Aquaculture Research

Aquaculture Research, 2015, 1–12 doi: 10.1111/are.12708

REVIEW ARTICLE

Tilapia polyculture: a global review

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Abstract

Tilapia are the second most farmed fish worldwide and their production has quadrupled over the past decade due to ease of aquaculture, marketability and stable market prices. Tilapia aquaculture must adopt sustainable practices (such as polyculture) for continuing increased production and improved sustainability. This article reviews tilapia polyculture around the world and discusses its benefits, strategies and practices. Tilapia polyculture improves feed utilization, enhances water quality, increases total yield and profit. Further investment will increase these gains. Research on tilapia polyculture in China was also summarized and addressed that polyculture in semi-intensive systems was a way of improving sustainability for tilapia aquaculture.

Keywords: crustacean, integrated farming, polyculture, tilapia

Introduction

Tilapia is the generic name for a group of cichlids consisting of three genera; *Oreochromis*, *Sarotherodon* and *Tilapia*. They are native to the Middle East and Africa. Today, all commercially important tilapia outside of Africa belong to the genus *Oreochromis*, and more than 90% of these farmed fish are Nile tilapia (*Oreochromis niloticus*). They are one of the most productive and internationally traded freshwater food fish. Farming of tilapia has increased in the last three decades as they are easy to grow and market. More than one hundred countries now farm tilapia (Food and Agriculture Organization of the United Nations (FAO) 2013), and 98% of them are grown outside their original habitat (Shelton 2002). Behind carps, they are the second most farmed fish in the world, with 3.96 million metric tonnes (MT) of fish produced, comprising 6.3% of global aquaculture production (Food and Agriculture Organization of the United Nations (FAO) 2011). China, Egypt, Indonesia, Philippines and Thailand produce the most Tilapia (Food and Agriculture Organization of the United Nations (FAO) 2013). Africa and Asia consume them as a traditional food, and they are now eaten in non-traditional countries and regions such as USA, Canada, Europe, Central and South America as well (Gupta & Acosta 2004).

Tilapia are efficient primary consumers and are commonly cultured in semi-intensive systems (Welcomme 1996). However, their culture faces problems including disease, and environmental pollution resulting from selective breeding programs focused only on growth and intensification. Disease resistance of tilapia has decreased as selection has been on growth and skin colour. In recent years, Streptococcus infection has contributed to severe economic losses in various countries, including the USA, Israel, Brazil and Thailand (Eldar, Bejerano & Bercovier 1994; Shoemaker, Klesius & Evans 2001; Suanyuk, Kong, Ko, Gilbert & Supamattaya 2008; Evans, Klesius, Pasnik & Bohnsack 2009; Mian, Godoy, Leal, Yuhara, Costa & Figueiredo 2009). In China, serious Streptococcus infection (*S. agalactiae)* has occurred in 2009, with a 20–50% infection rate, and 50–70% fish mortality in the main production area (Ye, Li, Lu, Deng, Jiang, Tian, Quan & Jian 2011). Strategies such as administration of antibiotics

& probiotics have been used to treat the problem. To date no chemotherapeutic or immunological measures have been developed to prevent or control this disease effectively (Zhang, Li, Guo, Zhang, Chen & Gong 2013). Breeding for resistance is now helping along with proper management and polyculture. Feed is the main input of intensive tilapia culture system, some of this is released into the water and not efficiently utilized especially in monoculture system. This leads to poor water quality and can cause disease. An optimum water quality parameter should be maintained to prevent 'stress' in fish which can lead to outbreaks of disease. Therefore, tilapia aquaculture will increasingly rely on environmentally sound aquaculture practices, e.g., polyculture and integrated fish farming. This article reviews these practices and summarizes their development and operating characteristics.

Integrated farming

Integrated fish farming involves raising fish along with livestock and/or agricultural crops. This enables effective utilization of land and water, through the use of carefully planned production methods (Krishnan & Rajendran 1998). Production is cost effective because wastes and byproducts from one system are recycled and available farming space is utilized effectively.

Integrated farming of tilapia is practised extensively worldwide. In Southeast Asia, especially Indonesia, Thailand, Vietnam, Cambodia and Myanmar, tilapia culture is widely integrated with agriculture & animal farming (Dey, Bimbao, Yong, Regaspi, Kohinoor, Pongthana & Paraguas 2000; Little 2000; Gupta & Acosta 2004). In Canada and the United States, an aquaponics system for tilapia culture has been reported to be feasible and profitable (Fitzsimmons 2000; Rakocy, Bailey, Shultz & Danaher 2011). In Africa, small-scale pond culture of tilapia integrated with crop farming e.g., vegetables, rice and other field crops, was economically attractive and environmentally friendly compared to non-integrated ponds (Jamu 2001). The effects of introducing tilapia into existing integrated farming systems in Bangladesh using the pond-like and associated systems were evaluated. It was found that addition of fish ponds to these systems, enhanced livelihoods and reduced poverty (Karim, Little, Kabir, Verdegem, Telfer & Wahab 2011). Ponds fertilized with chicken manure resulted in larger tilapia and higher net annual yields. Higher amounts of chlorophyll *a* and higher numbers of zooplankton were also found (Kang'ombe, Brown & Halfyard 2006). Investigation of the effects of livestock manure on the safety of aquatic environment and products found increasing pathogens, such as salmonella and coliform in water and tilapia intestine, especially with fresh manure (Cai, Liao & Wu 2009).

Polyculture

Polyculture is the farming of two or more species differing in feeding behaviour, habits and ecological requirements, to effectively increase production in the same pond (Zimmermann & New 2000). Polyculture is also called multi-trophic aquaculture, co-culture or integrated aquaculture (Bunting 2008). Generally, there are three types of polyculture; direct, cage-cum-pond and sequential (Yi & Fitzsimmons 2004).

In monoculture systems, the excess nutrients from uneaten food increase the phytoplankton and ammonia concentrations, and change the dissolved oxygen dynamics (Midlen & Redding 1998). Polyculture adds a secondary or subordinate species and improves the performance of the main cultured species by enhancing water quality (Wang, Li, Dong, Wang & Tian 1998; Tian, Li, Dong, Yan, Qi, Liu & Lu 2001). Therefore, polyculture fits the principles of sustainable aquaculture. It reduces the environmental impact of the activity, increases producer profitability, and provides benefits associated with advanced ecological stability and function by optimizing use of available resources (Wohlfarth, Hulata, Karplus & Havery 1985; McKinnon, Trott, Alongi & Davidson 2002).

Tilapia polyculture practices

Tilapia are omnivorous, and are capable of feeding on algae & detritus (Dempster, Beveridge & Baird 1993; Azim, Verdegem, Mantingh, Van Dam & Beveridge 2003). They can also convert feed into high quality protein, and are one of the best fish for aquaculture, because they reproduce easily, have a short food chain, and reach a marketable size within one growing season. It has been suggested that the polyculture of tilapia in combination with other teleosts, is one of the most promising production systems (Dadzie 1982). It is important to have a good knowledge of the species that are candidates for polyculture. Although an optimum solution will reflect local conditions, the methods will be able to be applied universally, and adjusted to any site with a similar environment. A summary of the species currently polycultured with tilapia is as follows, including crustaceans and other fish, with the emphasis on its strategies and benefits.

Tilapia - crustacean polyculture

Prawn/shrimp

The polyculture of freshwater prawns with non-carnivorous fish was first suggested by Ling (Ling 1962). Now tilapia have been reared with freshwater prawn (Garcia - Pérez, Alston & Cortés - Maldonado 2000; Uddin, Rahman, Azim, Wahab, Verdegem & Verreth 2007b; Tidwell, Coyle & Bright 2010) and marine shrimp (Tian *et al.* 2001; Jatobá, do Nascimento Vieira, Buglione-Neto, Mouriño, Silva, Seiftter & Andreatta 2011). Both types of polyculture are now common (Zimmermann & New 2000).

In tropical regions, the freshwater prawn *Macrobrachium rosenbergii* and Nile tilapia *O. niloticus* can be cultured year-round (Garcia - Pérez *et al.* 2000). Tilapia mainly occupy the water column. They eat zooplankton and are effective filter feeders of phytoplankton. This reduces the occurrence of deleterious algal blooms. Prawns live on the substrate and efficiently utilize the benthic production. Polyculture with these two organisms optimizes production of both species, and increases economic returns (Garcia - Pérez *et al.* 2000). Published research has been mainly about aspects such as stocking density (Uddin, *et al.* 2007b), profitability (Garcia - Pérez *et al.* 2000), and the effects of confined and unconfined tilapia on water quality (Danaher, Tidwell, Coyle, Dasgupta & Zimba 2007; Tidwell *et al.* 2010). For example, from an economical point of view, a stocking density of tilapia and freshwater prawn of 30 000 ha^{-1} with a ratio of 3:1 showed the best result (Uddin *et al.* 2007b).

In shrimp farming regions, tilapia are often grown in cages or hapas inside shrimp ponds, or are produced in supply channels or head ponds. In Latin American countries such as Brazil and Mexico, red tilapia hybrids are now cultured in brackish ponds traditionally used only for shrimp farming (Alceste, Illingworth & Jory 2001). In the Philippines, more than 60% of the shrimp farms employ tilapia – shrimp polyculture (Cruz, Andalecio, Bolivar & Fitzsimmons 2008). Farming tilapia and shrimp together, improves shrimp health and increases profits (Yuan, Yi, Yakupitiyage, Fitzimmons & Diana 2010; Hernández-Barraza, Loredo, Adame & Fitzsimmons 2012). Shrimp production was generally higher in polycultures than in monocultures (Li & Dong 2002). Tilapia/shrimp polyculture is important in the control of the luminous bacterial disease caused by *Vibrio harveyi* (Cruz *et al.* 2008). Studies have shown that the presence of genetically improved farmed tilapia (GIFT) reduced the luminous bacteria population and increased shrimp survival (Tendencia, Fermin & Choresca 2006). The ability of tilapia to control luminous bacteria has been extensively studied (Tendencia, Fermin, Lio-Po, Choresca & Inui 2004; Tendencia & Choresca 2006). Tilapia polyculture maintained a stable plankton environment, and increased shrimp survival (Cruz *et al.* 2008). Stocking performance, feeding strategies and productivity in shrimp/tilapia systems have been studied (Wang *et al.* 1998; Hernández-Barraza *et al.* 2012; Simão, Brito, Maia, Miranda & Azevedo 2013).

Crayfish

Australian redclaw crayfish *Cherax quadricarinatus*, was introduced into Mexico as a viable substitute for prawns. Redclaw larvae develop in freshwater, and availability of redclaw larvae is higher than prawn larvae. Trials have been carried out to ascertain the economic feasibility of the tilapia/redclaw system in Mexico. The pairing shortened investment return time and buffered the risk from changes in tilapia sale price (Ponce-Marbán, Hernández & Gasca-Leyva 2006). However, tilapia growth, reproduction, and food conversion, were adversely affected by the presence of crayfish (Brummett & Alon 1994). The aggregating behaviour of the benthic redclaw may disrupt the spawning behaviour of the tilapia and reduce their reproductive output. Decreased growth of redclaw in polyculture with tilapia was also reported. This could be due to that the non-aggressive feeding of crayfish was affected by tilapia (Rouse & Kahn 1998).

Tilapia polyculture with other teleosts

Tilapia start breeding before reaching marketable weight, so their recruits compete for limited resources, and this can cause stunted growth & undersized fish. In Africa & Asia, sex-reversed male tilapia populations are used when urban and international markets are supplied (Little & Edwards 2004). Rural markets demand small-sized tilapia (<200 g) (Hernández, Gasca-Leyva & Milstein 2014), and predators are used to control tilapia recruitment, rather than mono-sex hatchery technology. The quality of tilapia feed, availability of predator fingerlings, size and feeding habits of the predator, need to be considered in these types of systems (Fagbenro 2004). A model using native predators (tucunare, *Cichla monoculus*) to control overcrowding of Nile tilapia was reported (Fischer & Grant 1994). Another model for the production of Nile tilapia in mixed sex and all-male polyculture, with a predator (African catfish, *Clarias gariepinus* or African snakehead, *Parachanna obscura*), has been developed in African countries (de Graaf, Dekker, Huisman & Verreth 2005). African catfish was a competitor for the available food in the pond and large numbers of African catfish were required to control the reproduction of Nile tilapia fingerlings (Lazard & Oswald 1995). In Nepal, sahar (*Tor putitora*) was cultured with Nile tilapia to control recruitment. The presence of sahar reduced tilapia recruitment in a mixed-sex pond culture system, gave better growth and higher production. Stocking at a 1:16 sahar to tilapia ratio gave the best overall performance in terms of Nile tilapia growth, production, growth of sahar and gross income (Shrestha, Sharma, Gharti & Diana 2011). Polyculture of Nile tilapia and the native Mayan cichlid (*Cichlasoma urophthalmus*) in Mexico was tested (Hernández *et al.* 2014). The presence of the cichlid did not affect tilapia performance. Cichlid growth was inversely proportional to its density because they competed for available tilapia larvae.

Some studies have focused on determining the viability of tilapia culture with other freshwater fish such as carps. In Israel, sex-reversed male tilapia hybrids were cultured with carp (Milstein 1995). Culture of Nile tilapia, common carp *Cyprinus carpio*, and silver carp *Hypophthalmichthys molitrix*, is the major aquaculture practice in Egypt and other countries, because of their different feeding habits. This ensures maximum utilization of food (Abdel-Tawwab, Abdelghany & Ahmad 2007). The three species are commonly grown in semi-intensive systems with fertilization and supplemental feeding (Abdelghany, Ayyat & Ahmad 2002). Growth performance of common carp with tilapia has extensively been studied in freshwater ponds (Zweig 1989; Milstein 1995). The growth rate of carp, cultured with tilapia, depends upon the species percentage and the initial body size (Papoutsoglou, Petropoulos & Barbieri 1992; Milstein 1995). Scaled carp *Cyprinus carpio*, and blue tilapia *Oreochromis aureus*, in monoculture and two polyculture conditions, were investigated (Papoutsoglou, Miliou, Karakatsouli, Tzitzinakis & Chadio 2001). In the proportions of 40% carp and 60% tilapia, both species achieved the highest levels of growth rate, the lowest levels of food conversion ratio, and the lowest carcass lipid content. It was suggested that in an intensive system, improved growth and physiology result from decreased stress related to fish behaviour (Papoutsoglou *et al.* 2001). The advantages of intensive polyculture fish rearing come from changes in fish behaviour (Papoutsoglou *et al.* 1992). However, further explanation about the mechanisms which affect changes in the growth rates of carp and tilapia, especially at different percentages, is required. Carp farmers in China, Vietnam and Indonesia, have now incorporated tilapia into their traditional ponds and cages (Little & Bunting 2005). In Nepal, the cage-cum-pond integration with Nile tilapia in cage and carps in open pond increased production and provided profitability for small farmer (Mandal, Shrestha, Jha, Pant & Pandit 2011). Nile tilapia and Jundia (*Rhamdia quelen*) were introduced into the carp polyculture practiced in South Brazil. This had a positive effect on growth parameters when compared with carp-only polyculture (Da Silva, Barcellos, Quevedo, De Souza, Kessler A D, Kreutz, Ritter, Finco & Bedin 2008).

Tilapia are also reared with striped mullet *Mugil cephalus,* thinlip grey mullet *Liza ramada*, milkfish *Chanos chanos,* sharptoothed catfish *Clarias gariepinus* and silver barb *Puntius gonionotus* (Cruz & Laudencia 1980; Rothuis, Duong, Richter & Ollevier 1998; Omondi, Gichuri & Veverica 2001; Tahoun, Suloma, Hammouda, Abo-State & El-Haroun 2013). All-male Nile tilapia can be cultured with milkfish, without affecting their growth and production, at ratios of 1–3 tilapia to five milkfish (2:5 is the optimum ratio), because there is no food competition between the two species (Cruz & Laudencia 1980). Tilapia are also used to enhance the growth of cage cultured channel catfish (*Ictalurus punctatus*). Blue tilapia fed vigorously at all feeding periods, and this stimulated the channel catfish to higher feeding and growth rates (Williams, Gebhart & Maughan 1987). The effect of stocking different ratios of Nile Tilapia, striped mullet, and thinlip grey mullet in brackish water ponds, was investigated for yield and economic return. This study found improvement in the utilization of food resources; resulting in better environmental quality, system sustainability and net financial return (Tahoun *et al.* 2013).

Progress in China

China is the largest tilapia producing country, and its output & exports are rising rapidly. In 2010, China produced over 1 million MT of tilapia, accounting for about 40% of global production (Food and Agriculture Organization of the United Nations (FAO) 2013). Tilapia culture in China started in the early 1960s, but was not popular until the early 1980s (Qiuming & Yi 2004). Polyculture of tilapia in semi-intensive ponds is the dominant practice in most parts of China. The species composition varies in different areas, but carps are common (Qiao & Zhao 1994; Yang & Huang 2011). Aquaculture of tilapia with carp did not affect the growth of tilapia, but it improved the survival rate, the total net production of the pond and the water quality (Yang & Huang 2011). Total yield depends on various factors such as stocking size, stocking density and culture period (Table 1). The net production from culture of tilapia with other fish species, is generally higher than that reported in other countries (Rothuis *et al.* 1998). This may be due to a larger average body weight at stocking and a higher stocking density.

The culture of tilapia with Japanese seabass (*Lateolabrax japonicus*), black pacu (*Colossoma brachypomus*) and large yellow croaker (*Pseudosciaena crocea*), in the same pond with the appropriate stocking ratio, has been successful (Table 1). Japanese seabass and soft-shelled turtles (*Trionyx sinens*) in tilapia ponds, yielded economic and ecological benefits compared with monoculture of tilapia (He & Wang 2011). An intertidal mangrove-based polyculture system in the Pearl River Delta was constructed using tilapia as the principal fish. The carrying capacity was found to be a tilapia biomass of 5.8 MT ha^{-1} (Xu, Chen, Li, Huang & Li 2011). Although a varied range of tilapia polyculture was reported in China, most studies focused on the technical feasibility and economic return. All these studies have addressed that polyculture in semi-intensive systems was a way of improving sustainability for tilapia aquaculture.

Polyculture operating conditions

In polyculture systems, operating characteristics such as stocking densities, timing of culture of different species and age of polyculture species have attracted much attention in the previous research (Junior, Paula, Azevedo & Henry-Silva 2012; Simão *et al.* 2013; Tahoun *et al.* 2013). Other important aspects are the combination of species, and the culture model. Partitioning and multi-trophic polyculture appear to be the best options, because any conflict among species is minimized when they are separated. For example; unconfined tilapia in shrimp ponds can reduce shrimp production by reproducing uncontrollably and competing for food (Danaher *et al.* 2007), so net-isolated culture of Nile tilapia was used with the shrimp (*Penaeus vannamei*), and the prawn (*M. rosenbergii*) (Tidwell *et al.* 2010; Sun, Dong, Jie, Zhao, Zhang & Li 2011). The task of separating the different species at harvest was eliminated by culturing the fish in cages (Heinen, D'Abramo, Robinette & Murphy 1989). The Australian redclaw crayfish needed shelter and separation of feed rations when cultured with tilapia (Ponce-Marbán *et al.* 2006). Social and economic factors also need attention when tilapia are cultured with other species.

Since feed accounts for more than 60% of production costs for most species, lower feed costs are important for increasing efficiency and profitability. Use of substrates as feed was evaluated as a means of increasing pond efficiency. Culture of tilapia & prawn in ponds with periphyton substrates resulted in higher fish production (Uddin, Farzana, Fatema, Azim, Wahab & Verdegem 2007a). The presence of tilapia reduces prawn survival during moulting, so a substrate that provides shelter has been recommended (Uddin, Azim, Wahab & Verdegem 2006). The substrate material should have no adverse effect on water quality, and should promote periphyton development (Uddin, Azim, Wahab & Verdegem 2009). Further research will measure the contribution of substrates to both tilapia & prawn production, and make the systems robust & sustainable.

Prospects and challenges

There is considerable information and research on tilapia polyculture, and benefits have been achieved, such as improved performance of the cultured organisms, better pond water quality and

Table 1 Net production, survival rate, stocking density, average body weight at stocking (average W_o), average weight at harvest (average W_t) and culture period of tilapia and different fish species in polyculture or monoculture system in China. Data are based on recalculations of original data

Husbandry System	Species	Stocking Density (ha^{-1})	Average W_o (g)	Average W_t (g)	Period (days)	Net Production (Kg ha^{-1})	Survival Rate	References
Mono	Tilapia	22489	230	661.5	90	9493	98.6	(Yang & Huang 2011)
Poly								
Principal species	Tilapia	22489	230	646	90	9209	99.5	
Minor species	Grass carp	1799	250	1560	240	2357	100	
Poly								
Principal species	Tilapia	22489	230	658	90	9521	99.3	
Minor species	Grass carp	3148	250	1450	240	3773	99.9	
Poly								
Principal species	Tilapia	22489	230	650	90	9328	99.2	
Minor species	Grass carp	4498	250	1240	240	4363	98.4	
Poly								(He & Wang 2011)
Principal species	Tilapia	4301	42	1250	120	5196		
Principal species	Japanese seabass	5376		365	150			
Minor species	Soft-shelled turtles	129	400	1050	120	84		
Minor species	Silver carp	323		2650	210			
Poly								(Teng, Jin & Yang 2005)
Principal species	*Colossoma brachypomum*	9487	82	680	91	5605	91.4	
Principal species	Tilapia	7547	175	426	91	1894	100	
Minor species	Triploid crucian carp	3802	450	250	91	849	100	
Minor species	Silver carp	2830	750	900	91	1274	100	
Minor species	Bighead carp	566	25	1250	91	283	100	
Poly								(Liang, Ma, Shi, Sun, Zhang & Sun 2009)
Principal species	*Plagiognathops microlepis*	10500	75	430	150	3114	85.7	
Principal species	*Oreochromis niloticus* × *O. aureus*	10950	100	603	120	5316	96.8	
Minor species	Grass carp	2250	100	762	130	1456	98	
Minor species	Silver carp	3000	92	683	130	1760	99	
Minor species	Bighead carp	1500	105	729	130	925	99	
Minor species	Koi	1800	110	701	130	1053	98.5	
Poly								(Wang, Qi & Zhong 2012)
Principal species	*Oreochromis niloticus niloticus* L.	22500	150	662	192	3994	99	
Minor species	*Astronotus ocellatus*	5700	18	194	192	451	99.5	
Poly								(Xu 2013)
Principal species	Tilapia	10870	60	600	150	5645	96.6	
Minor species	*Pseudosciaena crocea*	450	6 cm	54	90		83.3	
Poly								(Qiao & Zhao 1994)
Principal species	Tilapia	67159	18	200	120	8193	70	
Minor species	Silver carp	9402	67	750	225	5010	80	
Minor species	Bighead carp	1007	100	1000	225	806	90	
Minor species	Grass carp	2418	55	1250	225	2008	71	
Minor species	Carp	1578	50	1000	210	1330	89	
Minor species	Mullet	1007		500	90		80	

increased economic yield (Table 2). Production cost for the polyculture system is lower compared with a monoculture system, allowing significant cost savings. Researchers practising polyculture also reported that the plankton bloom and pH are more stable. This can be attributed to the bioturbation activities, which facilitates the slow but continuous release of nutrients in the water

Table 2 Effect of tilapia polyculture on the pond environment and the biology & production

	Species	Biology Effect	Pond Environment	Production
Principal species Minor species	Prawn Tilapia	Higher average weight, and more efficient feed conversion of prawns (confined tilapia)[1]	Reduced phytoplankton densities and pH levels[2]	Higher total production1, reduced prawn production (unconfined tilapia)[3,4], increased total pond productivity without impacting prawn production (unconfined tilapia)[5]
Principal species Minor species	Tilapia Prawn		Improved system sustainability6	Increased total production6, 7
Principal species Minor species	Shrimp Tilapia	Controlled luminous bacteria[8, 9, 10]	Reduced phytoplankton biomass, improved the water quality[11, 13, 14]	Higher shrimp production[12,13]
Principal species Minor species	Tilapia Crayfish	Tilapia growth, reproduction and food conversion were adversely affected[15],crayfish growth were not affected[15]		Shortened investment return time and buffered risk related to changes in tilapia sale price[16]
Principal species Minor species	Tilapia Carp	Tilapia and carp showed a better specific growth rate[17, 18]		
Principal species Minor species	Carp Tilapia	Positive effect on growth parameters of carp[19]		
Principal species Minor species	Tilapia Tucunare	Controlled overcrowding of tilapia[20]		
Principal species Minor species	Tilapia African catfish or African snakehead	Controlled overpopulation of tilapia[21]		
Principal species Minor species	Tilapia Sahar	Controlled tilapia recruitment, produced better tilapia growth and production[22]		
Principal species Minor species	Tilapia Striped mullet		Better environmental quality, system sustainability[23]	Better feed utilization and net financial return[23]
Principal species Minor species	Milkfish Tilapia	Did not affect the growth of milkfish[24]		Did not affect the production of milkfish[24]
Principal species Minor species	Tilapia Large yellow croaker			Better feed utilization and net financial return[25]

[1]Danaher *et al.* (2007), [2]Tidwell *et al.* (2010), [3]Garcia - Pérez *et al.* (2000), [4]Siddiqui, Al Hinty and Ali (1996), [5]Tidwell, Coyle, VanArnum, Weibel and Harkins (2000), [6]dos Santos and Valenti (2002), [7]Uddin, *et al.* (2007a) and Uddin, *et al.* (2007b), [8]Tendencia *et al.* (2004), [9]Tendencia (2003), [10]Tendencia *et al.* (2006), [11]Sun *et al.* (2011), [12]Li and Dong (2002), [13]Akiyama and Anggawati (1998), [14]Wang *et al.* (1998), [15]Brummett and Alon (1994), [16]Ponce-Marbán *et al.* (2006), [17]Papoutsoglou *et al.* (1992), [18]Papoutsoglou *et al.* (2001), [19]Da Silva *et al.* (2008), [20]Fischer and Grant (1994), [21]Lazard and Oswald (1995), [22]Shrestha *et al.* (2011), [23]Tahoun *et al.* (2013), [24]Cruz and Laudencia (1980), [25]Xu (2013).

column. In addition, valuable byproducts can be obtained from the subordinate culture species. Polyculture increases the efficiency of food utilization, reduces the environmental impact of aquaculture, provides food security and sustainability. It is also a possible tool to control diseases, such as Streptococcus infection of tilapia. Despite the advances, however, the mechanism how polyculture positively affects the cultured species and its environment is not fully understood and seems to be more complex than what is currently understood. Polyculture changes the ecology of the pond environment. Changes are produced through a variety of processes, including productivity, decomposition and nutrient cycling. To a large extent, the problem is management of carbon flows. Better understanding of the dynamics and mechanisms are needed to allow refinement and improve production efficiency.

The knowledge of relationships between polyculture species and between fish and environment enables choosing adequate combinations of polyculture species, stocking rates, input types and rates, and other management strategies according to different local conditions: climate, quality of water supply and pond fertility, availability of fish fry and fingerlings, availability of feeds and fertilizers, and market requirements. It is important that the environmental requirements of polyculture species are similar, and that their feeding habits do not conflict. In polyculture systems, only a proper combination of ecologically different species at adequate densities will utilize the available resources efficiently, maximize the synergistic relationships between polyculture species and between fish and environment and minimize the antagonistic ones. To find an optimum stocking density of different species in polyculture, a modelling approach of polyculture systems might be useful to explore fish densities and ratios. Consideration of the relative size of the organisms, maintenance of oxygen levels, and economic investment, are required before practising polyculture. The future will also see investigation of new species, and new systems. Other species of food value and commercial value should be investigated as possible pieces of the system. More research on multiple species interactions is required. Investigations should continue on their ecological niches and their interactions.

Acknowledgments

Special thanks to Brian Dobson from Leigh Marine Laboratory, the University of Auckland, for his invaluable help in the revision of this manuscript. This work was supported by grant from China Agriculture Research System (CARS-49).

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