} ($= 37.67 \pm 4.89$ and 56.0 ± 6.13 mmol m^{−2} d^{−1}), respectively. The corresponding rates (-4.21 ± 4.54 and 41.01 ± 4.15 mmol m^{−2} d^{−1}) from the adjacent mangrove forests that were devoid of aquaculture wastewater were lower, while those from the adjacent mangrove forests (3.48 ± 7.83 and 73.02 ± 5.76 mmol m^{−2} d^{−1}) receiving aquaculture wastewater markedly increased. These effluxes are significantly higher than those reported for mangrove forests to date, which is attributable to the high nutrient levels and the physical disturbance of the substrate associated with the aquaculture operation. A rise of 1 °C in the sediment temperature resulted in a 6.56% rise in CO₂ released from the shellfish ponds. Combined with pond area data, the total CO₂ released from shellfish ponds in 2019 was estimated to be ~12 times that in 1983. The total annual CO₂ emission from shellfish ponds associated with mangrove conversion reached 2–5 Tg, offsetting the C storage by mangrove forests in China. These are significant environmental consequences rather than just a simple shift of land use. Around 30% higher CO₂ emissions are expected from aquaculture ponds (including shellfish ponds) compared to shellfish ponds alone. Total annual CO₂ emission from shellfish ponds will likely decrease to the level reported in early 1980 under the pond area-shrinking scenario, but it will be more than doubled under the business-as-usual scenario projected for 2050. This study highlights the necessity of curbing the expansion of aquaculture ponds in valuable coastal wetlands and increasing mangrove restoration to abandoned ponds.

Keywords: CO₂ emission; aquaculture ponds; land use; temperature; mangrove conversion; shellfish pond

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1. Introduction

Mangroves are evergreen plants that grow on tropical and subtropical coastlines. The trees and shrubs growing in mangrove forests display different root systems (e.g., plank or buttress, stilts, knee roots and pneumatophores) that aerate the system, stabilize plants during waves, slow down water flow and facilitate sediment deposition [1]. Mangroves provide a wide variety of ecosystem services, including but not limited to carbon sequestration, nursery habitats for juvenile prawns and fishes, wastewater treatment, coastal water quality improvement by removing pollutants before reaching coral reefs and seagrasses, storm/cyclone protection, and nutrient provision for adjacent coral reefs and seagrasses [2–4]. In contrast to their high ecosystem value, sustained mangrove forest losses have occurred in the last few decades due to reclamation, aquaculture development, urban and coastal development and overexploitation, waste dumping, and dredging

for navigational channels and marinas [5–7]. This situation is particularly alarming in Asia, where losses have averaged 1% or above in the past few decades [8], although loss rates appear to have decreased [9]. Aquaculture expansion into mangroves accounts for 51.9% of mangrove habitat loss in some South American and Asian countries [10]. In Asia, mangroves have also been confronted with degradation, resulting from conversion into aquaculture ponds [11]. China has the fastest expansion rate of coastal aquaculture globally. According to data from the State Fishery Administration of China, the area used in aquaculture rose from 3,269,135 ha in 1983 to 8,346,339 ha ($\sim 3\times$ increase) in 2016 [12].

The expansion of marine aquaculture, especially shellfish farming, contributes significantly to the loss of mangrove forests and the rise in CO₂ emissions from sediments. Coastal aquaculture in the highest-producing countries is dominated by seaweeds (plants), mollusks, crustaceans and finfish (fauna) [13,14], the expansion of which is undoubtedly disastrous to mangrove forests. Currently, recognition of the negative effects as a result of aquaculture is restricted to direct habitat loss, introductions and transfers of non-native species, bycatch and misuse of chemicals [7]. Little attention has been given to the indirect effects of mangrove conversion [15], such as CO₂ emission from mangrove forest loss and operation of the aquaculture pond replacing the mangroves. When mangroves are cleared to establish aquaculture ponds, there is a release of stored C back into the atmosphere [16] but even more from the perturbation and oxidation of sediments during pond construction [17]. Based on a life-cycle analysis approach, Kauffman, et al. [18] estimated that each kg of shrimps produced from ponds that were converted from mangrove forests would result in >16 kg of CO₂ emission.

Many methods have been developed to measure sediment CO₂ flux, accompanied by the technical development of measuring CO₂ flux from the water–air interface [19]. Among these methods, the dynamic chamber methods are well developed, and CO₂ concentration in the chamber is usually measured by an infrared gas analyzer. In particular, the commercially available systems tend to follow the closed dynamic chamber method, which avoids the problems of open dynamic systems, e.g., pressure sensitivity and a process that is time-consuming to reach stability. However, the closed dynamic system has the risk of building up CO₂ concentration in the chamber [20]. In this study, we utilized the closed dynamic system to measure CO₂ efflux and improved its performance by including a vent to allow pressure to balance between the inside and outside of the chamber, thereby preventing CO₂ partial pressure buildup.

In order to assess the effect of mangrove conversion on the dramatic increase in CO₂ efflux, we conducted field sampling to investigate CO₂ efflux from shellfish ponds constructed via mangrove conversion in Fujian Province, China. Efflux from mangrove forests in the same area was also measured for comparison. We performed the first analysis by scaling up the measured flux to CO₂ efflux from marine aquaculture ponds (including shellfish ponds), incorporating mangrove loss in China over the past 30 years when mangroves have been cleared for aquaculture development. This was based on our data, historical data on the areal changes in aquaculture/shellfish ponds, and published data on CO₂ efflux from other aquaculture ponds.

2. Materials and Methods

2.1. Sampling Site

This study was conducted in shellfish ponds adjacent to the Zhangjiangkou National Mangrove Nature Reserve (23°53′45″–23°56′00″ N, 117°24′07″–117°24′30″ E) in Yunxiao, southern Fujian Province, China (Figure 1). To allow comparison, measurement was also conducted in adjacent forests dominated by the mangrove varieties *Avicennia marina* and *Kandelia obovata*. The sampling site is located in the mid- to upper tidal region of the Zhangjiang estuary, which is semi-enclosed and opens into the Taiwan Strait. The estuary occupies ~2360 ha and is fringed by 117.9 ha of mangrove forests. Mangrove forests in the estuary are dominated by *Avicennia marina*, *Kandelia obovata* and *Aegiceras corniculatum*. The invasion of cordgrass, *Spartina alterniflora*, has resulted in the rapid encroachment

of the intertidal mudflat seaward to the mangroves, effectively suppressing mangrove expansion into the accreting coast. In 2020, the average annual rainfall was 2640.9 mm, and the average annual temperature was 22.6 °C. The average water salinity was 19%.

Figure 1. Sampling locations in mangroves and shellfish ponds adjoining the Zhangjiangkou National Mangrove Nature Reserve, Fujian, China.

Mangrove forests of the Zhangjiang estuary were cleared for mariculture before the 1990s. The intertidal areas of the estuary are now almost totally occupied by semi-intensive ponds for shellfish and crustacean aquaculture. The recent invasion of *S. alterniflora* on the unvegetated mudflat has caused the collapse of the shellfish collection fishery (mainly of the razor clam, *Sinonovacula constricta*), thus accelerating the conversion of mangrove forests into ponds for culturing the clam [21]. This scenario is a typical situation of mangrove forests in China, if not also Southeast Asia, where aquaculture development remains a strong driver for mangrove loss. These ponds are connected to seawater via sluice gates, which are only opened during the water exchange necessitated by maintenance or harvesting. The frequency and volume of water exchange between ponds and channels varied in light of the species' growth cycle and water salinity, fluctuating from 0% in the first month after stocking to 30% volume per week in the growth and harvesting stages [22].

According to the Marine Fishery Yearbook from the State Oceanic Administration of China (SOA), the major species raised in south China involved crabs, mollusks and shrimps. In the sampling site, the ponds culturing native razor clams, namely, *Sinonovacula constricta*, were selected for sampling sediment CO₂ efflux. The clam ponds are composed of a grow-out pond and a fodder pond. The grow-out ponds receive fertilizers (inorganic phosphorus and nitrogen) and food (algae) from the fodder ponds, as well as suspended organic particles from the flooded water of adjoining mangroves during spring tides. The rearing period continues from October to July in general. From August to September, pond owners would clear the surface sediments of the ponds with hydraulic pumps, and expose the ponds to the sun to disinfect them in the following week [23]. Fodder ponds are fertilized with chicken manure or other fertilizers to boost phytoplankton abundance, which sustains the filter-feeding razor clams in the grow-out pond.

2.2. Sampling Methods

To standardize the measurements, CO₂ efflux across the sediment–air interface was measured between 9:00 am and 1:00 pm in four clam grow-out ponds and six locations of mangrove forests on consecutive days from 30 March to 16 April 2015. Multiple replicates were measured at each pond and mangrove site. The locations were selected using a random sampling scheme. The sampling locations of mangrove forests were located near the discharge point of the aquaculture effluents. Both light and dark effluxes were measured using transparent polycarbonate chambers and chambers covered by aluminum foil, respectively. The chambers (diameter 35.5 cm, volume 5.7 L) were pushed down 0.5 cm into the sediment 30 min before CO₂ measurement, to allow the set-up to equilibrate while preventing an undue difference (e.g., temperature) in conditions between the two chambers. Each chamber had an air pump, with two sampling ports on opposite sides of the chamber through which a stream of airflow was maintained by the air pump at a 200 mL min^{−1} flow rate, to minimize gas buildup in the chamber. The pressure equilibrium between the air in the chamber and the surrounding air was maintained by a relief vent according to the design by Xu, et al. [24]. CO₂ efflux was measured by an SBA-5 infrared gas analyzer (PP System Inc., Amesbury, MA, USA) for up to 20 min, until a stable rate lasting for at least 2.5 min was obtained. The short incubation period was selected to avoid excessive environmental microclimatic changes (e.g., water content, sediment temperature and CO₂ concentration gradients), which may influence gas diffusivity. Zero calibration was conducted using a column of soda lime after every measurement to ensure accuracy. During each gas flux measurement, the air temperature was recorded, and sediment temperature was also recorded after measurement with temperature sensors. Wind speed was auto-recorded with a hand-held anemometer during the measurement.

2.3. Estimate of CO₂ Efflux from Aquaculture (Including Shellfish) Ponds in China

CO₂ efflux from aquaculture ponds was extrapolated by a combination of our measured efflux with the recorded total aquaculture/shellfish pond area in China. Data of marine aquaculture/shellfish pond area in China over the past 30 years were collected and collated from the *China Fisheries Yearbook* (1984–2020) [25] (Figure 2). The loss of mangrove forests in some provinces such as Guangdong may be exclusively attributed to aquaculture development over the last 20 years [26]. The average CO₂ efflux was estimated as the mean of dark and light efflux, based on an assumed average 12:12 light:dark period. These data were used to estimate the variation of CO₂ efflux from aquaculture/shellfish ponds in China over time, concomitant with the expansion of mariculture into mangrove forests, as well as to predict CO₂ efflux in 2050. CO₂ efflux from aquaculture/shellfish ponds in 2050 was estimated according to two scenarios. The first scenario is based on the temporal increase of pond area since the 1980s and was named the business-as-usual scenario, while the second scenario is based on the recent decrease of pond area since the 2010s and was named the area-shrinking scenario. Mangroves have been lost at a rate of 44% since the 1970s, attributable to aquaculture development in China [10], but there is some sign of area increase (around 13%) due to mangrove restoration programs from 1980 to 2010 [27]. These rates were used to estimate CO₂ efflux from the loss of mangrove forests due to aquaculture expansion, and to analyze the change in CO₂ efflux due to mangrove restoration.

Figure 2. Growth of aquaculture/shellfish pond area in China, 1983–2019. The pond area generally increases at an alarming rate, except for a steep and short decrease between 2006 and 2007 and between 2015 and 2019.

2.4. Data Analysis

Data were tested for normality using the Shapiro–Wilk test, and for homogeneity of variance with a Levene’s test ($\alpha = 0.05$). When the above assumptions were violated, data were logarithmic or square-root transformed. A paired-sample *t*-test was conducted to compare dark and light CO₂ efflux, recorded from the paired chambers. Linear regression was performed between CO₂ efflux and sediment temperature, as well as between shellfish pond area and time. The Monte Carlo method was employed to propagate uncertainties in CO₂ efflux. All statistics were run using the R programming language [28]. The R library “car” was employed to test the homogeneity of variance. Deviation of the data is expressed as the standard error (SE). The data were presented as mean $\pm$ SE.

3. Results and Discussion

3.1. CO₂ Efflux Variation with Temperature and Light Conditions

Average CO₂ dark efflux from the sediment–air interface was 2.46 ± 0.27 g CO₂ m^{−2} d^{−1} ($= 56.0 \pm 6.13$ mmol m^{−2} d^{−1}), while the average light efflux was 1.66 ± 0.22 g CO₂ m^{−2} d^{−1} ($= 37.7 \pm 4.89$ mmol m^{−2} d^{−1}) across all the shellfish ponds. Sediment CO₂ dark efflux is significantly higher than light flux (paired-sample *t*-test, $p = 0.011$).

Average CO₂ dark and light effluxes from the adjacent natural mangroves that were devoid of aquaculture wastewater were 1.80 ± 0.18 g CO₂ m^{−2} d^{−1} ($= 41.01 \pm 4.15$ mmol m^{−2} d^{−1}) and -0.18 ± 0.20 g CO₂ m^{−2} d^{−1} ($= -4.21 \pm 4.54$ mmol m^{−2} d^{−1}) over the same period. However, the dark and light efflux from the adjacent natural mangroves receiving aquaculture wastewater were 3.21 ± 0.25 g CO₂ m^{−2} d^{−1} ($= 73.02 \pm 5.76$ mmol m^{−2} d^{−1}) and 0.15 ± 0.34 g CO₂ m^{−2} d^{−1} ($= -3.48 \pm 7.83$ mmol m^{−2} d^{−1}).

Our study suggests that CO₂ dark efflux was significantly higher in comparison with light efflux. Settled phytoplankton are abundant in the shellfish ponds since they are the primary food for *Sinonovacula constricta*. The abundance of microphytobenthos may also be high on the sediment surface, as a result of the nutrient enrichment typical of this culture system. The level of sediment chlorophyll in the adjacent mangrove forest was high (mean 78.3 ± 0.5 μ g g^{−1}, range 31–124 μ g g^{−1} (Lee et al., unpubl. data)). The high microalgal abundance would have amplified the dark efflux and its difference from the light efflux. Under dark conditions, microalgae (settled phytoplankton plus the microphytobenthos) in the surface sediment contribute to sediment respiration, while their photosynthesis activity would assimilate CO₂ and reduce efflux under light conditions [29], as has been demonstrated by our data. Our sampling was undertaken in 2015 but the local shellfish

pond area has not decreased, according to recent data [25]. Therefore, the results of our study are valid for estimating CO₂ efflux from local shellfish ponds since that time.

Sediment CO₂ dark flux from shellfish ponds is significantly and positively correlated with sediment temperature ($R^2 = 0.22$, $p < 0.05$, Figure 3a). The relationship is much stronger between light efflux and sediment temperature ($R^2 = 0.87$, $p < 0.001$, Figure 3b). No statistically significant relationships were found between dark CO₂ efflux and average wind speed ($p = 0.892$), as well as light CO₂ efflux and average wind speed ($p = 0.204$).

Figure 3. The linear relationship between CO₂ dark (a) and light (b) efflux and surface sediment temperature. Dark flux shows a weak but significant correlation with sediment temperature ($R^2 = 0.22$, $p = 0.027$) while light flux is very strongly correlated with sediment temperature ($R^2 = 0.87$, $p < 0.001$).

Sediment CO₂ efflux from the shellfish ponds showed a consistent positive correlation with temperature under both dark and light conditions in our study. In particular, the slopes of the linear relationships between dark or light CO₂ efflux and temperature are 2.6 and 2.5, respectively, thereby reflecting the similar dependence of dark/light sediment respiration on temperature. Given a rise of 1 °C in sediment temperature, average dark and light CO₂ efflux from the ponds will increase from 41.52 and 36.22 mmol m⁻² d⁻¹ to 44.12 and 38.72 mmol m⁻² d⁻¹, respectively, based on the relationships between CO₂ efflux and temperature. This corresponds to the 6.56% increase in average daily CO₂ efflux from the ponds. Temperature is a critical factor in determining coastal sediment respiration [30,31]. Increases in temperature may stimulate microbial activities, contributing to C mineralization, resulting in increased sediment decomposition rates and, thereby, CO₂ efflux [32]. As our measurements were made in spring, which has intermediate temperatures with respect to the annual range, our data are expected to be close to the annual average efflux.

3.2. Sediment CO₂ Efflux from Aquaculture/Shellfish Ponds in China

Our extrapolated result indicates that the lower end of total CO₂ efflux from shellfish ponds ranged from 0.3 Tg yr⁻¹ to 4 Tg yr⁻¹, whereas the higher end varied between 1 Tg yr⁻¹ and 12 Tg yr⁻¹ during the period from 1983 to 2019. Likewise, total CO₂ efflux from aquaculture ponds varied from 0.5–2 Tg yr⁻¹ to 6–20 Tg yr⁻¹ from 1983 to 2019 (Figure 4), based on average CO₂ efflux (1.06 kg CO₂ m⁻² yr⁻¹) from different aquaculture ponds in China (Table 1). Taking into account a conversion rate of 44%, CO₂ efflux as a result of mangrove forest loss due to its replacement with shellfish ponds was 2–5 Tg, while replacement by aquaculture ponds was 3–9 Tg in 2019.

The area of shellfish ponds has been increasing almost continuously since the 1980s ($R^2 = 0.92$, $p < 0.001$, Table 2). Similarly, the area of an aquaculture pond is positively correlated with time ($R^2 = 0.94$, $p < 0.001$). However, the area of shellfish ponds has decreased and is negatively correlated with the passage of time since 2011 (2012) ($R^2 = 0.59$, $p < 0.05$), as is the area of an aquaculture pond ($R^2 = 0.63$, $p < 0.05$). We used the regression relationship between pond area and the passage of time since the 1980s to propagate CO₂ efflux from shellfish (aquaculture) ponds as scenario 1, and the relationship since the 2010s as scenario 2. Average CO₂ and all greenhouse gas efflux (including CO₂, CH₄ and N₂O) from aquaculture ponds in China reached 1.06 kg CO₂ m⁻² yr⁻¹ and 9.76 kg CO₂-eq m⁻² yr⁻¹, respectively (Table 1). Following the above propagation approach, CO₂ efflux from shellfish and aquaculture ponds converted from mangroves in China is expected to reach 8–29 and 18–64 Tg yr⁻¹, respectively, in 2050 under scenario 1 but only 0.3–1 and 3–10 Tg yr⁻¹, respectively, in 2050 under scenario 2. Similarly, all greenhouse gas efflux from aquaculture ponds are expected to reach 169–593 Tg yr⁻¹ in 2050 under scenario 1 but 28–97 Tg yr⁻¹ under scenario 2.

Figure 4. Estimated CO₂ release from shellfish (a) and aquaculture (b) ponds in China, 1983–2019. The propagation method indicates a CO₂ emission range from shellfish (aquaculture) at 4–12 Tg yr⁻¹ (6–20 Tg yr⁻¹) in 2019, much higher than that of 0.3–1 Tg yr⁻¹ (0.5–2 Tg yr⁻¹) in 1983. The lower and upper hinges correspond to the first and third quartiles, i.e., 25th and 75th percentiles, respectively. The lower and upper whiskers correspond to the lowest and highest values within 1.5 times of the interquartile ranges from the first and third quartiles, respectively.

Table 1. Greenhouse gas fluxes from marine aquaculture ponds in China. Global warming potentials of 45 and 270 for CH₄ and N₂O were used to transform CH₄ and N₂O efflux, and to estimate greenhouse gas flux, at kg CO₂-eq m^{−2} yr^{−1}.

Type of Ponds	Location	CO ₂ Efflux (kg CO ₂ m ^{−2} yr ^{−1})	CH ₄ Efflux (kg CH ₄ m ^{−2} yr ^{−1})	N ₂ O Efflux (kg N ₂ O m ^{−2} yr ^{−1})	References	Remarks
Shrimp	Mariculture base at Qingdao, China	-5.69×10^{-3}	5.70×10^{-4}	NA	[33]	Pond with feed supply
Shrimp—sea cucumber		1.12×10^{-2}	6.80×10^{-5}	NA		Pond without feed supply
Shrimp	Shanyutan Wetland, China	−0.16	0.2	NA	[34]	
Shrimp	Min River Estuary, China	0.56	NA	NA	[35]	
Shrimp	Jiulong River Estuary, China	0.48	NA	NA		
Shrimp	Shanyutan Wetland, China	0.12	5.70×10^{-4}	0	[36]	Measured during pre- and post-typhoon periods
Shrimp	Shanyutan Wetland, China	13.11	3.7	1.23×10^{-4}		Measured during typhoon
Shrimp	Min River Estuary, China	0.15	0.75	NA	[37]	
Shrimp	Jiulong River Estuary, China	0.13	0.08	NA		
Shrimp	Shanyutan Nature Reserve, China	2.89	0.92	7.52×10^{-3}	[38]	Drained ponds
Shrimp	Shanyutan Nature Reserve, China	0.19	0.1	3.85×10^{-6}		Undrained ponds
Clam	Yunxiao, China	0.76	NA	NA	This study	
All	China	1.06 (mean) 0.19 (median)	0.49 (mean) 0.15 (median)	2.52×10^{-3} (mean) 6.15×10^{-5} (median)		Greenhouse gas flux: 9.76 kg CO ₂ -eq m ^{−2} yr ^{−1} (mean); 2.66 kg CO ₂ -eq m ^{−2} yr ^{−1} (median)

Table 2. Relationships between shellfish/aquaculture pond area and the passage of time under different scenarios.

Pond Type	Scenario	Regression Relationship	Statistical Parameters
Shellfish	Business-as-usual	Pond area = $42.8 \times \text{Year} - 84,776.2$	F value = 398.9, R ² = 0.92, $p < 0.001$
	Area shrinking	Pond area = $76,907.7 - 37.5 \times \text{Year}$	F value = 9.9, R ² = 0.59, $p = 0.016$
Aquaculture	Business-as-usual	Pond area = $65.3 \times \text{Year} - 129,300$	F value = 600.1, R ² = 0.94, $p < 0.001$
	Area shrinking	Pond area = $86,133.6 - 41.7 \times \text{Year}$	F value = 10.1, R ² = 0.63, $p = 0.019$

Our results suggest that the calculated CO₂ efflux from aquaculture ponds in China has increased remarkably during the past 30 years. Both the lower and higher ends of flux in 2019 are an order of magnitude higher than those in 1980. Our estimated CO₂ efflux from shellfish ponds in 2019 (4–12 Tg yr^{−1}) is also comparable to CO₂ efflux from shrimp ponds in Indonesia (6–14 Tg yr^{−1}) [16]. CO₂ efflux from aquaculture ponds is well within the above efflux range of mangrove deforestation. This is another example of how resource management policy in the world's most populous country could influence the global environment. However, the overall area of mangroves in China has increased by 13% in the period from 1980 to 2010 [27] owing to mangrove restoration initiatives. Mangroves are known to be more efficient in carbon sequestration compared with terrestrial ecosystems [32] but the change in CO₂ efflux due to mangrove restoration depends on the land use types before they are restored. Furthermore, it is necessary to develop a temporal trajectory of the sediment CO₂ flux from mangrove seedlings to mature mangroves [39].

3.3. CO₂ Efflux Compared with Other Land Uses Transformed from Tropical Wetlands

Sediment CO₂ efflux in our study is comparable to reported efflux from land converted from mangroves and peatlands. In reported CO₂ efflux from deforested mangroves, our estimated CO₂ efflux (0.61–0.90 kg CO₂ m^{−2} yr^{−1}) is lower than the flux (1.60–10.60 kg CO₂ m^{−2} yr^{−1}) from mangrove forest converted to shrimp ponds or mangrove clearing [40]. Other studies have reported CO₂ efflux from land converted from tropical peatlands (Table 3). The CO₂ efflux in our study is close to the lower limit among

flux from these converted land uses ($0.75\text{--}9.4\text{ kg CO}_2\text{ m}^{-2}\text{ yr}^{-1}$), including paddy fields, cassava fields, rice–soybean rotation fields, sago and oil palm plantations, and pulpwood plantations. Other anthropogenic activities may also affect CO_2 efflux from mangroves. From mangrove forests, local communities may obtain fish, gastropods and crustaceans that contribute to CO_2 efflux from the sediment surface [29]. Other disturbances may destroy mangrove forests and affect CO_2 efflux from mangroves, including the historical development of urban centers, reclamation, silviculture, salt extraction and charcoal production [21,41].

Table 3. CO_2 from land uses in relation to (sub) tropical wetland loss.

Type of Conversion	Location	CO_2 Efflux ($\text{kg CO}_2\text{ m}^{-2}\text{ yr}^{-1}$)	Reference
Clam ponds	Fujian, China	0.61 (light) 0.90 (dark)	This study
Shrimp ponds	Bali, Indonesia	1.60–4.37	[16]
Mangrove clearing	Belize	2.90–10.60	[40]
Sago palm plantation	Riau, Indonesia	0.77–4.82	[42]
Pulpwood plantation	Sarawak Malaysia	1.1	[43]
	Sumatra, Indonesia	9.4	[44]
	Jambi, Indonesia	0.96	[45]
Paddy field	Kalimantan, Indonesia	1.4	[46]
	South Kalimantan, Indonesia	1.2–1.5	[47]
Cassava field	Jambi, Indonesia	6.42	[45]
	South Asia	0.75–1.10	[48]
Oil palm plantation	Sarawak Malaysia	1.1	[43]
Rice–soybean rotation field	Kalimantan, Indonesia	2	[46]

3.4. Pond CO_2 Efflux Compared with Mangrove Forests

CO_2 effluxes from converted and unconverted mangroves reported herein are close but higher than the average reported CO_2 efflux in the literature. Both average CO_2 dark and light efflux from shellfish ponds (2.46 and $1.66\text{ g CO}_2\text{ m}^{-2}\text{ d}^{-1}$) are higher than the adjacent natural mangroves without the influence of aquaculture wastewater (1.80 and $-0.18\text{ g CO}_2\text{ m}^{-2}\text{ d}^{-1}$), while average dark efflux is lower but light efflux is higher from shellfish ponds than those from the adjacent natural mangroves with the influence of aquaculture wastewater (3.21 and $-0.15\text{ g CO}_2\text{ m}^{-2}\text{ d}^{-1}$) (Lee et al. (unpubl. data)). Bouillon, et al. [49] reported that the dark fluxes from mangrove sediments averaged at $61\text{ mmol m}^{-2}\text{ d}^{-1}$ ($= 2.68\text{ g CO}_2\text{ m}^{-2}\text{ d}^{-1}$), while mean light fluxes reflected a net uptake of CO_2 at $-15\text{ mmol m}^{-2}\text{ d}^{-1}$ ($= -0.66\text{ g CO}_2\text{ m}^{-2}\text{ d}^{-1}$). Our measured dark fluxes from shellfish ponds are therefore 0.4 times higher than the measured fluxes from adjacent mangroves that are devoid of aquaculture wastewater but are 0.3 times lower than the measured fluxes from adjacent mangroves receiving aquaculture wastewater, comparable to these global averages. In contrast, under light conditions, there is a net CO_2 emission from shellfish ponds but CO_2 assimilation from the adjacent mangroves devoid of aquaculture wastewater, and from the global data. Combining dark and light fluxes, CO_2 effluxes from shellfish ponds are 1.54, 0.23 and 1.03 times higher than both the adjacent mangroves devoid of and receiving aquaculture wastewater, and global averages. As far as shellfish ponds are concerned, the notably high CO_2 efflux in this study may be primarily attributed to the high nutrient loading resulting from fertilizers added to stimulate phytoplankton bloom in the fodder ponds [23] and thereafter flushed into the shellfish ponds. As for the natural mangroves receiving aquaculture wastewater, CO_2 efflux is also rather high due to the high organic material and nutrient input [22] from adjacent aquaculture pond effluent during the tidal exchange. The sediment (%N) recorded in a parallel study in the mangrove forest ranged between 0.109 and 0.273% dry weight (Lee et al. (unpubl. data)). This hypothesis is confirmed by a study on shrimp farming [50], where the

authors suggested that mangrove sediment CO₂ efflux, influenced by the wastewater of shrimp ponds, was almost five times higher than that from areas unaffected by wastewater. Microbial respiration is promoted by the addition of nutrients in pond effluents.

Another significant process enhancing sediment respiration is the frequent physical disturbance caused by fishing activities in the ponds. Razor clams are sessile deep burrowers and are usually collected by hand, by fishermen traversing the sediment during draw-down periods. This disturbance increases sediment respiration by increasing the effective area of the sediment–air interface, as well as causing the exposure of organic matter stored in the deep sediment layers to oxidizing conditions.

3.5. Uncertainties and Implications

In this study, we have assumed that emissions from shrimp and razor clam production ponds are typical of other aquaculture operations developed from mangrove forest conversion in China. This is of course a big assumption, as different target species will involve dissimilar management protocols as well as different degrees of disruption of natural mangrove C biogeochemistry. Finfish aquaculture, for example, involves less frequent aerial exposure of the bottom sediment but a higher environmental C loss rate due to low feed-use efficiency and higher waste generation. Shrimp ponds usually operate with less fertilization, a lower percentage of sediment aerial exposure, or physical disturbance of the substrate, but they often still demonstrate heavy feed input. Razor clams are filter-feeders that need lower levels of organic matter and nutrients in comparison with fish and crabs. The different feeding habits of animals may influence their respired CO₂ flux [51]. Extreme weather events, e.g., typhoons, were found to lead to a significant increase in CO₂ and other greenhouse gas flux from shrimp ponds and mangroves [36,52]. A full picture of the consequences of mangrove conversion would only be possible with operation-specific emission data being available and uncertainties clarified resulting from other factors, e.g., extreme weather events. Our study focuses on the changes in CO₂ efflux arising from the conversion of mangrove forests to aquaculture ponds. The impact of other anthropogenic activities may also drive changes in CO₂ efflux from mangroves but does not fall in the scope of our study.

Our estimation raises concerns on mangrove management in countries where competing services, such as food production and emission reduction, threaten mangrove ecosystems. Until 2019, CO₂ efflux from shellfish ponds converted from mangroves in China was 2–5 Tg, not counting the fluxes from mangrove clearing and land disturbance during pond establishment. The current estimated C stocks of mangroves in China (6.9 Tg C) [53] are close to the higher end of the range of our estimated C efflux. Nevertheless, CO₂ released from shellfish ponds is far beyond our estimate if indirect CO₂ emissions are considered; the conversion of mangroves to shellfish ponds also indirectly promotes CO₂ emission from adjacent natural mangroves, as mirrored by the high CO₂ efflux from mangroves receiving aquaculture effluent in our study. Mangroves are known to fulfill a regulating function by tuning the local microclimate. The conversion of mangroves to shellfish ponds not only increases CO₂ efflux but may also counteract the microclimate-regulating effect of mangroves for the local communities. The expansion of shellfish ponds into mangrove areas must be managed as part of a comprehensive strategy to conserve the tropical shorelines of China since any effort to protect mangroves will be easily offset by uncontrolled aquaculture pond development, particularly when carbon-rich, mature landward forests are considered for conversion into high-emission aquaculture ponds.

4. Conclusions

The tested CO₂ efflux from shellfish ponds converted from mangroves in China revealed high levels of dark and light CO₂ efflux from these ponds (0.61 and 0.90 kg CO₂ m^{−2} yr^{−1}, respectively; equivalent to 37.67 and 56.0 mmol m^{−2} d^{−1}) compared with reported fluxes from land converted from tropical wetlands. These effluxes are comparable to effluxes from adjacent natural mangroves that are receiving aquaculture

wastewater. Both fluxes were positively correlated with sediment temperature, and the rise of 1 °C in sediment temperature corresponds to the 6.56% rise in CO₂ efflux from the ponds. CO₂ efflux from shellfish ponds soared from 0.3–1 Tg yr^{−1} in 1983 to 4–12 Tg yr^{−1} in 2019, and given the historical trend, is expected to hit 8–29 Tg yr^{−1} under the business-as-usual scenario but around 30 times lower (0.3–1 Tg yr^{−1}) under an area-shrinking scenario by 2050. In 2019, the flux resulting from mangrove conversion was 2–5 Tg, the C content of which approaches that of the total mangrove C stocks in China. When propagated to marine aquaculture ponds in China, the estimated CO₂ efflux is ~30% higher than that of shellfish ponds.

For the first time, in this study, we estimated the impact of mangrove conversion to aquaculture ponds on CO₂ efflux in China. The restoration of mangroves from aquaculture ponds in China was highlighted as a way to increase carbon storage without accounting for reduced CO₂ efflux [54], as demonstrated by our study. This study underscores the importance of mangrove conservation from the perspective of the “blue C” budget policy in China. As the lifespan of aquaculture ponds is limited, we echo calls for climate mitigation strategies (e.g., REDD+) to include mangrove restoration from abandoned mariculture ponds [55] where possible, in subtropical regions such as southern China. Ecologically sustainable aquaculture [56], without the need to invade mangroves, should be a priority consideration.

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