Chapter 1

Ecological Basis of Tilapia Co-culture Systems

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Abstract: The joint culture of multiple species or even multiple life stages of the same species in the same system is a long-practiced method identified as co-culture or polyculture. Stocking several species with different food habits allows the effective exploitation of a variety of available foods in the ecosystem, thus improving economics and sustainability. Tilapia are omnivorous fishes grown in co-culture with a variety of other fish and crustacean species for production purposes, and/or environmental control, and/or with a predatory fish species to control tilapia recruitment in growout ponds. Tilapia co-culture is carried out in fishponds, rice fields, cages and pens within ponds, periphyton-based ponds, and partitioned and other intensive aquaculture systems. In all cases, pond ecology will largely be determined by the relationships among the different co-cultured species, the environment, and management decisions and procedures that are applied.

The ecological basis governing the functioning of aquatic ecosystems applies to aquaculture systems. The components are primary producers, consumers, and decomposers, among which predator–prey and competition relationships determine nutrient and organic matter flows. Over this general pattern, the relationships between organisms and environment differ with the cultured species involved, and there are differences related to specific characteristics of each production system and its management. This chapter presents the role of tilapia in the pond ecosystem, ecological aspects of tilapia co-culture with fish and crustaceans in several production systems, tilapia co-culture as a management tool for environmental control, and tilapia co-culture with a predator to control tilapia recruitment. Examples of synergistic mutual effects through the food web and environment are described for tilapia co-culture with carp in ponds and in rice fields; tilapia co-culture with catfish in ponds; cage-cum-pond and partitioned systems; and tilapia co-culture with crustaceans in ponds; cage-cum-pond; and periphyton-based ponds. Conceptual graphic models of the ecosystem functioning for some of those co-cultures are presented.

Keywords: ecology, food web, polyculture, tilapia

Tilapia in Intensive Co-culture, First Edition. Edited by Peter W. Perschbacher and Robert R. Stickney.

Introduction

The joint culture of multiple species or even multiple life stages of the same species in the same system is a long-practiced method indistinctly called co-culture or polyculture. Stocking several species with different feeding habits allows effectively exploiting a variety of available foods in the ecosystem, thus improving economics and sustainability. In aquaculture systems, in which this technology is practiced with a wide range of species combinations (Milstein 2005), wastes produced by one species may be inputs for other species, and supplemented organic wastes and/or feeds act as fertilizers of the heterotrophic and autotrophic food chains besides being utilized directly by the target cultured organisms.

In such co-culture systems, stocking density is a key factor that affects the amount of natural food available per fish and the level of supplementary feeding required (Hepher and Pruginin 1981). On the other hand, synergism and antagonism between ecologically different species depend on stocking densities of each fish and on food availability. With increasing stocking density, competition increases, fish shift to less efficient foods as their preferred sources become depleted, and fish production slows down. A balanced combination of fish species maximizes synergistic and minimizes antagonistic fish–fish and fish–environment relationships (Milstein 1992). The idea of multispecies fish co-culture was derived originally from the Chinese philosophy of harmony. Chinese fish farmers have so managed their ponds that the fish they stock harmonize with available fish foods and among fish species within the pond (Tang 1970). Over 60% of world aquaculture production occurs in China (FAO 2014b), where polyculture is the main growout technology employed.

Tilapia of several species are important target organisms in warm-water aquaculture. Tilapia are often co-cultured with other fish or crustacean species for production purposes, and/or environmental control, and/or with a predatory fish species to control tilapia recruitment in growout ponds. In all cases, pond ecology will largely be determined by the relationships among the different species co-cultured, the environment, and the management decisions and procedures applied.

Aquaculture Production: Ecology in Tilapia Co-culture Systems

The ecological basis governing the functioning of aquatic ecosystems applies to aquaculture systems. The components are primary producers, consumers, and decomposers, among which predator–prey and competition relationships determine nutrient and organic matter flows. Over this general pattern, the relationships between organisms and environment differ with the cultured species involved, and there are differences related to specific characteristics of each production system and its management.

Fishpond Ecosystem

Driving forces in a fishpond ecosystem are schematically presented in Figure 1.1. Phytoplankton, the assemblage of microscopic autotrophic organisms in the water column, is a key driver in such green water ecosystems. Through photosynthesis, the phytoplankton community captures energy from the sun to produce biomass that constitutes food for many zooplanktonic organisms (e.g., rotifers, cladocerans, copepods, and nauplii) and filter feeding fish (e.g., silver

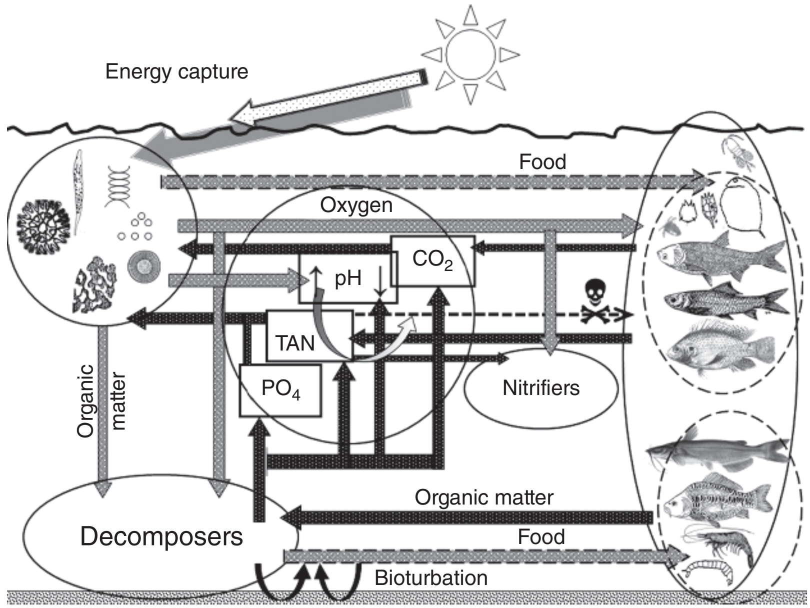

Figure 1.1 Relationships among organisms and environment in the fishpond ecosystem. Gray arrows: flow from phytoplankton. Black arrows: flow to phytoplankton.

carp [*Hypophthalmichthys molitrix*], mrigal or white carp [*Cirrhinus mrigala*], tilapia). Phytoplankton liberate oxygen to the water column, which is used by fish and various other animals in the water body (zooplankton) and pond bottom (benthos) for respiration and by bacteria for nitrification and aerobic decomposition. Dead phytoplankton settle on the pond bottom contributing to detritus formation that provides food for some benthic organisms. Phytoplankton remove carbon dioxide from the water, leading to increased water pH and nutrients (mainly ammonia and orthophosphate). Under high pH, ammonium turns into the toxic ammonia form, so its removal by phytoplankton and nitrifying bacteria helps maintain a healthy pond environment. Fish, zooplankton, and benthos liberate carbon dioxide into the water through respiration, ammonia through excretion, and organic matter in their feces, molts (in the case of invertebrates), and dead bodies. Organic materials originating in the water column or from the terrestrial environment accumulate on the pond bottom. These include waste feeds, feces, dead organisms, crustacean molts, leaves, and other materials with low-energy content that provide substrates for bacteria colonization. Bacteria decompose those materials turning the resulting detritus available as food for benthic organisms (e.g., chironomid insect larvae, freshwater prawn) and bottom feeding fish (e.g., catfish, common carp). Bacterial mineralization of organic matter releases orthophosphate into the water, which is the phosphorus form that autotrophic organisms can absorb. Bacterial mineralization of proteins releases ammonia into the water. Phytoplankton and nitrifying bacteria in the water column compete for ammonia, which is more efficiently absorbed by the former. Bioturbation of sediments by benthic fish and invertebrates (reviewed by Adámek and Maršálek 2013) favors nutrient diffusion into the water column.

Role of Tilapia in the Fishpond Ecosystem

The common name tilapia refers to a group of about 70 species of warm-water cichlid species in the genera *Tilapia*, *Sarotherodon*, and *Oreochromis*, which are native to Africa and the Middle East. Various tilapia species were introduced into many tropical, subtropical, and temperate regions of the world during the second half of the twentieth century. At present about 10 species and their hybrids are used in aquaculture, with Asia being the largest tilapia-producing continent. The aquaculture of Nile tilapia (*Oreochromis niloticus*) goes back to Ancient Egypt and nowadays this is by far the most widely cultured tilapia species. It has become an important cultured species in many Asian countries, including Bangladesh, China, Indonesia, Malaysia, Myanmar, the Philippines, Sri Lanka, Thailand, and Vietnam. Blue tilapia (*Oreochromis aureus*) is the northernmost natural occurring species, hence it is more cold tolerant than other tilapia species. The Mozambique tilapia (*Oreochromis mossambicus*) is native to eastward-flowing rivers of central and southern Africa. It grows slower than Nile and blue tilapia, withstands a wide range of water temperatures, and is one of the most salt-tolerant tilapia species.

Tilapia species are basically omnivorous, feeding on phytoplankton, zooplankton, periphyton, aquatic plants, small invertebrates, benthic fauna, detritus with its associated bacteria, commercial feeds, and agricultural by-products. Unlike most fish species, most tilapia species can easily digest the tough cells of blue-green algae (cyanobacteria) due to their high stomach acidity, which can have a pH as low as 1.4 depending on species (Moriarty 1973; Getachew 1989; Jančula *et al*. 2008; Riedel and Costa-Pierce 2005; Hlophe *et al*. 2014). Some tilapia species, such as Nile tilapia, entrap suspended particles (including phytoplankton and bacteria) on mucous in the buccal cavity, although their main source of nutrition is obtained by surface grazing on periphyton mats (FAO 2014a). Other species, such as the blue tilapia, can modify their feeding habits from pelagic filter feeding, such as in Lake Kinnereth (Spataru and Zorn 1978) to bottom grazing in polyculture ponds (Spataru 1976) when plankton densities are low (Mallin 1985), becoming mostly detritivorous (Jiménez-Badillo and Nepita-Villanueva 2000).

Tilapia are successfully co-cultured with a variety of fish and crustacean species in fishponds, rice fields, cages within ponds, periphyton-based ponds, and partitioned and other intensive aquaculture systems. When stocking densities of the involved species are balanced, synergistic effects among species lead to increased food resources for each species and improved water quality, usually resulting in better fish growth (Milstein 1992). Examples of synergistic mutual effects through the food web and environment when stocking densities of the co-cultured species are balanced are herein presented for some combinations of species and culture systems.

Tilapia Co-culture with Carp in Ponds

Polyculture of two to seven carp species with different feeding habits is a traditional and common practice in Asia that has also spread to other continents (Edwards 2004; Milstein 2005). With the development and expansion of tilapia culture in the second half of the twentieth century, these omnivorous African and Middle Eastern fishes were incorporated into Asian carp ponds as a way to diversify and increase fish production. For example, in Bangladesh, the addition of Nile tilapia at 2,000/ha to a co-culture of bottom feeding common carp (*Cyprinus carpio*) and phytoplankton filter feeding rohu carp (*Labeo rohita*), stocked at 5,000 and 15,000/ha, increased nutrient concentrations in the water column, reduced total suspended solids and phytoplankton biomass, and resulted in additional fish production without affecting the growth and production of rohu and common carp (Rahman *et al.* 2008). In another study, the addition of 2,200 Nile tilapia to a polyculture system that included the filter feeders catla (*Catla catla*), rohu, and silver carp; the bottom-dwelling giant freshwater prawn (*Macrobrachium rosenbergii*); and the small carp mola (*Amblypharyngodon mola*) stocked, respectively, at 1,000, 3,000, 3,000, 4,000, and 10,000 individuals/ha, which led to increased yields of prawn and silver carp and to higher total yields and economic benefits as opposed to the absence of tilapia (Shahin *et al.* 2011).

Tilapia–carp synergistic mutual effects through the food web and the environment in earthen ponds are exemplified in Figure 1.2, which was mainly based on the study by Milstein and Svirsky (1996) of hybrid tilapia (*O. niloticus* × *O. aureus*) and common carp co-culture at stocking densities of 7,000–12,500 and 1,600–4,000/ha, under Israeli fish farm conditions. When searching for food, common carp stir the mud of the pond bottom; and the more intensively the larger the fish (Valdenberg *et al*. 2006; Adámek and Maršálek 2013), and more intensively than other bottom feeders such as the Indian carp

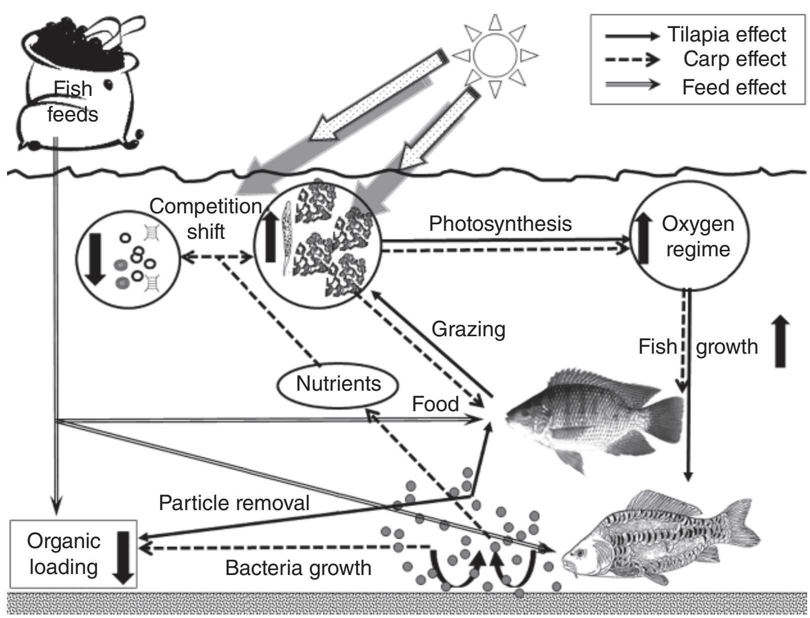

Figure 1.2 Synergistic mutual effects through the food web and environment between hybrid tilapia (*Oreochromis niloticus* × *O. aureus*) and the bottom feeder common carp (*Cyprinus carpio*). Adapted from Milstein and Svirsky (1996).

mrigal (Milstein *et al.* 2002). This common carp behavior increased contact between bacteria in sediments and water, promoting aerobic processes such as rapid uptake of inorganic nitrogen compounds needed by bacteria for body protein buildup. This also made nutrients in the sediments available for algae shifting phytoplankton competition toward larger-sized algae, mainly the blue-green *Microcystis* sp. that bloomed. This resulted in a decrease in smaller algae species, which otherwise would accumulate because hybrid tilapia cannot graze on them. The increased phytoplankton production improved the oxygen regime in the pond and food availability for tilapia that grew better (average 2 g/day) than in monoculture (average 1.3 g/day). In turn, the tilapia hybrids fed on the organic sediment of the pond bottom consuming particles resuspended by carp, thus preventing an increase in organic load in the sediment and the concomitant development of anaerobic conditions. In addition, tilapia grazing in the water column strongly stimulated the development of a bloom of the blue-green alga *Microcystis*, keeping the algal population in the log phase of growth that maximizes photosynthesis and net primary production. The improved oxygen regime in the pond produced better growth of common carp in co-culture with tilapia hybrids (average 4.1 g/day) than in monoculture (average 3.2 g/day).

Tilapia Co-culture with Carp in Rice Fields

In China and South and Southeast Asia, Nile tilapia are often stocked in rice fields (Fig. 1.3). The integration of fish into rice farming provides protein, especially for subsistence farmers who manage rain-fed agricultural systems. Relationships in the paddy–fish ecological system are exemplified in Figure 1.4, which was mainly based on the descriptions by Liu and Cai (1998) and Lu and Li (2006). Rice fields provide shade, shelter, and organic matter for fish, which in turn oxygenate soil and water, eat rice insect pests, and favor nutrient recycling. Shade reduces water temperature

Figure 1.3 Paddy–fish system in Bangladesh. Photograph by Ana Milstein.

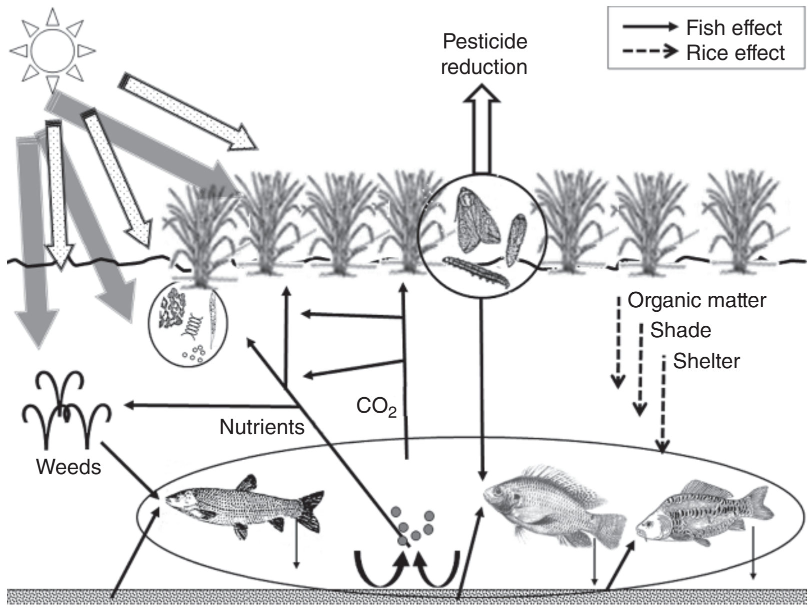

Figure 1.4 Rice–fish–environment relationships in the paddy–fish ecosystem.

that in summer may reach lethal levels for fish and also limit phytoplankton development. The decaying leaves of rice favor development of microorganisms and detritus, which are important sources of fish food. Detritus, phytoplankton, zooplankton, and benthic invertebrates in the paddies serve as the natural food for fish. Fish excreta and dead organisms contribute to detritus and serve as natural fertilizers for rice and soil enrichment. Fish movement and feeding on the bottom detritus help loosen the surface soil on which rice is planted, increasing permeability and oxygen content to the soil, and thus favoring the absorption of nutrients by the paddy but also by unwanted aquatic vegetation. This bottom activity also liberates nutrients into the water making them available for phytoplankton. Fish respiration provides carbon dioxide that promotes photosynthetic activity. Fish feeding on the unwanted aquatic plants (mainly by grass carp, *Ctenopharyngodon idella*) reduce competition for light, space, and nutrients between rice and other macrophytes. Fish feeding on insect pests (mainly detritivores such as tilapia and common carp) reduce the need to apply pesticides. The effect is the enhanced production of rice in addition to a fish crop, along with a substantial diminution in the use of commercial fertilizers and pesticides.

In Vietnamese rice fields, Nile tilapia is most often reared with common carp and silver barb (*Barbonymus* (=*Barbodes*) *gonionotus*). Fish production is determined by rice management factors rather than by a fish polyculture strategy (Vromant *et al*. 2002). In this approach of intensive rice culture combined with extensive fish culture, fish yields are usually very low (about 300 kg/ha) since the rice field is not very suitable for fish production: the aquatic phase is temporary; dissolved oxygen levels and temperature values often exceed the fish tolerance limits; and shading by the rice crop keeps phytoplankton and zooplankton densities low. Accordingly, rice–fish systems need a trench or other type of refuge area for the fish within or adjacent to the rice field. Besides suppressing unwanted vegetation in the rice fields, the presence of the fish increases water turbidity in the trench through suspension of mineral and organic material due to fish perturbation; this increases the availability of nutrients, resulting in higher amounts of phytoplankton and protozoa production in the trench, supplying reasonable amounts of phytoplankton and zooplankton to the fish (Vromant *et al.* 2001). Vromant *et al.* (2002) analyzed data generated in eight experiments in such rice–fish systems, where Nile tilapia constituted 7–30% of the fish stocked and total stocking density was 0.5–2.0 fish/m^2. They found that Nile tilapia often lacks food in rice fields, which increases intraspecific competition. As the growing season progresses and plankton abundance decreases due to increased rice biomass and consequent shading by the rice canopy, Nile tilapia shift to feeding on detritus, which increases interspecific competition with common carp. To improve the rice–fish system, those authors suggest either maintaining the current fish species combination but calculating their stocking density according to the trench area (not to the trench + rice-field as is the common practice) and increasing nutrient inputs in the trench (extra feed, fertilizing, manuring) to create distinguished trophic niches for the Nile tilapia and common carp, or omitting either Nile tilapia or common carp from the polyculture if increasing inputs is not possible.

Tilapia Co-culture with Catfish

Joint culture of several tilapia and catfish species is carried out in various culture systems. In Egyptian ponds, Nile tilapia and African catfish (*Clarias gariepinus*) when co-cultured in several proportions at a total stocking density of 30,000 fish/ha resulted in similar tilapia harvesting weight and growth rate compared to tilapia monoculture, better catfish growth rate than in catfish monoculture, and higher net profit in co-culture (Ibrahim and El Naggar 2010). In cage-cum-pond and pen-cum-pond systems in Asia (Yang and Lin 2000), high-valued fish species are stocked in cages and filter-feeding fish species are stocked free in the pond to utilize natural foods derived from cage wastes. A series of pond experiments carried out in Thailand integrating the intensive culture of hybrid catfish (*Clarias macrocephalus* × *C. gariepinus*) in cages or pens receiving formulated feed (stocking density equivalent to 3.5–25.0/m^2) and of Nile tilapia with natural food in the open pond (stocking density 2/m^2) showed that Nile tilapia can effectively recover nutrients contained in wastewater of intensive catfish culture while providing additional fish production (Lin and Diana 1995; Lin and Yi 2003; Yi *et al*. 2003).

In the southern United States, several channel catfish (*Ictalurus punctatus*) intensive culture facilities in which water flows through compartments containing either channel catfish or secondary species (including tilapia) were reviewed by Tucker *et al*. (2014). In those systems, energy is required to circulate the water, channel catfish are fed industrial feeds, and the secondary species feed on natural foods and wastes from the channel catfish compartments. In some of those facilities, the objective is to produce extra fish on otherwise unused food in catfish ponds, while in others the objective is also to provide a grazer to harvest phytoplankton and zooplankton, maintaining good water quality in the system. The ecology of those and other photosynthetic suspended-growth systems in aquaculture were reviewed by Hargreaves (2006).

Tilapia Co-culture with Crustaceans

Tilapia may be co-cultured with prawn (mainly *Macrobrachium rosenbergii*), crayfish (e.g., Rouse and Kahn 1998; Barki *et al*. 2001; Karplus *et al*. 2001; Ponce-Marban *et al*. 2005), and some marine shrimp species (e.g., Wang *et al*. 1998; Tian *et al*. 2001; Saelee *et al*. 2002; Yi *et al*. 2002; Yi and Fitzsimmons 2004; Cruz *et al*. 2008; Yuan *et al*. 2010; Sun *et al*. 2011; Bessa *et al*. 2012; Hernández-Barraza *et al*. 2013). This is done in several types of culture systems as a way to improve productivity, profitability, and nutrient utilization in relation to crustacean monoculture.

The co-culture of Nile tilapia with the giant freshwater prawn *M. rosenbergii* has expanded in tropical–subtropical regions. Studies have been done with both species free in regular fishponds in Bangladesh (Uddin *et al*. 2007), Brazil (dos Santos and Valenti 2002), Egypt (Rouse *et al*. 1987), Israel (Mires 1987), Puerto Rico (García-Pérez *et al*. 2000), Saudi Arabia (Siddiqui *et al*. 1996), and the United States (Tidwell *et al.* 2010). Co-culture of tilapia and giant prawn has also been conducted in rice paddies in Egypt (Sadek and Moreau 1998), with Nile tilapia in cages or hapas and the prawn free in the pond in Thailand (Fig. 1.5) and the United States (Danaher *et al*. 2007; Tidwell *et al.* 2000, 2010), and in periphyton-based ponds in Bangladesh (Uddin *et al*. 2007; Asaduzzaman *et al*. 2009; Wahab *et al*. 2012, Fig. 1.6). Those studies showed that in tilapia–prawn co-culture (stocking density 0.5–2 tilapia/m^2, 2–7 prawn/m^2) with both species free in the pond or paddy, the tilapia were not affected by the presence of prawn but the prawn often attained lower harvesting weight and yields in the presence of tilapia, but the combined total yield was higher in the co-culture than in monoculture. When tilapia were confined in cages suspended in prawn ponds (stocking density equivalent to 0.5–1.0 tilapia/m^2 of pond, 6–7 prawn/m^2), prawn performance was similar or better in the presence of tilapia than in monoculture, and total pond production increased in relation to prawn monoculture ponds.

Figure 1.5 Co-culture of Nile tilapia in hapas with freshwater prawn free on the pond bottom in a fish farm in Thailand. Photograph by Ana Milstein.

Figure 1.6 Co-culture of Nile tilapia with freshwater prawn in periphyton-based ponds in the experimental fishponds of the Bangladesh Agricultural University (BAU) at Mymensingh. Photograph by Ana Milstein.

In periphyton-based aquaculture systems (reviewed by van Dam *et al*. 2002; Azim *et al*. 2005; Milstein 2012; Milstein *et al*. 2013), substrates were installed in the water column to promote the development of microalgae, bacteria, detritus, and small animals on them. Periphyton-based aquaculture systems offer the possibility of increasing both primary productivity and food availability for cultured organisms able to graze on periphyton, hence increasing aquaculture production. In periphyton-based ponds, the co-culture of tilapia with freshwater prawn provides shelter for the latter and additional natural food for both species, improving their survival, growth, and production. In Bangladesh, the technology was developed for poverty alleviation and nutritional security for the households of poor farmers, with a suggested stocking ratio of Nile tilapia and freshwater prawn of 3:1 at a combined stocking density of 30,000 individuals/ha (Wahab *et al.* 2012). The addition of tilapia and periphyton substrates was shown to benefit the prawn culture through reducing toxic inorganic nitrogenous compounds in the water, enhancing the utilization of natural foods, improving prawn survival, and increasing production and economic benefit (Uddin *et al.* 2007, 2009; Hasan *et al*. 2012; Ahsan *et al*. 2014).

Tilapia–prawn relationships through the food web and the environment in periphyton-based ponds are exemplified in Figure 1.7. The addition of rigid surfaces in the oxygenated water column allows the development of attached photosynthetic organisms as well as aerobic decomposing bacteria and nitrifying bacteria. Most periphyton development occurs in the upper water layers where photosynthesis take place, while in the deeper and darker water only decomposition and nitrification takes place and there is less periphyton biomass. The attached periphytic algae compete with phytoplankton for light and nutrients. The nitrifying bacteria in the periphyton and in the pond sediments compete with attached and floating algae for ammonia. Tilapia feed mostly in the upper water column on periphyton, phytoplankton, and zooplankton. They may also feed

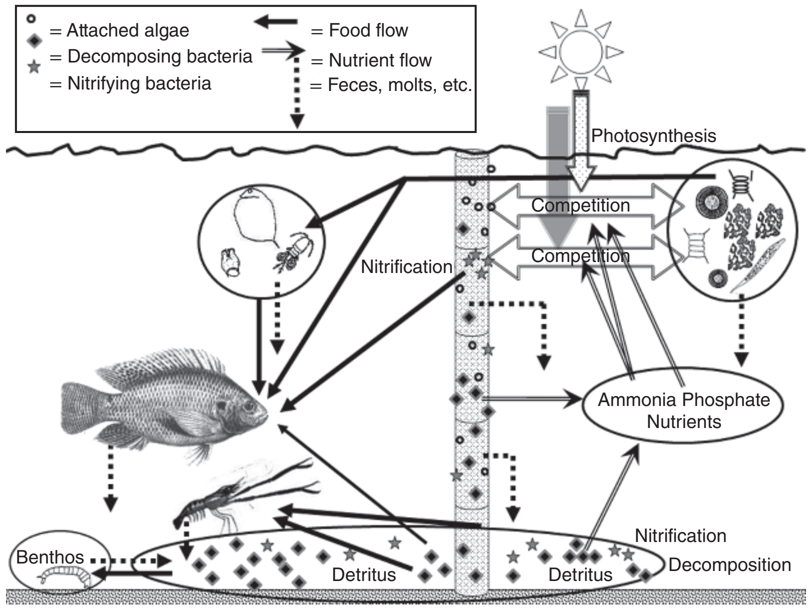

Figure 1.7 Tilapia–freshwater prawn relationships through the food web and the environment in periphyton-based ponds. Adapted from Milstein (2012).

on detritus. Freshwater prawn feed on pond bottom detritus and on periphyton near the pond bottom. Periphyton dislodgments and feces and wastes generated by tilapia, prawn, phytoplankton, zooplankton, and benthic organisms contribute organic matter for decomposing bacteria on the pond bottom. The decomposing bacteria in the periphyton and in the pond sediments liberate nutrients into the water column, for which the photosynthetic organisms and nitrifying bacteria compete.

Environmental Control: Tilapia Co-culture as a Management Tool

Fish feeding habits can be utilized as an environmental management tool. In Israel, water quality in drinking water reservoirs of the National Water Carrier is managed through fish stocking, with each species having a different task according to its feeding habits. Taking advantage of the detritivorous behavior of blue tilapia, that species is stocked to control bad tastes and odors originating in sediments (Leventer 1979; Rothbard 2008).

In Asian rice–fish farming, fish are viewed as a tool within an integrated pest management (IPM) system to make rice production more sustainable and environmentally friendly. The introduction of fish into the rice paddies has been shown to reduce the need for pesticides (Fig. 1.4), increase farm household income, and diversify agriculture production. Omnivorous fish such as Nile tilapia can prey on rice plant pests and, as a result, the use of pesticides can be substantially reduced in relation to rice monoculture (Liu and Cai 1998; Berg 2002; Lu and Li 2006; Halwart *et al*. 2012).

In the southern United States, off-flavor is a serious problem in channel catfish culture, as described by Hargreaves (2003), Perschbacher (2003a), Zimba and Grimm (2003), and Smith *et al*. (2008), among others. The problem is also discussed in Chapter 9. Typical pond management includes high fish stocking densities and feeding rates that result in eutrophic to hypereutrophic water quality conditions with prolific growth of algae during summer, particularly cyanobacteria. Cyanobacteria produce a number of secondary metabolites, including compounds imparting off-flavor to the water and fish. Fish are exposed to those compounds mainly through absorption of dissolved compounds from the water column and also through the ingestion of cyanobacteria, and consumption of contaminated prey or detritus. Ingestion of cyanobacteria can be accidental (catfish ingest surface scum while feeding on floating food pellets) or intentional (planktivorous tilapia and other fish species), with accidental ingestion more likely to occur in the presence of dense blooms. Fish with off-flavor are not acceptable for commercial processing and sale. Depuration of absorbed off-flavors by fish may require days to weeks. Collectively, off-flavor compounds result in inconsistent cash flow and sales, increased feeding costs associated with increased holding times, and the increased potential for disease/predation losses. Blue tilapia, a fish that can graze on cyanobacteria in the water column and on the pond bottom, has been used to prevent environment-derived off-flavors in channel catfish ponds. In fishponds, Torrans and Lowell (1987) found that channel catfish in polyculture with blue tilapia (stocked at 10,000 and 5,000 fish/ha) experienced off-flavor 8.3% of the times samples were taken compared with 62.5% for catfish reared in monoculture. In partitioned aquaculture systems (PAS), systems in which fish production and water quality control through phytoplankton are carried out in separate but linked compartments, the more herbivorous Nile tilapia has been stocked to manage algae populations and improve water quality for channel catfish. While catfish are fed, tilapia are not to ensure consumption of phytoplankton to provide algae control. In such a system, Nile tilapia successfully reduced cyanobacteria populations, shifting the primary producer community to the more desirable dominance of green algae, which resulted in a reduction in channel catfish off-flavors (Perschbacher 2003b; Brune *et al.* 2004; Tucker *et al*. 2014).

Tilapia Recruitment Control: Tilapia Co-culture with a Predator[1]

One of the major problems in tilapia culture is their early and excessive spawning in growout ponds. Under natural conditions Nile tilapia mature at 150–200 g, while under culture conditions maturation can occur at sizes as small as 30–50 g (De Graaf *et al.* 1999). This leads to overpopulation, which increases competition for food, oxygen, and space and reduces the growth of initially stocked fish, to the extent that they may not reach commercial size. Thus, tilapia recruitment control is essential for successful and profitable culture, particularly in regions where there is no market for small fish.

To cope with this problem, several methods have been proposed, including monosex culture (hybridization, manual sexing or grading, sex reversal by androgenic hormones), cage culture, high density stocking, selective harvesting, and use of predators (Mair and Little 1991; Fagbenro 2004). The use of predators results in a tilapia–predator co-culture, and the other methods can be applied when tilapia are cultured alone or in co-culture with other species. Which method to apply depends on

[1]This section is based on part of the PhD thesis of Martha Hernández, carried out at "Centro de Investigación y de Estudios Avanzados del IPN – CINVESTAV, Unidad Mérida, Yucatán, México," under the direction of Dr Eucario Gasca-Leyva.

economic considerations, feed costs and availability, and consumer preferences (De Graaf *et al.* 2005). For example, due to human health and possible environmental effects, the use of hormones for sex reversal needs a license in the United States and is forbidden in Europe (El-Sayed 2006). In Asia and Africa, where rural markets demand cheap tilapia of <200 g (Brummett 2000), early tilapia reproduction is not a critical problem if feeds are supplied (De Graaf *et al*. 1996). But if tilapia recruitment control is to be performed, stocking predators seems an appropriate technique to supply those rural markets compared to the use of expensive all-male tilapia methods; the latter are more appropriate when the targets are urban and international markets, which demand and can afford larger sized tilapia (Little and Edwards 2004).

Fish–environment relationships involved in tilapia recruitment control by predator fish are exemplified in Figure 1.8. In tilapia–predator co-cultures, the omnivorous tilapia feed on a wide range of natural foods as well as commercial feeds if offered, while the predators feed on the larvae and fingerlings released by the tilapia (as well as on commercial feeds if offered). The reduction/elimination of the excess tilapia increases natural food and feed availability for the stocked tilapia and reduces the amount of oxygen consumption and ammonia excretion due to the reduction or elimination of tilapia recruits. Thus, intraspecific competition is reduced and environmental conditions in the pond are improved (Milstein *et al*. 2000). The expected overall result of tilapia–predator co-culture is increased production of the stocked fish.

A number of predatory species, mostly catfishes and cichlids, have been evaluated in their ability to control recruitment of several tilapia species (Table 1.1). The efficiency of

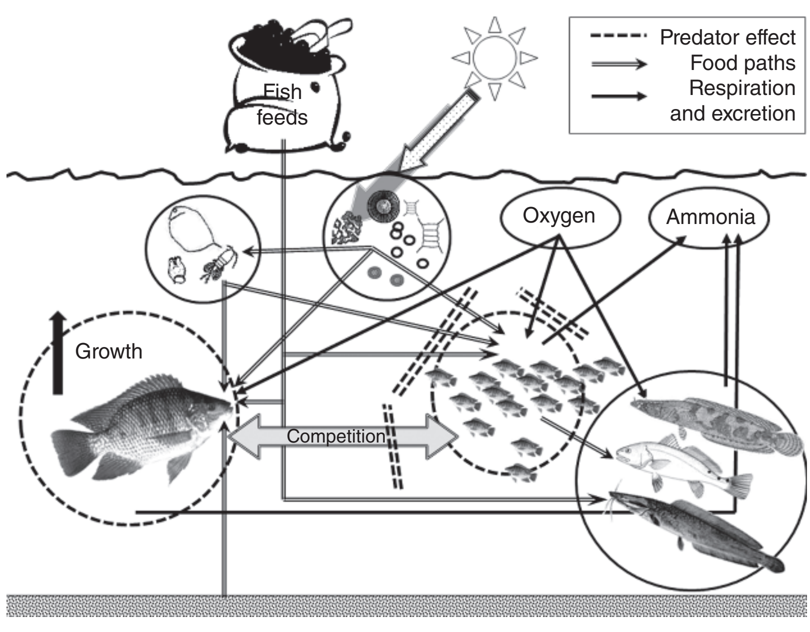

Figure 1.8 Fish–environment relationships involved in tilapia recruitment control by a predator fish. The predators represented are African snakehead *Parachanna obscura*, red drum *Sciaenops ocellatus*, and African catfish *Clarias gariepinus*.

Table 1.1 Species stocked in tilapia–predator co-cultures.

Tilapia prey	Predator	Author (year)
Oreochromis niloticus (Nile tilapia)	*Clarias gariepinus* (African catfish)	Abdel-Tawwab (2005)
		De Graaf, *et al.* (1996)
		El-Gamal *et al.* (1998)
		El-Naggar (2007)
		Oyelese (2007)
	Heteroclarias bidorsalis	Fagbenro (2004)
	Heteroclarias bidorsalis × *C. gariepinus*	Fagbenro (2000)
	Heteroclarias longifilis × *C. gariepinus*	Fagbenro (2000)
	Clarias spp.	Sadeu *et al.* (2013)
	Clarias macrocephalus × *C. gariepinus*	Lin and Diana (1995)
		Yi *et al.* (2003)
	Heterobranchus longifilis	Offem *et al.* (2009)
		Ofor *et al.* (2011)
	Parachanna obscura (= *Ophiocephalus obscurus*) (African snakehead)	De Graaf *et al.* (1996)
	Lates niloticus (Nile perch)	Bedawi (1985)
		El Gamal (1992)
		El-Gamal *et al.* (1998)
		Ofori (1988)
	Tor putitora (Sahar)	Shrestha *et al.* (2011)
	Cichlasoma urophthalmus (Mayan cichlid)	Hernández *et al.* (2014)
		Ross and Martinez (1990)
	Hemichromis fasciatus (jewel cichlid)	Fagbenro (2004)
	Cichla monoculus (tucunaré)	Fischer and Grant (1994)
	Micropterus salmoides (largemouth bass)	McGinty (1985)
O. aureus (blue tilapia)	*Cichlasoma managuense* (jaguar guapote)	Dunseth and Bayne (1978)
O. niloticus × *O. aureus*	*Morone saxatilis* × *M. chrysops* (hybrid bass)	Milstein *et al.* (2000)
	Sciaenops ocellatus (red drum)	Milstein *et al.* (2000)
O. mossambicus (Mozambique tilapia)	*Megalops cyprinoides* (tarpon)	Fortes (1985)

(*Continued*)

Table 1.1 (*Continued*)

Tilapia prey	Predator	Author (year)
Tilapia guineensis	*Clarias lazera* (= *Clarias gariepinus*) (African (sharptooth) mud catfish)	Fagbenro (2004)
	Parachanna obscura (African snakehead)	Fagbenro (2004)
	Clarias isheriensis	Fagbenro and Sydenham (1990)
Tilapia zillii	*Lates niloticus* (Nile perch)	Ofori (1988)
Sarotherodon galilaeus	*Lates niloticus* (Nile perch)	Ofori (1988)

the predator depends on a number of factors, including its feeding habits, stocking size, and the tilapia:predator ratio. Piscivorous species, such as the African snakehead, *Parachanna obscura*, are more efficient than omnivorous species, such as the African catfish, *C. gariepinus*. Correspondingly, a higher density of the omnivorous species is required to obtain a similar control effect on tilapia recruitment compared with stocking carnivores. For example, 8,300 catfish/ha versus 725 snakehead/ha were required to control a 20,000–22,000 Nile tilapia/ha population (De Graaf *et al*. 1996). The stocking size of the predator should be small enough that they are not able to prey on the initially stocked tilapia, and at the same time large enough to efficiently prey on the recruits. Within those limits, the larger the predator the better the control on tilapia recruitment. Stocking of larger predators resulting in better tilapia control and higher survival of the predator were observed in tilapia co-cultures with red drum, *Sciaenops ocellatus,* where predator stocking sizes were 78 g versus 18 g (Milstein *et al*. 2000); African catfish, *C. gariepinus*, where stocking sizes were 7–130 g versus <4 g; and African snakehead, *P. Obscura*, where stocking sizes were 75–206 g versus <2 g (De Graaf *et al*. 1996).

Swingle (1950) measured the efficiency of a predator as A_T, the percentage of the population harvested biomass formed by fish that attained commercial size, $A_T = 100\%$, indicating complete recruitment control and all harvested fish of commercial size. Table 1.2 presents A_T results obtained by different authors for tilapia grown with and without predators under a range of culture conditions. It can be observed that in all cases the presence of predators led to a higher proportion of marketable tilapia and higher harvesting weight and yield of the stocked tilapia than in the control ponds without predators. The increased A_T demonstrates that tilapia recruitment was controlled by the predator, while the increased final weight and yield of the stocked tilapia point to better results in the presence of a predator.

Concluding Remarks

Tilapia co-culture with fish or crustaceans has production and environmental advantages in relation to monoculture. Knowledge of the ecology of the production system and the nature of the relationships between tilapia and the other fish or crustacean species constitutes

Table 1.2 Studies on Nile tilapia recruitment control by predator fishes.

References	Predator	Stocking				Culture duration (days)	Harvesting						
							With predator				Control without predator		
		Tilapia		Predator	Ratio		Stocked tilapia			Predator	Stocked tilapia		
		Density (/ha)	Weight (g)	Weight (g)	til:pred (*x*:1)		Weight (g)	Yield (kg/ha)	A_T (%)	Weight (g)	Weight (g)	Yield (kg/ha)	A_T (%)
Bedawi (1985) [a]	*Lates niloticus*	10,000	5	5	5	210	227	2,272	94	33	161	1,623	77
					10		201	2,009	96	28			
					15		183	1,857	86	30			
Fagbenro (2000) [a]	*Clarias gariepinus* × *Heterobranchus longifilis*	20,000	44	152	5	240	216	3,748	99	882	130	1,710	53
					10		213	3,682	94	853			
					20		195	3,551	89	845			
Fagbenro (2000) [a]	*Clarias gariepinus* × *Heterobranchus bidorsalis*	20,000	44	152	5	240	212	3,682	98	879	124	1,644	55
					10		211	3,551	95	858			
					20		190	3,419	87	839			

Shrestha *et al.* (2011) [a]	*Tor putitora*	20,000	11	15	4	240	103	1,310	95	83	92	1,040	91
					8		107	1,190	94	91			
					16		112	1,580	94	109			
Shrestha *et al.* (2011) [a]	*Tor putitora*	20,000	55	15	16	151	169	3,532	86	83	138	2,620	81
					33		190	4,057	87	110			
McGinty (1985) [b]	*Micropterus salmoides*	9,500	27	11	66	184	439	3,906	92	303	347	3,036	72
					110		384	3,392	74	360			
					328		352	3,110	71	487			
Milstein *et al.* (2000) [c], [d]	*Morone saxatilis* × *M. chrysops*	15,000	65	135	20	150	400	4,850	95	294	346	4,100	77
Milstein *et al.* (2000) [c], [d]	*Sciaenops ocellatus*	15,000	65	60	20	150	399	4,500	95	219	346	4,100	77
Milstein *et al.* (2000) [c], [d]	*Sciaenops ocellatus*	15,000	75	18	15	150	428	4,700	97	253	383	4,125	74
				18	30	150	433	4,675	96	356			
				78	30	150	445	4,925	99	544			

[a] Mixed sex tilapia, tilapia, and predator stocked at 7.5 cm length.
[b] 90% Male tilapia.
[c] Tilapia was the hybrid *O. niloticus* × *O. aureus*.
[d] 95% Male tilapia.

an important tool for the proper management of such co-cultures.

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