Properties and Accumulation Rate of Sediments in Nile Tilapia (*Oreochromis niloticus*) Ponds and Ponds with Cages Containing Red Hybrid Tilapia (*Oreochromis niloticus × mossambicus*)

Idsariya Wudtisin* , Yuthapol Saeiam and Sitthi Kulabthong

ABSTRACT

Sediment samples were collected from six earthen ponds: three ponds for Nile tilapia culture and the other three ponds containing cages with red hybrid tilapia. All study ponds were located in the same farm in Nakhon Pathom Province, Thailand. The bulk density of Nile tilapia and red tilapia ponds did not differ ($P>0.05$), with average bulk densities of 0.77 ± 0.12 g•cm^{-3} and 0.86 ± 0.10 g•cm^{-3}, respectively. The percentage of silt and sand did not differ ($P> 0.05$) between the two culture systems, however, the percentage of clay in ponds with red tilapia cages was significantly ($P<0.05$) higher. Dry sediment pH of both tilapia culture systems were considered acidic, especially from ponds with red tilapia cages at an average of pH 4.47. The Nile tilapia ponds had 0.53 ± 0.03 % of total nitrogen while the average percentage of total nitrogen in the ponds with reed tilapia cages was 0.35 ± 0.09. The percentage of organic carbon in the ponds with red tilapia cages was 3.36 ± 0.39, which was significantly ($P<0.05$) higher than that in Nile tilapia ponds at 2.84 ± 0.44. Therefore, the ponds with red tilapia cages had a significantly higher ($P<0.05$) C:N ratio than the Nile tilapia ponds. The percentage of total phosphorus ranged between 0.11- 0.12 in both systems. The sediment depth of the three ponds with red tilapia cages averaged 15.82 ± 1.63 cm, whereas that in Nile tilapia ponds averaged 2.29 ± 0.44 cm. All analysis results of total sediment depth, sediment accumulation rate, and carbon burial rate differed ($P<0.05$) between the two culture systems. There were strong positive correlations ($P<0.01$) among C:N ratio, total sediment depth, and sediment accumulation rate. The sediment layers in all ponds were not suitable with regard to low pH level especially in ponds with red tilapia cages. Highly organic matter accumulation occurred underneath the cages in ponds over time. Following these findings, pond management practices related to pond bottom soil are strongly recommended to enhance and improve the capacity of the earthen ponds.

Keywords: Properties of sediment, sediment accumulation rate, Nile tilapia, red hybrid tilapia

Department of Aquaculture, Faculty of Fisheries, Kasetsart University, Bangkhen, Chatuchak, Bangkok, Thailand
*Corresponding author, e-mail: ffisiyw@ku.ac.th

INTRODUCTION

The environmental management of an earthen pond system in farms to generate best quality fish production does not consist only of water quality management, but also pond sediment quality management. Farmers pay careful attention to controlling pond water quality. Unfortunately, they normally have a lack of understanding of sediment characteristics and its management. There are strong relationships among water quality, sediment properties and fish yields (Boyd and Bowman, 1997). The microbial decomposition of organically enriched material at the bottom of the pond leads to oxygen depletion in the bottom areas. Anoxic conditions result and reduced substances such as hydrogen are released from the sediment layer to the pond water (Boyd and Tucker, 1998; Avnimelech and Ritvo, 2003). The liberated toxic substances can deteriorate the quality of water, and they are obviously harmful to aquatic animals. Bioturbation by some fish species increased the efficiency of oxygen transfer from water to pond bottom soil (Ritvo *et al.*, 2004). Thus, it is clear that there is a great interaction among water, sediment and fish production.

During culture period, large amount of inputs such as fish feeds and fertilizers are applied to the pond. Uneaten feeds, fish wastes, and dead organisms occur normally in the culture system, resulting in organic matter accumulation in the ponds. Excessive organic matter accumulation causes environmental conditions to deteriorate affecting water quality and making it time consuming to seine-harvest fish from the earthen pond (Steeby and Lovshin, 1993; Steeby *et al.*, 2004). The solution to improve the capacity of the earthen pond is the application of good pond management practices. Recent pond management procedures generally include drying out after draining, tilling the sediment layer during dry out, applying lime and probiotics, and removing sediments (Xinglong and Boyd, 2006; Nimrat *et al.*, 2008). Good pond management practices can enhance the use of fish ponds in the long term over 20-30 years (Wudtisin and Boyd, 2006).

In recent decades, there are a variety of tilapia culture systems in Thailand, but in general, they are: (1) net cage culture in the river or reservoir, (2) earthen pond, and (3) net cage culture in earthen pond. This study focused on two different tilapia culture systems: tilapia raised in earthen ponds and red hybrid tilapia raised in a multi-batch intensive culture system in net cages suspended in earthen ponds. The main focus of this work was to investigate the physical and chemical sediment properties and sediment accumulation rates in these two tilapia pond culture systems.

MATERIALS AND METHODS

Site selection and sediment sampling

The six earthen ponds used in this research were located in Nakhon Pathom Province, central part of Thailand. The ponds used were divided into two groups consisting of three earthen ponds for Nile tilapia culture and three ponds containing red tilapia net cages. Sediment samples were taken from the ponds in November 2013. At the time of

sediment sampling, all the Nile tilapia ponds were in their last week before harvesting, while the red tilapia cages in ponds had at least 1-2 months left before they were harvested. The farmer was interviewed to obtain information related to production practices.

The sediment depth could be elongated to several centimeters annually in turbid waters. The thickness or depth of sediment developed in ponds at the deeper water level (Tape and Boyd, 2002). Therefore, the location inside the pond that was proper to collect sediment samples was at the deep end of each pond where a large amount of organic matter had accumulated. Sediment samples were collected with a PVC pipe 5 cm in diameter and 30 cm. in length. Six points at the deep end of each pond were randomly selected for sediment sampling. In addition, in ponds were red tilapia cages were installed, sediment samples were also taken in two additional points per pond. These additional sampling locations were approximately 1 m away from the cage end. PVC pipe was inserted through the original pond bottom soil following the method of Munsiri *et al*. (1995). The topmost 5 cm sediment layer from two PVC pipe cores in each pond was kept in the can prepared for soil moisture analysis, while the first 5 cm sediment layer from other PVC pipe cores were mixed together to produce a composite sample. Soil sampling on the pond embankment was also conducted by digging approximately 10 - 15 cm deep in three random locations from each red tilapia pond. It was necessary to ensure that these soils had never been in contact with direct rainfall and air. Soil samples inside the pond embankment were collected and used as the representative of the original pond bottom soil. All methods of sediment analysis similar to sediment samples from six ponds were applied to these particular soil samples. This analysis was helpful to provide baseline information on the original pond bottom soil quality.

The sediment depth was measured following Steeby *et al*. (2004). A clear PVC pipe 5 cm in diameter and 50 cm in length was attached with a ruler to measure the height of the sediment depth. The sediment depth was randomly measured at ten places around the deep areas of each experimental pond. There were five additional points for measuring sediment depth located approximately 1 m away from the cage end in each red tilapia pond.

Sediment analysis methods

In each pond, all sediment variables were measured in two replicates except for total nitrogen which was analyzed once per pond. Sediment samples were dried at 102°C for analysis of dry bulk density according to the method described in Blake and Hartge (1986). A hydrometer method (Weber, 1977) was followed to analyze soil particle-size distribution. A glass electrode technique (Thunjai *et al*., 2001) was conducted for dry sediment pH. Dried sediment samples at 60°C prepared for organic carbon analysis were strongly oxidized using the Walkley Black method (Nelson and Sommers 1982). Following the Walkley Black method, organic carbon in sediment was strongly oxidized using potassium dichromate. The Gravimetric method was used to measure

the percentage of sediment moisture (Black, 1965). Total nitrogen concentration in sediment was analyzed with the Kjedahl method as described by Bremner (1996) and total phosphorus was determined using the dry ash method following Tavares and Boyd (2003).

Based on the calculation method described by Boyd *et al.* (2010) and Adhikari *et al.*(2012), sediment accumulation rate was estimated by dividing sediment depth with the age of the ponds; moreover, the sediment accumulation rate, percentage of organic carbon, and bulk density were used to estimate the carbon burial rate or carbon sequestration in the aquaculture pond.

The calculations were as follows (Boyd *et al.*, 2010; Adhikari *et al.*, 2012):

Sediment accumulation rate (cm•yr^{-1})

$$= \frac{\text{Average total sediment depth (cm)}}{\text{pond age (yr)}}$$

Carbon burial rate (g C•m^{-2}•yr^{-1})

= Sediment accumulation rate (cm•yr^{-1}) x dry bulk density of sediment (g•cm^{-3}) x percentage of organic carbon x 10^{4}

Data analysis

Mean and standard variation of all physical and chemical sediment variables were calculated and tested by analysis of variance (Anova) and the Duncan multiple range test. The relationships among sediment variables were analyzed by Pearson correlation. Sediment accumulation rate and total sediment depth were tested by Independent sample T-test (Steel and Torries, 1980). In case data violation of parametric assumptions occurred, these data were transformed to perform parametric procedures.

Culture practices

The Nile tilapia (*Oreochromis niloticus)* intensive culture began in 2008. Pond water surface areas ranged from 1.6 to 1.92 ha with an average depth of 1.5 to 2.5 m. Irrigation canal outside the farm was used to supply the water which was stored in the farm reservoir. Water was exchanged when water quality in the pond deteriorated. Fish were fed commercial pelleted diets only. No fertilizers were applied. Mechanical aerators were employed at night. The culture period was approximately 6 months. After harvesting, ponds were drained and dried, then lime was applied to the pond bottom. The amount of feed utilization in each pond was approximately 25,000 kg per crop. Fish yield in each pond was approximately 15-30 tons per crop.

The red tilapia hybrid (*Oreochromis niloticus × mossambicus*) intensive culture has been practiced in the farm since 2008, with several 3 x 6 m net cages suspended in earthen ponds. Pond water surface areas ranged from 1.6 to 1.92 ha with average depths of 2 to 3 m. Water was sourced from an irrigation canal outside the farm and stored in the farm reservoir. Pond water was always well-circulated. There were 40 net cages in each pond. Fish were fed with commercial pellets only. No fertilizers were applied. Mechanical aerators were used at night. The operation culture period was longer than Nile tilapia culture, at 7-9

months for one crop. No pond bottom soil management practices were employed. The amount of feed utilization in each pond was approximately 30,000 kg per crop. Fish production from each pond was approximately 20-30 tons per crop.

The three ponds containing red tilapia cages were located close to the farm reservoir while the Nile tilapia ponds were located far from the reservoir. The water surface area of the farm reservoir was 4.8 ha. The total water surface area of all fish ponds in this farm were approximately 35.2 ha. The farmer has never applied any pond soil management procedures in the ponds with red tilapia cages over the six years since the farm started. However, the earthen ponds used for intensive Nile tilapia culture were drained and dried with lime application between crops but sediment layers have never been removed. It is doubtful that these two tilapia culture ponds would be sustainable over a long period of time.

RESULTS AND DISCUSSION

Sediment properties

Dry bulk density is the weight of dry soil solids in the known total bulk volume with air space (Brady and Weil, 2007). Bulk density of the two tilapia culture ponds did not differ (P>0.05), with an average bulk density of 0.77 ± 0.12 g•cm^{-3} and 0.86 ± 0.10 g•cm^{-3}, respectively (Fig. 1). Both culture ponds had bulk density levels lower (P< 0.05) than original pond soil (1.27 ± 0.04 g•cm^{-3}). Munsiri *et al*. (1995) reported bulk density of original pond bottom soil in Alabama

was 1.4 g•cm^{-3} or higher. The average bulk density of the original pond soil in recent study was close to those reported above. Typically mineral soil had bulk density approximately 1-2 g•cm^{-3}. Bulk density will be reduced in the sediment accumulation areas inside a pond (Boyd, 1995). Soft flocculent layer was originated by enriched organic matter accumulation underneath the pond resulting in soil compaction reduction (Steeby *et al*., 2004; Avnimelech *et al*., 2001; Ruehlmann and Körschens, 2009).

Soil texture of the original pond soil and the Nile tilapia pond bottom soil was sandy clay loam. The red tilapia pond bottom soil had a clay loam texture. In particle size distribution analysis, the results showed that the percentages of silt did not differ (P> 0.05) among the original pond soil, the red tilapia ponds and the Nile tilapia ponds, which were 16.50 ± 0.84, 18.02 ± 1.30, 23.76 ± 12.33 %, respectively, while sand percentage of the original pond soil was higher (*P*< 0.05) than that of the two tilapia ponds. Clay particle concentrations differed among sample groups (P<0.05). The red tilapia net cage culture suspended in earthen pond had the highest clay concentration. Embankment erosion caused by wave and rainfall increased clay concentration in the culture system. The main mineral components of clay particles were silica, iron and aluminum. High clay concentrations tended to generate acidity due to octahedral sheet in clay contained aluminum which was considered a source of acidity (Sankaram, 1977). Although clay particles could cause turbidity when sediments re-suspend in the water column leading to photosynthesis reduction, these particles have the ability to keep plant
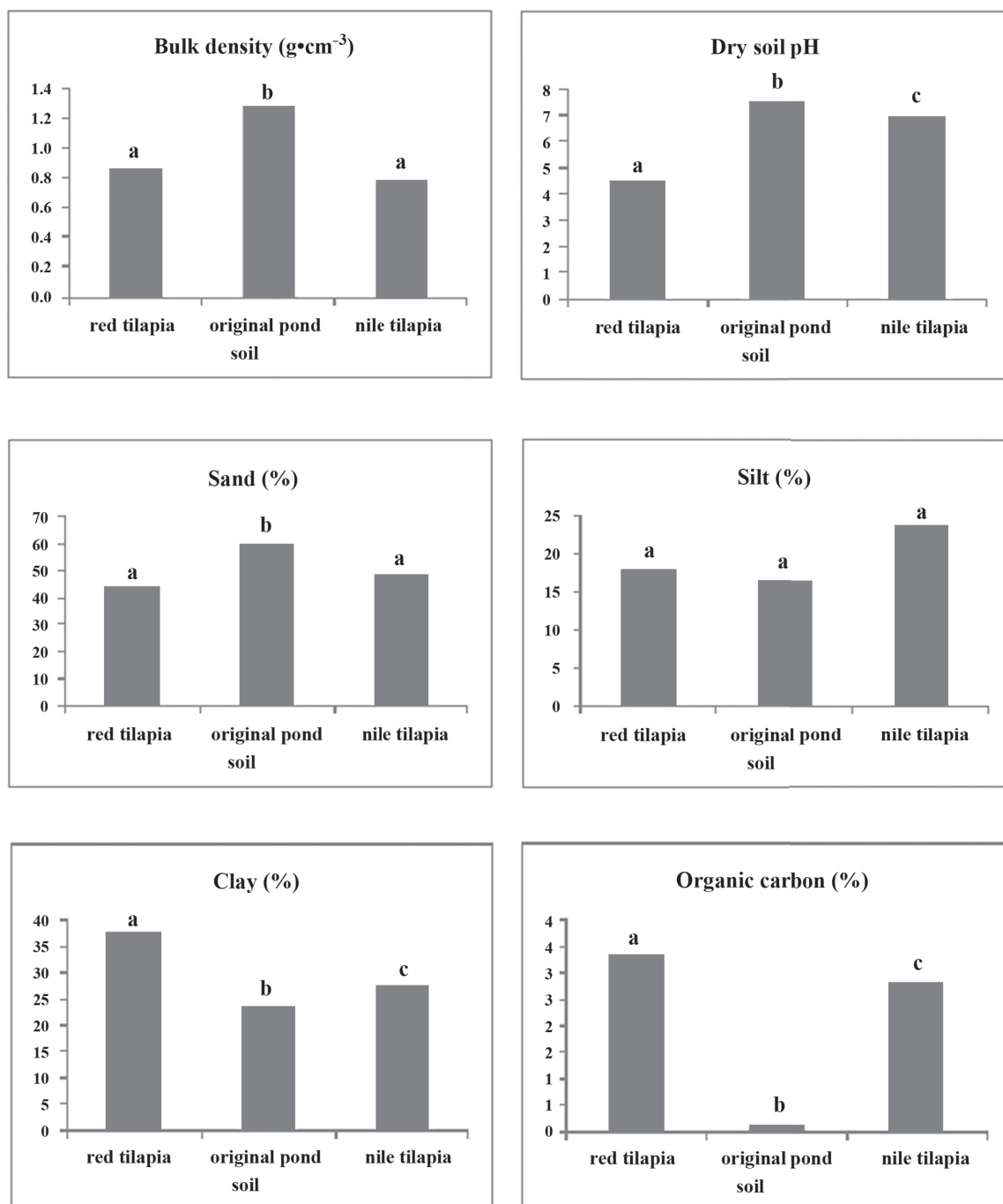
Figure 1. Histogram displaying average concentration of sediment variables in two culture ponds and average concentration of original pond soil variables. The same letter in the figure did not differ (P>0.05)
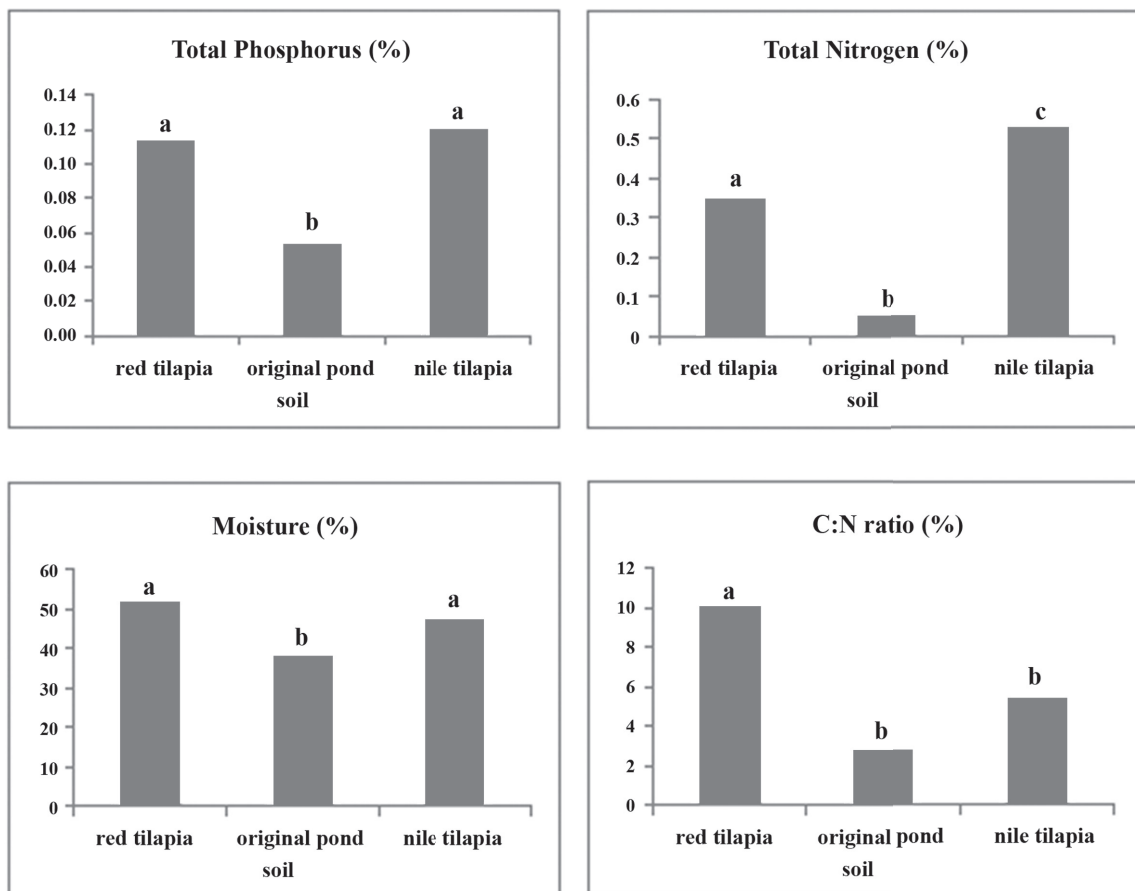
Figure 1.   continued. Histogram displaying average concentration of sediment variables in two culture ponds and average concentration of original pond soil variables. The same letter in the figure did not differ (P>0.05)

nutrients (Sankaram, 1977). Sediment with high clay contents in ponds after adjusting pH would be useful for planting.

Dry sediment pH of both tilapia pond systems were considered acidic, especially in the sediments from red tilapia ponds, while the original pond soil samples were slightly alkaline. All samples differed (P< 0.05) among three sample groups, which showed the average pH of 6.95±0.29, 4.47±0.21 and 7.52±0.05 from the Nile tilapia ponds, red tilapia ponds and the original pond soil,

respectively. There are many factors affecting soil pH such as the amount of $CaCO_3$ and Na_2CO_3 applied in pond soil, carbonic acid liberated from respiration process (Sankaram, 1977), then the degradation of organic matter in sediment layers could provide carbonic acid which is dissolved in sediment solution. This process over time could cause pH reduction in pond sediment. However, the Nile tilapia ponds had added lime material when the pond was being dried resulting in higher pH levels in their sediments than in red tilapia ponds. The fact that mineral

particles, especially clay content, in sediment layers had never been removed and that lime material had never been applied in the red tilapia ponds might be the reason for pH reduction in the sediments. Boyd and Pipoppinyo (1994) concluded that the suitable pH range for aquaculture pond soil was 7.5 -8.5. At this pH range, microbial activity was effective during rapid decomposition in sediment. Sediment pH from both tilapia pond systems failed to meet the suitable pH level as mentioned above. For pond sediment pH improvement, the lime requirement analysis is necessary to determine the right amount of lime to be applied.

The concentration of total nitrogen from three sample groups indicated significant differences (P< 0.05) among them. The original pond bottom soil had the lowest percentage of total nitrogen at 0.05±0.00. The Nile tilapia ponds had an average percentage of 0.53±0.03 in total nitrogen which was higher than that of 0.35±0.09 percent in red tilapia ponds. In comparison with Wudtisin and Boyd (2006), total nitrogen percentages from both tilapia cultures in this research were higher than carp ponds, freshwater prawn ponds, and catfish ponds located in the central part of Thailand. Those three species from former research described above had average percentage of total nitrogen from 0.28±0.12, 0.14±0.04, 0.18±0.11, respectively. There were many factors influencing the concentration of total nitrogen in ponds. The difference in feed quality, amount of feed, fertilization use, culture species, pond preparation practices and water quality managements led to different level of total nitrogen deposition in pond ecosystem. Acosta-Nassar et al. (1994) studied the

nitrogen budgets in a semi-intensive fish pond. They found that major nitrogen input came from feed 87 percent and nitrogen mostly accumulated into the sediment layer.

The organic carbon concentration also showed significant differences (P< 0.05) among the three sample groups similar to total nitrogen. The red tilapia ponds, the Nile tilapia ponds and the original pond bottom soils had average organic carbon concentrations of 3.36±0.39, 2.84±0.44, 0.15 ±0.06 %, respectively. Boyd et al. (2002) categorized organic matter concentration in ponds, concluding that 1-3 % of organic matter contents were considered an optimum range for pond aquaculture. They also explained that soil organic matter contains 45-50 % of organic carbon. A simple formula to convert organic carbon into to organic matter is to multiply organic carbon by 2. According to Boyd et al. (2002), the organic matter content of the two types of tilapia ponds from this recent study did not fall within the best range mentioned above.

Thunjai (2004) investigated the sediment quality of seventeen Nile tilapia earthen ponds in Samut Prakan Province. The average percentage of organic carbon was just 1.86±0.15. Pond management practices such as pond draining and drying for 1-6 weeks, sediment removal and lime application were practiced in the previous study cited above. Those practices could help to reduce the organic carbon concentration in pond sediments.

C:N ratio could be calculated by dividing the percentage of organic carbon by the percentage of total nitrogen. When the

proportion of nitrogen concentration was not suitable, the nitrogen concentrations were inadequate to enhance microbial activity and the decomposition process would be carried out slowly (Boyd, 1995). In this study, C:N ratio was 10.10±2.97 and 5.40±2.97 in red tilapia ponds and Nile tilapia ponds, respectively. The original pond bottom displayed the lowest C:N ratio at 2.81±1.49. The red tilapia ponds had a C:N ratio which was significantly different (P< 0.05) from the other two sample groups.

The total phosphorus percentages were 0.11±0.03 and 0.12±0.03 in red tilapia and the Nile tilapia ponds, respectively. These values were not significantly different (P>0.05). However, that of the original pond bottom soil was significantly lower at a percentage of 0.05±0.01. Normally phosphorus was concentrated in the sediment more than in the water column. Pond bottom sediment was the major sink of phosphorus compounds (Boyd and Tucker, 1998).

The sediment quality of the two tilapia pond culture systems was not good especially total nitrogen, organic carbon and sediment pH. Although the Nile tilapia ponds were drained and dried before starting the new crop, the water circulation system in these ponds was ineffective. This could be due to the great distance of the ponds from the reservoir. Moreover, the water in Nile tilapia ponds was circulated only when plankton bloom occurred towards the end of cropping period. The farmer only dried the Nile tilapia ponds for less than one week which was not enough for sediment degradation, which meant that the total nitrogen and organic carbon remained in the

ponds. The ponds with red tilapia cages in had the advantage of having good water circulation system because they are nearer to the reservoir. Pond water was circulated continuously but the sediments were kept in the ponds for six years and the ponds have never been limed leading to lower sediment pH.

Sediment accumulation rate and carbon burial rate

Pond soil profile, as described in Munsiri *et al.* (1995), showed clearly that five soil layers developed in the pond. These were F (flocculent layer), S (stirred or mixed sediment), M (mature bulk un-mixed sediment), T (transitional layer) and P (original, undisturbed pond bottom) layers arranged from the soil-water interface to the original pond bottom. Total sediment depth (S+M layer) in this present study was investigated under the water level in a pond approximately down to 2-3 m in depth.

The mean and standard deviation of total sediment depth values in each pond were calculated. Pond age was five years when sediment samplings were conducted (Table 1). Sediment depth of the three ponds with red tilapia cages averaged 15.82 ±1.63 cm, whereas that in Nile tilapia ponds was 12.29±0.44 cm. The annual sediment accumulation rate from ponds with red tilapia cages and Nile tilapia ponds averaged 3.16±0.33 cm•yr^{-1} and 2.46±0.01 cm•yr^{-1}, respectively. The average carbon burial rates were 917.52±130.05 g C•m^{-2}•yr^{-1} and 603.67±10.32 g C•m^{-2}•yr^{-1}, respectively. Total sediment depth, sediment accumulation rate, and carbon burial rate were significantly

Table 1. Comparison of the total sediment depth, sediment accumulation rate, and carbon burial rates between Nile tilapia ponds and ponds with red tilapia cages, Nakhon Pathom, Thailand

Pond	Nile tilapia	Red tilapia
Pond age during sediment collection (yr)	5	5
Total sediment depth (cm)	12.29 ± 0.44^a	15.82 ± 1.63^b
Sediment accumulation rate (cm•yr^{-1})	2.46 ± 0.01^a	3.16 ± 0.33^b
Carbon burial rate (g C•m^{-2}•yr^{-1})	603.67 ± 110.32^a	917.52 ± 130.05^b

Different superscripts in each row mean there is a significant difference (T values, $P<0.05$).

different ($P<0.05$) between the two pond culture systems. There are two explanations relative to the highest sediment depth and accumulation rate of red tilapia ponds. First, several net cages suspended in water would deter water flow, therefore contributing to sediment deposition. Second, the ponds where the red tilapia cages were installed had never been drained nor their sediments removed. The Nile tilapia ponds were drained and dried after harvesting. Draining practice might allow some of the organic matter to be discharged with effluent (Adnikariet *et al.*, 2012). However, overall results from the specific three variables from both pond culture systems were still higher compared to other related investigations. Data from Wudtisin and Boyd (2006) summarized by Boyd *et al.* (2010) revealed that the carbon burial rates in carp ponds, freshwater prawn ponds, and catfish ponds were 318, 28, 64 g C•m^{-2}•yr^{-1}, respectively. The carbon burial rate of different fish species depended upon the carbon input and carbon output which varied among culture species in a variety of culture managements.

Boyd *et al.* (2010) stated that the carbon burial rate of aquaculture ponds might benefit as carbon reduction credit in some carbon emission programs. Although carbon burial rate capacity for possible carbon reduction credit in aquaculture ponds was not the main focus of our investigation, this is interesting to study for future use due to the increasing concern about carbon emissions from the agriculture sector.

Correlation among sediment variables

Pearson correlation was performed to find out the correlation coefficient among sediment variables. All sediment variables from both tilapia culture pond systems were incorporated for this investigation. Strong positive correlations ($P<0.01$) were found among C:N ratio, total sediment depth, and sediment accumulation. All variables above had correlation coefficients r = 0.987. Dry soil pH had strongly negative correlation ($P<0.01$) to clay concentration with r = -0.975. At significant probability levels of 0.05, organic carbon concentration positively correlated to carbon burial rate with r = 0.913. Total sediment depth and sediment accumulation rate positively correlated to clay concentrations, with similar r = 0.840. Dry soil pH had strongly negative correlation with total sediment depth and sediment accumulation rate, with variables having

similar $r = 0.812$. Jiménez-Montealegre *et al*. (2002) had tested two tailed Pearson correlation of sedimentation rate collected by sediment traps in tilapia ponds. There were positive correlations (P<0.01) among sedimentation rate, fish weight, fish feed, fish biomass, and chlorophyll *a* concentration.

This part of research aimed to seek some variables which can be used to evaluate overall sediment quality. According to our results, few variables were correlated, therefore none of the sediment variables studied could be used as an indicator of overall sediment quality.

CONCLUSION

The main focus of this research was to investigate sediment quality of two tilapia culture pond systems. Both sediment layers of ponds used were not suitable with regard to low pH level especially the ponds with red tilapia cages, where highly organic matter accumulated on the pond bottom over time. The anoxic condition in sediment layers can occur when oxygen is depleted. Possible toxic substances such as hydrogen sulfide could be released to waters (Boyd and Tucker, 1998; Avnimelech and Ritvo, 2003). This finding suggests that sediment removal is necessary for both culture pond systems. According to Yuvanatemiya and Boyd (2006), sediment removal can improve the physical and chemical properties of soil, and decrease toxic substances in sediment. After draining and drying the pond, lime should be applied. Lime requirement method is important to calculate the exact amount of lime application rate in particular ponds. To sustain pond productivity, pond best management practices relevant to bottom pond should be applied to improve the capacity of fish ponds for future use.

LITERATURE CITED

Acosta-Nassar, M.V. , J. M. Morell and J. E. Corredor. 1994. The Nitrogen Budget of a Tropical Semi-Intensive Freshwater Fish Culture Pond. **Journal of the World Aquaculture Society** 25: 261–270.

Adhikari, S., R. Lal, and B. C. Sahu. 2012. Carbon sequestration in the bottom sediments of aquaculture ponds of Orissa, India. **Ecological Engineering** 47:198–202.

Avnimelech, Y., G. Ritvo, L. E. Meijer and M. Kochba. 2001. Water content, organic carbon and dry bulk density in flooded sediments. **Aquacultural Engineering** 25 : 25–33.

Avnimelech, Y. and G. Ritvo. 2003. Shrimp and fish pond soils: processes and management. **Aquaculture** 220: 549–567.

Blake G.R. and K.H Hartge. 1986. Bulk density. In: **Methods of Soil Analyses, Part 2: Chemical and Microbiological Properties** (ed. A. Klute), pp. 363-375. American Society of Agronomy and Soil Science Society of America, Madison.

Boyd C.E. and C.S. Tucker. 1998. **Pond Aquaculture Water Quality Management.** Kluwer Academic Publishers, Boston, 700 pp.

Boyd C.E., C.W. Wood, P.L. Chaney and J.F. Queiroz . 2010. Role of aquaculture pond sediments in sequestration of annual global carbon emissions. **Environmental Pollution** 158: 2537 –2540.

Boyd, C. E. 1995. **Bottom Soils, Sediment, and Pond Aquaculture**. Chapman and Hall, New York. 347 pp.

Boyd, C. E. and S. Pipoppinyo. 1994. Factors affecting respiration in dry pond bottom soils. **Aquaculture** 120:283 – 293.

Boyd, C. E. and J. R. Bowman. 1997. Pond bottom soils. In: **Dynamics of Pond Aquaculture** (ed. H.S. Egna and C.E. Boyd), pp. 135-162. CRC Press Boca Raton, New York.

Boyd, C. E., C.W. Wood, and T. Thunjai. 2002. **Aquaculture Pond Bottom Soil Quality Management**, Pond Dynamics /Aquculture Collaborative Research Support Program. Nineteenth Annual Technical Report. Oregon State University. Oregon, USA, 1-48 pp.

Brady N.D.C. and R. R. Weil 2007. **The Nature and Properties of Soils,** 14 [th] ed. Prentice Hall, New York. 980 pp.

Bremner, J.M. 1996. Nitrogen total. In **Methods of Soil Analysis, Part 3: Chemical Methods** (ed. D.L Sparks), pp.1085–1121. Soil Science Society of America: Madison, Wisconsin.

Jiménez-Montealegre R., M. Verdegem, J.E. Zamora, and J. Verreth. 2002. Organic matter sedimentation and resuspension in tilapia (*Oreochromis niloticus*) ponds during a production cycle. **Aquacultural Engineering** 26:1–12

Munsiri P., C.E. Boyd and B.J. Hajek. 1995. Physical and chemical characteristics of bottom soil property in ponds at Auburn, Alabama, and a proposed method for describing pond soil horizons. **Journal of the World Aquaculture Society** 26: 346-377

Nelson, D. W. and L. E. Sommers. 1982. Total carbon, organic carbon, and organic matter. In: **Methods of Soil Analysis, Part 2: Chemical and Microbiological Properties** (ed. A.L. Page, R.H. Miller and D.R. Keeney), pp. 539-579. American Society of Agronomy, Madison.

Nimrat, S., S. Suksawat, P. Maleeweach and V. Vuthiphandchai. 2008. Effect of different shrimp pond bottom soil treatments on the change of physical characteristics and pathogenic bacteria in pond bottom soil. **Aquaculture** 285: 123–129

Ritvo, G., M. Kochba and Y. Avnimelech. 2004. The effects of common carp bioturbation on fishpond bottom soil. **Aquaculture** 242: 345–356.

Ruehlmann J. and M. Körschens. 2009. Calculating the effect of soil organic matter concentration on soil bulk density. **Soil Science Society of America Journal** 73 (3): 876 –885.

Sankaram, A. 1977. **Soil science: chemical properties.** Bangalore Printing and Publishing Co., Bangalore. 184 pp.

Steeby, J. A., J.A. Hargreaves, C.S.Tucker, and S. Kingsbury. 2004. Accumulation, organic carbon and dry matter concentration of sediment in commercial channel catfish ponds. **Aquaculture Engineering** 30:115–126.

Steeby, J.A. and L.L. Lovshin. 1993. Comparison of seines equipped with rubber roller or gathered-netting mud lines for harvesting channel catfish in earthen ponds. **Progress. Fish-Cult** 55: 133–136.

Steel, R. G. D and Torrie, J. 1980. **Principle and procedure of statistics. A biometric approach, 2nd edn.** McGraw-Hill, New York. 633 pp.

Tavares, S. L. H. and C. E. Boyd. 2003. Comparison of a dry ash method with perchloric acid digestion for total phosphorus analysis of pond sediment. **Journal of Aquaculture in the Tropics** 18(3): 239-244.

Tepe Y. and C.E. Boyd. 2002. Sediment quality in Arkansas bait minnow ponds. **Journal of the World Aquaculture Society** 33: 221-232.

Thunjai T., C.E. Boyd and M. Boonyaratpalin. 2004. Bottom soil quality in tilapia ponds of different age in Thailand. **Aquaculture Research** 35:698-705.

Thunjai, T., C. E. Boyd and K. Dube. 2001. Pond soil pH measurement. **Journal of the World Aquaculture Society** 32: 141-152.

Weber, J. B. 1977. Soil properties, herbicide sorption and model soil systems. In: **Research Methods in Weed Science, 2nd edition** (ed. B. Truelove), pp. 59-62. Southern Weed Science Society, Auburn.

Wudtisin, I. and C. E. Boyd. 2006. Physical and chemical characteristics of sediments in catfish, freshwater prawn, and carp ponds in Thailand. **Aquaculture Research** 37:1202 – 1214.

Xinglong, J. and C. E. Boyd. 2006. Relationship between organic carbon concentration and potential pond bottom soil respiration. **Aquacultural Engineering** 35:147 – 151.

Yuvanatemiya, V. and C. E. Boyd. 2006. Physical and chemical changes in aquaculture pond bottom soil resulting from sediment removal. **Aquacultural Engineering** 35:199 – 205.