Effect of Different Feed Loading on Sediment Accumulation Rate and Carbon Burial Rate in the Polyculture System of Nile Tilapia (*Oreochromis niloticus*) and Pacific White Shrimp (*Litopenaeus vannamei*)

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ABSTRACT

A study on the effect of different feed loading on sediment accumulation rate and carbon burial rate in the polyculture of Nile tilapia and Pacific white shrimp was conducted in six ponds located in Phan Thong District, Chonburi Province, in eastern Thailand. The ponds were grouped by level of feed loading: low, moderate and high. The sediment accumulation rate and other parameters were measured at three sites in each pond, one at the feeding area and two at the deep end of the pond. The ponds with high feed loading had the highest mean sediment accumulation rate (35.50 ± 4.71 $cm\cdot yr^{-1}$), higher than the moderate (16.80 ± 1.86 $cm\cdot yr^{-1}$) and low (5.40 ± 0.00 $cm\cdot yr^{-1}$) groups. The group with high feed loading also had the highest mean carbon burial rate (69.87 ± 17.16 $g\ C\cdot m^{-2}\cdot yr^{-1}$), significantly higher ($p<0.05$) than the groups with moderate (17.57 ± 2.59 $g\ C\cdot m^{-2}\cdot yr^{-1}$) and low feed loading ($6.19\pm1.23$ $g\ C\cdot m^{-2}\cdot yr^{-1}$). The results suggest that sediment accumulation rate average exceeds 23.67 cm, the farmer should reduce feeding rate.

Keywords: Carbon burial rate, Pacific white shrimp, Tilapia, Sediment accumulation rate

INTRODUCTION

Commercial culture of Nile tilapia (*Oreochromis niloticus*) plays an important role in the economy of Thailand. Demand has increased from both domestic and foreign markets, including USA, France and Saudi Arabia. In 2014, Nile tilapia production totaled 300,000 tonnes, or about 31 percent of the value of Thailand's freshwater animal production (DOF, 2014).

Tilapia culture in Thailand uses three culture-management systems: extensive, semi-intensive, and intensive. Recently, many farmers are interested in raising tilapia together with Pacific white shrimp, with tilapia being the primary species, and shrimp the secondary. Under this culture practice, significant economies are successful, since only tilapia feed is required. The shrimp, in turn, feed on the excreta and residue in the pond bottom. Despite the growing adoption of combined culture practices, an in-depth understanding of the environmental characteristics in this form of polyculture, especially sediment characteristics and the rate of accumulation remain relatively under-investigated. Greater knowledge of these characteristics is needed for improved planning, controlling and managing the various environmental factors in the pond. Boyd *et al*. (2002) found that the accumulation of sediment components in culture ponds, especially organic matter, nitrogen, and phosphorus, were higher near time of harvest compared to ponds without culture species or ponds at the beginning of a crop.

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Although aquaculture in earthen ponds is considered a source of carbon emissions, the earthen pond could serve in storage of carbon as well. The process that can reduce carbon dioxide in the atmosphere is carbon sequestration. In this process, forms of carbon can be stored in different areas, namely water bodies, agriculture areas, soil, etc. (Dean and Gorham, 1998). The rate of carbon fixation in the sediment in aquaculture ponds is called the carbon burial rate of sediment. Recently, there have been many studies exploring this process, especially in agricultural areas. Nutrient-enriched water can release carbon dioxide (CO_2-C emission) up to 33.1 g $C{\cdot}m^{-2}{\cdot}yr^{-1}$ (Xing *et al*., 2005). Aquaculture pond water can generate and emit carbon dioxide that causes the greenhouse effect (greenhouse gas). At the same time, carbon may be stored in organic compounds accumulated in the form of sediment at the pond bottom. Carbon burial rate can be used as the carbon credit to compensate for the carbon emission from ponds (Boyd *et al*., 2010). However, the study of carbon burial rate in aquaculture ponds is still relatively limited. Boyd (1995) reported that sediment-water interaction impacts water quality in the pond. Therefore, the sediment is an important aspect of pond management for environmental sustainability. Sediment research, which provides support for pond management, is the key for improving the sustainable management of aquaculture ponds.

Therefore, this research aims to examine the effect of different feed loadings on sediment characteristics, sediment accumulation rate and carbon burial rate in ponds used for tilapia and shrimp polyculture in Thailand. This study will provide beneficial data on sediment characteristics from this type of culture, and the results will be helpful for sediment quality management during production to achieve high productivity of both marketable species and to improve environmental sustainability.

MATERIALS AND METHODS

Site selection

Phan Thong District, Chonburi Province is located in eastern Thailand. Based on the data from the Meteorological Department, the area has relatively low rainfall during January-May, and water shortages during February-April. As a result, aquaculture farmers must adapt some culture techniques such as drying their ponds within a short time. As such, they often do not remove sediment from the pond after harvest. None of the ponds in this study exchanged water during the culture period because of insufficient water availability. Pond depth, in all cases, was between 1.5-2.0 m. The main water source used for fish and shrimp raising in this area is from irrigation canals that receive water from Klong Luang Rachalotorn Reservoir.

Ponds in this study had been used for shrimp culture for about 21 years. The change to polyculture of fish and shrimp occurred recently. Ponds had ever been renovated and dried since 1996. The main culture species was tilapia, while shrimp was cultured for supplementing the economic returns from fish. The polyculture strategy generally applied feed for tilapia only, while shrimp fed on the uneaten feed and wastes excreted by fish.

The six ponds used for this study were located in Phan Thong District, Chonburi Province, eastern Thailand (Figure 1). The ponds were divided into three groups, based on feed loading rate (low, moderate, and high), with two ponds in each group. Average pond size was 0.48 ha in the low feed loading group, 0.96 ha in the moderate feed loading group and 0.24 ha in the high feed loading group.

The feed loading categories indicated the amount of commercial feed used per crop. The low-feeding farms used an average of 44 $kg{\cdot}ha^{-1}{\cdot}month^{-1}$, moderate-feeding farms used 313 $kg{\cdot}ha^{-1}{\cdot}month^{-1}$ and the high-feeding farms used more than 488 $kg{\cdot}ha^{-1}{\cdot}month^{-1}$. Rice bran (average 313 $kg{\cdot}ha^{-1}$) and chicken manure (average 1,875 $kg{\cdot}ha^{-1}$) were applied at the beginning of the crop in the high-feeding group (Table 2). The percentages of inputs per crop in the high-feeding group were 64 % commercial feed, 31 % chicken manure and 5 % rice bran. All farms used diets with the same protein percentage (32 percent from January to March; 25 percent from April to October).

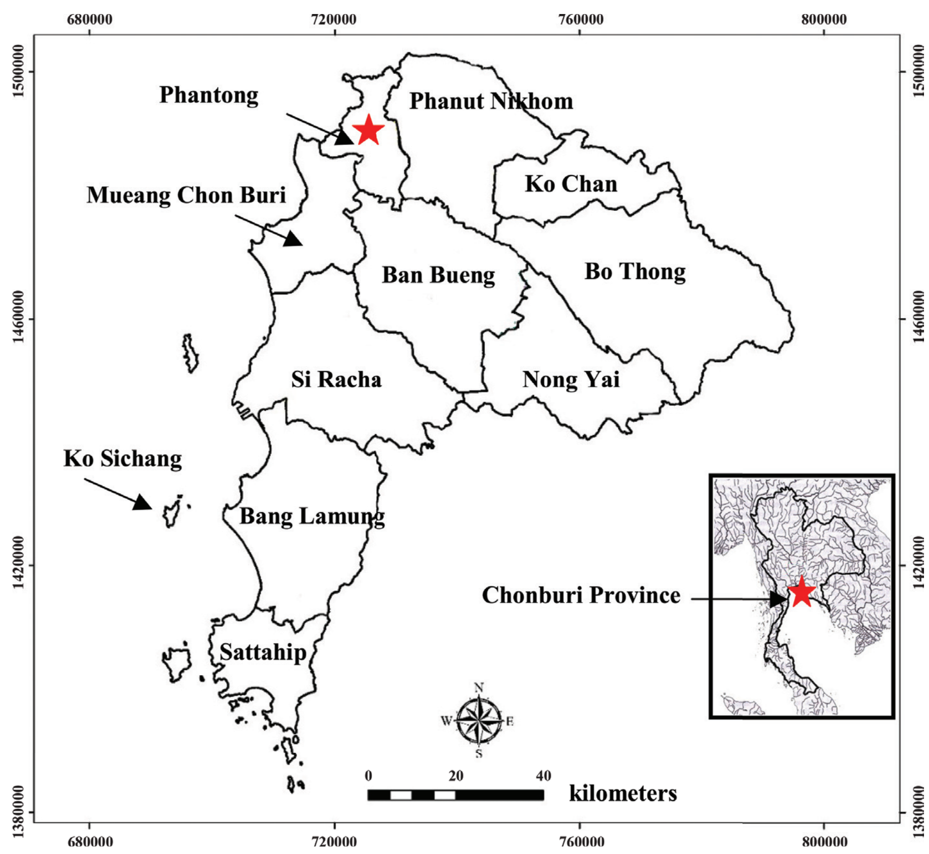

Figure 1. Location of polyculture farms of tilapia and shrimp in Phan Thong District, Chonburi Province, eastern Thailand.

Sediment sampling and analysis methods

Sediment samples were taken from the ponds between January and October 2016. The duration of the crops of the low and moderate feed loading groups was ten months, while the high feed loading group was eight months. The duration of culture and timing of harvest were determined by fish growth performance (to reach the marketable size of 0.7-1 kg) and the market price of tilapia at that time.

Physical and chemical characteristics of the collected sediment were studied. Sediment samples were collected at sediment deposition points from three sites in the pond; one at the feeding area and two sites at the deep end of the pond (Figure 2). Naturally, the sediment would accumulate more at the deepest point in the pond, but as the feeding area may have some leftover feed, sampling was done in both areas. Three to four replicate sediment samplings were obtained from each site to make composite samples.

Sediment depth was collected using a transparent PVC pipe, 5 cm in diameter and 50 cm in length, with a measurement scale. A disposable 4 cm wooden dowel was used to extract the sediment from the pipe, following the method of Tape and Boyd, 2002. Sediment samples for bulk density were collected by 7.5 cm diameter x 4.5 cm high cylindrical metal container. The sampling of sediment depth and sediment bulk density were collected three times at each sediment deposition point in the pond (i.e., one at the feeding area, two in the deep end).

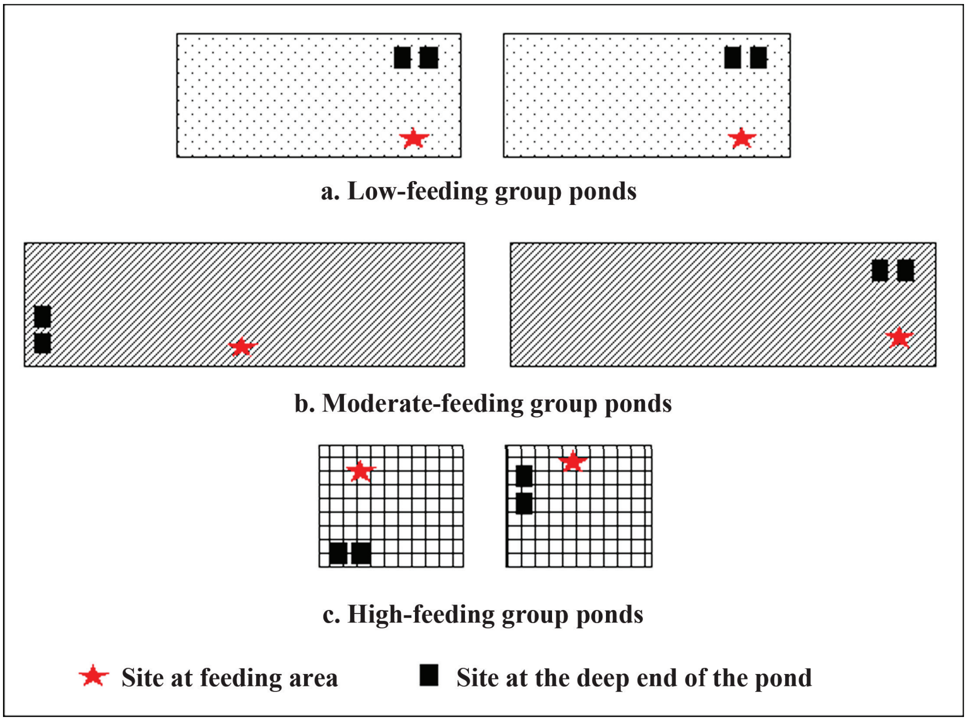

Figure 2. Locations of three sediment sampling sites in tilapia-shrimp polyculture ponds; one site at feeding area and two sites at the deep end of the pond.

Organic carbon was collected by core sampler, at five centimeters of sediment depth; this sample was also collected at the three sediment deposition points.

All samples were stored at 4 °C for analysis in the laboratory. After air drying completely, the three sediment samples were mixed together. The methods of analysis of the various sediment parameters are shown in Table 1.

Sediment accumulation rate and carbon burial rate

The calculations of sediment accumulation rate and carbon burial rate were adapted from Boyd *et al*. (2010) and Adhikari *et al*. (2012). The sediment accumulation rate is the mass of sediment buried per unit area and per unit time ($cm \cdot yr^{-1}$) and in this study, the sediment accumulation rate refers to sedimentation per year in the pond.

$$\text{Sediment accumulation rate } (cm \cdot yr^{-1}) = \frac{\text{Average total sediment depth (cm)}}{\text{Age of rearing (yr)}}$$

$$\text{Carbon burial rate } (g\ C \cdot m^{-2} \cdot yr^{-1}) = \text{Sediment accumulation rate } (cm \cdot yr^{-1}) \times \text{dry bulk density of sediment } (g \cdot cm^{-3}) \times \text{percentage of organic carbon} \times 10^4$$

Remark: The sediment accumulation rate ($cm \cdot yr^{-1}$) in this study did not represent the sediment accumulation rate per pond area but rather the sediment accumulation rate at the deposition point in the pond, as described in the sediment sampling and analysis method above.

Table 1. Sediment analysis methods used in the present study.

Sediment parameters	Analytical venue		Analytical method
	Field	Laboratory	
Sediment depth	X		Steeby *et al*. (2004)
Bulk density		X	Clod method (Blake and Hartge, 1986)
Sediment water content		X	Black (1965)
Sediment texture		X	Hydrometer (Weber, 1977)
Sediment pH		X	1:1 mixture (Thunjai *et al*., 2001)
Total nitrogen		X	Kjeldahl method (Bremmer and Mulvaney, 1982)
Total phosphorus		X	Use $HClO_4$, spectrophotometer (Olsen and Sommer, 1982)
Organic carbon		X	Walkley-Black (Nelson and Sommers, 1982)
CN-ratio		X	Walkley-Black (Nelson and Sommers, 1982)
			Kjeldalh method (Bremmer and Mulvaney, 1982)
Sediment salinity		X	Electrical conductivity at Saturation sediment extract

Statistical Analysis

Sediment quality parameters, sediment accumulation rate, and carbon burial rate of sediment samples were tested for parametric statistical conditions. If the data set did not meet the statistical conditions, data for that parameter would be transformed before analysis. Statistical analysis was done using ANOVA, and all means from pond groups were compared by Duncan multiple range test at 95 % confidence interval. Comparison of sediment quality parameters was made using the repeated measures ANOVA.

RESULTS AND DISCUSSION

Management and characteristics of the culture ponds

The average tilapia stocking rate was 6,250 fish·ha^{-1} and the average shrimp stocking rate was 16,000 shrimp·ha^{-1}. In the low-feeding and moderate-feeding systems, the feeding period was 10 months (January to October) and in the high-feeding system it was 8 months (January to August). All ponds and feed level groups were managed the same way, such as drying the pond but not removing the sediment after harvest, with no water exchange during the culture period but water was added to compensate for seepage and evaporation.

Shrimp were fed on leftover feed and waste from tilapia. Shrimp were stocked 1-2 times during the fish crop cycle depending on each farmer's preference. Unfortunately, farms did not have records on shrimp growth performance.

Sediment characteristics in culture ponds

A crop duration in this study was divided into four periods in accordance with monthly rainfall volume reported by Thai Meteorological Department. The periods were as follows: Preparation period–January 2016 (during this period there were no tilapia or shrimp); Beginning period–February-April 2016; Middle period–May-July 2016); and End period (August-October 2016).

Physical and chemical parameters of sediment

Sediment parameters in ponds of the three feed loading groups were analyzed and compared (Table 3). Three of the parameters, sediment depth, sediment water content and bulk density were collected only during the Preparation and End periods. Other parameters including percentage of sand, silt, clay, pH, total nitrogen, total phosphorus, organic carbon, CN-ratio, and sediment salinity were collected in all periods.

Table 2. Management and characteristics of culture ponds and average tilapia survival rate.

Characteristics	**Feeding rate**		
	Low	**Moderate**	**High**
Pond number	2	2	2
Pond size (ha)	0.48	0.96	0.24
Pond depth (m)	1.5-2.0	1.5-2.0	1.5-2.0
Pond age (years)	21	21	21
Stocking density of tilapia (fish·ha^{-1})	6,250	6,250	6,250
Stocking density of shrimp (shrimp·ha^{-1})	20,831	69,794	50,000
Tilapia culture period (months)	Jan-Oct (10)	Jan-Oct (10)	Jan-Aug (8)
Tilapia average feed loading (kg·ha^{-1}·month^{-1})	44	313	488
Tilapia average survival rate (%)	57.32	56.65	44.28

In comparing sediment characteristics in the three different culture groups (Table 3), it was found that the sediment depth of high-feeding ponds changed from 14.67±3.06 to 38.33±6.51 cm (an increase of 161.2 %), moderate-feeding ponds changed from 11.67±2.89 to 25.67±1.15 cm (119.9 %), and low-feeding ponds changed from 4.00±0.00 to 8.50±0.00 cm (112.5 %). These data indicate that the feeding rate may affect the sediment depth. The data from bulk density sampling showed that for the low feeding rate, bulk density increased from 0.69±0.03 to 0.97±0.04 g·cm^{-3} (average change 0.28 g·cm^{-3}), for the moderate feeding rate it increased from 0.50±0.03 to 0.95±0.05 g·cm^{-3} (average change 0.45 g·cm^{-3}), and for the high feeding rate it increased from 0.53±0.05 to 1.33±0.03 g·cm^{-3} (average change 0.80 g·cm^{-3}). This indicated that the feeding rate may also affect the bulk density of sediment. The average sediment pH from all feeding groups at the preparation period was over 7, but pH decreased to less than 7 by the end of the crop in all groups. The sediment pH of the high-feeding ponds fell to under 7 from the beginning period till the end of crop.

For other sediment quality parameters, such as total nitrogen, total phosphorus, organic carbon, and CN-ratio, there was non statistically significant difference ($p>0.05$) between the three feed loading groups (Table 4).

Nutrient composition of sediment

The accumulation of major nutrients such as total nitrogen, total phosphorus, organic carbon and carbon-nitrogen ratio (CN-ratio) in pond sediments showed non significant difference ($p>0.05$) among the different feed loadings (Table 4). Changes of the nutrient composition among the different feeding levels (between groups) and by duration (within group) were analyzed by one-way repeated measures ANOVA. Comparison of the different sediment parameters for the three groups were analyzed by Duncan multiple range test at 95 percent confidence level. Results of these comparisons are summarized below (Table 5).

The nutrient composition (i.e., total nitrogen, total phosphorus, organic carbon, and CN-ratio) of sediments was not significantly different ($p>0.05$) among the different feeding rate groups. The data showed that different feeding rates in the study area did not cause a difference of the main nutrients accumulated, because all pond groups had sufficient dissolved oxygen for organic decomposition and inorganic oxidation, as reflected by total nitrogen, total phosphorus and organic carbon.

Changes of the nutrient composition in the ponds at different culture periods were studied

Table 3. Mean±SD (range) of sediment characteristics at different crop durations, grouped by feed loading.

Parameters	Crop duration											
	Preparation period			Beginning period			Middle period			End period		
	L	M	H	L	M	H	L	M	H	L	M	H
Sediment depth (cm)	4.00±0.00 (4.00-4.00)	11.67±2.89 (10.00-15.00)	14.67±3.06 (12.00-18.00)	-	-	-	-	-	-	8.50±0.00 (8.50-8.50)	25.67±1.15 (25.00-27.00)	38.33±6.51 (32.00-45.00)
Sediment water content (%)	51.10±0.43 (50.68-51.53)	57.36±1.76 (56.29-59.39)	60.56±7.61 (51.77-65.01)	-	-	-	-	-	-	39.66±0.67 (39.09-40.39)	33.29±1.44 (32.40-34.96)	39.99±0.50 (39.64-40.56)
Bulk density ($g \cdot cm^{-3}$)	0.69±0.03 (0.66-0.72)	0.50±0.03 (0.46-0.52)	0.53±0.05 (0.48-0.58)	-	-	-	-	-	-	0.97±0.04 (0.93-1.00)	0.95±0.05 (0.89-0.98)	1.33±0.03 (1.30-1.35)
Sand (%)	49.21±2.60 (47.27-52.16)	46.71±2.07 (44.96-48.99)	52.20±1.62 (50.75-53.94)	48.25±5.64 (44.28-54.71)	44.54±4.86 (40.62-49.98)	53.82±2.02 (51.51-55.28)	51.35±3.78 (47.72-55.26)	46.65±2.85 (45.00-49.94)	56.53±1.89 (54.61-58.38)	47.50±9.13 (42.07-58.04)	39.89±1.53 (38.56-41.56)	50.87±2.03 (49.56-53.20)
Silt (%)	34.13±2.05 (31.83-35.75)	32.77±2.42 (30.06-34.74)	32.54±0.63 (31.82-32.95)	31.15±4.56 (25.93-34.31)	34.74±4.54 (29.88-38.87)	28.94±0.08 (28.88-29.03)	27.94±1.84 (25.82-29.18)	31.41±2.21 (28.86-32.87)	25.21±2.15 (23.41-27.60)	29.81±4.88 (24.18-32.82)	32.86±3.12 (30.36-36.36)	28.69±2.75 (26.36-31.72)
Clay (%)	16.66±0.56 (16.01-17.00)	20.53±0.36 (20.30-20.94)	15.26±1.03 (14.24-16.30)	20.60±1.09 (19.36-21.4)	20.71±0.68 (20.15-21.47)	17.24±1.95 (15.51-19.47)	20.71±2.16 (18.92-23.10)	21.94±0.67 (21.20-22.51)	18.26±0.49 (17.79-18.78)	22.69±4.25 (17.78-25.17)	27.25±2.84 (24.08-29.58)	20.44±2.00 (18.44-22.44)
pH	7.99±0.03 (7.98-8.03)	8.37±0.04 (8.35-8.42)	7.44±0.09 (7.37-7.84)	7.21±0.21 (6.97-7.36)	7.18±0.02 (7.17-7.20)	6.79±0.30 (6.51-7.10)	7.01±0.21 (6.78-7.15)	6.97±0.18 (6.77-7.12)	6.56±0.05 (6.50-6.59)	6.58±0.12 (6.47-6.70)	6.55±0.10 (6.47-6.66)	6.06±0.39 (5.84-6.51)
Total nitrogen (%)	0.11±0.05 (0.05-0.16)	0.19±0.02 (0.18-0.21)	0.21±0.03 (0.18-0.24)	0.17±0.03 (0.14-0.19)	0.16±0.02 (0.15-0.18)	0.16±0.02 (0.14-0.17)	0.16±0.03 (0.12-0.19)	0.11±0.01 (0.10-0.12)	0.12±0.02 (0.10-0.14)	0.11±0.02 (0.10-0.13)	0.09±0.01 (0.08-0.10)	0.16±0.03 (0.13-0.19)
Total phosphorus (%)	0.02±0.01 (0.01-0.03)	0.03±0.00 (0.02-0.03)	0.03±0.00 (0.03-0.04)	0.04±0.01 (0.03-0.06)	0.04±0.02 (0.02-0.06)	0.04±0.01 (0.03-0.05)	0.04±0.00 (0.03-0.04)	0.04±0.02 (0.04-0.07)	0.05±0.02 (0.04-0.07)	0.04±0.00 (0.04-0.05)	0.05±0.04 (0.03-0.10)	0.07±0.04 (0.04-0.11)
Organic carbon (%)	1.33±0.28 (1.01-1.50)	1.51±0.10 (1.42-1.62)	1.50±0.20 (1.27-1.67)	1.90±0.35 (1.50-2.12)	1.59±0.14 (1.43-1.68)	1.45±0.07 (1.31-1.51)	1.97±0.07 (1.93-2.05)	1.31±0.23 (1.07-1.52)	1.47±0.06 (1.43-1.54)	1.18±0.23 (0.92-1.35)	1.11±0.09 (1.10-1.18)	1.46±0.20 (1.23-1.59)
CN-ratio	14.68±4.68 (10.59-20.06)	8.14±0.90 (7.40-9.14)	7.37±0.93 (6.65-8.41)	13.78±1.45 (12.88-15.45)	11.98±3.43 (9.85-15.93)	11.19±0.81 (10.28-11.83)	14.22±3.86 (11.93-18.68)	13.60±2.90 (11.67-16.93)	12.78±1.06 (11.76-13.87)	14.15±2.68 (11.07-15.89)	12.32±0.99 (11.50-13.42)	9.96±1.78 (8.77-12.01)
Sediment salinity (% of salt in sediment)	0.49±0.07 (0.41-0.54)	0.72±0.11 (0.62-0.83)	0.51±0.02 (0.49-0.53)	0.57±0.03 (0.53-0.58)	0.73±0.01 (0.72-0.74)	0.49±0.02 (0.47-0.50)	0.71±0.05 (0.56-0.75)	(0.81±0.0 0.72-0.88)	0.57±0.06 (0.51-0.62)	0.68±0.04 (0.63-0.72)	0.73±0.03 (0.70-0.75)	0.48±0.06 (0.45-0.55)

L=low feed loading, M=moderate feed loading, H=high feed loading.

Table 4. Mean±SD (range) of sediment characteristics in different feed loading groups.

Parameters	Feeding level group		
	Low feed loading	**Moderate feed loading**	**High feed loading**
Sand (%)	49.08±5.20[a] (42.07-58.04)	44.45±3.92[a] (38.56-49.98)	53.35±2.73[a] (49.56-58.39)
Silt (%)	30.76±3.88[a] (24.18-35.75)	32.94±3.00[a] (28.86-38.87)	28.85±3.10[a] (23.41-32.28)
Clay (%)	20.16±3.10[ab] (16.01-25.17)	22.61±3.13[b] (20.15-29.58)	17.80±2.34[a] (14.24-22.44)
pH	7.20±0.55[b] (6.47-8.03)	7.27±0.7[b] (6.47-8.42)	6.71±0.56[a] (5.84-7.54)
Total nitrogen (%)	0.14±0.04[a] (0.05-0.19)	0.14±0.04[a] (0.08-0.21)	0.16±0.04[a] (0.10-0.24)
Total phosphorus (%)	0.04±0.01[a] (0.01-0.06)	0.04±0.02[a] (0.02-0.10)	0.05±0.03[a] (0.03-0.11)
Organic carbon (%)	1.60±0.42[a] (0.92-2.12)	1.38±0.24[a] (1.00-1.68)	1.47±0.13[a] (1.23-1.67)
CN-ratio	14.21±2.97[a] (10.59-20.06)	11.51±2.92[a] (7.40-16.93)	10.33±2.31[a] (6.65-13.87)
Sediment salinity (% of salt in sediment)	0.61±0.10[b] (0.41-0.75)	0.75±0.07[c] (0.62-0.88)	0.51±0.05[a] (0.45-0.62)

Different superscript letters in the same row indicate significant difference ($p<0.05$).

Table 5. Results of ANOVA showing source of variation, F value and p-value for sediment quality parameters among feeding groups and culture period within each group.

Parameters	Source of variation	F	p-value
Sand (%)	Culture period	7.456	0.002
	Feeding group	5.298	0.047
	Culture period * Feeding group	1.006	0.452
Silt (%)	Culture period	6.731	0.003
	Feeding group	2.836	0.136
	Culture period * Feeding group	1.165	0.367
Clay (%)	Culture period	26.373	0.000
	Feeding group	8.815	0.016
	Culture period * Feeding group	1.792	0.158
pH	Culture period	121.992	0.000
	Feeding group	28.970	0.010
	Culture period * Feeding group	1.801	0.156
Total nitrogen (%)	Culture period	12.064	0.000
	Feeding group	1.472	0.302
	Culture period * Feeding group	10.592	0.000
Total phosphorus (%)	Culture period	5.766	0.032
	Feeding group	0.492	0.634
	Culture period * Feeding group	0.494	0.691
Organic carbon (%)	Culture period	15.599	0.000
	Feeding group	1.584	0.280
	Culture period * Feeding group	9.415	0.000
CN-ratio	Culture period	4.118	0.022
	Feeding group	4.104	0.075
	Culture period * Feeding group	1.543	0.221
Salinity (‰)	Culture period	8.416	0.001
	Feeding group	71.878	0.000
	Culture period * Feeding group	2.294	0.080

by one-way repeated measures ANOVA. There was statistically significant difference ($p<0.05$) in all major nutrients across the culture period (within group). The major nutrients tended to increase with the growing period.

Sedimentation and carbon burial rates

The ponds in this study had been used since 1996 for shrimp farming, but in the past, farmers reared only pacific white shrimp. After a disease outbreak in shrimp, farmers began using a polyculture of tilapia and shrimp, although the exact time was not known. Therefore, in this study, the researchers considered the time period, sediment quality data, sediment accumulation rate data and carbon burial rate data in the period of the most recent crop only. The crop length for ponds with low and moderate feed loading was 10 months (0.83 yr), while it was 8 months (0.67 yr) for the high feed loading ponds.

The ponds with high feed loading had the highest mean sediment accumulation rate (35.50± 4.71 $cm{\cdot}yr^{-1}$), followed by the ponds with moderate feed loading (16.80±1.86 $cm{\cdot}yr^{-1}$) and low feed loading (5.40±0.00 $cm{\cdot}yr^{-1}$). The sediment depth data (Table 6) indicated that the group with high feed loading accumulated sediment at a rate of more than 488 $kg{\cdot}ha^{-1}{\cdot}month^{-1}$. With moderate feed loading, the rate was 313 $kg{\cdot}ha^{-1}{\cdot}month^{-1}$, or 52.7 % lower, while with low feed loading, the rate was 44 $kg{\cdot}ha^{-1}{\cdot}month^{-1}$, or 84.8 % lower than the high feed loading group.

Sediment depth and sediment accumulation rates differed significantly among feeding groups. Mean sediment depth of the high feed loading rate ponds (23.67±3.51 cm) was significantly higher ($p<0.05$) than both the moderate (14.00±1.73 cm) and low (4.50±0.00 cm) feed loading rate ponds. The mean sediment depth of the moderate and low feed loading groups also were significantly different ($p<0.05$). Boyd *et al*. (2010) studied the sediment depth of 233 ponds from 9 countries around the world. The sediment depth ranged from 4-36 cm, with an average of 16.80±11.00 cm; average sediment accumulation rate was 14,400 $cm^3{\cdot}m^{-2}$. Mean sediment depth and pond age were highly correlated ($r=0.78$; $p<0.01$).

In this study, the average sediment depth of both high and moderate feed loading rate ponds were higher at the end of crop than the recommendation by Boyd (1995). Boyd suggested that the suitable sediment depth for aquaculture ponds with the same pattern of water management as in this study should not exceed 20.00 cm. Sediment depth is likely to increase toward the end of the crop. It was found that the low feed loading group had an increase in sediment depth of 112.5 %, while sediment depth increased by 119.9 % for the moderate

Table 6. Mean±SD (range) of sediment accumulation rate, carbon burial rate and related parameters for pond sediment, grouped by feed loading rates.

Feeding levels	Number of ponds	Pond age (yr)	Sediment depth (cm)	Sediment accumulation rate ($cm{\bullet}yr^{-1}$)	Dry bulk density of sediment ($g{\bullet}cm^{-3}$)	Percentage of organic carbon	Carbon burial rate ($g\ C{\bullet}m^{-2}{\bullet}yr^{-1}$)
Low feed loading	2	0.83	4.50±0.00 (4.50-4.50)	5.40±0.00^a (5.40-5.40)	0.97±0.03 (0.93-1.00)	1.60±0.42 (0.92-2.12)	6.19±1.23^a (4.61-7.09)
Moderate feed loading	2	0.83	14.00±1.55 (12.00-15.00)	16.80±1.86^b (14.40-18.00)	0.95±0.04 (0.89-0.98)	1.38±0.24 (1.00-1.68)	17.57±2.59^a (15.66-20.99)
High feed loading	2	0.67	23.67±3.14 (20.00-27.00)	35.50±4.71 (30.00-40.00)^c	1.33±0.02 (1.30-1.35)	1.47±0.13 (1.23-1.67)	69.87±17.16^b (48.07-84.16)
Average of all groups	6	0.77	14.06±8.27 (4.50-27.00)	19.23±13.06 (5.40-40.50)	1.08±0.18 (0.89-1.35)	1.48±0.29 (0.92-2.12)	31.21±30.05 (4.61-84.16)

Different superscript letters in the same column indicate significant difference ($p<0.05$).

feeding group and by 161.2 % for the high feeding group. Based on these percentages, it was evident that a higher amount of feed volume led to a higher sediment depth and sediment accumulation rate in the ponds. It should also be noted that in the high feeding rate group, chicken manure was one-third of the total inputs in the ponds. It is possible that the organic chicken manure may cause more rapid sediment accumulation in the ponds.

The average carbon burial rate of all ponds was 31.21±30.05 g $C·m^{-2}·yr^{-1}$. The ponds with high feed loading had significantly higher ($p<0.05$) carbon burial rate (69.87±17.16 g $C·m^{-2}·yr^{-1}$) than the groups with moderate feed loading (17.57±2.59 g $C·m^{-2}·yr^{-1}$) and low feed loading (6.19±1.23 g $C·m^{-2}·yr^{-1}$). The ponds with low and moderate feed loading were not significantly different ($p>0.05$).

Boyd *et al*. (2010) reported that carbon burial rate correlated with pond age, sediment depth, dry bulk density of sediment and percentage of organic carbon. In this study, the percentage of organic carbon was not significantly different ($p>0.05$) among groups. However, in the group with high feed loading, the dry bulk density of sediment was 1.33±0.02 $g·cm^{-3}$. This was significantly higher ($p<0.05$) than that of the other groups (0.95±0.04 $g·cm^{-3}$ in moderate level and 0.97±0.03 $g·cm^{-3}$ in low level). This is because the high feed level ponds had higher sediment accumulation rate than the other feed levels. As a result, carbon burial rate of the group with high feed loading was the highest (Table 6). Boyd *et al*. (2010) reported that carbon sequestration in aquaculture ponds holds interesting possibilities for the agricultural sector. It may reduce atmospheric carbon dioxide and it is an eco-friendly form of food production. China is the highest source of carbon sequestration in aquaculture ponds in the world, accounting for 55.9 % of the world's aquaculture areas, higher than Africa, America and Europe.

The bulk density in this study tended to increase with increasing culture period. At the end of the crop, the average bulk density of sediment in ponds increased by 0.51±0.23 $g·cm^{-3}$. This value was consistent with a study of Boyd *et al*. (2010), who studied the bulk density of sediment of 233 ponds from nine countries around the world. They reported an average bulk density of about 0.17-0.76 $g·cm^{-3}$, and found that the bulk density and organic matter were moderately correlated (r= - 0.691). The bulk density of sediment is an important indicator of the amount of space between the particles of sediment. If the bulk density is high, the amount of gaps between the particles of sediment will be less. The gaps allow water to enter between sediment particles, and the amount of water in sediment is very important for organisms in sediment such as benthic fauna or microorganisms. Water is critical for many metabolic processes, so if the sediment in the pond has proper bulk density, it will have a positive effect on the activity of microorganisms in the sediment, and particularly, the microbial decomposition process.

Along with sediment accumulation rate and bulk density, the percentage of organic carbon (OC) is a factor in the calculation of carbon burial rate in the ponds. It was found that the organic carbon of the three feed loading pond groups were not significantly different ($p>0.05$). In low, moderate, and high feed loading groups, the means and standard deviations of organic carbon were 1.60±0.42, 1.38±0.24 and 1.47±0.13 %, respectively. Boyd (1995) reported that the appropriate organic carbon of sediment in freshwater aquaculture ponds is 1.00-2.50 %. Sediment with high organic carbon is not suitable for aquaculture due to low pH in the sediment. The decomposition of organic matter will cause gaps and allow for erosion in the area. Boyd *et al*. (2002) and Boyd and Tucker (2014) classified the sediment by the proportion of organic carbon in the pond, as follows: 1) low organic carbon soil (<1 % OC); 2) moderate organic carbon soil, the best value for aquaculture (1.0-3.0 % OC); 3) high organic carbon soil (3.1-15.0 % OC); and 4) organic soil (>15 % OC). In this study, the amount of organic carbon was in the desirable range.

The results showed that different feed intake levels did not affect the organic carbon content of sediment at the pond bottom. As observed during sediment sampling, macro-invertebrates in the high feed loading group were rather dense, while moderate and low feed loading groups had a lower number of macro-invertebrates in the sediment. The most common benthic macro-invertebrate was *Tarebia* sp. It uses organic matter in the pond bottom soil, which is the source of organic carbon accumulation.

To summarize, the different feed loadings in this study resulted in significantly different levels of carbon burial rate in the ponds. High feed loading ponds had the highest rate of carbon burial, which was a result of having higher sediment accumulation rate and higher bulk density of sediment than the other two groups.

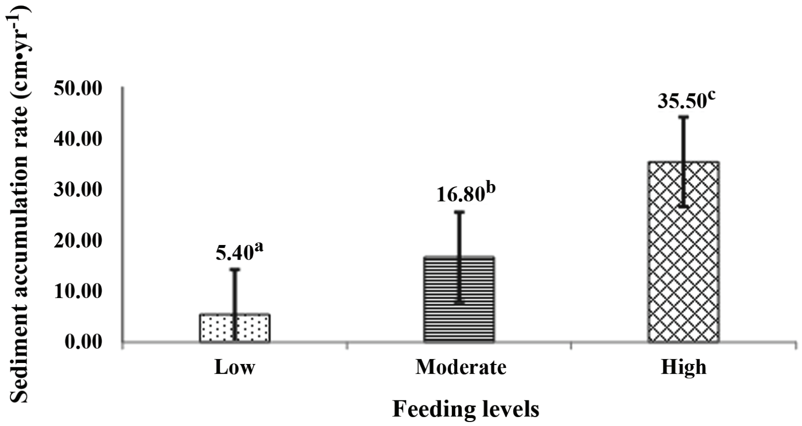

Figure 3. Sediment accumulation rate for each feeding level.
Different letters above the bars refer to statistically difference (p<0.05).

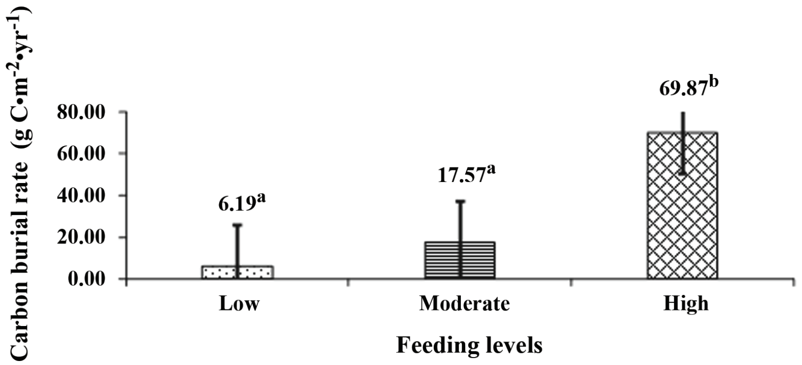

Figure 4. Carbon burial rate for each feeding level.
Different letters above the bars refer to statistically difference (p<0.05).

CONCLUSION

Based on the data collected from polyculture ponds in this study, it can be concluded that different feed loadings did not affect the the accumulation of major nutrients in sediment (i.e., total nitrogen, total phosphorus, organic carbon, and CN-ratio). This suggested that all pond groups had sufficient dissolved oxygen for organic decomposition and inorganic oxidation. The different feed loadings did significantly affect ($p<0.05$) some physical parameters of sediment, including depth, bulk density, percentage of clay, sediment pH and sediment salinity. The high-feeding level resulted in higher values for sediment quality parameters than those of the moderate- and low-feeding levels.

The ponds with high feed loading also had the highest sediment accumulation rate and carbon burial rate. Carbon burial rate is correlated with sediment depth, bulk density of sediment and organic carbon in sediment.

These findings can be used to provide appropriate guidelines for the management of sediment quality and related water quality for tilapia and shrimp culture as follows: 1) According to the results in the study, sediment pH dropped below the standard before the end of crop, therefore water pH near the pond bottom should be monitored; 2) If the pH of sediment is below the standard (below 7.5) at the end of crop, lime addition is necessary for pond preparation before the next crop. Changes in pH also depend on the decomposition efficiency of the organic matter; 3) If the sediment accumulation rate average exceeds 23.67 cm, the farmer should reduce feeding rate.

According to the results of the study, the average survival rate of tilapia in high feeding load ponds was not satisfactory (lower than 50 % survival), and better feed management should be applied. Farmers should adjust feed rates frequently in relation with fish average daily growth rate and approximate survival rate. The records of fish growth performance and fish mortality in each pond is necessary for feeding management.

Excessive feeding in fish pond leads to high sediment accumulation, which can deteriorate pond sediment. Ponds with high accumulation need to be prepared with proper practices, such as pond drying and sediment removal. The removed sediment should be kept far from water courses.

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