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Inland saline aquaculture increased carbon accumulation rate and stability in pond sediments under semi-arid climate

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Abstract

Purpose: Similar to fresh- and brackish water aquaculture ponds, commercial shrimp farming in degraded saline areas holds the potential to bury carbon (C) in the sediments. However, studies on the mechanisms of sediment C dynamics and C-flux in response to inland saline aquaculture management practices are still scarce. Therefore, the objectives of the present study are to quantify the C burial rate in inland saline aquaculture ponds and assess the impact of inland saline aquaculture on sensitive C fractions in the bottom sediment of the ponds.

Materials and methods: The sediment samples ($n = 12$ from each pond) were collected from six shrimp farming ponds (1000 m^2 area of each pond) of different ages. The sediment depth, sediment accumulation rate and the levels of total carbon (TC), total organic carbon (TOC) and sediment oxidizable organic carbon (SOC) and its different fractions were determined using standard procedures. The data were analysed by one-way analysis of variance (ANOVA), followed by the Duncan's multiple range test for comparing the means, and the Pearson correlation test was used to assess the relationship between the different pond sediment parameters and SOC content.

Results and discussion: The results revealed that the annual C accumulation rates varied from 902 to 1346 kg C ha^{-1} $year^{-1}$ in 7-year-old earthen ponds (EPs) and bottom cemented ponds (BCPs), respectively. The sediment C fractions, including TC, TOC, SOC and its fractions (very labile, VLc; labile, Lc; less labile, LLc), and non-labile carbon (NLc)) were progressively increased over the pond age. The inland saline aquaculture practices over the years increased both active (AC) and passive carbon (PC) pools in the pond sediments, helped in the restoration and improvement of sediment quality and enhanced C sequestration potential of the sediments. Furthermore, a significant increase in the level of particulate organic carbon (POC) in BCPs justified that the non-ploughing practices at BCPs facilitated the formation of macro- and micro-aggregates, thereby increasing the C retention and stability of the pond sediments.

Conclusion: This study suggested that the shrimp farming ponds in semi-arid saline soils represented considerable C burial hotspots, enhanced the stable passive C pools and improved the sediment quality.

Keywords: Carbon accumulation, sensitive C fractions, Particulate organic carbon, Shrimp farming, aggregate formation, Active and Passive C pools.

1. Introduction

Soil salinization is a major land degradation problem affecting crop productivity worldwide (Moreira et al. 2020). Globally, saline soils cover an area of 954 million hectares (Mha) and account for 7-9% of agricultural productivity loss (Meena et al. 2019; Mukhopadhyay et al. 2020). In India, a total 6.73 Mha area is affected by soil salinization, comprising 3.77 and 2.96 Mha sodic and saline soils, respectively (Sharma et al. 2020).

Inland saline aquaculture is widely practiced to utilize degraded saline soils and saline groundwater in the USA, Israel, India and Australia for generating income through enhanced production of euryhaline, shrimp and marine fish species with high growth potential (Allan et al. 2009; Singha et al. 2020). Inland saline aquaculture ponds cover 650 ha area in India, and is projected to be increased further in the near future.

Freshwater and brackish water aquaculture ponds together cover 0.79 Mha in India, and have an enormous potential to bury carbon (C) in sediments (Adhikari et al. 2012, 2019). Globally, aquaculture ponds cover an area of 11.1 Mha and accumulate an estimated 16.6 million tons C per year (MT yr^{-1}) (Boyd et al. 2010). Similarly, the C accumulation rate in

0.79 Mha of aquaculture ponds of India could vary from 0.6 to 1.2 tera gram (Tg) C yr^{-1} (Adhikari et al. 2012). Although similar cultural practices are followed in inland saline aquaculture (shrimp farming) over a wide range of areas in the world, the saline sediments pose different physico-chemical and biological properties due to different geological origins of the sediments and climato-ecological conditions (Partridge 2008; Raul et al. 2021). These saline sediments differ in their physico-chemical and biological properties, including higher sediment electrical conductivity (EC), higher bulk density and higher porosity, less SOC, poor nutrient content and availability, and pose higher salt-stress on sediment microorganisms and enzyme activities (Mukhopadhyay et al. 2020; Basak et al. 2021; Raul et al. 2021). Therefore, quantification of the rate of sediment C accumulation in inland saline shrimp farming ponds is much needed.

In addition, the proportion of different bottom sediment C fractions evolving in response to land-use changes could be applied as a useful tool to identify desired management practices that potentially protect C stock in the soil. Thus, the quantification of shrimp aquaculture pond sediment oxidizable organic carbon (SOC) pool is essential to understand the changes in the sediment C dynamics and C-fluxes from the shrimp aquaculture ponds. Depending on the residence time, the soil organic carbon is categorized into active (AC) and passive carbon (PC) pools (Chan et al. 2001). The AC pool constitutes the easily oxidizable C with a residence time of less than five years, while the fractions of higher residence time than AC are categorized as PC pools (Ramesh et al. 2019). Additionally, some of the critical labile pools such as particulate organic carbon (POC), permanganate oxidizable carbon ($KMnO_4$-C), microbial biomass carbon (MBC) are widely used as the most sensitive indicators to assess the effect of different agricultural management practices on the levels of soil organic carbon and soil quality (Chen et al. 2016a; Duval et al. 2018; Thangavel et al. 2018).

Among all the C fractions, POC is the most sensitive C fractions for assessing the management-induced changes in the levels of soil organic carbon, and poses a significant relationship with soil physical properties and agronomic productivity (Duval et al. 2018). However, till date no report is available that has assessed the impact of aquaculture management practices on the levels of SOC and sediment quality. Thus, an understanding on the changes in the labile C fractions in pond sediments in response to aquaculture management practices are important to address the concern about maintaining and restoring sediment quality and sustainable shrimp biomass production.

The carbon accumulation rates in different aquaculture ponds with different cultural practices have been quantified (Adhikari et al. 2012, 2019; Kunlapapuk et al. 2019), but options for different inland saline aquaculture farming systems have not been studied yet. Moreover, mechanisms and understanding on the changes of labile sediment C fractions in response to other management practices such as ploughing, liming, manuring and feeding in inland saline aquaculture systems are required for maintaining and restoring bottom sediment organic matter (SOM) to achieve good quality sediment. Keeping the above views, the present study was formulated to: (a) quantify C burial rate in inland saline aquaculture ponds, and (b) assess the impact of inland saline aquaculture on sensitive C fractions in the bottom sediment of the ponds.

2. Materials and methods

2.1 Study area and shrimp pond systems

The study area comprised of six inland saline shrimp farming ponds in Rohtak, Haryana, India (28.8618° N, 76.4747° E). These ponds were managed by the ICAR - Central Institute of Fisheries Education, Rohtak, Haryana, India. The Pacific White shrimps (*Litopenaeus vannamei*) were cultured in these ponds for 5-8 years. The mean annual temperature of the region is 31.8°C with an average rainfall of 597 mm, and much of the rain received during June to September. The experimental pond sediments (0-15 cm depth) were sandy loam in texture. Among six sampling ponds three earthen ponds (EPs) and three bottom cemented ponds (BCPs), having a 1000 m^2 area (50×20 m^2) were selected for the study. The EPs were excavated earthen ponds and completely constructed from sediment materials, whereas BCPs were earthen type ponds with bottom layer lined with a layer of cement (10-15 cm thick) and a layer of sediment (10-15 cm) to control the seepage loss of water.

2.2 Shrimp pond management

The sediment cores were collected from six shrimp farming ponds of known age. The pond descriptions are listed in Table 1. Since the optimal requirement of temperature for shrimp (*Litopenaeus vannamei*) culture is 22 to 35°C, shrimp production in these ponds took place between July to October (3-4 months), with only a single production cycle per annum. A water level of 1.5-2.0 m was maintained in the ponds for 3-4 months during the shrimp production (July – October), and then 90% water of the ponds was drained up during harvest (November-December). The remaining 10% water was drained before the onset of the new culture cycle (May). Overall, the pond sediments remained completely dry for only one month during May just before the onset of the new culture cycle.

With the start of the new production cycle, the ponds were drained and dried for one month following the standard practices to remove pathogenic organisms and obnoxious gases (Kumar et al. 2013; Abraham et al. 2020). Additionally, ploughing was carried out at EPs after drying the ponds, and then water was filled by pumping saline groundwater in all the ponds up to a height of 1.5- 2.0 m. An organic fertilizer (fermented rice bran (*Oryza sativa*)), was prepared by mixing rice bran, yeast and water overnight (Adhikari et al. 2012), and applied at the rate of 250 kg ha^{-1} to all the ponds one week before releasing the shrimp seeds into the ponds. The shrimp seeds were stocked at the rate of 35-40 numbers m^{-2} at 05:00-07:00 AM after acclimatizing for 30 min in pond water. Shrimps were fed with artificial feeds containing a minimum level of 35% crude protein and 35-40% C (on a dry weight basis). Feeding was carried out by applying three different feeds, i.e., starter feed, grower I, and grower II feeds of having different pellet sizes and shapes (Table S1). The feeds were provided based on the total expected biomass weight of the shrimps at each pond. The timelines of feeding were 6:00 AM, 10:00 AM, 2:00 PM, and 6:00 PM during each day. In each pond, one 1500 W paddlewheel aerators were operated twice a day, 4:00-8:00 AM and 18:00-22:00 PM, to maintain the dissolved oxygen levels at above 5 ppm in the water. The water (pH = 8.37±0.1) chlorophyll-a concentration was estimated routinely using a UV-visible spectrophotometer (Hack DR6000^{TM}, USA) following the method of (Suzuki and Ishimaru 1990), and the average values are listed in Table 1.

2.3 Collection and analysis of sediment samples

Four sampling sites in each pond (total 6 ponds) were selected based on the adopted feeding locations and aerator's positions (Fig. 1). From each sampling site, three intact sediment cores were collected manually (total 12 samples from each pond) using a metallic core of 7.5 cm inner diameter and 15 cm length, according to the methodology described by Steeby et al. (2004). The sediment depth of EPs was determined using the method suggested by (Steeby et al. 2004). The transparent plastic core sampler was slowly inserted into the pond sediment until the marked resistance indicated that contact with the original compact soil was made. Once the sediment core was collected, the sediment depth was determined by measuring the point of top layer of sediment to the point on the lower boundary, where lighter parent pond sediment could be distinguished from the darker accumulated sediment. Later on, all 12 sediment cores collected from each pond were mixed to make a single composite sample representing individual pond, and were stored temporarily at 4°C. A portion of the core samples was oven-dried at 105°C for 48-72 h, and the sediment dry bulk density (BD) was computed and expressed as Mg m^{-3} (Kadam et al. 2005). A part of the air-dried, pulverized and sieved sediment sample was analysed for SOC using the dichromate oxidation technique by rapid titration method (Walkley and Black 1934). The rate of C accumulation in the pond sediment was estimated using Eq. 1 (Boyd et al. 2010; Adhikari et al. 2012, 2019):

Rate of C accumulation in sediment = [sediment BD × sediment accumulation rate × SOC (%)] (Eq. 1)

The relevant sediment physicochemical parameters were analysed using the standard American Society for Testing Materials (ASTM D-2216-05, 2008) (Table S2). Triplicate sub-samples were analysed from each of the composite sediment samples. Total carbon (TC) and total nitrogen (TN) levels (g kg^{-1}) in the sediment samples were analysed by dry combustion method on a CHNS elemental analyser (Perkin Elmer, 2400 Series II CHNS/O, USA) (Nelson and Sommers 1996). Total organic carbon (TOC) was analysed by acid fumigation (Harris et al. 2001) followed by dry combustion method using the CHNS elemental analyser (Perkin Elmer, 2400 Series II CHNS/O, USA) (Nelson and Sommers 1996). Different fractions of SOC comprising of very labile (VLc), labile (Lc), less-labile (LLc) and non-labile (NLc) carbon were determined using sulphuric acid (H_2SO_4) aqueous solution ratios of 0.5:1, 1:1, and 2:1 (corresponding to 12 *N*, 18 *N*, and 24 *N* H_2SO_4) (Chan et al. 2001). The VLc fraction was determined by oxidizing with 12 *N* H_2SO_4; Lc fraction was determined by calculating the difference between SOC extracted between 18 *N* and 12 *N* H_2SO_4; LLc fraction was determined by calculating the difference between SOC extracted between 24 *N* and 18 *N* H_2SO_4; NLc fraction was calculated from the difference between

TOC and SOC oxidized with 24 *N* H_2SO_4. Among the SOC fractions, VLc and Lc are AC pools, while LLc and NLc are PC pools. The POC level was determined by calculating the difference between the SOC of the whole sediment and SOC of particles that passed through 53 µm sieve (Cambardella and Elliott 1992).

2.4 Statistical analysis of data

The experimental design was a completely randomized design (CRD) with a total sample size of 12 (n=12) from each pond. The SPSS version 19.0 (SPSS Inc., USA) analytical software package was used for all the statistical analysis of data. The data were analyzed by one-way analysis of variance (ANOVA), followed by Duncan multiple range test at a 5% level of significance for comparing the means. Pearson correlation was used to assess the relationship between the different pond sediment parameters and sediment oxidizable organic carbon (SOC), and significant correlations were identified at 95% and 99% confidence level of intervals. The results were presented as mean ± standard error, and all the statistical plots were generated using Origin Pro 8.5 software package (OriginLab Corp. USA).

3. Results and discussion

3.1 Role of shrimp pond types on sediment carbon contents

The sediment depth varied from 9.05 ± 0.8 cm in 5 year old EP to 13.6 ± 1.4 cm in 8 year old BCP (Table 2). The ponds were drained and dried before starting a new production cycle; thereby, a considerable amount of sediment was lost through runoff (Boyd et al. 2010; Adhikari et al. 2012). The sediment depth was strongly correlated with the pond age (r = 0.96, $p < 0.01$). The sediment accumulation rate in these ponds varied from 1.57 to 1.87 cm year^{-1} (Table 2), and it declined with the pond age (r = -0.76, $p < 0.05$). Boyd et al. (2010) and Steeby et al. (2004) also observed a decline in sediment accumulation rate as the aquaculture age increased for ponds in Thailand and Mississippi (USA), respectively. The sediment accumulation occurred due to accumulation of unconsumed feeds, fertilizers/organic manures, algae and algal-related organic matter at the pond sediment (Flickinger et al. 2020; Türk Çulha and Karaduman 2020; Junior et al. 2021). In the present study, the higher input of fertilizers (25 kg pond^{-1} year^{-1}) and feed (220 kg pond^{-1} year^{-1}) could be the major reason for the higher sediment accumulation in these ponds. Moreover, the higher sediment accumulation rate at younger aged ponds might be associated with higher levees erosion at the younger ponds (Steeby et al. 2004). This could also be related to the increased primary production when considering the higher chlorophyll-a concentration (Table 1) in 5 years old ponds than 8 years old earthen ponds (Ramos e Silva et al. 2017; Junior et al. 2021).

The BD of the pond sediments ranged from 0.97 to 1.14 g cm^{-3}, and was negatively correlated with pond age (r = -0.58, $p < 0.05$) and sediment depth (r = -0.73, $p < 0.01$) (Table 3). In addition, BD also showed a significant negative correlation with SOC concentration (r = -0.77, $p < 0.01$) (Table 3). The negative relationship between BD and SOC concentration was mainly attributed to the likely conversion of some micropores into large macropores due to the cementing action of polysaccharides and organic acids formed during the decomposition of SOM (Brar et al. 2013). The SOC concentration gradually increased over the years of the culture period, with the lowest concentration of 0.48% in 5 years old EP to 0.80% in 7 years old BCP (Table 2). The observed SOC concentrations were lower than the values reported by Adhikari et al. (2019) in the sediments of freshwater aquaculture ponds of Andhra Pradesh, India. However, the values were similar to values reported by Anikuttan et al. (2016) (0.32-0.91%) in the sediments of freshwater aquaculture ponds of Orissa, India.

Noteworthy that the SOC concentrations in aquaculture ponds may vary on several factors including pond age, primary productivity, climato-ecological and hydrological conditions, and aquaculture practices (Boyd et al. 2010; Adhikari et al. 2012; Chen et al. 2016b; Flickinger et al. 2020; Junior et al. 2021).

The carbon accumulation rate in the pond sediment varied from 902 kg C ha^{-1} year^{-1} in 7 years old EP to 1346 kg C ha^{-1} year^{-1} in 7 years old BCP, respectively (Table 2). The carbon accumulation rate at BCPs was 7% and 49% higher than EPs of 5 years and 7 years old ponds, respectively. Our results corroborated with the previous results in shrimp culture ponds (1099 ± 75 kg C ha^{-1} year^{-1}) of Odisha, India (Adhikari et al. 2012). Similarly, Boyd et al. (2010) observed the similar values in 11 years old shrimp ponds (940 kg C ha^{-1} year^{-1}) at Choluteca, Honduras. However, our observed values were much lower than those reported by Boyd et al. (2010) in 5 years old shrimp ponds (2740 kg C ha^{-1} year^{-1}) of Khao Chakan, Thailand. The feed and fertilizer inputs, and photosynthetic activity (chlorophyll-a, (Table 1)) of phytoplankton might have contributed to the accumulation of SOC in the pond bottom sediment (Chen et al. 2016b; Flickinger et al. 2020). The lower C: N ratio (4.47-6.84) and higher N content (5.64-7.78%) of the shrimp feeds (Table S1) and available C source from the organic wastes could have increased the autotrophic and heterotrophic activities at the pond sediment (Junior et al. 2021; Xu et al. 2016) and resulted in the formation of stable SOC in the pond sediments. The results indicated that the inland saline shrimp farming ponds accumulated a comparable amount of C to the previous reported figures for freshwater and brackish water ponds of India (Adhikari et al. 2012, 2019). Thus, the present study revealed that the conversion of degraded saline soils into shrimp farming ponds could help to accumulate a considerable amount of C over an extended period.

3.2 Effect of aquaculture practices on carbon stock

At 0-10 cm sediment depth, the sediment TC levels varied from 8.7 to 12.96 g kg^{-1} of sediment (Fig.2). The TC levels were 2%, 24%, and 18% higher at 5 years, 7 years, and 8 years old BCPs than EPs, respectively. Among all the ponds, P2 had the most elevated TC levels, whereas P5 had the lowest TC concentration. The TOC levels in aquaculture ponds ranged from 8.17 to 12.04 g kg^{-1} of sediment, accounting for 87 - 98% of the TC stock. The TOC levels in 5, 7, and 8 years BCPs were observed to be relatively higher than respective EPs; however, significantly higher TOC was observed in 7 years old BCP than same age EP. In comparison to the Eps, the BCPs had higher TOC in 5 years and 8 years old ponds likely due to ploughing which significantly affected the distribution and stabilization of SOC, thereby depleted the TOC over a long period of aquaculture practices (Briedis et al. 2012; Bongiorno et al. 2019). The TIC accounted for 2.5-12.5% of the sediment TC levels across the ponds.

The feeding and fertilization of the ponds resulted in higher CO_2 fixation by phytoplankton and increased the TOC and TIC levels of the pond sediment (Chen et al. 2016b; Flickinger et al. 2020; Junior et al. 2021). Anikuttan et al. (2016) reported a lower TOC concentration at unutilized aquaculture ponds than regularly used aquaculture ponds. Flickinger et al. (2020) observed a strong positive correlation between chlorophyll-a content and total suspended solids during sedimentation, and suggested that the primary production was a key process in the aquaculture ponds by absorbing CO_2 from atmospheric and autochthonous sources leading to an increase in TOC levels in the pond sediments. Compared to EPs, the BCPs had 6.1 to 39.7% higher TOC concentration in the pond sediments. The management practices in EPs involved regular ploughing of the pond bottom, which disturbed the distribution and stabilization of sediment aggregates, and exposed SOC to rapid microbial decomposition and subsequently depleted the TOC (Plaza-Bonilla et al. 2014; Prasad et al. 2016). In the present study, the TC and TOC levels were found to progressively increase with pond age (Fig 2), indicating that the aquaculture practice enhanced the C stock in the pond sediments through sediment carbon accumulation. The pond sediment had a pH value around 8.2 ± 0.4 (Table S2), which indicated the possibility of carbonates and bicarbonates of Na^+, Ca^{2+} and Mg^{2+} in the pond sediments (Choudhary and Kharche 2018). This could be the reason of formation of TIC in the pond sediments over the years at the semi-arid study location in India.

3.3 Effect of aquaculture practices on sediment oxidizable organic carbon (SOC) and its fractions

The sediment TOC was further divided into an oxidizable labile fraction and non-labile fraction to assess the impact of aquaculture management practices on SOC. The different SOC fractions significantly ($p < 0.01$) varied with the chrono-sequence, and increased dramatically over the pond age (Table 4). The SOC levels varied from 4.81- 6.19 g kg^{-1} in EPs to 5.17- 8.01 g kg^{-1} in BCPs, accounting for 59- 67% of TOC in the pond sediments, and in all the ponds, SOC progressively increased over the pond age (Table 4). The non-labile fraction of C ranged from 3.36 to 5.31 g kg^{-1} of sediment, contributing 38-44% of TOC levels of the ponds. Previous studies reported that the feed organic C input accounted for 80 to 94% of all C inputs to the SOC, and this could play a significant role in the aquatic C cycle (Flickinger et al. 2020; Zhang et al. 2018). Similarly, Flickinger et al. (2020) reported that the absorption of atmospheric CO_2 by planktons in freshwater aquaculture ponds was approximately 6 to 23 times that of CO_2 emitted to the atmosphere, which was pivotal source of organic C accumulation in the pond sediments (Flickinger et al., 2020; Zhang et al., 2018). High input of atmospheric CO_2 and increased accumulation of C in the pond sediments suggested a rapid conversion of CO_2 by phytoplankton into SOC (Flickinger et al. 2020; Zhang et al. 2020). In the current study, the TC added to each pond through shrimp feeds was 7661- 8487 kg C ha^{-1} pond (Table S1), which could be the major source of SOC into these aquaculture ponds. Also, the feed input provided major nutrients to microorganisms and facilitated the higher atmospheric CO_2 fixation at the pond sediments (Silva et al. 2017; Junior et al. 2021). The rapid conversion of CO_2 by phytoplankton could be observed from the trend of the chlorophyll-a data analysed in the pond water (Table 1), and this could also justify the increased SOC in the pond sediment. Furthermore, the higher bioturbation produced by the shrimps might have exposed more buried organic C to aerobic mineralization and liberation of nutrients to the water column, increasing the photosynthesis and fixation of C at the pond bottom sediments (Green and Boyd 1995; Joyni et al. 2011; Flickinger et al. 2020).

In the sediment samples, the relative magnitude of the different SOC fractions followed the trend: VLc > Lc > LLc, which respectively comprised of about 43-54%, 31-41% and 9-22% of SOC. The increased levels of NLc over the years of shrimp culture was likely due to the non-degradable refractory fractions of algae, algal organic matter, including non-hydrolysable biopolymers (algeanans) (Marin-Batista et al. 2020.; Ras et al. 2011) and antibacterial chlorophyll-derived compounds (e.g., chlorophyllides) (Jewell and McCarty 1971).

Of TOC, active pools (VLc + Lc) constituted 47- 56% of TOC, and were prone to be lost easily (Fig. 3). The PC pools (LLc + NLc) accounted for 40-49% of sediment TC, and 44-53% of TOC of pond sediments (Fig 3, Table S3). In BCPs, the PC pools accounted for 48-53% of sediment TOC levels, whereas it accounted for 44-50% of sediment TOC in EPs. The quantity and quality of added organic matter and the nutrient availability in the ponds governed the concentration of different C pools and C accumulation patterns (Bhardwaj et al. 2019). The relative proportions of AC and PC were dependent upon the availability of nutrients (Nath et al. 2018), and a large portion of passive pools indicated the relative stability of the organic C stock in the system (Sarkar et al. 2015). Since PC pools are less prone to oxidation than AC pools (Sarkar et al. 2015; Nath et al. 2018), the high proportion of PC pools in BCPs indicated the relative stability of SOC in BCPs compared to EPs. Thus, the inland saline aquaculture in degraded saline soils increased both AC and PC pools in the pond sediments, helped in the restoration and improvement of sediment quality, and enhanced the retention and stability of C in the pond sediments.

3.4 Effect of aquaculture practices on particulate organic carbon (POC)

The POC is mainly composed of decomposing plant, animal and microbial residues (Feller and Beare 1997; Yan et al. 2007; Mi et al. 2016). The POC differed statistically between all the aquaculture ponds, and ranged from 0.29 to 4.09 g kg^{-1} (Fig. 3, Table S3). Here, we observed an increasing trend in the concentration of POC from 0.29 to 1.024 g kg $^{-1}$ of sediment in EPs, and the mean POC concentration in BCPs varied from 1.32- 4.09 g kg^{-1}, accounting for 15 to 34% of the TOC levels. The dominant chemical constituents of POC includes phenol, hemicellulose, and microbial and fungal derived xylanase and chitin (Lavallee et al. 2020). The low C: N ratio (4.47-6.84) of shrimp feeds might have facilitated the faster decomposition of SOM, and increased the levels of phenol, hemicellulos, microbial and fungal residues in the pond sediments, thereby facilitating the macro- and micro-aggregate formation (as POC) over time (Mi et al. 2016) . The low level of POC in EPs might be attributable to the intensive management practices employed to the pond sediments, i.e., ploughing once in a year. Ploughing might disrupt both macro- and microaggregates, increase the sediment temperature and aeration, facilitating the release of C from SOM which was otherwise protected in sediment aggregates (Six et al. 1999; Bongiorno et al. 2019). Ploughing could facilitate the incorporation of organic matter into soils, favouring the mineralization of POC by soil microorganisms (Bongiorno et al. 2019; Kan et al. 2020; He et al. 2021). The input of allochthonous organic debris from bottom macrophytes might have reinforced the development and stabilization of micro-aggregates within macro-aggregates of the sediments that would help to protect POC from rapid decomposition in BCPs (Thangavel et al. 2018; Bongiorno et al. 2019; Kan et al. 2020). The SOM added through allochthonous and autochthonous sources could have experienced greater physico-chemical transformation, and then were stabilized in the aggregates through binding on to the mineral surfaces and became biochemically recalcitrant (Krull et al. 2003; Ramesh et al. 2019) in the pond sediments over many years of cultural practices.

4. Conclusions

This study was focussed to evaluate the sediment C accumulation potential and sensitive sediment C fractions of inland saline shrimp farming ponds. The sediment accumulation rate and SOC increased over the years of culture practices with much higher levels in BCPs than EPs. Overall, the SOC accumulation rates in these inland saline shrimp farming ponds ranged from 902 to 1346 kg C ha^{-1} yr^{-1} with maximum accumulation potential was observed in BCPs compared to EPs. Nonetheless, both AC and PC pools increased with pond age, with PC pools were significantly higher in non-ploughed BCPs than EPs. The evaluation of POC revealed that the ploughing practices in EPs disrupted the macro- and micro-aggregates and could have accelerated the decomposition of labile C pools which resulted in lower TOC in EPs. Therefore, the inland saline shrimp farming ponds could act as critical C burial hotspots in semi-arid areas of the world, and over the years of culture, could increase the C stock of the systems, enabling SOC restoration. Further investigations are needed to assess the impact of ploughing, manuring, and feeding practices on changes in the sensitive C fractions and C management indices in the saline aquaculture pond systems.

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Availability of data and material

The data that support the findings of the study are available from the corresponding author upon reasonable request.

Conflict of interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

VKA: Experiment design, execution, sampling and analysis, Manuscript first draft preparation and revisions, VSB: Conceptualization of the research idea, Experimental design and supervision, RM: Co-supervision, Manuscript preparation, improvement and editing, SP: Execution of the experiments, Manuscript editing, VH: Execution of the experiments, GRB: Manuscript editing, GT: Conceptualization of the research idea, GK: Conceptualization of the research idea, BS: Data interpretation, Manuscript preparation, improvement and editing.

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Title of tables

Table 1. Characteristics of different aquaculture ponds and their corresponding management practices

Table 2. Carbon accumulation rates in sediments from different shrimp farming ponds

Table 3. Pearson correlations between pond sediment parameters and sediment oxidizable organic carbon (SOC)

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Figure 1. Location of the different sampling sites in the inland saline shrimp farming ponds (P1- Pond 1, P2- Pond 2, P3- Pond 3, P4-Pond 4, P5- Pond 5, P6- Pond 6; S1-Sampling Site 1, S2-Sampling Site 2, S3- Sampling Site 3, S4- Sampling Site 4; Total sample size n=12 from each pond).

Figure 2. Effect of shrimp farming management practices on sediment C fractions (g kg^{-1}) (n = 12, $p < 0.05$) of different shrimp aquaculture ponds.

Figure 3. Effect of shrimp farming on active C-fractions (AC), passive C- fractions (PC) and particulate organic carbon (POC) (g kg^{-1}) (n = 12, $p < 0.05$) in shrimp aquaculture pond sediments.

Tables

Table 1. Characteristics of different aquaculture ponds and their corresponding management practices

Pond	Pond type	Age	Initial chlorophyll-a content (mg L^{-1})	Final chlorophyll-a content (mg L^{-1})	Management practices
P1	Earthen pond	8	0.08	1.08	Ploughing, draining, drying, fertilization and feeding.
P2	Bottom cemented earthen pond	8	0.06	1.02	No ploughing, draining, drying, fertilization and feeding.
P3	Bottom cemented earthen pond	7	0.05	1.02	No ploughing, drying, draining, fertilization, and feeding.
P4	Earthen pond	7	0.08	1.03	Ploughing, drying, draining, fertilization and feeding.
P5	Earthen pond	5	0.14	1.20	Ploughing, draining, drying, fertilization and feeding.
P6	Bottom cemented earthen pond	5	0.10	1.18	No ploughing, drying, fertilization and feeding.

Table 2. Carbon accumulation rates in sediments from different shrimp farming ponds

Pond	Age	Sediment depth (cm)	Sediment accumulation rate (cm yr^{-1})	Sediment dry bulk-density (g cm^{-3})	Sediment oxidizable organic carbon (%)	**Carbon accumulation rate in sediment (kg ha^{-1} yr^{-1})**
P1	8	12.9 ± 1.2[¶]	1.62 ± 0.02	1.07	0.62^{b} ± 0.04	1073^{b} ± 75
P2	8	13.6 ± 1.4	1.71 ± 0.01	0.97	0.64^{b} ± 0.01	1054^{b} ± 30
P3	7	11.6 ± 1.2	1.66 ± 0.02	1.01	0.80^{c} ± 0.01	1346^{c} ± 28
P4	7	10.8 ± 1.4	1.57 ± 0.03	1.14	0.50^{a} ± 0.02	902^{a} ± 28
P5	5	9.05 ± 0.8	1.81 ± 0.03	1.13	0.48^{a} ± 0.015	987^{ab} ± 52
P6	5	9.35 ± 0.5	1.87 ± 0.05	1.09	0.52^{a} ± 0.01	1055^{a} ± 54

[¶] Values within a column followed by different letters are significantly different at $p < 0.05$, as obtained from Duncan multiple range test.

Table 3. Pearson correlations between pond sediment parameters and sediment oxidizable organic carbon (SOC)

	Age of the pond	Sediment depth	Sediment accumulation rate	Dry bulk-density	Sediment oxidizable organic carbon (%)
Age of the pond	1	0.96**	-0.76**	-0.58*	NS
Sediment depth		1	NS	-0.73**	NS
Sediment accumulation rate			1	NS	NS
Dry bulk-density				1	-0.77**

* and **, significant at $p < 0.05$ and $p < 0.01$ respectively, NS: non-significant

Table 4. Changes in the level of SOC and its fractions (g kg^{-1}) over the years of shrimp farming practices

Pond	Total organic carbon	**Sediment oxidizable organic carbon (SOC)**	Very-labile carbon (VLc)	Labile carbon (Lc)	Less-labile carbon (LLc)	Non-labile carbon (NLc)
P1	9.96^{ab}[¶]	$6.19^{b} \pm 0.36$	$3.34^{c} \pm 0.44$	$2.26^{abc} \pm 0.51$	$0.58^{a} \pm 0.2$	$3.77^{a} \pm 0.36$
P2	12.04^{b}	$6.74^{b} \pm 0.33$	$3.06^{bc} \pm 0.29$	$2.62^{bc} \pm 0.01$	$1.06^{a} \pm 0.04$	$5.31^{b} \pm 0.07$
P3	11.98^{b}	$8.01^{c} \pm 0.145$	$3.42^{c} \pm 0.07$	$2.84^{c} \pm 0.22$	$1.75^{b} \pm 0.15$	$3.98^{a} \pm 0.14$
P4	8.57^{a}	$5.02^{a} \pm 0.22$	$2.47^{ab} \pm 0.14$	$1.75^{ab} \pm 0.29$	$0.8^{a} \pm 0.22$	$3.54^{a} \pm 0.22$
P5	8.17^{a}	$4.81^{a} \pm 0.15$	$2.18^{a} \pm 0.15$	$1.97^{abc} \pm 0.07$	$0.65^{a} \pm 0.07$	$3.36^{a} \pm 0.14$
P6	8.67^{a}	$5.17^{a} \pm 0.07$	$2.84^{abc} \pm 0.07$	$1.6^{a} \pm 0.14$	$0.73^{a} \pm 0.01$	$3.5^{a} \pm 0.07$

[¶] Values within a column followed by different letters are significantly different at $p < 0.05$, as obtained from Duncan multiple range test.

Figures

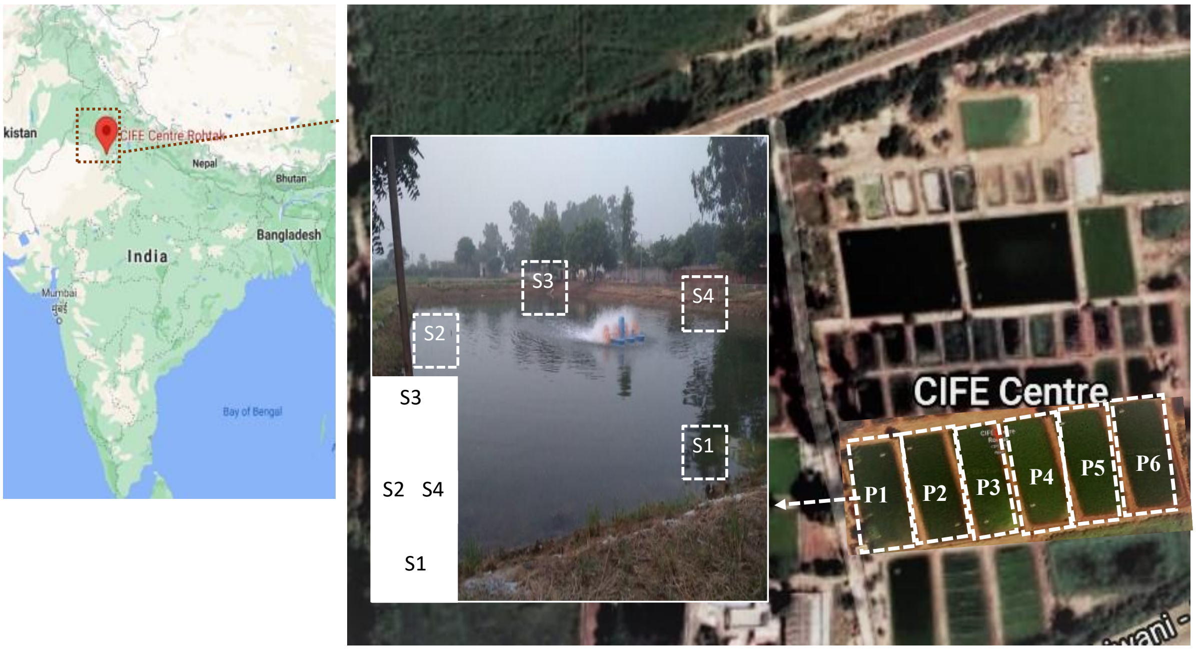

Fig. 1. Location of the different sampling sites in the inland saline shrimp farming ponds (P1-Pond 1, P2- Pond 2, P3- Pond 3, P4-Pond 4, P5- Pond 5, P6- Pond 6; S1-Sampling Site 1, S2-Sampling Site 2, S3- Sampling Site 3, S4- Sampling Site 4; Total sample size n=12 from each pond).

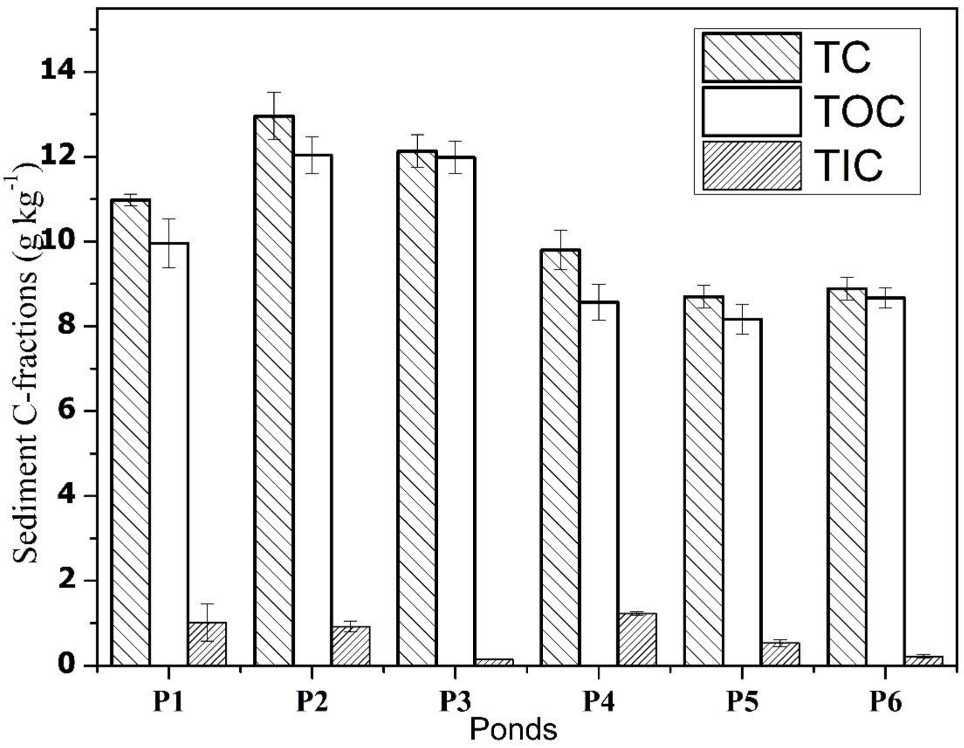

Fig 2. Effect of shrimp farming on sediment C fractions (g kg^{-1}) (n = 12, $p < 0.05$) of different shrimp aquaculture ponds.

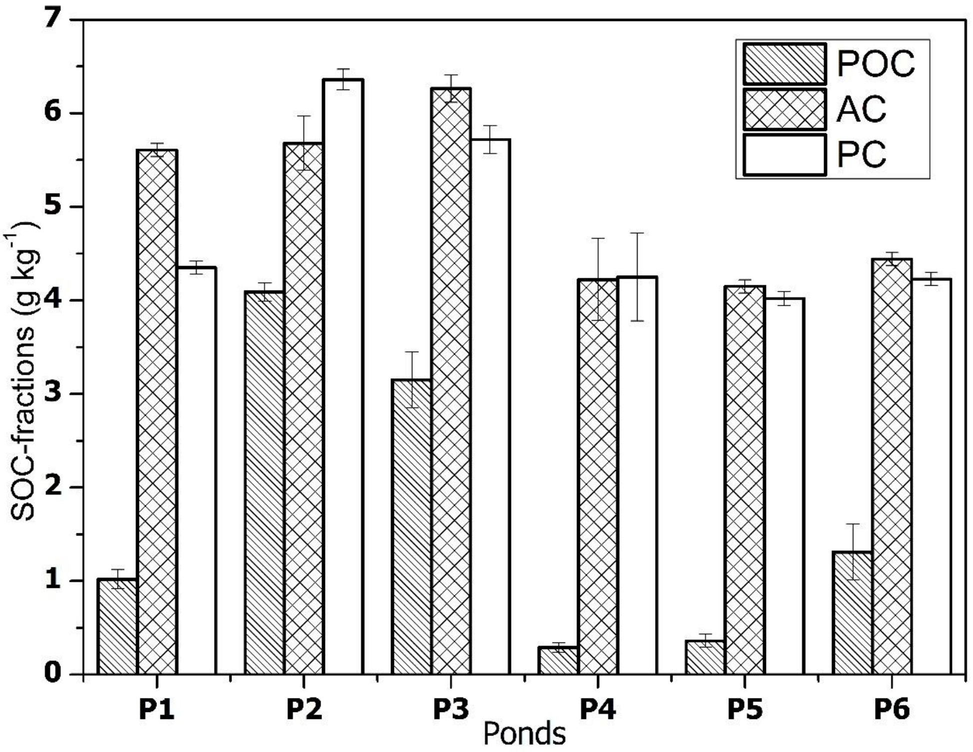

Fig 3. Effect of shrimp farming on active C-fractions (AC), passive C- fractions (PC) and particulate organic carbon (POC) (g kg^{-1}) (n = 12, $p < 0.05$) in different shrimp aquaculture pond sediments.

Supporting Information for:

Inland saline aquaculture increased carbon accumulation rate and stability in pond sediments under semi-arid climate

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Tables

Table S1. Classification of culture periods based on feeding strategy

Culture stage	Duration (days)	Feed type	Feed shape and size	Feeding frequency (kg ha^{-1})	% TC	% TN	C:N ratio
Initial	0-30	Starter feed	Crumble and 0.9-1.2 mm	40	38.58	5.64	6.84
Middle	31-60	Grower I	Pellet and 1.2 × 2-3 mm	80	34.82	7.78	4.47
Final	60-120	Grower II	Pellet and 2 × 3-4 mm	100	37.50	7.78	4.82

TC: total carbon; TN: total nitrogen

Table S2. Initial physicochemical parameters of pond sediments

Sediment parameter	Value
pH	8.2 ± 0.4
EC (dS m^{-1})	5.37 ± 0.14
Organic carbon (%)	0.59 ± 0.02
Total carbon (%)	1.058 ± 0.35

Bulk density (g cm^{-3})	1.06 ± 0.09

Table S3. Effect of 5-8 years of aquaculture practices on different C-fractions (g kg^{-1})

Pond	Active C pool	Passive C pool	POC
P1	$5.61^{b} \pm 0.07$[¶]	$4.35^{a} \pm 0.07$	$1.024^{bc} \pm 0.15$
P2	5.68^{b} ± o.29	$6.36^{b} \pm 0.29$	$4.09^{d} \pm 0.14$
P3	$6.26^{b} \pm 0.14$	$5.72^{b} \pm 0.14$	$3.15^{d} \pm 0.29$
P4	$4.22^{a} \pm 004$	$4.25^{a} \pm 0.44$	$0.29^{a} \pm 0.05$
P5	$4.15^{a} \pm 0.07$	$4.02^{a} \pm 0.07$	$0.37^{ab} \pm 0.07$
P6	$4.44^{a} \pm 0.07$	$4.23^{a} \pm 0.07$	$1.32^{c} \pm 0.29$

[¶] Values within a column followed by different letters are significantly different at $p < 0.05$ as obtained from Duncan multiple range test.