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Role of aquaculture pond sediments in sequestration of annual global carbon emissions

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Aquaculture ponds sequester about 16.6 MT yr^{-1} of organic carbon worldwide representing around 0.21% of annual, global carbon emissions.

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1. Introduction

Efforts to quantify carbon sequestration in inland water bodies have focused on inland seas, natural lakes, and large river impoundments (Mulholland and Elwood, 1982; Dean and Gorham, 1998). A recent study in Iowa (Downing et al., 2008) suggested that small, agriculturally-eutrophic impoundments bury carbon at an average rate of 2122 g m^{-2} yr^{-1} – five times higher than in large, river impoundments, 30 times more than in small, natural lakes, and over 400 times greater than in inland seas and large natural lakes (Mulholland and Elwood, 1982; Dean and Gorham, 1998). The combined water surface area of small impoundments in farming areas was estimated at 21,000 km^2 in the United States and 77,000 km^2 globally (Smith et al., 2002; Downing et al., 2006), and these impoundments may bury more carbon than the world's oceans (Downing et al., 2008).

The area of agriculturally-eutrophic impoundments used for estimating carbon sequestration (Downing et al., 2008) did not include aquaculture ponds. According to statistical data on aquaculture production maintained by the Food and Agriculture Organization (FAO) of the United Nations, there are 110,830 km^2 of aquaculture ponds worldwide (Verdegem and Bosma, 2009). Aquaculture ponds also may be important in global, carbon sequestration.

Aquaculture ponds do not have large external sediment loads typical of river reservoirs or small, watershed ponds in agricultural or other rural areas (Boyd, 1995). However, earthwork of aquaculture ponds is eroded by rain, waves, and water currents generated by mechanical aerators, activities of culture species, and harvesting operations. Manure, grass, and other agricultural wastes traditionally have been applied to ponds as organic fertilizer to increase aquatic animal production, but high-quality, pelleted feeds are rapidly replacing fertilizers as a means of achieving greater production (Boyd and Tucker, 1998). Fertilizers and feeds contain inorganic nutrients that stimulate organic carbon production by phytoplankton photosynthesis in ponds (Boyd and Tucker, 1998).

Coarse, soil particles suspended by internal erosion settle near edges of ponds while smaller particles tend to settle in deeper areas (Boyd, 1995). Organic matter from dead plankton, organic fertilizers, uneaten feed, and excrement of culture species settles on pond bottoms and gradually mixes with soil particles. Aquaculture management favors microbial decomposition of organic matter. For

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example, organic matter inputs usually have a narrow carbon: nitrogen ratio, ponds with acidic, bottom soils are limed, and mechanical aeration avoids oxygen-depletion at the sediment–-water interface (Boyd and Tucker, 1998). Much recently-settled organic detritus is discharged when ponds are drained for harvest (Ayub et al., 1993). After draining, pond bottoms usually are dried to enhance soil aeration and accelerate decomposition of labile organic matter (Boyd, 1995). Nevertheless, a layer of sediment with an organic carbon concentration higher than that of the original pond bottom soil and with a characteristic profile of well-defined strata or horizons develops (Munsiri et al., 1995).

2. Materials and methods

The United States Agency for International Development funded the Pond Dynamics Aquaculture Collaborative Research Support Program (ACRSP) from 1984 to 2008. As part of this project, sediment cores were taken from 233 aquaculture ponds of known age at 25 locations in nine countries according to the methodology described by Munsiri et al. (1995). Ponds were used to culture a total of eight common species or species groups. Forty-two of the ponds were located on research stations while the rest were on commercial farms (Table 1). Ponds on research stations were 0.04–0.5 ha in area. Accurate data on pond area could not be obtained for many commercial ponds, but most were larger than 0.5 ha and some exceeded 5 ha in water surface area. Most ponds were embankment or excavated ponds with average depths of 1–1.5 m. Analyses of sediment cores done by standard techniques (Munsiri et al., 1995) included sediment depth, sediment accumulation rate, dry bulk density, and percentage organic carbon in sediment. Organic carbon burial rate was estimated by multiplying the dry weight of sediment accumulation per year by the organic carbon concentration in sediment.

3. Results and discussion

Ponds age ranged from 1 to 52 yr (Table 1) with an average age of 14.9 ± 10.4 yr. Sediment depth varied from 4 to 36 cm (average 16.8 ± 11 cm), and the average rate of sediment accumulation was 1.44 ± 0.79 cm yr^{-1} (range 0.5–3.7 cm yr^{-1}). Sediment had been removed on one or more occasions from some of the ponds in Thailand, but sediment depth was correlated with pond age ($r = 0.78$; $P < 0.01$). The annual rate of sediment deposition averaged 14,400 $cm^3\ m^{-2}$ (144 $m^3\ ha^{-1}$). According to a study by Steeby et al. (2004), sediment accumulation in channel catfish ponds in Mississippi declined as ponds aged. In the first year, the rate of sediment accumulation averaged 12.5 cm; in years 2–5, the rate was 3 cm yr^{-1}; in years 6–10, the rate was 1.8 cm yr^{-1}; in years 11–15, the rate was 1.3 cm yr^{-1}; in years 16–21, the rate was 1.3 cm yr^{-1}. In the present study, there also was a tendency for sediment accumulation rate to decline with pond age ($r = -0.50$; $P < 0.05$).

The dry bulk density of sediment ranged from 0.176 to 0.760 g cm^{-3} (Table 1) (average = 0.475 ± 0.187 g cm^{-3}). Dry bulk density was not correlated with either pond age ($r = 0.04$; $P > 0.05$) or sediment depth ($r = 0.11$; $P > 0.05$). Avnimelech et al. (2001) found that sediment dry bulk density was inversely related to the organic carbon concentration ($r = 0.84$) for a diverse group of sediment samples including rivers, lakes, and fish ponds. However, no such relationship was found in the present study ($r = 0.33$; $P > 0.05$). The average weight of sediment accumulation in ponds included in the present study was 6840 g $m^{-2}\ yr^{-1}$ (68.4 T $ha^{-1}\ yr^{-1}$).

Organic carbon concentration in sediment ranged from 1.08 to 7.01% (Table 1) (average = 2.46 ± 1.21%). Information on organic matter inputs to ponds in organic fertilizers and feeds could not be obtained, but there were no clear trends in organic carbon concentration related to culture species or intensity of culture. Percentage organic carbon in sediment was not correlated with pond age ($r = 0.03$; $P > 0.05$). Steeby et al. (2004) found that organic carbon concentration in sediment of channel catfish ponds in Mississippi (USA) ranged from 0.76 to 3.43% with an average of 1.66%. They did not observe a relationship between organic carbon concentration and pond age or production intensity.

Annual, carbon burial rate estimated from sediment accumulation rate, dry bulk density of sediment, and percentage carbon in

Table 1
Summary of data from analyses of sediment cores from 233 aquaculture ponds.

Location and type of pond	*n*	Age (yr)	Sediment depth (cm)	Sediment accumulation (cm yr^{-1})	Sediment dry bulk density (g cm^{-3})	Organic carbon (%)	Carbon burial (g $m^{-2}\ yr^{-1}$)	Source
Chapeco, Brazil (tilapia)	3	25	36	1.4	0.602	2.90	244	Unpublished
Jundiai, Brazil (tilapia)	3	24	26	1.1	0.420	5.43	251	Unpublished
Pirassununga, Brazil (Research Station)	3	20	22	1.1	0.340	2.58	96	Unpublished
Abassa, Egypt (Research Station)	6	11	12	1.1	0.434	2.40	115	Munsiri et al. (1996)
Choluteca, Honduras (shrimp)	3	11	10	0.9	0.500	2.10	94	Unpublished
El Carao, Honduras (Research Station)	3	17	12	0.7	0.743	2.02	105	Unpublished
Sagana, Kenya (Research Station.)	3	10	8	0.8	0.368	3.12	92	Boyd et al. (1998)
Iquitos, Peru (Research Station)	3	8	4	0.5	0.485	2.22	54	Boyd et al. (1999)
Munoz, Philippines (Research Station)	3	15	10	0.7	0.682	2.05	98	Unpublished
Hoedspruit, South Africa (tilapia)	3	3	6	2.0	0.213	7.01	299	Unpublished
Nelspruit, South Africa (tilapia)	3	2	6	3.0	0.760	1.46	333	Unpublished
Messina, South Africa (tilapia)	3	4	8	2.0	0.715	1.60	229	Unpublished
Ayutthaya, Thailand (Research Station)	3	20	34	1.7	0.525	1.08	96	Unpublished
Chiangrai, Thailand (tilapia)	17	14	16	1.1	0.463	3.03	154	Thunjai et al. (2004)
Khao Chakan, Thailand (shrimp)	3	5	6	1.2	0.625	3.66	274	Boyd et al. (1999))
Rangsit, Thailand (Research Station)	3	2	6	3.0	0.567	1.76	299	Boyd et al. (1997)
Rangsit, Thailand (Research Station	3	18	22	1.2	0.531	1.81	115	Boyd et al. (1997)
Sakaew, Thailand (carp)	3	17	22	1.3	0.740	1.69	163	Boyd et al. (1999)
Samutprakarn, Thailand (tilapia)	35	15	16	1.1	0.234	2.96	76	Thunjai et al. (2004)
Suphan Buri/Sara Buri, Thailand (*Clarias* catfish)	42	8	20	2.5	0.176	1.46	64	Wudtisin and Boyd (2006)
Suphan Buri/Sara Buri, Thailand (freshwater prawn)	40	11	12	1.1	0.182	1.38	28	Wudtisin and Boyd (2006)
Suphan Buri/Sara Buri, Thailand (carp)	18	9	33	3.7	0.285	3.02	318	Wudtisin and Boyd (2006)
Auburn, Alabama USA (Research Station)	3	2	5	2.5	0.317	2.33	185	Munsiri et al. (1995)
Auburn, Alabama, USA (Research Station)	3	23	25	1.1	0.355	2.54	99	Munsiri et al. (1995)
Auburn, Alabama, USA (Research Station	3	52	48	0.9	0.502	2.29	103	Munsiri et al. (1995)
Beauregard, Alabama, USA (channel catfish)	3	22	20	0.9	0.324	2.67	78	Unpublished
Clayton, Alabama, USA (channel catfish)	3	18	27.5	1.5	0.430	3.16	204	Unpublished
Lonoke, Arkansas, USA (bait minnow)	3	7	8	1.1	0.514	1.34	76	Tepe and Boyd (2002)
Lonoke, Arkansas, USA (bait minnow)	3	22	12	0.6	0.563	1.53	52	Tepe and Boyd (2002)
Lonoke, Arkansas, USA (bait minnow)	3	33	24	0.7	0.336	1.88	44	Tepe and Boyd (2002)
Stoneville, Mississippi, USA (Research Station)	3	13	27.5	2.1	0.468	1.81	178	Unpublished

Table 2
Typical inputs and outputs of organic carbon in ponds for tilapia culture. Gross photosynthesis data are for ponds with inputs of carbon and nutrients similar to those used in the calculations (Boyd, 1973; Boyd and Tucker, 1998).

Variable	Organic carbon ($g\ m^{-2}\ yr^{-1}$)		
	Manured pond[a]	Chemically-fertilized pond[b]	Feed Applied[c]
Inputs			
Organic fertilizer	1440	–	–
Feed	–	–	450
Gross photosynthesis	1095	1460	1460
Water	10	10	10
Outputs			
Effluent	30	30	40
Fish	22	13.2	66
Inputs–outputs	2493	1426.8	1814
Carbon burial[d]	124.6–249.3	71.3–142.7	90.7–181.4

[a] Organic fertilizer = 20 kg dry weight day^{-1} for 8 months, C = 40% dry weight; gross photosynthesis = 3 g C $m^{-2}\ day^{-1}$; fish production = 2000 kg ha^{-1}; fish contain 11% C (live weight).
[b] Fertilized with 20% N and 20% P_2O_5 applied at 50 kg ha^{-1} every 2 weeks.
[c] Feed = 10,000 kg ha^{-1}, feed contains 48% C; gross photosynthesis = 4 g C m^{-2} day^{-1}; fish production = 6000 kg ha^{-1}.
[d] The smaller value is based on 95% of the difference between inputs and outputs being decomposed annually while the larger value assumes that 90% of the difference is decomposed each year.

sediment ranged from 28 to 333 $g\ m^{-2}\ yr^{-1}$ (Table 1) (average = 148.9 ± 90.3 $g\ m^{-2}\ yr^{-1}$). Average carbon burial rate was not clearly related to aquatic animal production intensity in ponds. For example, the lowest carbon burial rates were found in freshwater prawn ponds (28 $g\ m^{-2}\ yr^{-1}$) and bait minnow ponds (57 $g\ m^{-2}\ yr^{-1}$) that had low production. However, *Clarias* catfish ponds that had high production did not have much higher rates of carbon burial (64 $g\ m^{-2}\ yr^{-1}$). The highest carbon burial rates were for tilapia ponds (264 $g\ m^{-2}\ yr^{-1}$) and carp ponds (240 $g\ m^{-2}\ yr^{-1}$). Both tilapia and carp stir pond sediment in search of food organisms, and tilapia sweep out large holes in pond bottoms to make nests. These actions possibly incorporate recently-deposited organic matter into sediment to minimize its loss during pond draining for harvest.

Typical organic matter input and production data for tilapia were used to make organic matter budgets for tilapia ponds managed by different procedures. The differences in carbon inputs and carbon outputs represent carbon sequestration. The estimated rates of carbon burial of 90.7–249.3 $g\ m^{-2}\ yr^{-1}$ (average = 143.3 $g\ m^{-2}\ yr^{-1}$) (Table 2) were similar to rates determined by sediment core analysis.

The estimated, average, annual carbon burial rate for aquaculture ponds was lower than that of large, river impoundments and small, agriculturally-eutrophic impoundments, but higher than that of inland seas and natural lakes (Table 3). The major reason

Table 3
Global areas of inland water bodies and annual rates and amounts of organic carbon burial in these systems.

Water body	Global area (km^2)	Carbon burial rate ($T\ ha^{-1}\ yr^{-1}$)	Global carbon burial ($MT\ yr^{-1}$)
Large lakes and inland seas[a]	2,180,000	0.05	11
Small lakes[a]	320,000	0.72	23
Large, river reservoirs[a]	400,000	4.0	160
Aquaculture ponds[b]	110,800	1.5	16.6
(Freshwater)	(87,500)	(1.5)	(13.1)
(Brackishwater)	(23,330)	(1.5)	(3.5)
Agricultural impoundments[c]	77,000	21.2	163

[a] Dean and Gorham (1998).
[b] Smith et al. (2002).
[c] Downing et al. (2008).

Table 4
Continental aquaculture pond areas extrapolated from 2006 total inland aquaculture production of 28,324,018 T and a global pond area of 110,830 km^2.

Continent	Total inland production[a] ($T\ yr^{-1}$)	Extrapolated pond area (km^2)
Africa	198,300	2008
North America	465,115	1837
South America	282,650	1116
Asia	26,658,331	105,300
Europe	423,494	1672
Oceania	4128	16

[a] FAO (2010).

aquaculture ponds buried carbon at a lesser rate than large impoundments and agricultural impoundments was the relatively small input of external sediment and associated organic matter to aquaculture ponds compared with the other two types of impoundments. Moreover, as mentioned above, aquaculture pond management minimizes organic matter accumulation.

Based on combined area and average carbon burial rate, aquaculture ponds sequester an estimated 16.6 $MT\ yr^{-1}$ of carbon globally. Most carbon sequestration by aquaculture ponds occurs in Asia and particularly in China. China has 62,595 km^2 or 55.9% of global aquaculture pond area (Verdegem and Bosma, 2009). By extrapolation of the ratio of 0.395 between global pond area and total, inland, aquaculture production, Africa, North America, South America, and Europe have 1116–2008 km^2, while Asia has 105,300 km^2 or 94% of the global aquaculture pond area (Table 4).

Estimated annual carbon sequestration by aquaculture ponds exceeds that of inland seas and large lakes and is about 70% of that of small lakes (Table 3). It is much less than that of river reservoirs which have been estimated to bury between 160 and 180 $MT\ yr^{-1}$ (Dean and Gorham, 1998; Cole et al., 2007) and agricultural impoundments that bury 163 $MT\ yr^{-1}$ (Downing et al., 2008). Nevertheless, aquaculture ponds bury 0.21% of current, annual, global carbon emissions of about 8000 $MT\ yr^{-1}$ and represent a small but previously un-quantified sink for carbon emissions that will be useful in considerations of global carbon balance.

Aquaculture ponds, unlike other inland water bodies, contribute to carbon emissions through management inputs to produce aquatic animals (Boyd et al., 2007). The carbon sequestration capacity of aquaculture ponds could be used as carbon reduction credits against carbon emissions from aquaculture production. Net carbon sequestration (carbon emissions–carbon sequestration) by aquaculture operations could be traded as carbon credits. Detailed analyses of carbon emissions and carbon sequestration by aquaculture ponds will be needed to ascertain whether or not the aquaculture sector might benefit from participation in carbon emission “cap and trade” programs.

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