On-farm feeding and feed management practices for sustainable aquaculture production: an analysis of case studies from selected Asian and African countries

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ABSTRACT

Aquaculture production reached some 79 million tonnes in 2010. During the period from 1998–2010, production from feed-dependent aquaculture increased more than twofold from 20 to 45 million tonnes, largely through intensification. The use of exotics with established technologies such as tilapias, carps, shrimps and salmonids provided firm market opportunities for increasing production and driving production efficiency.

This review considers changes in feed and feed management practices in selected countries (Bangladesh, China, Egypt, Ghana, India, the Philippines, Thailand and Viet Nam) that contributed to this increase. Four major farmed species groups of freshwater finfish and shellfish: tilapias, catfishes and Indian major carps, and shrimps and prawns are considered. These groups showed a phenomenal growth in production, increasing from 1.6 million tonnes in 1988 to 16 million tonnes in 2010, with a single species within each species group dominating production. The contributions of these species to production are presented. Ponds (1–5 ha) continued to be the predominant production system but the use of cages in countries such as Egypt, the Philippines and Ghana is on the increase. The types and changes in farming practices are discussed. The key trigger for change in culture practices was market opportunities, combined with the need for increased production and productivity to reduce costs.

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Two fundamental changes in farming practices that contributed to this increase are evident and discussed: the increase in the use of formulated farm-made and commercial aquafeeds and the concomitant aeration of ponds/tanks. In India the introduction of stocking large fish, together with supplementary feeding, was a notable shift in farming practice. For tilapia, intensification through the introduction of stocking larger fish, aeration, increased feed inputs and a shift to culture in cages characterized the changes in farming practices in countries such as the Philippines, Egypt, and Ghana. The high international prices and availability of hatchery reared postlarvae encouraged many small to medium-sized farmers in Bangladesh and India to change culture practice to focus only on freshwater prawns and shrimps in larger ponds (0.2–0.4 ha) using supplementary feeds and aeration, pushing shrimp yields up to 3–5 tonnes/crop. Such developments and their associated challenges and approaches for improving production and production efficiencies and reducing feed costs for the selected countries are detailed in the review. Additionally, the implications of fish mortality on feed utilization efficiencies and cost are modelled using case study scenarios.

1. OVERVIEW OF GLOBAL PRODUCTION

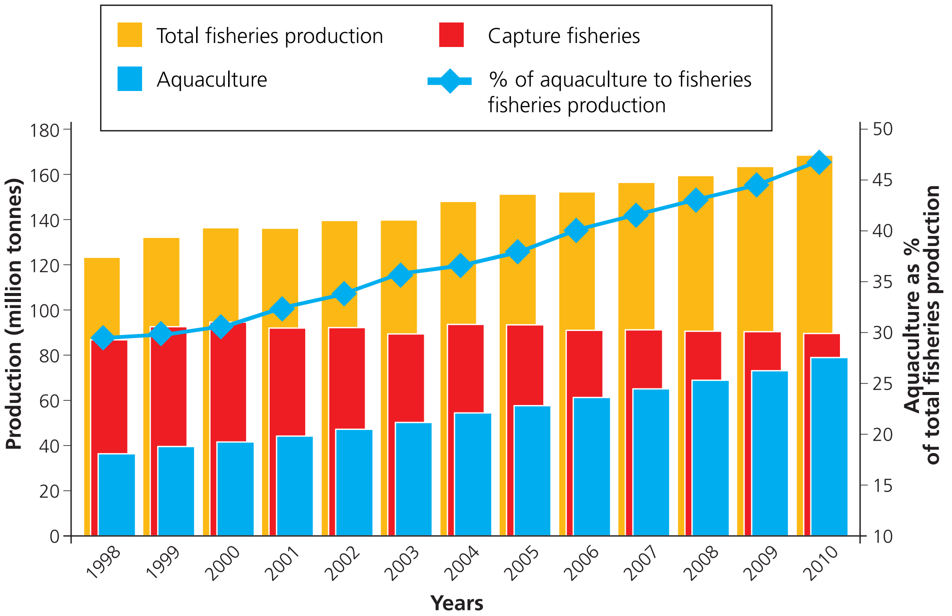
1.1 Global aquaculture production

It is now internationally accepted that the increased supply of fish products required to meet global demand cannot be sourced from wild fisheries, which are either stagnant or declining (FAO, 2012a). To meet their national and international demand, nations around the world have continuously developed and improved technologies and management, especially feed and feed management practices, to increase production volumes and efficiencies for a range of aquatic organisms in an environment of limiting natural resources.

Although there are large intercountry differences in sector growth, aquaculture has collectively achieved the highest average growth rate among the animal production sectors. In 2010, global aquaculture production reached 79 million tonnes, growing at an annual rate of 9.7 percent since 1998, while technological advances in equipment and feed and greater areas under culture have led to an increase in its proportional contribution to total fisheries (Figure 1). In 1988, aquaculture contributed only 15 percent of total global fisheries production; by 2010, however, this had risen almost threefold to 47 percent. This increased contribution, however, is largely an Asian phenomenon, as Asia accounted for 72 million tonnes or 91.5 percent of total world aquaculture production in 2010, while the Americas, Africa and Europe contributed only 3.3, 1.8 and 3.2 percent, respectively. Global production was valued at US$125 billion, with the share of the Asian region being US$102 billion, or 81 percent of total world aquaculture value. This increasing trend is projected to continue in future decades; consequently, the aquaculture sector is expected to play a significantly greater role in contributing to food security, poverty alleviation and economic improvement for the poor.

Over the past 15–20 years, more than 60 countries have engaged in farming over 200 species or species groups of aquatic animals and plants in a vast range of production systems, ranging from low-input extensive to high-input intensive aquafarms using ponds, caged enclosures and tanks. In broad terms, aquaculture systems used for the production of these aquatic animals and plants can be divided into feed-dependent systems or "fed aquaculture" (e.g. finfish and crustaceans) or non-fed aquaculture systems, where culture is predominately dependent on the natural environment for food and nutrients (e.g. aquatic plants and molluscs).

FIGURE 1
Global trends in contribution of aquaculture to fisheries production, 1988–2010



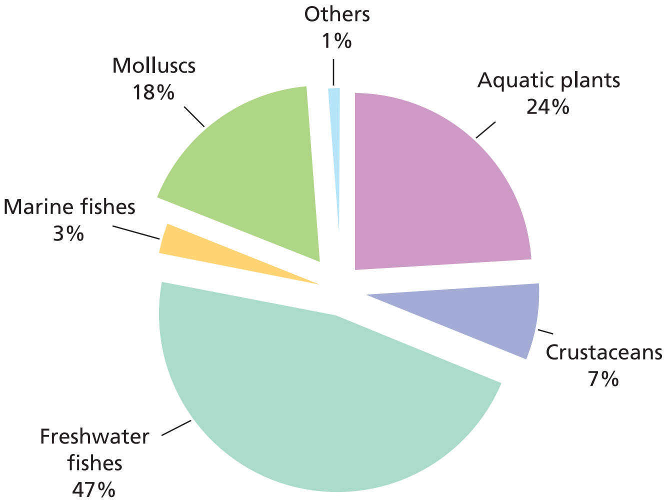
Source: Adapted from FAO (2012b).

1.2 Global and country profiles of species and species group utilization in aquaculture

Although more than 200 aquatic species or species groups are farmed, the majority of production stems from a few species and species groups that are cultured with minimum impact on the environment when compared with other food production sectors such as agriculture and livestock, while still maximizing benefits to society.

In 2010, freshwater fish accounted for 47 percent of global production, while the remaining 53 percent was of marine origin (Figure 2). Of this 53 percent, about 92 percent comprised aquatic plants and shellfish (except abalone), which are not dependent on feed and, as such, actually remove nutrients such as nitrogen and phosphorus originating from anthropogenic activities, especially agriculture and sewage disposal. Seaweeds and algae utilize these nutrients for growth, and shellfish filter the resultant algae as food. Similarly, freshwater and marine fish species that filter algae and zooplankton can also have the same positive impact. This removal of nutrients from the water can reduce the risk of coastal algal blooms and ameliorates the negative impacts of the agriculture sector, which is a significant contributor of these nutrients through the use of

FIGURE 2
Global output of aquaculture by species group, 2010



Source: Adapted from FAO (2012b).

fertilizers. Indeed, in 2007, more than 200 million tonnes of fertilizers (nitrogen-potassium-phosphorus [NPK]) were used globally in agriculture; much of this eventually entering the aquatic environment, both through runoff and via groundwater.

1.3 Range of species and species groups used globally in aquaculture

In 2010, only about a dozen species and species groups accounted for almost all global finfish production, with a few species dominating each region (Table 1). In Asia, carps (Chinese, Indian major and common), tilapias, catfishes, milkfish, shellfishes including crustaceans and seaweed predominate in regional production. In the Americas, salmon, trout and catfish predominate, accounting for 43 percent of total regional production. In Chile, salmonids, destined for export markets in the United States of America, Japan and Europe, dominate aquaculture production, while in the United States of America catfish are predominately produced for the domestic market. In Europe, almost half (46 percent) of the total regional production originates from just two species (salmon and trout) and, in both cases, most is exported, but largely within the European region. Species diversity within Africa is also narrow, with more than 77 percent of regional production originating from three species – Nile tilapia (*Oreochromis niloticus*), North African catfish (*Clarias gariepinus*) and flathead grey mullet (*Mugil cephalus*) – all for domestic consumption, with Egypt being the focus of production. Similarly, in Oceania, two species (salmon and mussels) account for almost 80 percent of the production of the region, with mussels being mainly exported. About half of the salmon farmed in Australia and New Zealand is consumed domestically.

A global snapshot of aquaculture production in 2010 by region and key aquaculture countries is presented in Table 1. This table also provides an assessment of scale, measure of biodiversity utilized in aquaculture and key purposes of production. In addition, the production by country is ranked within each region, and the countries included represent 80–97 percent of the total aquaculture output of their region and 99.8 percent of world output. Overall, freshwater fish are by far the most widely farmed group. An understanding of the fate of national aquatic output is valuable, as it may shed some light on macro-government policy on food security and economic development, especially as pertains to feed inputs.

The main destinations of national aquatic products are colour-coded in blue and purple font in Table 1. It is noteworthy that the vast majority of species and species groups of farmed aquatic products, that are freshwater fish, are destined mainly for domestic consumption. According to (FAO, 2012b), about 994 000 tonnes of freshwater fish (aquaculture and capture fisheries including river eels) entered the export market globally in 2009. This estimation includes products in all forms (fillets, fresh frozen, etc.) and therefore whole body weight equivalent is likely to be double that level. Nevertheless, this quantity is still a small proportion of total freshwater production. In contrast, 28.4 million tonnes of marine finfish and shellfish (aquaculture and capture) were exported globally during the same period, but the proportion of farmed marine finfish and shellfish contributing to total exports is unknown. Known species of shrimps that are mainly farmed accounted for 396 000 tonnes of exports in 2009 (FAO, 2012b), but given the final product forms, the whole body weight equivalents will be higher. About 3.2 million tonnes of shrimps and freshwater prawns were farmed globally (FAO, 2012b), although Table 1 shows global production as 2.92 million tonnes because it includes only major aquaculture producing countries in the world. With rising living standards in many Asian countries, a greater share of these products will enter the domestic and regional markets.

TABLE 1

Aquaculture production (thousand tonnes) hotspots by species and species groups ranked by country within regions in 2010.
[Product destination: numbers in blue font - largely domestic; purple font - largely exports; yellow cells denote use of exotic species]

		Finfish												Shellfish									
		Salmon	Trout	Chinese carp	Indian carps	Common carp	Tilapias	Catfish	Milkfish	Grey mullet	Seabream	Seabass	Freshwater fish nei	Mitten crab	Freshwater prawns	*P. monodon*	*P. vannamei*	Clam	Oysters	Mussel & abalone	Seaweed	Country total (thousand tonnes)[1]	% of country total[2] and regional total[3] (% of world share)[4]
Asia	China	1	16	10 381		2 538	1 332	792				106	626	593	15	56	1 223		3 643	759	7 884	47 830	63
	India			146	4 076								232			96	10		3	15	3 915	4 653	98
	Indonesia					283	459	374	422				143			125	207					6 278	94
	Philippines						259	3	349							48	5		23	21	1 801	2 546	99
	Viet Nam					110	76	1 150					188			333	137				35	2 707	75
	Thailand				3	3	179	135					5			5	561		28	167		1 286	84
	Bangladesh			223	600	46	25	140					29		6	43						1 309	85
	Myanmar			36	624	23	41	25								46						851	93
Total		**1**	**16**	**10 786**	**5 303**	**3 003**	**2 371**	**2 619**	**771**	**0**	**0**	**106**	**1 223**	**593**	**21**	**752**	**2 143**	**0**	**3 697**	**962**	**13 635**	**67 459**	**72 2033 (92.5)[4]**
% of regional total		0	0	15	7	4	3	4	1	0	0	0	2	1	0	1	3	0	5	1	19	93	
Americas	Chile	247	220																	225	12	713	99
	USA	20	15				10	217									1	30	138	2		495	87
	Brazil		5			95	155	5					10				69		2	14		480	74
	Ecuador						48										223					272	99
	Canada	114	7										1						11	24		161	98
Total		**380**	**247**	**0**	**0**	**95**	**213**	**218**	**0**	**0**	**0**	**0**	**11**	**0**	**0**	**0**	**293**	**30**	**151**	**265**	**12**	**2 122**	**2 589 (3.3)**
% of regional total		15	10	0	0	4	8	9	0	0	0	0	0	0	0	0	11	1	6	10	0	82	
Africa	Egypt					92	557	10		116	15	16										920	88
	Nigeria						12	133														201	72
	Uganda						32	63														95	99
	Madagascar					3										4					4	11	99
	South Africa		1																	2		5	58
Total		**0**	**1**	**0**	**0**	**95**	**601**	**206**	**0**	**116**	**15**	**16**	**0**	**0**	**0**	**4**	**0**	**0**	**0**	**2**	**4**	**1 231**	**1 427 (1.8)**
% of regional total		0	0	0	0	7	42	14	0	8	1	1	0	0	0	0	0	0	0	0	0	86	
Europe	Norway	928	55																	2		1 008	98
	Spain		17								20	11							2	189		252	95
	France	1	33			4					1	3						2	96	77		225	97
	Italy		36								6	6								64		153	73
	UK	155	14																1	30		201	99
	Greece		3								54	31								23		113	98
	Russia	5	19	25		57																121	87
	Ireland	16	1																7	22		46	99
Total		**1 104**	**178**	**25**	**0**	**61**	**0**	**0**	**0**	**0**	**81**	**51**	**0**	**0**	**0**	**0**	**0**	**2**	**106**	**407**	**0**	**2 120**	**2 523 (3.2)**
% of regional total		44	7	1	0	2	0	0	0	0	3	2	0	0	0	0	0	0	4	16	0	44	
Oceania	NZ	13																	2	95		111	99
	Australia	32																	15	4		70	73
Total		**45**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**17**	**99**	**0**	**180**	**199 (0.3)**
% of regional total		22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	50	0	91	

Notes: USA = United States of America; UK = United Kingdom; Russia = Russian Federation; NZ = New Zealand.;
[1] Total aquaculture production including all other species/species groups; [2] Percentage of aquaculture production contributed by the species and species groups shown in this table; [3] Total aquaculture production of each region/continent; [4]Value in parentheses is the percentage of world share of aquaculture production contributed by the continent.

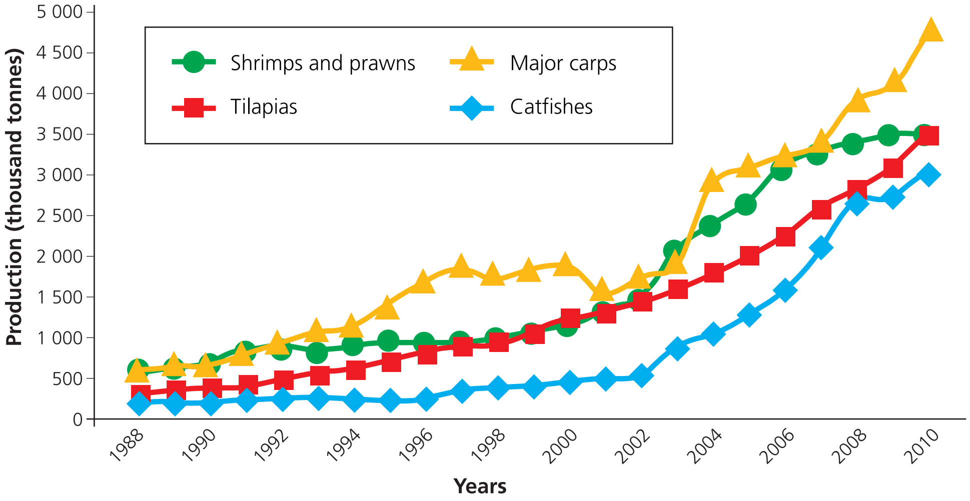
Source: FAO (2012b).

1.4 Synthesis of development trends for selected species/species-groups and countries

This review synthesizes the information derived from 11 case studies on feeding and feed management practices carried out in selected countries for eight species in four major farmed species groups of freshwater finfish and shellfish: shrimps and prawns, tilapias, catfishes and Indian major carps. These four farmed species groups totalled 14.8 million tonnes accounting for 24.7 percent of world finfish and shellfish production in 2010. For these species groups, the review focuses on country-specific case studies carried out for: Nile tilapia (*Oreochromis niloticus*) in China, Egypt, Ghana, the Philippines and Thailand; Indian major carps (rohu [*Labeo rohita*], catla [*Catla catla*] and mrigal [*Cirrhinus cirrhosus*]) in Bangladesh and India, giant river prawns (*Macrobrachium rosenbergii*) in Bangladesh; striped catfish (*Pangasianodon hypophthalmus*) and whiteleg shrimp (*Litopenaeus vannamei*) in Viet Nam; and black tiger shrimp (*Penaeus monodon*) in India.

The production of the above four species groups collectively increased from 1.6 million tonnes in 1988 to 14.8 million tonnes in 2010 (Figure 3), representing an annual average increase in production of 10.7 percent. Specific species, however, showed phenomenal growth. For example, annual production of whiteleg shrimp, increased from 77 000 tonnes in 1988 to 2 710 000 tonnes/year in 2010, an increase of more than 35 times (Figure 4). Globally, a single species within each species group dominated production. In 2010, the whiteleg shrimp accounted for 67 percent of all shrimp and prawn production, with 45 percent of world production reported from China (Table 2).

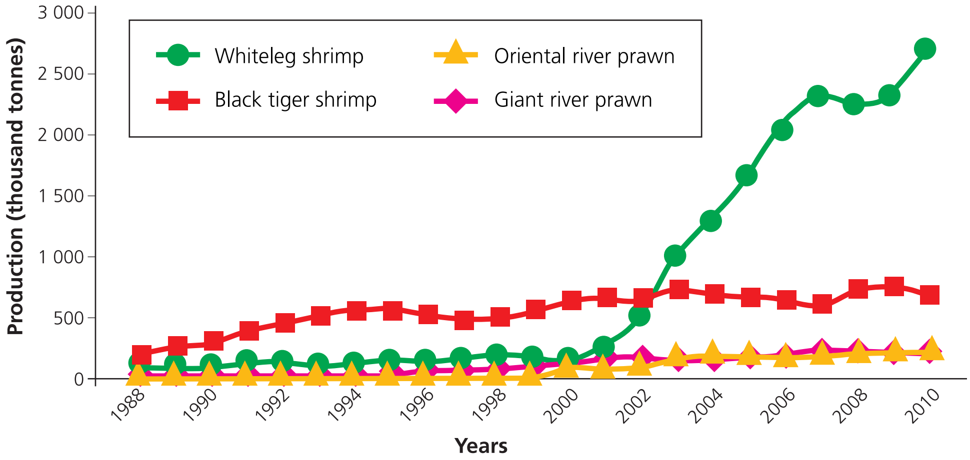
FIGURE 3
Production trends of selected species groups of finfish and shrimps and prawns, 1988–2010



Source: Adapted from FAO (2012b).

Similarly, in 2010, Nile tilapia, striped catfish and catla accounted for 73, 43 and 71 percent of production, respectively, in their species groups (Table 2). However, this dominance or ranking of preferred farmed species within species groups shows temporal variation both globally and nationally. In 1994, black tiger shrimp dominated production at 62 percent (559 000 tonnes), while whiteleg shrimp contributed only 13 percent (121 000 tonnes) of global shrimp and prawn production; however, by 2010 the trend had reversed, with black tiger shrimp production slipping to just 19 percent (685 000 tonnes) and whiteleg shrimp surging to 67 percent (more than 2 710 000 tonnes) of global shrimp and prawn production (Figure 4, Table 2).

FIGURE 4
Temporal changes in contribution of major species to global shrimp and prawn production, 1988–2010

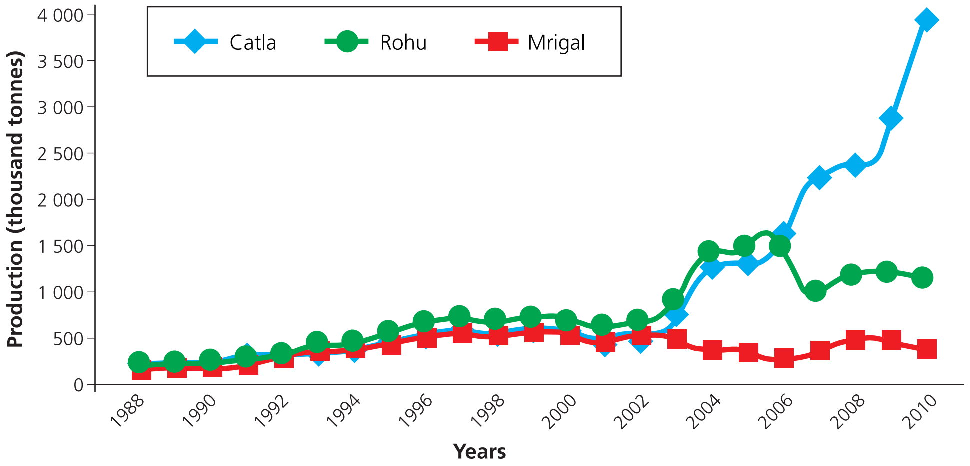


Source: Adapted from FAO (2012b).

For tilapias, there is a strong preference for farming *O. niloticus* over *O. mossambicus*. Since 1988, the contribution of *O. niloticus* to farmed tilapias has increased by more than 1.6 times, increasing from 45 percent in 1988 to 73 percent in 2010, with China and Egypt reporting 39 percent and 22 percent of world production, respectively (Table 2).

The United States of America was the main catfish (channel catfish) producer in the 1980s and 1990s, but it has been surpassed in this millennium by the phenomenal growth in striped catfish (tra or pangas) production in Viet Nam. By 2010, striped catfish production reached 1.14 million tonnes in Viet Nam, representing 37 percent of all global catfish production (Table 2), 87 percent of which was produced in Viet Nam. Channel catfish, which accounted for 80 percent of all catfish production in 1988, plummeted to just 15 percent by 2010 (Table 2) and about half (217 303 tonnes) of this was produced in China. Although China does not report any striped catfish production, it monopolizes the production of Amur and yellow catfish (Table 2).

FIGURE 5
Global production of Indian major carps



Source: Adapted from FAO (2012b).

TABLE 2

National and global aquaculture production of the selected species and species group in selected countries in 2010

Species group	Global	National production								
		China	Viet Nam	India	Bangladesh	Thailand	Philippines	Ghana	Egypt	Others
	Thousand tonnes (% of group)	Thousand tonnes [numbers in parentheses indicate % of global species production								
Shrimps & prawns										
Whiteleg shrimp	2 721 (67)	1 223 (45)	137 (5)			561 (21)				785 (29)
Black tiger shrimp	783 (19)	57 (7)	333 (43)	97 (12)	43 (6)	5 (1)	48 (6)			199 (25)
Giant river prawns	215 (5)	125 (58)	8 (4)	14 (6)	31 (14)	26 (12)				12 (6)
Others	316 (8)									
TOTAL	**4 034**									
Tilapias										
Nile tilapia	2 538 (73)	999 (39)				179 (7)	168 (7)	9 (0.4)	557 (22)	625 (24.6)
Others	959 (27)									
TOTAL	**3 497**									
Catfishes										
Pangas catfishes nei	1 307 (43)		1 140 (87)							167 (13)
Channel catfish	445 (15)	217 (49)								228 (51)
Amur catfish	380 (12)	374 (99)								6 (1)
Catfish, hybrid	117 (4)					117 (100)				0
North African catfish	191 (6)							0.570 (0.3)		190 (99.7)
Chinese long snout catfish	17 (1)	17 (100)								0
Yellow catfish	184 (6)	184 (100)								0
Others	409 (13)									
TOTAL	**3 049**									
Indian major carp										
Rohu	1 167 (22)			313 (27)	254 (22)					600 (51)
Catla	3 870 (71)			3 598 (93)	196 (5)					75 (2)
Mrigal	379 (7)			164 (43)	149 (39)					65 (17)
TOTAL	**5 416**									

Note: nei = not elsewhere included.
Source: FAO (2012b).

The Indian major carps are mainly farmed in India, Myanmar and Bangladesh, with India accounting for 75 percent of world production in 2010. Catla was the most popular major carp (Figure 5). The production of catla reported since 2003 has increased dramatically and in 2010 accounted for 71 percent of all Indian major carp production (Table 2). India produced 93 and 43 percent of all reported global catla and mrigal production, respectively, in 2010 (Table 2).

2. PRODUCTION SYSTEMS AND CHANGES IN CULTURE PRACTICES IN SELECTED COUNTRIES AND SPECIES

2.1 Types of production systems

Aquaculture practices are now driven by the basic economic criteria of income generation. However, productivity and production (and therefore subsequent income of farmers) in many parts of the world are still governed by the balance between availability and affordability of production inputs, in particular aquafeeds, which typically account for 50–70 percent of production costs (Hasan, 2007; Hasan *et al*., 2007). The increasing competition for common resources such as land and water is dictating a global trend of intensification in aquaculture production. The degree of intensification in countries varies, being governed by species, market price and available resources. These key trends are considered for freshwater finfish and shellfish species in the selected countries shown in Table 3.

TABLE 3

Geographic scope and species considered in this synthesis

	Bangladesh	China	India	Viet Nam	Thailand	Philippines	Egypt	Ghana
Nile tilapia		X			X	X	X	X
Major carps	X		X					
Striped catfish				X				
Whiteleg shrimp				X				
Black tiger shrimp			X					
Giant river prawns	X							

For all freshwater finfish species, pond culture is the most commonly used farming method in all countries, followed by cage culture (Table 4). Cage farming of tilapias is most prevalent in the Philippines and Egypt, accounting for 32 and 21 percent of national tilapia production, respectively.

TABLE 4

Types of production systems for selected countries and freshwater finfish species

Country	Bangladesh	India	Viet Nam	China	Thailand	Philippines	Egypt	Ghana
Species	**Major carps**	**Major carps**	**Catfish**	**Tilapia**	**Tilapia**	**Tilapia**	**Tilapia**	**Tilapia**
Cages			X		X	XX (32)[1]	XX (21)	X
Pond size range (ha)	0.13–0.80		0.30–0.33	0.30–3.30	0.1–5.0	1–3	0.5–3.0	0.1–0.5
Extensive	XXX	X		X	X		X	XXX
Semi-intensive	XX	XX		XX	X	X	XX	X
Intensive		X	XXX	X	XX	XX	X	X

[1] Number in parenthesis accounts for percent of national production.

Note: X = seldom used; XX = widely used; XXX = most commonly used farming method.

Typically, all ponds used for farming these freshwater species are relatively small (0.1–5 ha). In Bangladesh and Viet Nam, ponds are considerably smaller, at less than 1 ha (Table 4). Pond depths, however, vary considerably. Although ponds are generally about 1 m deep, catfish ponds in Viet Nam are typically 3–4 m deep, facilitating high production. In the last two decades, there has been a gradual shift from extensive to semi-intensive production of the Indian major carps and tilapias in most countries. Extensive farming practices, however, are still common in Bangladesh for Indian major carps and in Ghana for tilapia (Table 4). Catfish, on the other hand, are now mainly produced intensively in small but deep ponds yielding production in excess of 100 tonnes/ha (Nguyen, 2013).

Shrimps and prawns are exclusively farmed in small ponds (0.2–2.0 ha), with all countries except Viet Nam farming extensively and semi-intensively (Table 5). Whiteleg shrimp are mainly farmed intensively in Viet Nam, with yields of 20–40 tonnes/ha. On the other hand, in Bangladesh, giant river prawns are typically farmed extensively and semi-intensively in very small ponds (0.2–0.5 ha) with correspondingly lower yields of 0.35–0.7 tonnes/ha (Table 5). In India, black tiger shrimp are farmed extensively and semi-intensively in larger ponds.

TABLE 5

Types of production systems in selected countries for selected prawn and shrimp species

Country	Bangladesh	India	Viet Nam
Species	**Giant river prawns**	**Black tiger shrimp**	**Whiteleg shrimp**
Pond size (ha)	0.2–0.5	0.5–2.0	0.3–0.6
Extensive (yield – tonne/ha)	XXX (0.35)	XX (0.5)	–
Improved extensive (yield – tonne/ha)	XX (0.5)	XX (1–2)	X
Semi-intensive (yield – tonne/ha)	XX (0.7)	XX (2–4)	
Intensive (yield – tonne/ha)			XXX (20–40)

Note: XXX = predominant type; XX = commonly used; X = seldom used.

2.2 Brief summary of change in culture practices

The trigger for change in culture practices is market opportunity combined with the need for increased production and productivity while ensuring the delivery of required environmental services for aquaculture. A varying combination of technological advances and effective knowledge transfer, access to natural resources, and state intervention in the reference countries created country-specific opportunities to change culture practices. In common for all countries, the key technological drivers and milestones significantly directing these farming practice changes were the successful closure of the Indian major carps and striped catfish breeding cycles and the mass production of seed, creating the platform for expansion and change.

2.2.1 Indian major carps (Labeo rohita, Catla catla and Cirrhinus cirrhosus)

As the largest producer of Indian major carps, India has set the pace for change and innovation in culture practices since the 1960s. The successful artificial breeding of major carps through hypophysation in 1957 transformed and facilitated expansion of Indian carp culture from small backyard ponds in the eastern Indian states of West Bengal, Orissa and Bihar to significant commercial-scale operations in states such as Andhra Pradesh, Punjab, Haryana, Karnataka and Tamil Nadu.

In addition, three prominent factors governed and facilitated the pace of change in Indian major carp culture practices and expansion:

- the concerted demonstration effort by government of the composite culture of Indian major carps and Chinese carps through Fish Farmers Development Agencies located throughout the country;
- the ease of paddy conversion to ponds using flood water and saline waters;
- the deceasing net returns from paddy crops.

Andhra Pradesh, which in 2008 accounted for 30 percent of national Indian major carp production, was the central state in developing local innovative changes to basic polyculture practices resulting in new opportunities in the production value chain. The composite culture of carps initially practised in the 1980s using small (5–10 g) Indian major and Chinese carp fingerlings and 5–7 tonnes of supplementary feed often produced undersized fish (<500 g), arising from premature harvesting owing to poor pond conditions. These fish, known as "zero fish", typically fetch less than one third to half the price of normal market-sized fish (1–2 kg). These zero fish created a new farming segment, as innovative farmers bought these as stocking material for on-growing to acceptable size in just six months, thus halving the growing period. This, together with the exploitation of compensatory growth response in fish, resulted in creating a new subsector for the semi-intensive polyculture industry using major carp juveniles of 50–125 g. Thus, composite extensive backyard carp polyculture has evolved over two to three decades into semi-intensive carp polyculture by stocking predominantly larger major carp yearlings, yielding 8–10 tonnes of fish using 23–28 tonnes of supplementary feed. Such changes in culture practices are also mirrored in Bangladesh. Market opportunities in both India and Bangladesh created impetus for further changes in culture practices as farmers introduced a larger species mix into this farming system. In India, Indian major carps have been reared in mixed semi-intensive culture with black tiger shrimp, striped catfish, giant river prawns and pirapatinga (*Piractus brachypomus*) since 1990, 1995, 2000 and 2008, respectively.

2.2.2 Nile tilapia (*Oreochromis niloticus*)

The Nile tilapia is principally farmed in ponds in China and Thailand, and in addition in cages in lakes in the Philippines, Egypt and Ghana. Intensification through the use of larger fingerlings (50 g), aeration, increased feed inputs and a shift to culture in cages have characterized the changes in tilapia culture practices in these countries. The reasons for the shift and scale of change have varied depending on the phase of national aquaculture development.

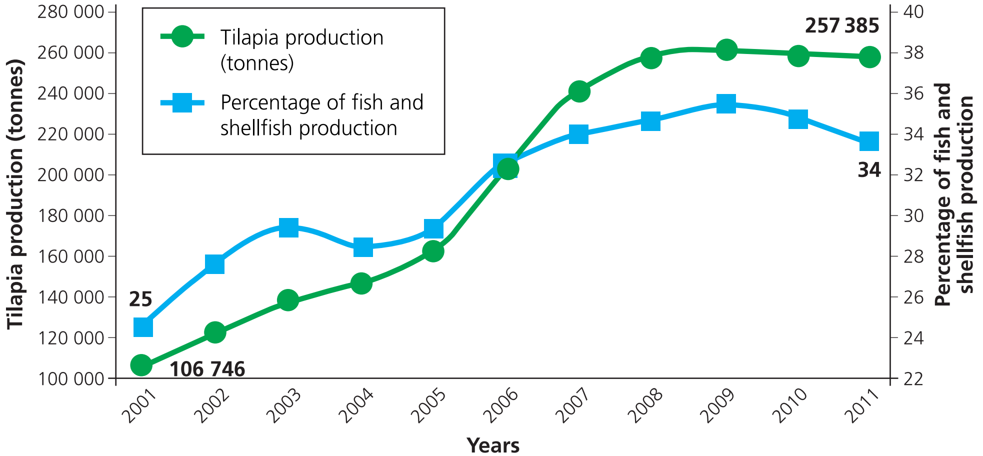
Although China has farmed Mozambique tilapia (*O. mossambicus*) since 1950 in traditional integrated production systems with carps, this species was not in high demand owing to its relatively high cost and poor growth rate. However, the open-door policy, sharply rising living standards of the 1980s and a switch to farming Nile tilapia provided the impetus for a dramatic increase in production, especially in the provinces of Guangdong and Hainan, which accounted for about 66 percent of Chinese tilapia production in 2010 (Liu *et al*., 2013). Although polyculture is still a common practice among small-scale farmers (typically 2–4 ha) with limited capital investment, tilapia farming has evolved to take advantage of increasing demand and better prices. Typically, tilapia was used as a minor component in polyculture with carps, yielding about 2 500 kg/ha tilapia, but this changed as many farmers reversed culture practice to make tilapia the major stocked fish, with yields of 7–8 tonnes/ha using in-pond aerators and pelleted feeds. This shift also created new opportunities within the production value chain for dedicated broodstock and fingerling and yearling (overwintered) seed production farms. Good prices and demand also spurred a shift from traditional polyculture to monoculture, on-growing fingerling and yearling tilapias using multiple cropping systems. Larger commercial farms (typically, 20–30 ha), with substantial local investment, local government support and attracted inward investment, began to farm tilapia intensively in the 1990s using larger, deeper ponds, aerators, automated feeders and extruded pellets, with yields of up to 15 tonnes/ha (Liu *et al.*, 2013). Culture practices were further influenced by the availability of warm spring water and heated water from power stations, allowing tilapia to be farmed intensively in the colder northern provinces such as Beijing.

Tilapia did not feature in statistics for the Philippine until the 1990s, as its production from freshwater and brackishwater ponds, cages and pens increased in significance. The contribution of tilapia to total fish and shellfish production from these production systems almost doubled over the decade, increasing from 25 percent (107 000 tonnes) in 2001 to 34 percent (257 000 tonnes) in 2011 (Figure 6). The main change in tilapia farming practices in the Philippines was characterized by a shift in choice of the tilapia species farmed in the 1970s from *O. mossambicus* to *O. niloticus*. Irrespective of species farmed, the typical market size of tilapias is much smaller, at 200–250 g, compared with other regional countries such as China. From the late 1980s, increased production of Nile tilapia in the Philippines was further aided by the use of hormonally manipulated tilapias and genetically improved strains (e.g. GIFT). By this millennium, more than half of the farmers were using genetically enhanced stock. Tilapia culture using recent innovations and saline-acclimated Nile tilapia has also gained from the idle and underutilized brackishwater shrimp (and milkfish) ponds this millennium arising from disease outbreaks. Taking advantage of niche market opportunities for organic produce also further changed culture practices with the use of all-natural inputs in each phase of the operation. The eutrophic inland water bodies such as Laguna Lake made possible the use of pens and cages for tilapia culture using minimal inputs for fingerling and on-growing production. The increasing switch to higher stocking densities in cages (up to tenfold) and the use of commercial feed in the last decade has increased unit production 5–6-fold over semi-intensive culture (Romana-Eguia, Laron and Catacutan, 2013). Finally, the demand for tilapia in the export market has attracted some Philippine farmers to engage in the production of export-size tilapia. The method used normally requires stocking and feeding advanced tilapia fingerlings of 50 g (compared with the normal 10–20 g size) with complete commercial diets until the fish reach 750–800 g.

Overall, production has increased, spurred by formulated diets and larger fingerlings of improved stock; however, growth has not been linear, probably being affected by natural-resource limitations. In this millennium tilapia production increased linearly to about 2007 but has since plateaued. The greatest increase in tilapia production originated from freshwater ponds, followed by freshwater cages up to 2007 (Figure 7). Production from brackishwater and marine areas has been limited, but any further increase in tilapia production may be expected from these environments.

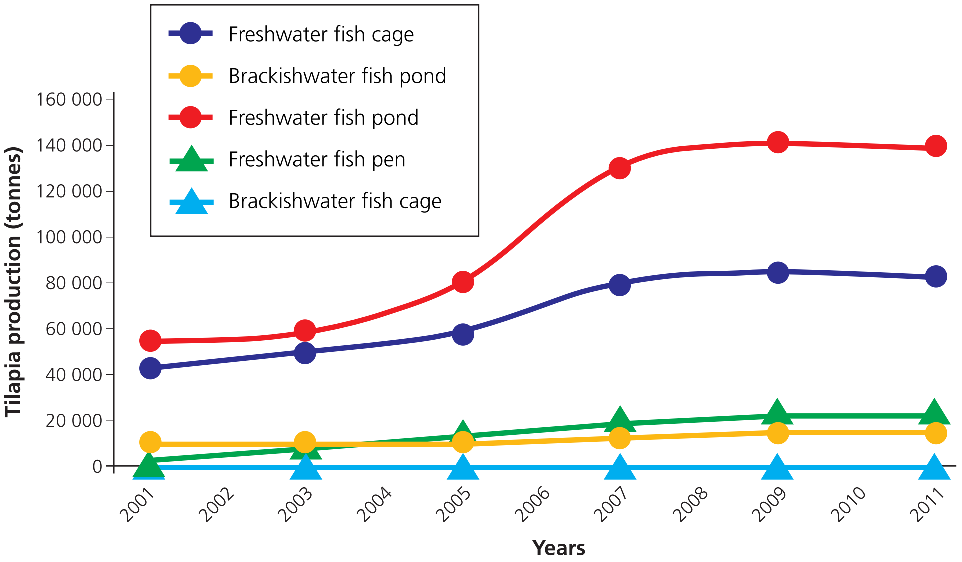
FIGURE 6

Changes in contribution of Nile tilapia to total fish and shell fish production in the Philippines



Source: Adapted from www.bfar.da.gov.ph/

FIGURE 7
Changes in contribution of Nile tilapia production from freshwater and brackishwater ponds, cages and pens in the Philippines



Source: Adapted from www.bfar.da.gov.ph/

As in the Philippines, tilapia farming in Thailand began in the late 1950s and since then, its culture has gradually moved from extensive to semi–intensive pond culture. Although a large majority of farmers still farm semi-intensively in ponds, there was a trend towards intensive farming in cages in rivers; but owing to pollution risks, some farmers, recognizing the benefits of cage culture, switched to siting cages in large ponds. Opportunities for intensification of tilapia production were made possible by feed companies that entered into contract farming, providing feed with a buy-back scheme in the late 1990s. The provision of feed by feed companies on a credit scheme made possible the sole use of commercial feed using larger fingerlings (30–50 g) to achieve two crops of fish per year with yields of 50 kg/m^3 crop of fish averaging 900–1 000 g (Bhujel, 2013).

Tilapia culture practices in Africa are also undergoing changes to meet the challenges of increasing demand. With tilapia prices rising, there is greater investment is countries such as Egypt and Ghana.

In contrast to Asia, Egypt traditionally utilizes brackishwater ponds to farm tilapia in polyculture with carps and mullets. Since the late 1990s, however, the value of tilapia has increased, and this system has been gradually replaced with semi-intensive monoculture of tilapia stocked at 12 000–40 000 fish/ha in earthen brackishwater ponds. With the advent of all-male Nile tilapia fingerlings, more than 75 percent of farmers switched over to mono-sex farming of tilapias. By 2008, more than 80 percent of tilapia were produced in semi-intensive systems (El-Sayed, 2013). By 1999, the number of fish farms utilizing intensive pond culture techniques had increased to 68, covering a total area of 1 088 ha. This created a new and growing demand for large tilapia fingerlings (especially monosex tilapia) and pelleted feed (both extruded and expanded). In less than six years, the number of fish hatcheries increased from 28 freshwater fish hatcheries to more than 350 hatcheries in 2009 (FAO, 2003–2013).

The use of ground water in the desert for integrated tilapia culture is a new feature of Egyptian aquaculture this millennium. Desert land owners rear fish in the tanks used as water reservoirs for irrigation. With continued government technical support, farmers have brought integrated fish farming into their agribusinesses, producing more than

1 000 tonnes of tilapia. With government support, this trend is expected increase to several hundred of such farms within five years. Good economic returns have also resulted in Egyptian farmers progressing to intensive tilapia farming in ponds and cages. Under intensive conditions, ponds are aerated with air compressors or paddles, stocked at 50 000–100 000 fish/ha and commercial feeds applied. The fish reach 200–250 g in 7–9 months, with a total yield of 12–25 tonnes/ha.

The use of cages of varying sizes (30–600 m^3) in rivers, especially in the northernmost branches of the Nile Delta, has also gained momentum in the last decade. While in 1993, only 355 cages were in operation, there are more than 4 500 cages in use. Annual production from cages increased 49 percent per year, rising from 12 900 tonnes in 1999 to reach 69 108 tonnes in 2008. In recent years, some farmers in Egypt have invested in intensive culture of tilapia in concrete tanks under greenhouses (Figure 8), especially in arid and semi-arid areas where freshwater or brackishwater is limited. Most tilapia farmers raise all-male Nile tilapia in aerated tanks stocked at 25–100 fish/m^3 fed on commercial floating pellets for 6–9 months with yields of 10–30 kg/m^3 of 200–400 g/fish.

FIGURE 8
Tank culture of Nile tilapia in Kafr El-Shaikh, Egypt

COURTESY OF FAO/A.-F.M. EL-SAYED.

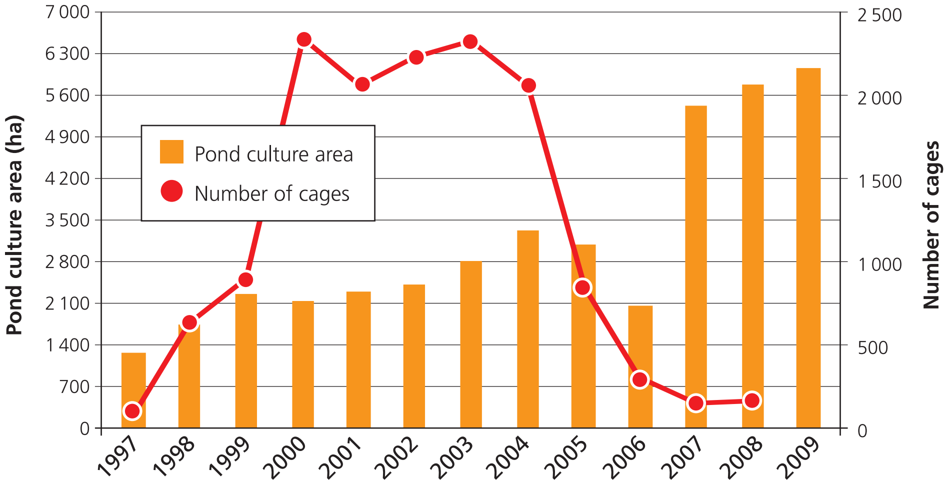
Ghana has typically farmed tilapia extensively in household ponds since the 1950s and to some extent under semi-intensive conditions using supplementary feeds. With market prices exceeding US$3/kg, farmers in Ghana targeted the intensification of tilapia culture, with the first cage farm being established in the late 1990s and the second in 2005 on Lake Volta. Locally made cages are stocked in a two-stage system, initially with fish weighing 5–8 g at 100 000 fry/cage. When they reach 40–50 g (2 months), they are transferred to other cages at half the stocking density and reared to a selling size of 250 g (2–3 months). Since 2005, cage-culture technologies have been developed for smallholder farmers. Typically, these cages (50 m^3) are stocked with 3 000–9 000 fingerlings of 10–30 g and fed on pelleted diets for 5–7 months.

2.2.3 Striped catfish (*Pangasianodon hypophthalmus*)

Viet Nam is the epicentre of Asian and global catfish culture, the practice of which was transformed in 2000 with the all-year-round availability of seed and a shift in cultured species and production system. Two species have dominated catfish culture in Viet Nam since the 1960s, “basa” (*Pangasius bocourti*) reared in cages and pens, and striped catfish or “tra” (*Pangasianodon hypophthalmus*) reared in ponds using traditional farming methods. Beginning in the mid-1990s, however, cage and pen culture practices declined, and then collapsed after 2004 (Figure 9), primarily owing to the cost of cages, poor growth performance, and increasing mortalities and disease outbreaks compared with pond culture (Nguyen *et al.*, 2004; Nguyen and Dang, 2009). The culture of striped catfish in small farms (<5 ha) using small (0.4 ha), deep (3.5–4.5 m) ponds predominated (Phan *et al.*, 2009), the total area of which had increased to 5 800 ha by 2008 (Figure 9). Since 2000, the farming practice has been characterized by a switch from farm-made pellets to complete commercial extruded diets (Nguyen and Dang, 2009).

FIGURE 9

Changes in production systems used for farming striped catfish in Viet Nam



Source: Nguyen (2013).

2.2.4 Giant river prawns (*Macrobrachium rosenbergii*)

In the last three decades, the farming of giant river prawns (*Macrobrachium rosenbergii)* has attracted considerable attention because of export potential. About 14 percent of the global production originates from Bangladesh. In this country, farming giant river prawns is a widespread small-scale activity where farmers integrate rice culture with rearing mainly wild-caught prawn postlarvae (PL) in small (0.2 ha) paddy fields. Inputs are limited and feeding is often characterized by the capacity of resource-poor farmers to procure feeds (mainly snail meat), with prawn yields of 350 kg/ha. In the 1990s, however, the high international prices and availability of hatchery-reared PL encouraged many small to medium-sized farmers to change their culture practice to focus only on farming in larger ponds (0.2–0.4 ha) using supplementary feeds, with yields of about 500 kg/ha. Rice fields were converted by raising the water dykes or bunds to deepen ponds and installing a deep channel to hold water during the dry season, a practice known as *gher* farming. The high returns have also attracted investment, and larger semi-intensive farms have been established since the mid-1990s using industrial feeds, with yields of 700 kg/ha. In all farming systems, mortalities were high and in the last few years farmers have introduced a nursery phase in ponds whereby PL are reared in hapas for 4–6 weeks before being introduced into ponds.

2.2.5 Black tiger shrimp (*Penaeus monodon*)

Asia is the most important shrimp-producing region of the world in terms of farmed black tiger shrimp output, with Viet Nam (43 percent), Indonesia (16 percent), India (12 percent), China (7 percent), Bangladesh and the Philippines (6 percent each) sharing most of the global production (Table 2).

The great bulk (90 percent) of shrimp farming in India is based on the extensive farming system. In recent years and particularly since the 1990s, there has been a trend towards increased intensification. Extensive and modified extensive farms are shifting towards semi-intensive farming of shrimps. For better management, pond units are much smaller (0.1–1.0 ha) but deeper (1.5–2.0 m). Stocking density ranges from 100 000 to 200 000 PL/ha per crop, with crop yields of 3–5 tonnes/ha using complete artificial feeds, increased aeration and intensive monitoring.

2.2.6 *Whiteleg shrimp (Litopenaeus vannamei)*

Following the downturn in black tiger shrimp production in the late 1990s owing to disease outbreaks, whiteleg shrimp offered an acceptable substitute, and by 2010 it was the dominant shrimp species, with a global production of 2.7 million tonnes. Although farmed illegally in Viet Nam since 2000, the Government of Viet Nam allowed the culture of whiteleg shrimp in the Mekong Delta in 2006. Hence whiteleg shrimp culture is relatively new in Viet Nam. In the last decade, farms have mainly practised intensive culture using commercial feeds and stocking densities of 100–200 hatchery-reared PL per square metre, but avoiding the use of fertilizers. The majority of farms are less than 1 ha in size, typically, less than 0.3 ha.

3. UTILIZATION OF AQUAFEEDS

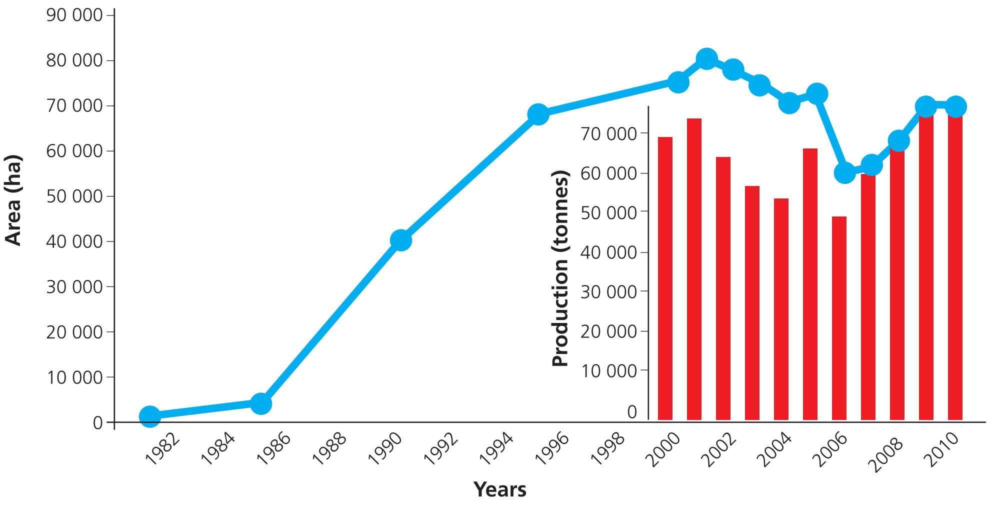
3.1 Implications of diminishing resources for aquafeeds and feed management

Feedback from farmers in all case studies considered in this synthesis points to a varying degree of intensification to increase production volume and efficiency, this increase being principally achieved through using larger fingerlings, deeper ponds and varying levels and quality of supplementary or complete feeds. At a national level, however, improved production efficiencies and increased production are fast becoming a necessity to ensure national food security. In an environment of diminishing natural resources and rising costs, governments will have to develop policies specifically focusing on sustainable productivity, as countries already show resource-limited production.

Expansion of aquaculture in India, especially in key states such as Andhra Pradesh, may be limited by natural resources. The production of major carps in Andhra Pradesh follows and is capped by the area of ponds under cultivation (Figure 10). Under such conditions increases in production can only be achieved through improved productivity.

FIGURE 10

Estimated changes in area used to culture Indian major carps in Andhra Pradesh from 1981–2010 in relation to production

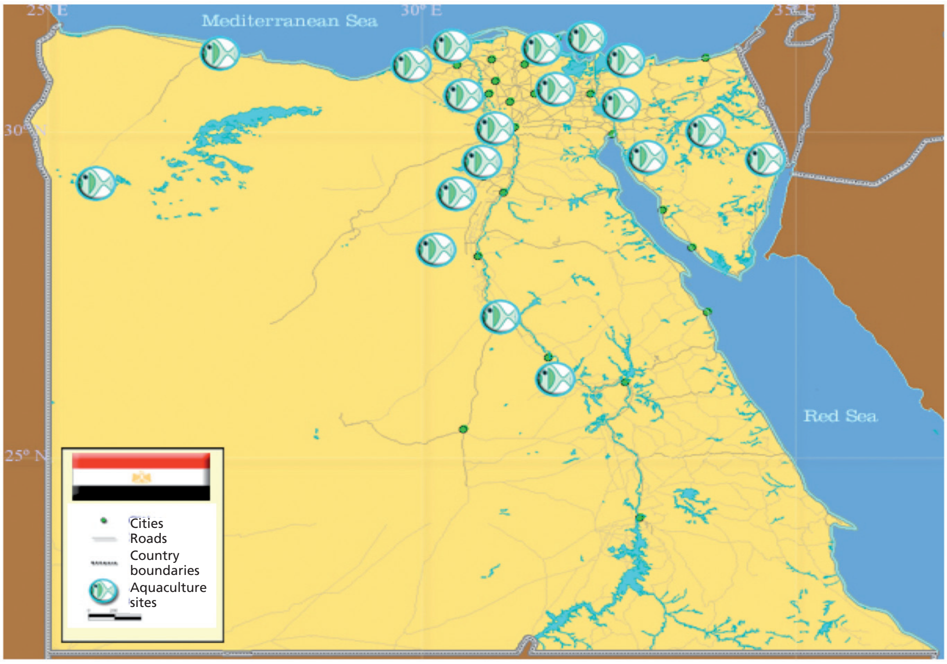


Source: Adapted from Ramakrishna, Shipton and Hasan (2013).

The area dedicated to the culture of Indian major carps plateaued at 80 000 ha in 2000 (Figure 10). Opportunities for expansion into new species, however, were confined to this area. During the expansion of catfish culture, 10 000 ha of ponds originally used for Indian major carps were converted for mono or mixed culture of striped catfish, which were introduced to Andhra Pradesh in the mid-1990s from Bangladesh *via* West Bengal State, India. Thus the culture area for Indian major carps was reduced to an estimated 70 000 ha. Currently, the total area in the state devoted to striped catfish is estimated to be 20 000 ha and is increasing at the expense of Indian major carps (Ramakrishna, Shipton and Hasan, 2013). In such circumstances, if additional land is not made available, farmers are likely to make an economic decision on the species to be farmed based on returns; traditional species are likely to be compromised or have their production intensified to secure greater returns. Such an approach will also require financial incentives from government. To meet this challenge, the Indian National Fisheries Development Board (NFDB) was established in 2006 under the administrative control of the Department of Animal Husbandry to empower all Indian states and union territories to promote aquaculture and provide financial support, mainly through subsidies for other feed inputs and on-farm feed production.

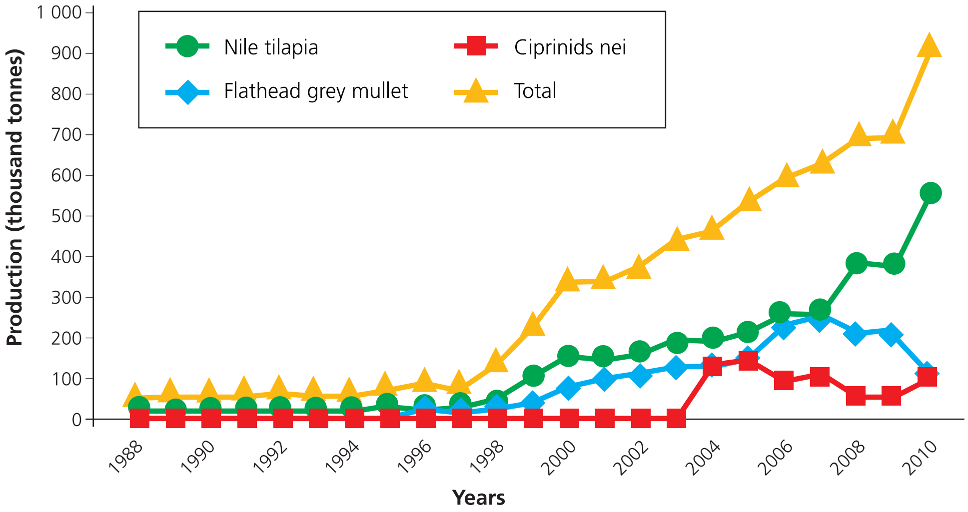
The availability of land and water is also a significant challenge in Egyptian aquaculture, with available areas showing saturation. Most aquaculture activities are located in the northern Nile Delta region, with fish farms clustered in the areas surrounding the four delta lakes (Maruit, Edko, Boruls and Manzala) and along the Nile River (Figure 11). Expansion in most of these areas is constrained by the lack of sites for land-based aquaculture and conflicts over water use. Despite water limitations and most of the land suitable for pond aquaculture being already in use, the target of the government to produce 1.5 million tonnes/year by 2017 is expected to be reached by converting traditional farms to intensive pond-culture systems. Within this paradigm, the competition for space and resources may also be reflected in the choice of species cultured. In recent years, there has been a shift from cyprinids to tilapias, as farm practices switch from polyculture to monoculture. In the last reporting year, this trend was also seen for mullets. In the last ten years tilapia production increased dramatically from 157 000 to 557 000 tonnes (Figure 12). In addition to natural resource constraints, these shifts in culture practices are also influenced by rising feed prices and lower market fish prices (Rana, Siriwardena and Hasan, 2009).

FIGURE 11
Geographic distribution of aquaculture production sites in Egypt



Source: Adapted from FAO (2003–2013).

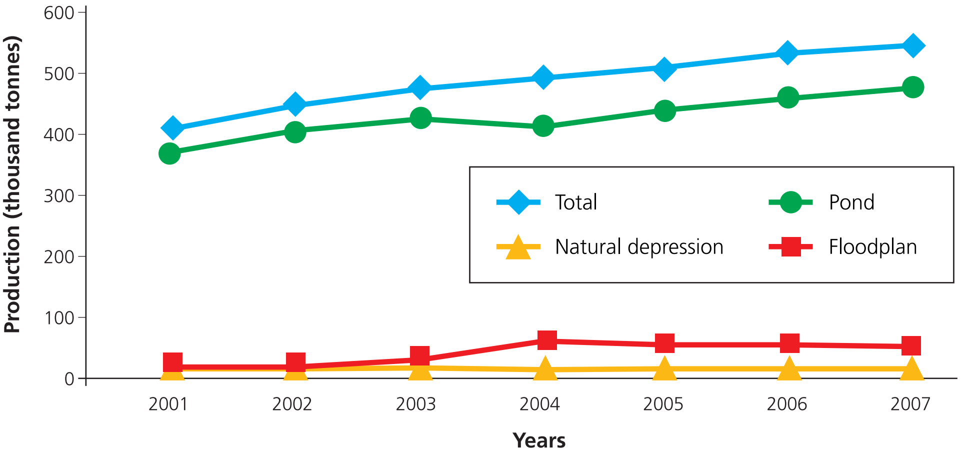
FIGURE 12
Changes in species cultured as sites in Egypt became limiting (1988–2010)



Source: Adapted from FAO (2012b).

Notable strains on farming systems and land resources are also evident in Bangladesh. Ponds are the predominant method of production, followed by floodplains and natural depressions (Figure 13). However, production from ponds has only increased by 5 percent annually in this millennium, and it actually decreased by 1–4 percent per year between 2004 and 2008 for production from floodplains and natural depressions (Figure 13). Fragmentation of landholdings for cultural reasons has significantly increased the number of small farms. Prawn farms average 0.31 ha compared with 0.60 ha for rice-only farms. With the increase in population, the average size of rice farms declined from 1.43 ha in 1961 to 0.87 ha in 1994, and is now just 0.60 ha (Rahman and Parkinson, 2007). Prawn farms were also larger more than a decade ago, averaging 0.35 ha. The reduction in pond size will inevitably result in a lower pro-rata net income for resource-poor farmers, and this calls into question the sustainability of such activities. Increased productivity through better feeds and feed and pond management practices is therefore imperative.

FIGURE 13
Temporal changes in production from different resource types used for aquaculture in Bangladesh



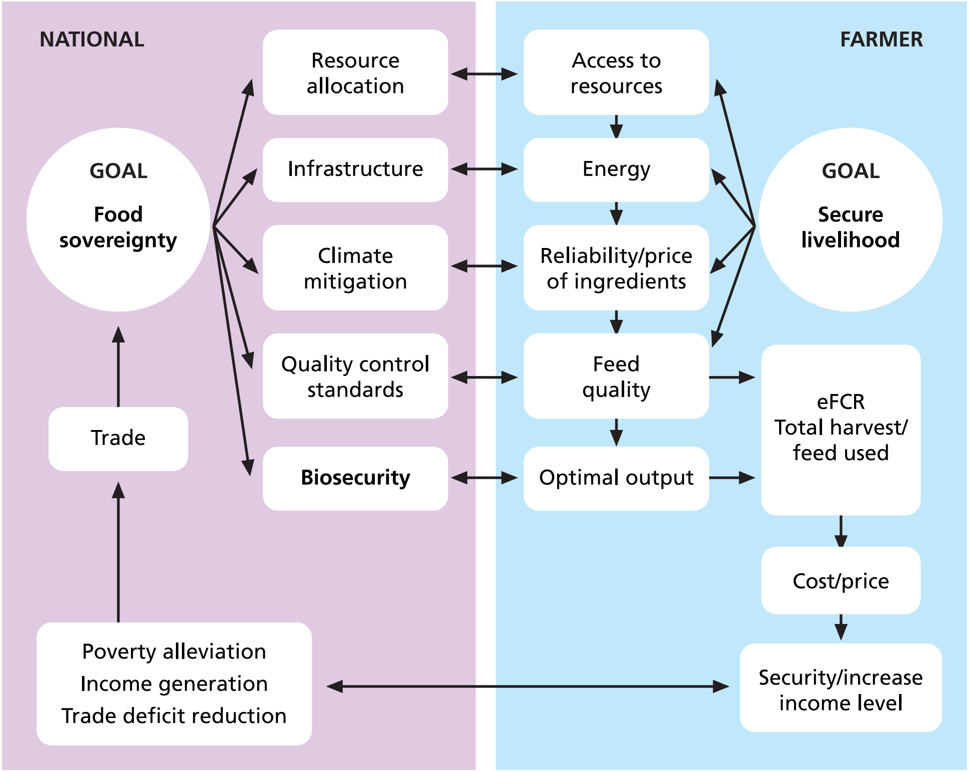
Source: Adapted from Sarder (2013).

3.2 Improving production volumes and efficiencies

3.2.1 Relationships between national and farmer aspirations

Government and individual farmers will have synergetic roles in contributing to increased aquaculture output, with government taking the lead role to address capacity and constraints to improve efficiency through prioritized research and development with measurable impacts. The key issues and roles of government that will affect farmers, especially as they relate to feed inputs, are highlighted in Figure 14. In order to address the national goal of food security, governments will have to put in place measures to secure and increase natural resources, improve farmer access for aquaculture and improve infrastructure to minimize the transaction costs of farmers while ensuring fair prices for energy that will be increasingly required to raise productivity. Securing aquafeed ingredients, either through increases in domestic production or by increased imports, will be key to future development of aquaculture, while quality control of manufactured feeds will be crucial to ensuring optimal use of feed ingredients. To maximize outputs, governments and farmers alike will have to put in place improved pragmatic management practices to reduce mortality.

FIGURE 14
Interrelationships between national roles and farmer aspirations to address aquaculture production constraints



Source: Compiled by authors.

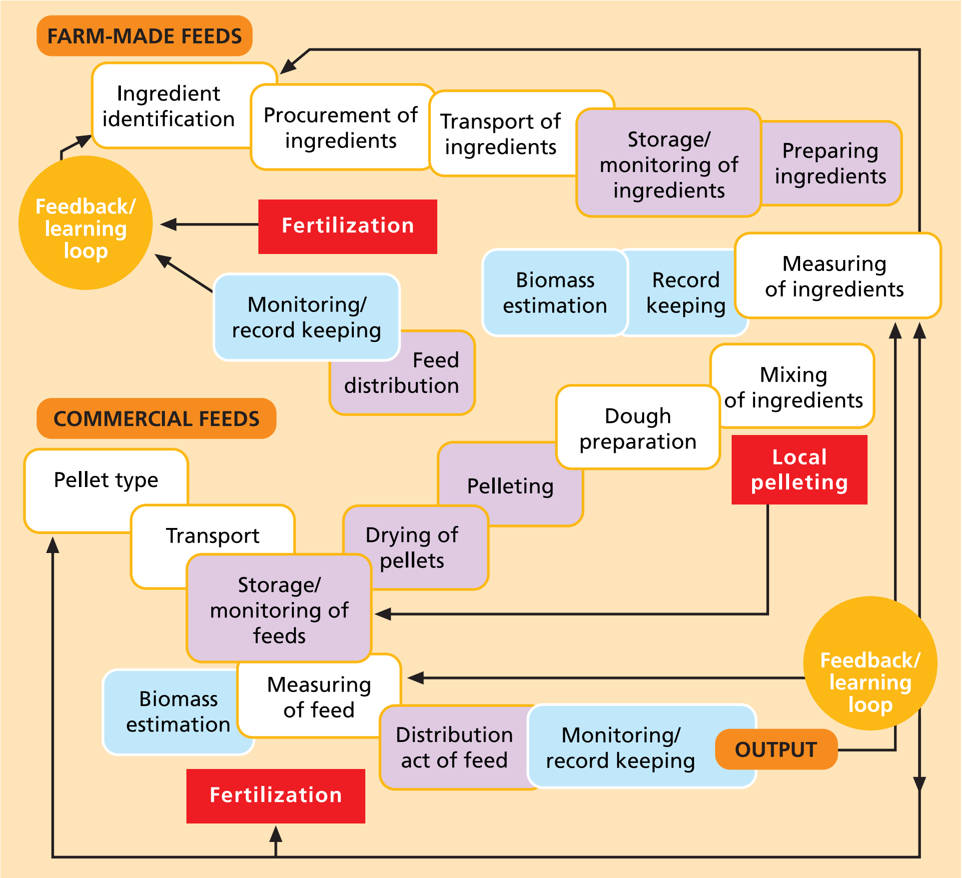
3.2.2 Use and management of on-farm feeds in selected countries

Farmers in the survey countries (Bangladesh, China, Egypt, Ghana, India, the Philippines, Thailand and Viet Nam) deploy a spectrum of practices for securing aquafeeds. Aquafeeds may be prepared with procured or home-grown ingredients on the farm or bought as complete manufactured feeds. Farmers deploy a range of options to secure aquafeeds. Farmers that make their own farm-made feeds often buy ingredients from local suppliers. These ingredients are transported to the farm site where they are milled, if required, or taken to local millers who prepare the ingredients for inclusion in diets. Depending on resources, farmers may distribute these ingredients as a powdered diet, but this practice is fast dwindling as farmers mix ingredients with water to produce dough balls; these are fed directly to fish either on trays or dispersed over ponds (e.g. major carps in Bangladesh) or pelleted in a simple pelletizer, the pellets then being air dried, stored and fed as required (Figure 15).

Where resources or credit facilities are available, farmers prefer to use commercially manufactured sinking or floating pelleted aquafeeds. In countries such as Egypt, 40 percent of the farmers surveyed used extruded feeds, often using demand feed dispensers.

FIGURE 15

Composite of specific components of on-farm feed production and management chain



Source: Compiled by authors.

3.2.3 *Significance of feed cost*

The use of concentrated feed in the form of floating or sinking pellets has been the key contributory factor to increased production, together with aeration and improved water management. In the last two decades, however, the price of ingredients has multiplied and significantly affected aquafeed prices. These impacts and consequent challenges for the sustainability of aquaculture have recently been reviewed by Rana, Siriwardena and Hasan (2009).

In a context of increasing feed and production costs, feed utilization efficiency is of paramount importance. The contribution of feed as a proportion of production cost is typically greater than 50 percent, irrespective of scale or intensity of production (Table 6). In China, where tilapias are cultured as the major crop in polyculture or intensive monoculture, feed accounts for 70–80 percent of production costs. Similarly, in Viet Nam feed contributes more than 80 percent of production costs for striped catfish production. Overall, the proportional cost of feed was lower when farm-made feeds (FMFs) were used. In India, where FMFs were used for Indian major carps, feed costs were below 60 percent. Similarly, for giant river prawns in Bangladesh, the use of on-farm feeds maintained feed costs below 35 percent. Irrespective of intensity of stocking or species, the use of commercial feed increases feed contribution to production costs. Although black tiger shrimp were farmed extensively in India, the use of commercial feeds increased feed costs to about ~60 percent of production costs (Table 6). In all scenarios, feed is the single most important production cost item; therefore, any management interventions to reduce feed input costs will have a significant bearing on the sustainability of aquaculture operations.

TABLE 6

Cost of feed as percentage of production cost for selected countries and pond-cultured species

Country	Species mix	Production system	Feed as % of production cost	Yield (tonnes/ha)	Source
Finfish					
China	Tilapia	Ponds – tilapia main crop polyculture + commercial feeds	68–84	7–9	Liu *et al.* (2013)
		Ponds – monoculture + commercial feed		8–12	
Philippines	Tilapia	Ponds – monoculture + commercial feed	50–60	7–15	Romana-Eguia, Laron and Catacutan (2013)
		Ponds – monoculture Farm-made +commercial feed		1–3	
Viet Nam	Striped catfish	Monoculture + commercial feed	83	325	Nguyen (2013)
		Monoculture + farm-made feed	77	398	
India	Indian major carps	Typical Indian major carps- mash	54	7	Ramakrishna, Shipton and Hasan (2013)
		Zero point culture – Indian major carps	48	5–6	
		Zero point culture – Indian major carps-mash-pellet	49	–	
		Zero point culture –Indian major carps-mash	41	–	
Shrimps and prawns					
Viet Nam	Whiteleg shrimp	Monoculture + commercial feed	66–69	9–15	Hung and Quy (2013)
Bangladesh	Giant river prawns	Extensive + snail meat	15	0.35	Ahmed (2013)
		Improved extensive + farm-made aquafeed	25	0.48	
		Semi-intensive + commercial feed	33	0.72	
India	Black tiger shrimp	Extensive + farm-made feed	52	0.38	Ramaswamy, Mohan and Metian (2013)
		Modified extensive Commercial feed + farm-made feed	59	1.3	
		Semi-intensive Commercial feed	62	2.8	

3.2.4 Risk options for farmers

Nations will have to prioritize how their resources are used. In the case of aquaculture, governments have two options to increase output: increase land and water area under cultivation; and/or increase unit productivity. An evaluation of the case studies suggests that farmers are faced with increasing uncertainty of feed price rises and limiting natural resources; consequently, farmers are intensifying production as one means of mitigation. However, the benefit-cost ratio (BCR) of aquaculture operations can be similar irrespective of feeding regime (Table 7) or intensification (Table 8). In India, the BCR ranged from 1.2 to 1.3 despite the use of improved feeds. In the case of Bangladesh, this ratio was greater, at 1.7–1.8, due to the higher price of prawns irrespective of intensification. Similarly, for semi-intensive culture of whiteleg shrimp in Viet Nam, the BCR was 1.6–1.7 (Hung and Quy, 2013). These data suggest that neither intensification, feed quality nor feed management by themselves necessarily increase returns on investment, yet where possible, farmers have intensified. The principal likely driver therefore for the increase in absolute net income is increase in farm size. For example, in Bangladesh, although the BCR was similar for extensive and semi-intensive culture, increasing farm size with intensification from 0.2 to 0.5 ha more than doubled annual net income from US$1 000/ha to US$2 100/ha (Ahmed, 2013). Data also suggest that increasing farm size and feed input may not necessarily result in increased unit returns.

TABLE 7

Benefit-cost ratio for culture of Indian major carps in India under various feed management conditions

Parameters	Zero point Indian major carp culture			
	Typical mash	Mash	Mash + pellet	Pankaj – mash
Annual net income (US$)	1 129	495	2 020	3 061
Annual net income (US$/ha)	1 505	914	3 730	5 247
Benefit-cost ratio	1.2	1.1	1.3	1.3

Source: Adapted from Ramakrishna, Shipton and Hasan (2013).

TABLE 8

Benefit-cost ratio for giant river prawn culture in Bangladesh under varying intensification conditions

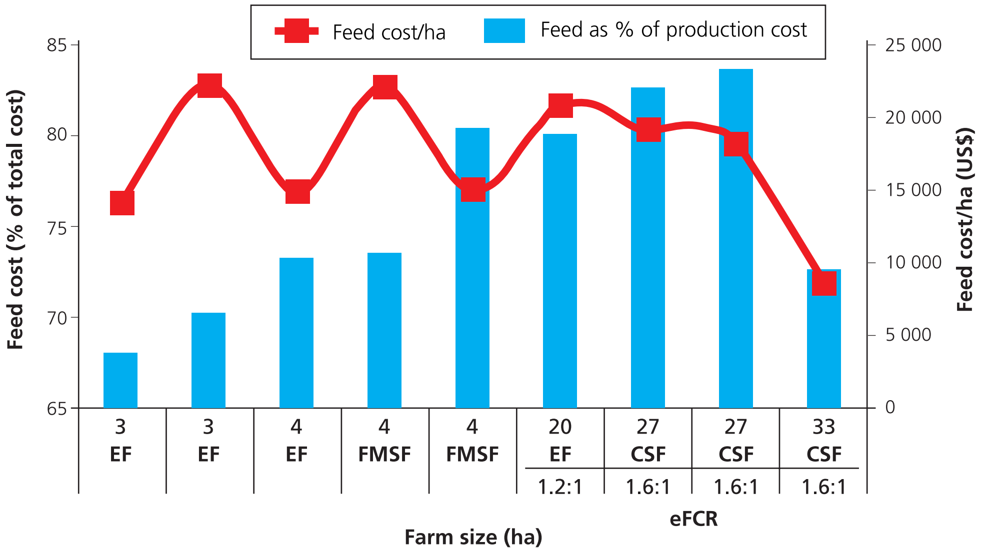
Parameters	Extensive	Improved-extensive	Semi-intensive
Annual income (US$/ha)	1 092	1 445	2 162
Benefit-cost ratio	1.7	1.7	1.8

Source: Adapted from Ahmed (2013).

In China, economic data suggest that larger intensive monoculture farms may not necessarily be as efficient as smaller polyculture units, and that larger farms could comprise feed management by virtue of their size (Figure 16). As farm size increased from 3 to 33 ha, the proportion of feed to total production cost increased, with one exception (33.3 ha), from 68 to 84 percent, showing no meaningful economies of scale. The per-hectare feed costs were similar, ranging from US$14 000 to 22 000/ha, with one exception. Increasing farm size was also not translated into improved feed conversion efficiencies of 1.6:1 (Figure 16).

FIGURE 16

Relationship between farm size, feed cost and feed utilization in China



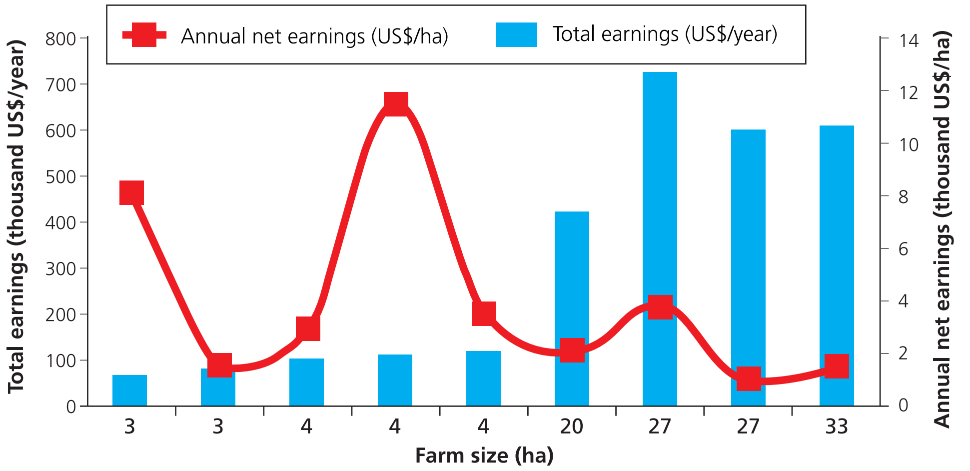
Source: Adapted from Liu *et al*. (2013).

Notes: EF = extruded feed; FMSF = farm-made sinking feed; CSF = commercially pelleted sinking feed; eFCR = economic feed conversion ratio. The feed conversion ratio is the ratio between the dry weight of feed fed and the weight of yield gain. It is a measure of the efficiency of conversion of feed to fish (e.g. FCR = 2.8:1 means that 2.8 kg of feed is needed to produce 1 kg of fish live weight). Two additional terms are used by the farmer, the biological FCR (bFCR) and the economic FCR (eFCR). The bFCR is the net amount of feed used to produce 1 kg of fish, while the eFCR takes into account all the feed used, meaning that the effects of feed losses and mortalities, for example, are included (adapted from FAO, 2010).

The larger, more intensive farms in China also did not necessarily translate into increased unit income (Figure 17). Although farms smaller than 4 ha showed a large range, their annual average earnings were US$8 400/ha compared with only US$2 000/ha for farm sizes between 20 and 33 ha, and larger farms showed no benefits, instead spending 2–4 percent of production costs on drugs and feed additives. Overall, the data suggest that increased income was attained by having a larger number of ponds and farm size rather than through improved production efficiencies.

FIGURE 17

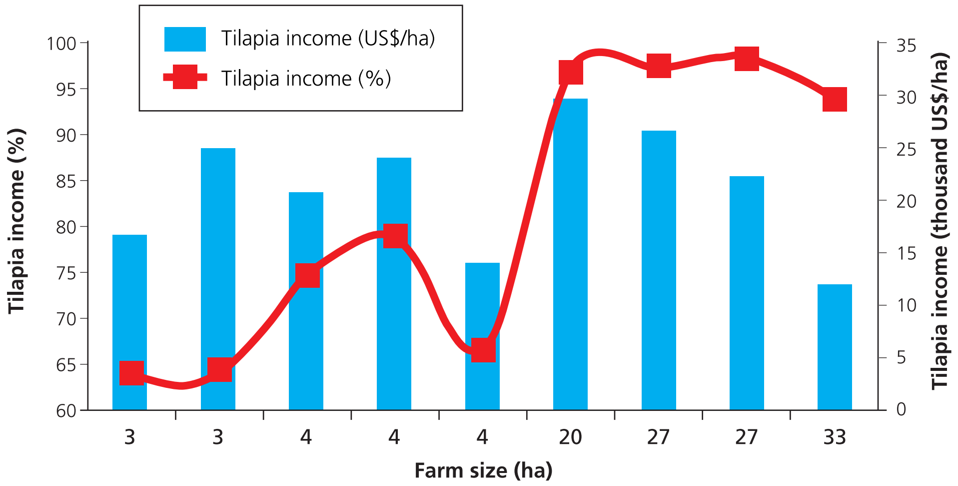
Relationship between Chinese farm size and total and unit area income



Source: Adapted from Liu *et al*. (2013).

The proportion of income from tilapia by farms of varying size is given in Figure 18. The contribution of tilapia income to farm income varied with type of production system and farm size. Farms of 4 ha and smaller adopted polyculture, a method in which tilapia was the main species, contributing 63–68 percent of total income. In the larger monoculture tilapia farms (> 20 ha), tilapia accounted for 94–97 percent of farm income. When the total farm revenue is considered, however, unit income decreased as farm size increased, while in smaller farms revenue from tilapia was similar (Figure 18). Overall, the Chinese experience points to larger monoculture farms being more inefficient, and increase in income is achieved by increasing farm size; this questions the resilience of the farming systems as currently managed.

FIGURE 18
Effect of increasing farm size on income from Nile tilapia in China



Source: Adapted from Liu *et al.* (2013).

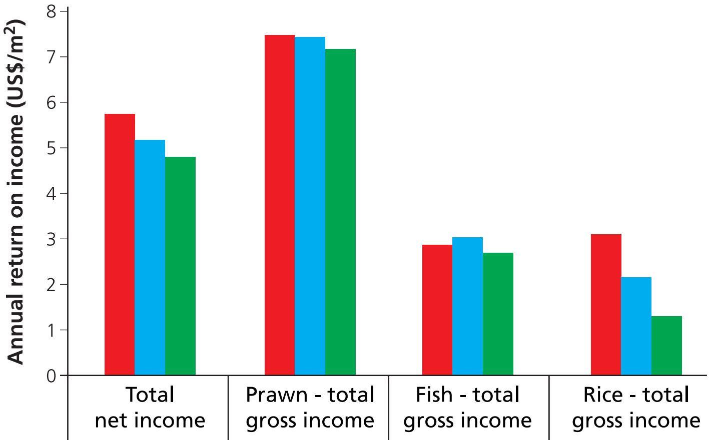
3.2.5 Resilience of farming system to uncertainty of natural resources and feeds

Resource-poor farmers have limited capacity and resources to procure commercial feeds or to buffer themselves against escalating prices. Their ability to increase their net income from their aquaculture operations and to raise productivity is curtailed by virtue of their small farm size and limited capacity to secure finance. In countries such as Bangladesh, farms that are typically less than 0.3 ha are becoming smaller through subdivision when the land is transferred from parents to their children. Under these conditions, diversifying food production is a necessary livelihood strategy for sustained income. In this scenario, farmers have adapted, using local resourcefulness and knowledge, to stabilize and secure production (e.g. use of snail meat in Bangladesh). In addition, to increase net income from their small operations, farmers have switched to higher-valued species. In Bangladesh, for example, rice farmers have focused on rearing giant river prawns with fish and rice to successfully raise income and spread risk, the extent of increased production being feed-dependant. Nevertheless, 80 percent of farmers still farm using extensive (50 percent) or improved extensive (30 percent) methods with snail meat and farm-made feeds to earn between US$190/year (US$1 000/ha per year) and US$420/year (US$1 500/ha per year), respectively (Ahmed, 2013). The case study from Bangladesh also suggests that larger, more intensively farmed operations using commercial feeds are at best similar or poorer than extensively farmed operations and that increases in absolute income were achieved simply by virtue of their larger acreage.

In the case of giant river prawns, data suggest that extensive farming systems with fish and rice may be more resilient to external shocks such as feed price hikes, disease outbreaks and increases in fuel costs. The annual unit net income of such farms was on average, US$5.7/m^2, 19 percent higher than the unit income from semi-intensive farms, while that from prawns and fish was similar (Figure 19). The switch by semi-intensive farmers from rice to prawns drastically reduced their income from rice by 58 percent and reduced the overall unit income by about US$1/m^2 (Figure 19).

FIGURE 19

Income of giant river prawn farmers practising varying levels of intensive farming in Bangladesh



	Total net income	Prawn - total gross income	Fish - total gross income	Rice - total gross income
🟥 Extensive (190 m^2)	5.7	7.5	2.9	3.1
🟦 Improved extensive (280 m^2)	5.2	7.4	3.0	2.2
🟩 Semi-intensive (450 m^2)	4.8	7.2	2.7	1.3

Annual return on income (US$/m^2)

Source: Adapted from Ahmed (2013).

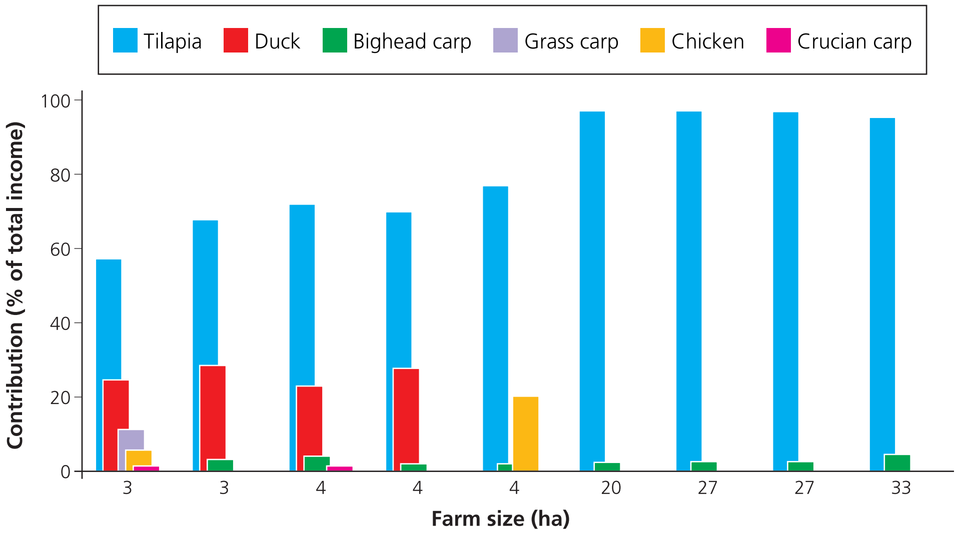
Note: Pond size (in square meters) is given in parentheses.

A similar trend is seen in China. Smaller fish farms diversify their farming activities through horizontal integration with poultry. These practices display a greater resilience compared with monoculture through spreading risk and improving cash flow. About 25–30 percent of income in these farms is derived from either ducks or chickens (Figure 20). Similar to Bangladesh, a few anomalies are seen; the unit return from the larger monoculture farms was similar to or lower than that of small, horizontally integrated farms, with no clear evidence for efficiency gains from scale. However, overall, greater income returns were achieved owing to larger farm size (see Figure 17).

In India, there is also a trend to intensify farming practices to improve the productivity and production of black tiger shrimp (Ramaswamy, Mohan and Metian, 2013). As elsewhere, the merits of such an approach will be determined by the degree of return on investment, in terms of both time and money. Black tiger shrimp farming in India is practised at three levels, with varying degrees of increasing inputs: extensive, improved extensive and semi-intensive (Table 9). Key features of intensification in black tiger shrimp farming in India include increase in stocking density from 4 to 8–20 PL/m^2, use of commercial feeds, water exchange and aeration (Table 9). Although these inputs increased production, the net return from such interventions in semi-intensive shrimp culture resulted in less than half the net unit return compared with improved extensive management.

FIGURE 20

Relationship between farm size and diversification of farming activities in China



Source: Adapted from Liu *et al*. (2013).

TABLE 9

Inputs, yield and returns with intensification of black tiger shrimp farming in India

	Extensive	Improved extensive	Semi-intensive
Pond size (ha)	0.5–2.0	0.5–1.5	0.3–1.0
Water exchange (%/day)	–	0–10	5.0–20.0
Stocking density (PL/m^2)	<4	4–8	8–20
Feed	SF/FMF	SF	MPF
Aeration	none	partial aeration	continuous aeration
eFCR	1.27	1.31	1.38
Annual yield (tonnes/ha)	0.2–0.5	0.8–1.7	1.8–3.3
Net income (INR/kg shrimp)	59 (US$1.3)	50 (US$1.1)	24 (US$0.5)

Notes: SF = supplementary feed; FMF = farm-made feed; MPF = manufactured pelleted feed; eFCR= economic feed conversion ratio; US$1.0 = Indian rupees (INR) 46.4 using 2010 exchange rate.
Source: Adapted from Ramaswamy, Mohan and Metian (2013).

Overall, all these case studies suggest that there appears to be no automatic benefit of scale with regard to productivity, the higher incomes from intensive farms being mainly derived by virtue of their larger farm sizes.

4. OPTIONS TO IMPROVE PRODUCTIVITY

4.1 Approaches for improvements

The main purpose of intensification is to increase production volume and efficiency while reducing costs. Such increases are achieved through a spectrum of physical interventions and feed management strategies. Fish ponds continue to be a choice of production method. This synthesis acknowledges that farm output is the summation of all interrelated interventions but elaborates on the performance of feed and feed management practices as measured by production volumes and efficiencies.

Although the case studies illustrate that higher productivity is not automatically achieved with increasing inputs, various feed and feed management options are proposed in these case studies and these are tabulated in Table 10.

TABLE 10

Focus areas advocated for improving aquafeed performance and feed management and reducing feed costs

Diet performance	Feed management
• Promote nutritionally balanced feeds	• Maintain appropriate timing of feeding
• Reduce fishmeal content	• Alternate higher and lower protein diets
• Increase digestibility	• Use mixed feeding schedules
• Choose appropriate pellet type	• Delay onset of external feeding
	• Optimise feed administration

Progress on diet performance and feed management is discussed in detail in the individual case studies presented on the CD–ROM accompanying this publication (Ahmed, 2013; Awity, 2013; Bhujel, 2013; El-Sayed, 2013; Hung and Quy, 2013; Liu *et al.*, 2013; Nguyen, 2013; Ramaswamy, Mohan and Metian, 2013; Romana-Eguia, Laron and Catacutan, 2013; Sarder, 2013) and in Ramakrishna, Shipton and Hasan (2013). For this synthesis, case study data are evaluated to understand which interventions are increasingly deployed and having an impact on increased farm outputs.

4.2 Interpretation and evaluation of productivity

Given that aquafeeds account for up to 80 percent of production costs, their use, together with other interrelated synergistic farm management practices and interventions, has to translate into increased production while reducing production costs. The principal indicator used in aquaculture to evaluate feed performance is the economic food conversion ratio (eFCR), and this is used here to compare the outcomes of feed and feed management practices in selected countries using varying levels of feed inputs. Indeed, some salmon companies in Scotland, the United Kingdom of Great Britain and Northern Ireland, use eFCR as an incentive indicator for employee bonus (K.J. Rana, personal communication, 2011).

When feed inputs are increased, four key synergistic physical management interventions apparent in the case studies must also be recognized for their role in increasing overall output and extracting the best performance from diets:

- aeration of ponds;
- increased stocking density;
- increased water exchange;
- deeper ponds.

Increased aeration of ponds using an array of aeration types is the most common management intervention. In China, Egypt, India and the Philippines, aerators are used in ponds. However, such an intervention, together with increased stocking density can only be justified if reliable and reasonably priced energy supply and infrastructure can be secured to optimize feed utilization.

Although production from ponds is often cited as weight per unit area (usually hectares), this assumes that ponds are about the same depth, typically between 0.8–1.0 m. In recent years, farmers in, for example, China and notably in Viet Nam, have increased their tilapia and catfish pond depths to 1.5–2 m and 4–6 m, respectively, as a means of increasing output (Liu *et al.*, 2013; Nguyen, 2013). Accordingly, production from these ponds is typically 8–12 tonnes/ha and 360 tonnes/ha, respectively. Using the averages and adjusting production to a typical pond depth (1 m), such production for tilapia (Liu *et al.*, 2013) and carps

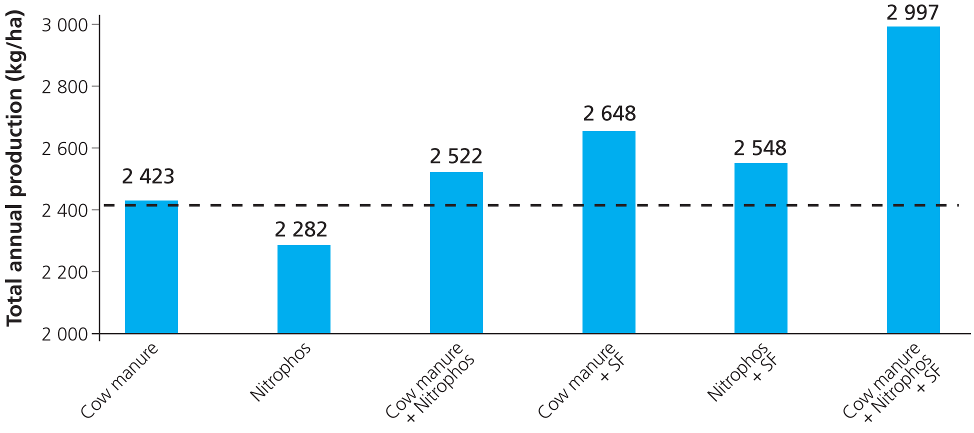
(Ramakrishna, Shipton and Hasan, 2013) is only 4–6 tonnes/ha, which can be easily attained from well-managed fertilized ponds. Careful evaluation of striped catfish farming in Viet Nam also suggests that productivity may not be as high as first envisaged, given the farming practice. Striped catfish ponds in Viet Nam are on average 4.4 m deep and 0.32 ha in size. Given this depth, the very high daily water exchange, typically 30–100 percent/day, and that water volumes in these ponds are typically 4–5 times that of standard ponds, it may be more prudent to interpret production in cubic metres rather than in two dimensions (square metres). For the average striped catfish pond farm yielding 360 tonnes/ha, this translates to only about 8 kg/m^3. This is significantly lower than 100–150 kg/m^3 for the African catfish reared in simple concrete tanks in Nigeria (K.J. Rana, personal communication, 2011) and for cage-farmed tilapia in Egypt (25–30 kg/m^3; El-Sayed, 2013) and the Philippines (4–40 kg/m^3, Romana-Eguia, Laron and Catacutan, 2013).

4.3 Performance of feeds used in aquaculture

This discussion focuses on the eFCR as a measure of feed performance in the selected case studies with reference to international benchmarks and later to the scope for improvement. An evaluation of diet performance based on eFCR as reflected by growth and production in these systems, however, is difficult owing to the confounding effect of unpredictable levels of natural feed in these rearing systems, which can make a significant contribution to overall production (Figure 21). Under comparable polyculture, natural food derived from organic and inorganic fertilizers alone resulted in annual carp production levels of 2.2–2.4 tonnes/ha. When 50 percent of nitrogen (N) for fish in ponds was provided in the form of supplementary feeds, the gross fish production increased by only a further 0.5 tonne/ha (Figure 21). Thus, the value and perceived efficacy of artificial feeds, especially supplementary feeds, will need to be more carefully evaluated. Nevertheless, irrespective of the contribution of natural feeds, given the high proportional production cost of feed incurred by farmers, eFCR is a valid and widely used index to evaluate the merits and justification of artificial feeds. In integrating such data for diet performance, however, due cognizance must be taken of the fact that eFCR is the outcome of the whole farming management system and not diets *per se*.

FIGURE 21

Impact of natural feed derived from a combination of organic and inorganic fertilizers and supplementary feeds on carps reared under similar pond polyculture conditions



Source: Adapted from Abbas *et al*. (2010).

Note: SF = supplementary feed.

The reported eFCRs for tilapias, Indian major carps, catfishes, shrimps and prawns reared on farm-made and commercial feeds from various production systems and intensity of production are given in Tables 11–13. While high water turnover tends to reduce the contribution of natural feeds in cages sited in rivers and lakes (unless highly eutrophic, e.g. Laguna de Bay, the Philippines), natural feeds can and do make a notable contribution in ponds where water exchange is limited. Under cage-farming conditions, natural feeds are generally limited. For cage-farmed tilapia using commercial, mainly extruded feeds, reported eFCR ranged from 1.2:1 to 1.5:1 (Table 11). Data on eFCR for farm-made feeds, which are often presented to fish in powdered form, were scanty but, where available, were notably higher. For striped catfish in Viet Nam and major carps in India, this ranged between 2.9:1 and 2.3:1 to 4.1:1, respectively (Table 12).

TABLE 11

Feed performance (eFCR) for Nile tilapia farmed in countries using various systems

	China	Thailand		Philippines		Egypt		Ghana	
System	**Pond**	**Pond**	**Cage**	**Cage**	**Pond**	**Cage**	**Pond**	**Cage**	**Pond**
Commercial feed	1.69:1[1]		<1.5:1[1]	1.50–1.71:1[1,2]	–	1.00–1.21:1 floating*	1.5–2.5:1[1] sinking	1.2–1.4:1[1] Coppens	1.8– 2.3:1[3]
Farm-made feed	NA	<1[4]	–		XX	Not used		NA	
Fertilizers	XX[5]	XX	–	Not used	XXX	–	X	Not used	xxx

Notes: [1]Intensive. [2]Semi-intensive (farm-made feeds). [3]Extensive (+ limited supplementary feeds). [4]Low FCR is probably due to availability of natural food in the pond. [5]X = not commonly used; XX = commonly used; XXX= frequently used. *Extruded floating feed.

Source: Liu *et al.* (2013); Bhujel (2013); Romana-Eguia, Laron and Catacutan (2013); El-Sayed (2013); Awity (2013).

TABLE 12

Feed performance (eFCR) for striped catfish and Indian major carps farmed in countries using various culture systems

	Viet Nam	Bangladesh	India
Species	**Striped catfish**	**Indian major carps**	**Indian major carps**
System	Ponds: intensive	Ponds: semi-intensive	Ponds: semi-intensive
Commercial feed	1.6:1	NA	1.8:1–3.4:1
Farm-made feed	2.9:1	1.3:1–2:1	2.3:1–4.1:1
Fertilizers	Not used	XX	XX

Note: NA = data not available; XX = commonly used.

Source: Nguyen (2013); Sarder (2013); Ramakrishna, Shipton and Hasan (2013).

Such relatively high eFCRs (2.1:1–4:1) were also evident for giant river prawns in Bangladesh fed both commercial and farm-made feeds. The performance of marine shrimps reared in fertilized semi-intensive ponds in Viet Nam and India and fed commercial diets, however, was low at 1.0:1–1.4:1 (Table 13).

TABLE 13

Feed performance (eFCR) for shrimps and prawns farmed in countries using various culture systems

	Bangladesh	India	Viet Nam
Species	**Giant river prawns**	**Black tiger shrimp**	**Whiteleg shrimp**
System	Ponds: semi-intensive	Ponds: semi-intensive	Ponds: intensive
Commercial feed	2.30:1	1.27:1–1.38:1	1.00:1–1.20:1
Farm-made feed	2:1–4:1	NA	NA
Fertilizer	XX	XX	XX

Note: NA = data not available; XX = commonly used.
Source: Ahmed (2013); Ramaswamy, Mohan and Metian (2013); Hung and Quy (2013).

4.4 Presentation of nutrients

Although the data are far from complete, the reported eFCRs shown in Table 14 provide an indication of the broad trend. Farm-made feeds were poorer (1.9:1–4.1:1) when compared with manufactured feeds (1:1–2:1). For pelleted feeds either manufactured by local mills or commercial feed companies, diets appeared to yield similar results. Moreover, there were no clear performance differences between sinking and extruded diets or species, and performance was similar between countries (Table 11). Performance of feeds from cage-reared fish (eFCR 1:–1.5:1) was slightly better than that from pond-reared fish (eFCR 1.2:1–2:1) except for pond-reared whiteleg shrimp where eFCR varied between 1.0 and 1.2 (Table 14).

TABLE 14

Economic feed conversion ratios (eFCRs) for feed types used for farming finfish and shrimps in ponds and cages

Feed type	eFCR	Species	Rearing system	Country	Source
Farm-made feed					
Mash	2.3:1–4.1:1	Major carps	Pond	India	Ramakrishna, Shipton and Hasan (2013)
Mash + pellet	1.9:1	Major carps	Pond	India	Ramakrishna, Shipton and Hasan (2013)
Moist pellets	2.9:1	Striped catfish	Pond	Viet Nam	Nguyen (2013)
Manufactured pellets					
Sinking pellets	1.5:1	Nile tilapia	Cage	Egypt	El-Sayed (2013)
Sinking pellets	1.6:1–2.0:1	Nile tilapia	Pond	China	Liu *et al.* (2013)
Sinking pellets	1.3:1–2.1:1	Major carps	Pond	Bangladesh	Sarder (2013)
Extruded pellets	2.0:1	Nile tilapia	Pond	Ghana	Awity (2013)
Extruded pellets	1.6:1	Striped catfish	Pond	Viet Nam	Nguyen (2013)
Extruded pellets	1.5:1–1.7:1	Nile tilapia	Pond	Philippines	Romana-Eguia, Laron and Catacutan (2013)
Extruded pellets	1.2:1–1.4:1	Nile tilapia	Cage	Ghana	Awity (2013)
Extruded pellets	1.0:1–1.2:1	Whiteleg shrimp	Pond	Viet Nam	Hung and Quy (2013)
Extruded feeds	1.2:1–1.5:1	Nile tilapia	Cage	China	Liu *et al.* (2013)
Extruded feeds	1:1	Nile tilapia	Cage	Egypt	El-Sayed (2013)

It should be noted that the outcomes of diet performance were similar, irrespective of differences in feed administration methods and frequency, whether hand fed or automatically dispensed. Overall, presentation of the nutrient ingredients to fish seems most crucial. Better utilization is achieved through presenting nutrients in a concentrated form, typically as pellets.

4.5 Reduction of protein and fishmeal in diets

Farmers and feed manufacturers alike are attempting to reduce feed cost and secure ingredients to produce cost-effective diets. Several avenues have been explored. In particular, significant effort has been devoted to research into reducing fishmeal for inclusion in diets. This section evaluates data from farm surveys to assess which interventions may have the greatest impact.

A considerable amount of effort continues to be devoted to fishmeal replacements on the grounds of cost and availability (Rana, Siriwardena and Hasan, 2009; Tacon, Hasan and Metian, 2011), and there is a view that protein levels, including fishmeal, in diets are overprescribed. Specifically, the contention is that fish diets contain too much protein, and that protein reduction, which may increase grow-out time, may result in better economic gain (De Silva, 2010). However, as shown in Table 15, the crude protein levels in aquafeeds from across Asia and Africa (see case studies), with a few exceptions (e.g. shrimp, 35–40 percent) are relatively low, typically between 15–30 percent, with fishmeal only constituting up to 5–10 percent of diets (Table 15). In the last 13 years for which data are available (1995–2008), fishmeal inclusion in major fish and shrimp diets declined considerably (FAO, 2012a). Tacon, Hasan and Metian (2011) point to a reduction of fishmeal use at the global level, reporting the decline in fishmeal inclusion levels from 10 to 3 percent, from 10 to 5 precent and from 28 to 20 percent from 1995 to 2008 for fed carps, tilapias and marine shrimps, respectively.

Striped catfish feeds in Viet Nam, for example, which are estimated to be almost 2 million tonnes, only contain 18–20 percent crude protein, and any further reduction is unlikely to affect costs and will increase feed requirements and other variable costs with no likely gain in farm-gate price. Based on the case study data, a daily delay in harvesting due to an extended growth period will require, each day, an additional 6, 0.3 and 0.16 tonnes of feed per hectare for catfish, whiteleg shrimp and Nile tilapia, respectively (Table 16). Moreover, as the key plant protein sources are internationally traded commodities (e.g. soybean meal, wheat and corn), the bulk sourcing of these ingredients is on a par with fishmeal (Rana, Siriwardena and Hasan, 2009). From the perspective of farmers, the merits of advocated protein reduction will therefore have to be considered from a financial rather than a biological perspective. This is especially so as it will, in addition, incur other higher variable costs such as drugs, pumping, labour, which for striped catfish farming adds up to 8 percent of production costs (Nguyen, 2013).

TABLE 15

Crude protein levels in commercial diets reported in case studies for on-growing of various fish and shrimp species

	Species	Crude protein (%)	Fishmeal (%)	References
Ghana	Nile tilapia	30	NA	Awity (2013)
Egypt	Nile tilapia	25	6	El-Sayed (2013)
Thailand	Nile tilapia	16–30	NA	Bhujel (2013)
Viet Nam	Black tiger shrimp	36–42	NA	Hung and Quy (2013)
	Whiteleg shrimp	32–35	NA	
Philippines	Nile tilapia	22–32	NA	Romana-Eguia, Laron and Catacutan (2013)
Viet Nam	Striped catfish	18–20	3–20	Nguyen (2013)
India	Major carps	8–30	3.5	Ramakrishna, Shipton and Hasan (2013)
Bangladesh	Major carps	25–30	5–10	Sarder (2013)
China	Nile tilapia	28–30	NA	Liu *et al.* (2013)

NA = Data not available.
Source: Case study data.

TABLE 16
Implication of delayed harvesting on additional feed requirements

Case study examples	Standing stock at normal harvest (tonnes/ha)	Extra feed (2%/ha)	
		Tonnes/day	Tonnes/week
Striped catfish	300	6	42
Whiteleg shrimp	15	0.3	2.1
Nile tilapia/Indian major carps	8	0.16	1.12

Source: Case study data.

4.6 Least-cost prioritization options to address feed efficiency - where should the focus be?

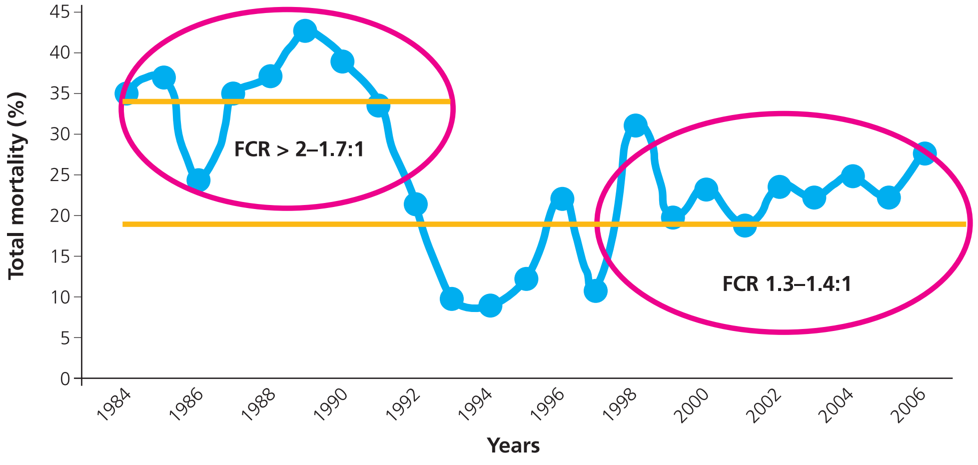
First, it is necessary to revisit the indicator is used for evaluating the farm diet performance (i.e. eFCR), which is a ratio of actual total weight gain and actual total weight feed used (or perhaps more relevantly, the total quantity of feed procured). Hence, without changing feed quality, any improvement in increased harvested tonnage and/or reduced feed usage will improve eFCR. Therefore, it is also necessary to take due cognizance of those factors that could most significantly influence these two variables. Based on the case studies, three main factors are considered here:

- mortality;
- feed presentation;
- storage.

4.6.1 Mortality and eFCR

As indicated in Tables 11–14, the eFCRs in many instances are relatively low and similar to the economic feed conversion efficiencies of the salmonid industry (Kaushik, 2013) and, in many instances, better than those of the seabass and seabream industry in Europe. In Turkey, for example, the FCR is about 1.6:1–2.0:1 for seabream and 1.8:1–2.2:1 for seabass (Okumus, 2005). Nevertheless, lessons may be evident from the historic evolution of diet performance in Europe. Prior to the 1990s, salmon farming in Scotland, the United Kingdom of Great Britain and Northern Ireland, was characterized by relatively high mortalities, with eFCRs in the range of 2:1 and the use of moist diets (Kaushik, 2013). Such performance is similar to that attained

FIGURE 22
Trends in reported Scottish salmon industry mortality pattern *versus* the industry-wide eFCR

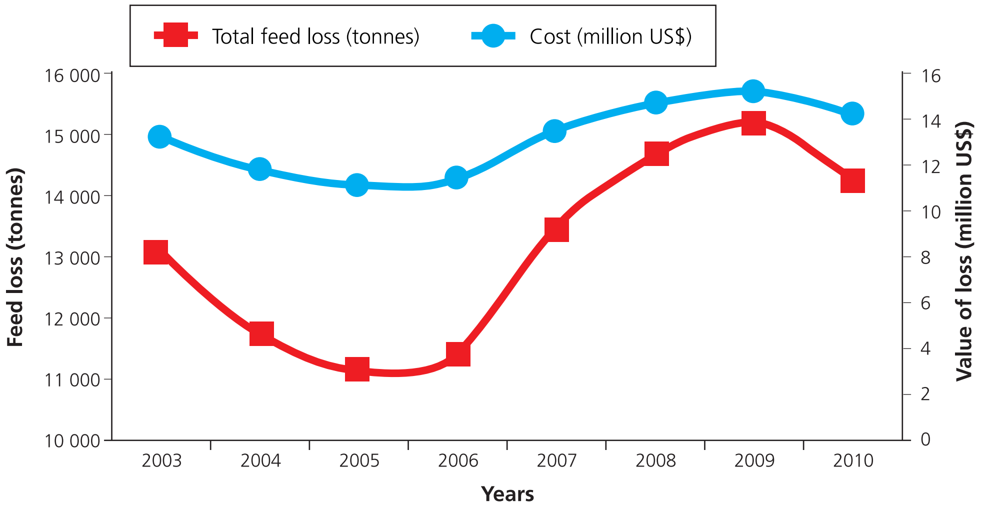


Source: Adapted from www.seeradonline.gov.uk and F. Johnston, FEAP, personal communication (2011).

by farmers using farm-made feeds (Tables 12–14). At the pragmatic farm level, the advent of pelleted feeds in the salmon industry and the improvement in industry-level survival by about 10–15 percent has improved feed performance from 2:1 to 1.3:1–1.4:1 (Figure 22). This was achieved by better accountability for ingredient utilization and improved feed usage through reduced mortality, reflecting higher harvested tonnage.

Taking into account that salmon farms hold two- and three-year-class fish, the feed loss for the industry, which in 2009 produced 144 000 tonnes, can be significant. In 2009, this loss was estimated at 15 000 tonnes valued at US$15 million (Figure 23).

FIGURE 23
Total annual feed loss by, and cost to, the Scottish salmon industry resulting from mortality based on stocked and harvested age classes reported to the Scottish Executive Environment and Rural Affairs Department



Source: Adapted from www.seeradonline.gov.uk

Note: Feed cost = US$1 000/tonne.

The above scenario represents a sector using a single production system, intensive cages. Where national production is significantly higher (e.g. Asia), and where production systems are diverse and operate at varying levels of intensification, total mortality may be significantly higher owing to a number of additional factors. Hence, a consideration of the contributing factors to total mortality may be useful and effective in improving eFCR and hence feed utilization efficiency.

The total mortality during the rearing phase represents all unaccountable fish based on initial stocking density. Losses may be due to a number of factors such as predation, theft, disease, handling and transport losses and escapes (Box 1). Given that the eFCR is a ratio of net weight gain and total feed used (Box 1), it would be prudent for farmers to target their efforts to identify significant contributors to total mortality to improve eFCR, irrespective of the type and quality of on-farm feed used. The Asian and African case studies suggest total mortalities may be significantly higher than in Europe, ranging between 30 and 50 percent during the grow-out phase (Table 17). An appreciation of the contributing factors to total mortality may therefore be useful in improving feed utilization efficiency.

Box 1

Mortality, net weight and eFCR

Total mortality (weight) = Total biomass loss from predation over production cycle + theft + disease + handling + grading + escapes

Total net weight at harvest = harvest weight – stocking biomass (if large fingerlings/yearlings used)

$$\text{eFCR} = \frac{\text{Total net weight gain at harvest (kg)}}{\text{Total feed used or procured}}$$

TABLE 17

Mortalities reported during the grow-out phase on farms in various countries

Country	Species	Mortality (%)	Stocking size (g)	Source
Egypt	Nile tilapia	25–35	NA	El Naggar, Ibrahim and Abou Zead (2008)
China	Nile tilapia	Up to 50–60	Up to 50	Liu *et al.* (2013)
Thailand (ponds)	Nile tilapia	40–50	NA	Bhujel (2013)
Thailand (cages)	Nile tilapia	35–40	30–50	Bhujel (2013)
Viet Nam (if harvested at 1.2 kg)	Striped catfish	38–40	50	Nguyen (2013)
Bangladesh	Giant river prawns	30	NA	Ahmed (2013)
Bangladesh	Indian major carps	35	NA	Sarder (2013)
Philippines	Nile tilapia	40	50	Romana-Eguia, Laron and Catacutan (2013)

NA = data not available.

The reasons for such mortalities or why such losses occur during the grow-out phase are unclear from the case studies in this document but they are crucial to understanding and developing strategies for improving on-farm feed utilization efficiencies. In these case studies for finfish, high mortality immediately post-stocking may be relatively rare given that larger fingerlings are stocked. In China, Thailand and Viet Nam, for example, 50 g fingerlings are used (Table 17). In instances where small fry or fingerlings (e.g. 3 cm) are used, predation could be higher. With larger fish, losses from theft and diseases are likely to be greater. In China, farmers have reported up to 30 percent losses due to bacterial diseases, possibly initiated by inadequate water quality management (Liu *et al.*, 2013). Such mortalities are likely to be increasingly prevalent as stocking densities are increased and total biomass increases beyond the carrying capacity of the rearing system. In such cases, relatively larger fish will be lost, reducing the harvestable yield and increasing feed loss and the eFCR of diets used.

The details on such impacts are limited in the literature and are unavailable in the case studies. However, modelling such losses can shed some insight into their significance. The impact of total mortality on potential farm feed wastage using a typical growth rate (1.9 percent/day) and simulated survival pattern under different production levels (Table 18) is illustrated for tilapia in Figure 24. If the production of one tonne of fish incurs a total loss of 20 percent, then, over a seven month production cycle, 0.14 tonnes of feed would be wasted. Similarly, 5 tonnes of tilapia production would incur 0.7 tonnes of feed loss. At 50 percent mortality, such waste escalates to 0.4 and 1.9 tonnes, respectively. In Bangladesh (Sarder, 2013), the Philippines (Romana-Eguia, Laron and Catacutan, 2013), Egypt (El-Sayed, 2013) and Ghana (Awity, 2013), where feeds prices are reported as US$435, US$500, US$650 and US$1 000/tonne, respectively, farmers producing one tonne of fish and incurring 20 percent total mortality would lose

US$61, US$70, US$91 and US$140/tonne of fish harvested, respectively. At 50 percent mortality, these losses would reach US$170–390/tonne of fish harvested (Table 19).

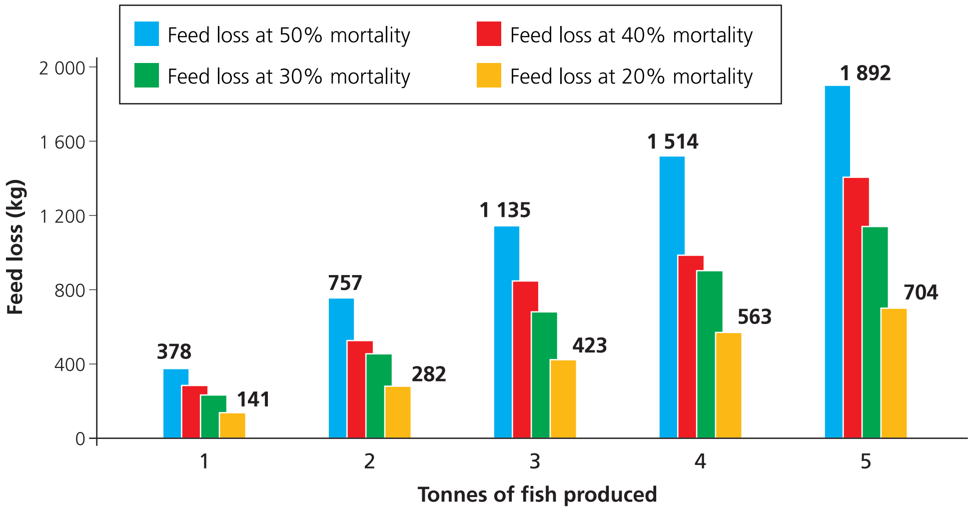
TABLE 18

Simulated survival pattern for four final mortalities

Month	Final mortality (%) at end of 7 month grow-out phase			
	20	30	40	50
	Simulated survival pattern (%)			
1	100	100	100	100
2	95	90	80	80
3	90	85	75	70
4	90	85	75	65
5	85	80	70	60
6	85	75	65	55
7	80	70	60	50

FIGURE 24

Predicted feed loss under various final total mortality scenarios and production levels of tilapia



Source: This review.

Note: Survival pattern used in model for mortality scenarios given in Table 17.

The later and greater the mortalities occur in the production cycle (i.e. the greater the biomass), the higher the financial losses are. The significance of mortality and its financial impact on economic viability also varies between countries depending on the price of feeds. Irrespective of diet quality, the financial loss in Ghana is 2.3 times greater than in Thailand for the same amount of fish produced (Table19). Therefore, irrespective of diet type and quality, the first priority of farmers to improve eFCR must be to assess and critically reduce mortality to increase tonnage harvested and reduce financial loss.

TABLE 19

Monetary loss for each tonne of tilapia produced under various mortality scenarios

Country	Feed cost (US$/tonne)[1]	Feed loss (US$/tonne of fish produced)			
Total mortality at harvest (%)		20	30	40	50
Thailand	435	61	100	122	170
Philippines	500	70	115	140	195
Egypt	650	91	150	182	254
Ghana	1 000	140	230	280	390
Feed loss (tonnes/tonne fish of harvested		0.14	0.23	0.28	0.39

[1] Feed price based on case study data, feed loss from Figure 24.

4.6.2 Feed presentation

The highest cost component in feed production is the ingredients. Therefore, the key consideration in improving eFCR should be maximization of feed ingredient utilization by the fish. The presentation of ingredients to fish is briefly explored here, based on case study information from the countries.

Feed is presented to fish in ground and powdered form (Sarder, 2013), as dough balls (Sarder, 2013; Ramakrishna, Shipton and Hasan, 2013) and in two pelleted forms, sinking and extruded (Nguyen, 2013). Overall, where feed presentation is powdered or a dough, the eFCR is notably higher than if the ingredients are presented in a pelleted form (Table 12). For this case study, it should be noted that both pelleted and mash diets use similar inclusion levels of key ingredients such as soybean meal and rice bran. The inefficiency of single or multiple ingredient presentation to fish as powdered or mashed diet can be illustrated for Indian major carps in India using the bag–mash feeding method in which mixed ingredients are placed. The eFCRs for mash-fed systems are 2.3:1–4.1:1, whereas those of pelleted feeds are acknowledged as one third that of mashed feeds (Ramakrishna, Shipton and Hasan, 2013). However, data on comparative unit costs of feeds were unavailable. Farmers broadcast or place such feeds in bags in ponds, and the capacity of fish to acquire and utilize these dispersed feed ingredients is low. Thus, it is prudent for farmers to develop simple on-farm pelleting and drying of feeds using the same ingredients to ensure better acquisition of ingredients with reduced effort and wastage. Therefore, the second priority is to encourage farmers to switch from using single-ingredient or moist diets to compressing the same single or mixed ingredients into dry pellets.

Pellet stability

The case studies highlight two key areas for consideration for pelleted feeds: cohesion of major ingredients in pellets; and stability of pellets in water. Both have an impact on wastage and utilization. Poorly compressed and bound pellets can result in unacceptable breakage resulting in "fines" or dust that is unlikely to be consumed by fish and becomes an expensive route to fertilize ponds. Pelleted diets produced by smaller feed factories in China were regarded as of inferior quality (Figure 25). According to Liu *et al.* (2013), ingredients used for diets were not adequately ground and hence pellet integrity was poor, resulting in a high percentage of powdered diet being wasted. Poor pelleting is not just a concern for farm-made feeds. In Malawi, compressed pellets manufactured by feed mills can also be of suboptimal quality (Figure 26). In some instances this can exceed 15 percent (K.J. Rana, personal communication, 2011), contributing to financial loss and poorer eFCR. This hidden cost can be significant for larger farms, and it varies between countries owing to price differences (Table 20). The cost implication of varying amounts of fines and dust per tonne of fish feed and for a tonne of fish produced using feed with 5 percent fines and dust at various eFCR is presented in Table 21 for various countries. Depending on the eFCR achieved, farmers in Bangladesh will incur losses of between US$19 and US$31 for each tonne of fish produced, whereas in Ghana, where feed price is considerably higher, these losses equate to US$40–58.

TABLE 20

Monetary loss for each tonne of fish and shellfish produced under varying mortality scenarios

Country	Feed price (US$/tonne)[1]	Monetary cost of "fines" (US$) at 80% feed wastage		
Percentage fines		2.5	5	10
Major carps, Bangladesh	390	8	16	31
Nile tilapia, Egypt	425	9	17	34
Major carps, India	450	9	18	36
Nile tilapia, Philippines	600	12	24	48
Nile tilapia, China	560	11	22	45
Black tiger shrimp, India	640	13	26	51
Nile tilapia, Ghana	720	14	29	58

[1] Based on estimates from case studies.

FIGURE 25

Locally pelleted feed in China

[Note the high level of disintegrated pellets and dust]

Source: Liu *et al*. (2013).

FIGURE 26
Pelleted feed produced in Malawi
[Note the high level of dust and crumbled pellets]

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TABLE 21
Financial loss incurred by farmers per tonne of fish and shrimp produced at various eFCR using diets containing 5 percent fines and dust

Country	Financial loss (US$) per tonne fish produced at 5% dust and fines in diets at various eFCRs				
	1.2	1.4	1.6	1.8	2
Bangladesh	19	22	25	28	31
Egypt	20	24	27	31	34
India (fish)	22	25	29	32	36
Philippines	27	31	36	40	45
China	29	34	38	43	48
India (shrimp)	31	36	41	46	51
Ghana	35	40	46	52	58

Related to compression is the binding of ingredients in pellets to optimize their water stability such that fish consume the whole pellets, thus benefiting from a complete diet. The third priority should be to focus on methods to reduce dusts and fines in feeds and optimize the binding properties of pellets to improve pellet hardness and water stability.

4.6.3 Feeding strategy options

In most cases, farmers feed their fish a ration of 2–3 percent of body weight per day, 1–2 times a day. Smaller farmers disperse their feeds by hand (e.g. Ghana, the Philippines and Thailand) or in bags (India), whereas larger farms deploy automated (e.g. China) or demand feeders (e.g. Egypt); however, there appear to be limited gains in reduction in FCR through use of the latter. The priority of farmers is to reduce feed costs, and they have responded to this challenge by adopting various cost-saving strategies in the administration of feeds. These include the use of:

- fertilizers;
- alternate day feeding;
- alternative feeds with low and high-quality diets;
- feeding to satiation.

The most notable and promising approaches seem to be restricted feeding regimes and alternate use of high and low-protein diets.

Use of fertilizers

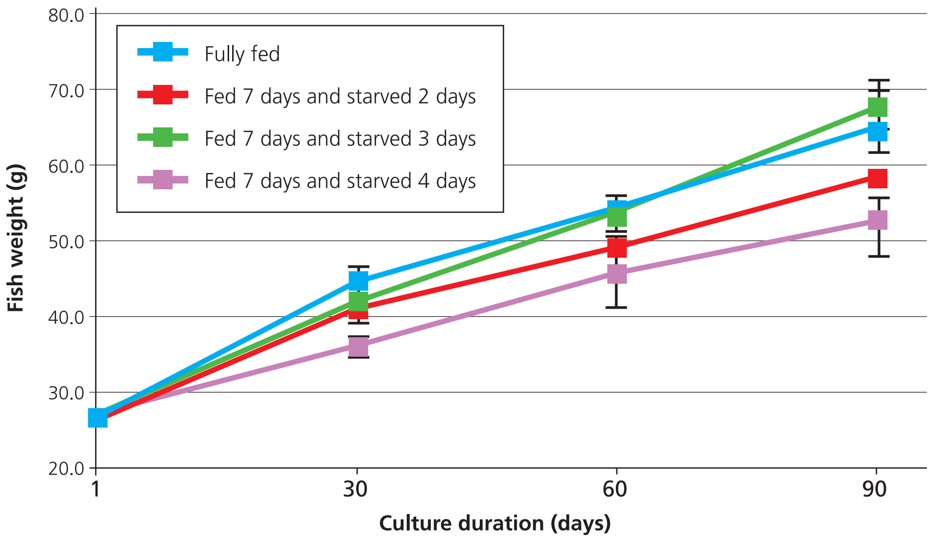
Fertilizers, both organic and inorganic, are extensively used to provide natural food. Poultry and cattle manure is predominantly used at annual rates of up to 13 tonnes/ha (India). In view of projected demands for fish globally and changes in land use patterns, the required tonnage of organic manures to provide the nutrient source for natural foods and fish is unlikely to be available and therefore, reliance on such fertilizers will be increasingly unpredictable. Moreover, some studies have indicated that the cost of macronutrients in dry chicken manure (on the basis of available amount of nutrients per 100 kg of manure and fertilizer) is seven times greater than inorganic urea for N and four times more than triple super phosphate for P (Knud-Hansen, 1998). In addition, the action of inorganic fertilizers is faster than organic manures; they require less labour and have a lower demand on dissolved oxygen. The value of fertilizers in providing micronutrients via natural food, however, may be a useful contribution to reducing on-farm feed costs, and the matter requires further research. A more promising farmer-driven approach is alternate day and diet feeding.

Restricted feeding and alternate feeding regimes with low and high-quality diets

Restricting feeding frequency to once a day was reported to reduce eFCR for striped catfish by 17 percent (Nguyen, 2013) for fish more than 500 g, and further reductions can be achieved by extending this feeding regime over the entire cycle, although this may extend the grow-out period by three weeks (Nguyen, 2013); however, the extra cost for three weeks of rearing is unclear. The growth of fish fed for 7 days and then starved for up to 3 days was not significantly different from that of fish fed daily (fully fed; Figure 27), and reduced eFCR by 18 percent (Nguyen, 2013).

FIGURE 27

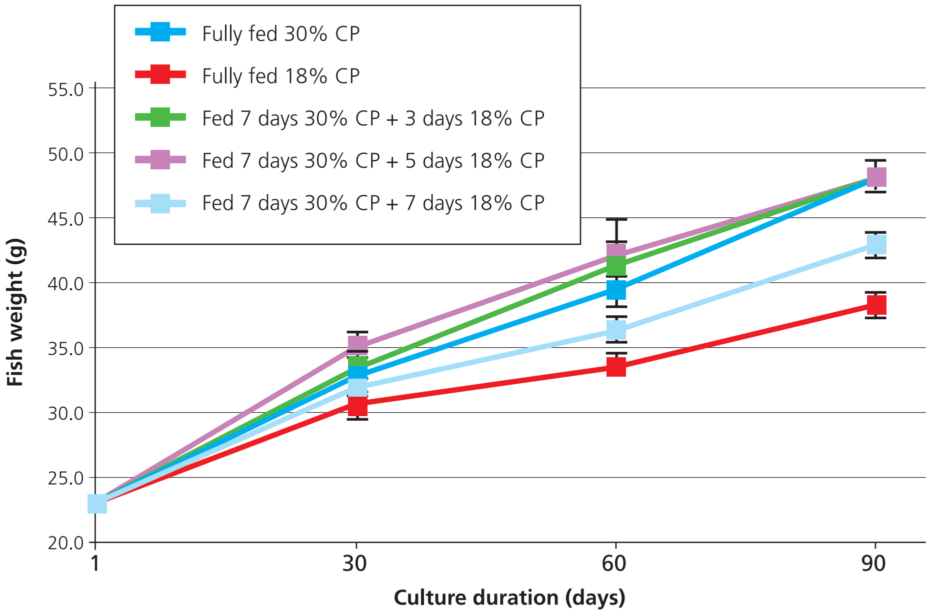
Growth of striped catfish fed different restricted feeding regimes



Source: Nguyen (2013).

In the Philippines, alternate feeding has shown promising results, and farmers who have adopted the schemes have noted a positive impact on reducing production costs (Romana-Eguia, Laron and Catacutan, 2013). Alternate feeding with high and low-protein commercial pellets also appears to be effective in reducing eFCRs. The growth rates of striped catfish fed 30 percent protein pellets for 7 days and then fed on 18 percent protein pellets for the next 3 or 5 days were not significantly different when compared with those fed only 30 percent protein diets all of the time (Figure 28), although it should be noted that these and other studies were conducted on fingerlings.

FIGURE 28
Growth of striped catfish fingerlings fed different alternate feeding regimes of high- and low-protein commercial diets



Source: Nguyen (2013).

Note: CP = crude protein.

Mixed feeding schedules using high and low-protein diets were demonstrated to be useful for many other cultured species, such as common carp (*Cyprinus carpio*) (Srikanth *et al.*, 1989); catla (*Catla catla*), rohu (*Labeo rohita*) and common carp (Nandeesha, De Silva and Krishna Murthy, 1993; Nandeesha, Gagadhara and Manissery, 2002); Nile tilapia (Santiago and Laron, 2002; Patel and Yakupitiyage, 2003); striped snakehead (*Channa striata*) (Hashim, 1994); and tilapia in on-farm trials (Bolivar, Jimenez and Brown, 2006). These studies report better FCRs and suggest significant savings on feed costs. The fourth priority should therefore be for farmers to reduce the extent to which higher protein diets are used.

4.6.4 Feed transport, storage and handling

The final value of feeds to farmers is a summation of all the stages in the production and value chain for fish diets. The transport and storage conditions of diet ingredients and post-manufacture handling and storage conditions of feeds are as important as the nutritional quality of the diet. Inadequate attention to pre- and post-manufacture phases can significantly reduce the economic benefits of any commercial or on-farm feed to the farmer. High humidly (up to 90 percent), high ambient temperatures (up to 50 °C), and improper storage and handling are key factors affecting the end-use quality of feeds and are therefore of particular, although not exclusive, importance in non-temperate countries. Such conditions may result in fungal contamination of both feed ingredients and feeds, reduce nutritional value of ingredients, especially micronutrients, and increase the amount of dust and fines in bagged feed and losses due to pests.

Transport

Imported commercial diets (i.e. Ghana and Nigeria) are particularly vulnerable to spoilage as they have to be shipped by sea freight adding up to 25–45 days to delivery times (from Northern Europe to West Africa) to farms with uncertainty concerning the date of manufacture and transit storage conditions. Bagged diets are often packed in closed metal containers without any climate control, adding to potential diet deterioration caused by high temperatures and humidity build-up. Moreover, in Ghana, feeds are transported in metallic containers on vehicles from the ports to central warehouses in Accra (Awity, 2013) and subjected to higher ambient temperatures and humidity.

Transport of feeds or feed ingredients to farms in open trucks or on motorbikes and bicycles also increases transport times, often compounded by poor road conditions, causing bags to bounce, increasing friction between pellets and hence fines in bags.

Storage conditions and handling

Three key considerations are relevant to optimize feed usage: the control of pests such as rodents, temperature, and humidity; these are of concern in most developing countries. In the central warehouses of large importers in Ghana feeds were stored on pallets above ground level and crevices around buildings were plugged to keep out rodents. Small farmers, however, are unable to invest in dedicated storage facilities; feed storage is poor and simple good practices are not followed by farmers. In Ghana, farmers stacked feed directly on the floor during storage. At farms of this type that were visited, gnawed bags with feed spillage and escaping mice were evident. The store rooms at most of the farms visited were not designed to prevent the entry of rodents. One farmer stored feed in the open covered with a tarpaulin at night to keep off the rain (Awity, 2013).

Although private feed mills in Egypt have excellent handling, storage and transportation facilities, complying with the Code of Practice for Good Animal Feeding (FAO, 1998), this is not universal. In Egypt, handling of tilapia feed and storage facilities are regarded as the most serious problem facing the Egyptian aquafeed industry (El-Sayed, 2013). Feed stores at many feed mills have inadequate basic storage and handling standards. Ingredients are piled outdoors on the ground and exposed to direct sunlight, heat, moisture, and other weather conditions (Figure 29).

FIGURE 29

An example of poor feed ingredient storage in the open in Egypt

Source: El-Sayed (2013).

Pellets with high stability have good handling characteristics. If feed ingredients for formulated and on-farm feeds are not finely and uniformly ground and the binders used are inadequate their pellet strength and hardness may not be ideal; this increasing the incidence of pellet collapse and feed dust and fines (Figure 26). This can be especially high, resulting from compression and abrasion between pellets following the rough handling of bagged feeds and by people walking on bags. While not feasible for small operations, the use of forklifts and pallets, or hand-trucks and mini-pallets, to handle multiple bags minimizes handling. Larger fish farms with high volumes of fish inventories requiring significant qualities of feeds have the capacity to build dedicated storage facilities, as seen on striped catfish farms in Viet Nam (Figure 30).

FIGURE 30
Examples of feed storage on striped catfish farms in Viet Nam
(Note that the feed bags off floor on pallets and away from walls.)

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In China, smaller farmer with limited resources also store feed under poor conditions (Figure 31 left). Larger operators procure feed regularly, and this is transported to fish farms by the feed producers. There, it is usually stored on-farm in well-ventilated brick-tile buildings (Figure 31 middle) or in concrete buildings (Figure 31 right). Whilst these feed stores are watertight, the bags are stacked against walls, reducing air circulation and causing damp spots (Figure 31 middle and right). Storing ingredients and feeds on the floor is also common among small farmers in Viet Nam. The majority (>85 percent) of whiteleg shrimp small farmers in Central Viet Nam keep their feed in their houses (Figure 32) where humidity and temperatures are high.

FIGURE 31
Examples of tilapia feed stores in Guangdong and Hainan provinces, China
(left: shanty store in Guangdong Province; middle: brick-tile house in Guangdong Province; and right: concrete building in Hainan Province

COURTESY OF FAO/JIASHOU LIU (LEFT); AND LIU ET AL. (2013) (MIDDLE AND RIGHT).

Examples of poor storage practices also include farmers who were observed to store purchased sacked feed along pond dykes in open weather conditions. This is common in Thailand, where farmers keep feed in covered plastic buckets (Figure 33), where temperatures can be very high, causing loss of micronutrients (Bhujel, 2013).

Many smaller farmers with limited financial resources procure feed ingredients in small quantities from local markets and make on-farm feeds on a daily or weekly basis, thus minimizing on-site storage and reducing the risk of ingredient and feed spoilage.

FIGURE 32
A typical in-house feed store in whiteleg shrimp farm, central Viet Nam

Source: Hung and Quy (2013).

FIGURE 33
Feed stored in plastic bucket at pond side in hot and humid conditions, Thailand

Source: Bhujel (2013).

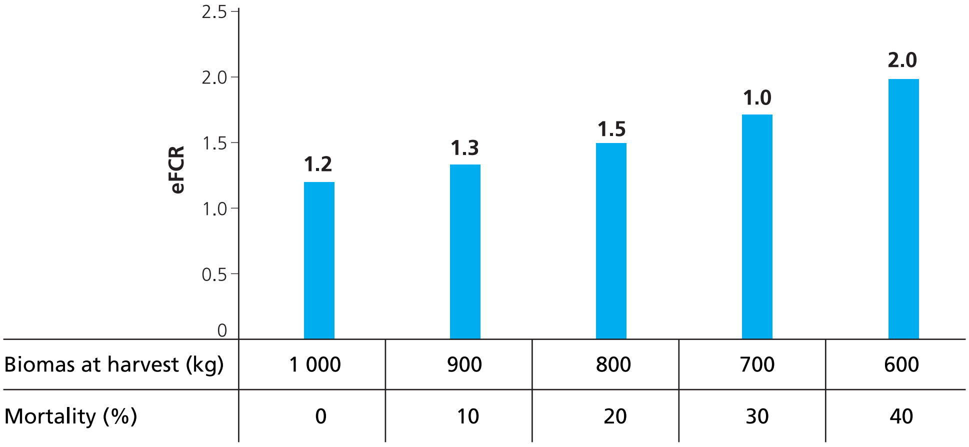
5. CONCLUSIONS – FOCUS FOR IMPROVING FEED EFFICIENCIES.

In this assessment, the eFCR has been used as a primary indicator for on-farm feed utilization efficiency. Where available, data in case studies where commercial feeds are used suggest that eFCR is comparable with developed-country benchmarks for species such as Atlantic salmon in Europe (cf. Table 14 versus Figure 22).

As indicated in Table 10, several options are advocated to improve feed efficiencies. However, farmers will have to prioritize options to focus on those providing the best gains. In this synthesis, it has been shown that total fish mortality has a significant bearing on feed wastage. At just 20 percent total mortality, about 140 kg of feed is wasted (Figure 24) for every tonne of tilapia produced. The impact of such losses on eFCRs is illustrated in Figure 34. In an ideal scenario of no mortality, and using better management practices (BMPs), one can assume an eFCR of 1.2:1 (or the requirement of 1.2 tonnes of feed to produce one tonne of fish). Using the same feed quantity and a mortality rate of 20 percent will increase the eFCR to 1.5:1, and similarly at 40 percent mortality the eFCR jumps to 2:1, irrespective of diet quality. This highlights the paramount importance of mortality reduction strategies as a primary measure to improve feed utilization efficiencies. In addition, for tilapia, 20 percent mortality also incurs a financial loss of feed to the value of US$60–140/tonne of fish produced (Table 19).

FIGURE 34

Hypothetical changes in eFCR with increasing mortality



Source: This review.

Note: 1 000 kg fish at 0% mortality at ideal eFCR of 1.2:1 (1 200 kg feed); if same feed volume used with 10% mortality, eFCR increases to 1.3:1 and to 2.0:1 at 40% mortality.

Concentrating feed ingredients into compressed pellets has been equally important in reducing improving) eFCR from 3:1 – 4:1 to 2:1 – 3:1. Pellet quality is also crucial in maximizing the value of diets. Poor pelleting results in dusts and fines and, at just 5 percent, will cost farmers US$19–38/tonne fish produced at an eFCR of 1.2:1. In countries where feed prices are higher and where eFCRs are poorer, these losses will be greater (Table 21).

Considering the factors of mortality, dust in feed, and pellet stability alone, farmers may lose between US$79 and US$178/tonne of fish produced, which highlights where farmers should focus their efforts.

Alternate feeding strategies with high- and low-protein commercial pellets have also proved to be effective in reducing eFCR, with a possible role for fertilizers in fulfilling micronutrient needs of fish. The data in the case studies provide no clear evidence for choosing the more expensive extruded feed over sinking pellets, and it would seem likely that any differences are probably due to the water stability of sinking pellets rather than to any difference in nutritional quality.

REFERENCES

Abbas, S., Ahmed, I., Salim, M. & Rehman, K. 2010. Comparative effects of fertilization and supplementary feed on growth performance of three fish species. *International Journal of Agriculture and Biology*, 12 (2): 153-168.

Ahmed, A. 2013. On-farm feed management practices for giant freshwater prawn (*Macrobrachium rosenbergii*) farming in southwest Bangladesh. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 269–301. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Awity, L.K. 2013. On-farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in Ghana. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 191–211. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Bhujel, R.C. 2013. On-farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in Thailand. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 159–189. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Bolivar, R.B., Jimenez, E.B.T. & Brown, C.L. 2006. Alternate-day feeding strategy for Nile tilapia grow-out in the Philippines: marginal cost-revenue analysis. *North American Journal of Aquaculture*, 68: 192–197.

De Silva, S.S. 2010. Feed management in small-scale aquaculture in the Asia-Pacific. A review prepared for FAO. 23 pp. (*unpublished*).

El Naggar, G.O., Ibrahim, N.A. & Abou Zead, M.Y. 2008. Influence of fertilizers' types and stocking density on water quality and growth performance on Nile tilapia-African catfish in polyculture system. *In* H. Elghobashy, K. Fitzsimmons & A.S. Diab, eds. Proceedings of 8th International Symposium on Tilapia in Aquaculture, pp. 157–170. Cairo, Egypt.

El-Sayed, A-F.M. 2013. On-farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in Egypt. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 101–129. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

FAO. 1998. Animal feeding and food safety. *Food and Nutrition Paper*. No. 69. Rome, FAO. 45 pp.

FAO. 2010. *Report of the FAO Expert Workshop on on-farm feeding and feed management in aquaculture.* Manila, the Philippines, 13–15 September 2010. FAO Fisheries and Aquaculture Report No. 949. Rome, FAO. 37 pp.

FAO. 2003-2013. National Aquaculture Sector Overview. Egypt. National Aquaculture Sector Overview Fact Sheets. Text by A.M. Salem & M.A. Saleh. *In FAO Fisheries and Aquaculture Department* [online]. Rome. Updated 16 November 2010. [accessed 21 January 2013]. (available at www.fao.org/fishery/countrysector/naso_egypt/en).

FAO. 2012a. *The State of World Fisheries and Aquaculture 2012*. Rome, FAO. 209 pp.

FAO. 2012b. *Fishstat Plus, Vers. 2.32*. Rome, FAO. (available at www.fao.org/fishery/statistics/software/fishstat/en).

Hasan, M.R., ed. 2007. *Economics of aquaculture feeding practices in selected Asian countries.* FAO Fisheries Technical Paper No. 505. Rome, FAO. 205 pp.

Hasan, M.R., Hecht, T., De Silva, S.S. & Tacon, A.G.J., eds. 2007. *Study and analysis of feeds and fertilizers for sustainable aquaculture development.* FAO Fisheries Technical Paper No. 497. Rome, FAO. 510 pp.

Hashim, R. 1994. The effect of mixed feeding schedules of varying dietary protein content on the growth performance of *Channa striata* fry. *Asian Fisheries Science*, 7: 149–155.

Hung, L.T. & Quy, O.M. 2013. On-farm feeding and feed management in whiteleg shrimp (*Litopenaeus vannamei*) farming in Viet Nam. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 337–357. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Kaushik, S.J. 2013. Feed management and on-farm feeding practices of temperate fish with special reference to salmonids. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 519–551. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Knud-Hansen, C.F. 1998. *Pond fertilization: ecological approach and practical applications*. Aquaculture Collaborative Research Support Program, Corvallis, Oregon State University, 125 pp.

Liu, J., Li, Z., Li. X. & Wang, Y. 2013. On-farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in southern China. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 71–99. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Nandeesha, M.C., De Silva, S.S. & Krishna Murthy, D. 1993. Evaluation of mixed feeding schedule in two Indian major carps, catla (*Catla catla*) and rohu (*Labeo rohita*). *In* S.J. Kaushik & P. Luquet, eds. *Fish nutrition in practice. 4th International Symposium of Fish Nutrition and Feeding, Biarritz, France, June 1991*, pp. 753–765. Paris, INRA. 972 pp.

Nandeesha, M.C., Gangadhara, B. & Manissery, J.K. 2002. Further studies on the use of mixed feeding schedules with plant-and animal-based diets for common carp, *Cyprinus carpio* (Linnaeus). *Aquaculture Research*, 33: 1157–1162.

Nguyen, T.P. 2013. On-farm feed management practices for striped catfish (*Pangasianodon hypophthalmus*) in Mekong River Delta, Viet Nam. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 241–267. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Nguyen, N.P., Pham, M.D, Vu, N.S. Tran, V.B. & Au, T.A.N. 2004. *A review of the application of bio-technologies for quality improvement and production cost reduction of giant freshwater prawn (*Macrobracium rosenbergii*), catfishes (*Pangasius bocourti *and* Pangasius hypophthalmus*) and Tilapia (*Oreochromis niloticus*) farming in An Giang province.* Report submitted to the Department of Science and Technology of An Giang province, 24 pp. (in Vietnamese).

Nguyen, T.P. & Dang, T.H.O. 2009. Striped catfish (*Pangasianodon hypophthalmus*) aquaculture in Viet Nam: an unprecedented development within a decade. *In* S.S. De Silva & F.B. Davy, eds. *Success Stories in Asian Aquaculture*, pp. 133–149. Springer, NACA and IDRC, Dordrecht, Bangkok and Ottawa. 214 pp.

Okumus, I. 2005. *The marine aquaculture and management in Turkey*. Rize, Faculty of Fisheries, Rize University. 13 pp.

Patel, A.B. & Yakupitiyage, A. 2003. Mixed feeding schedules in semi-intensive pond culture of Nile tilapia, *Oreochromis niloticus*, L.: is it necessary to have two diets of differing protein content. *Aquaculture Research*, 34: 1343–1352.

Phan, L.T., Bui, T.M., Nguyen, T.T.T., Gooley, G.J., Ingram, B.A., Nguyen, H.V., Nguyen, P.T. & De Silva, S.S., 2009. Current status of farming practices of striped catfish, *Pangasianodon hypophthalmus* in the Mekong Delta, Vietnam. *Aquaculture*, 296: 227–236.

Rahman, S. & Parkinson, R.J. 2007. Productivity and soil fertility relationships in rice production systems, Bangladesh. *Agricultural Systems*, 92: 318–333.

Ramakrishna, R., Shipton, T. & Hasan, M.R. 2013*. Feeding and feed management of Indian major carps in Andhra Pradesh, India*. FAO Fisheries and Aquaculture Technical Paper No. 578. Rome, FAO. 90 pp.

Ramaswamy, U.N., Mohan, A.B. & Metian, M. 2013. On-farm feed management practices for black tiger shrimp (*Penaeus monodon*) in India. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 303–336. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Rana, K.J., Siriwardena, S. & Hasan, M.R. 2009. *Impact of rising feed ingredient prices on aquafeed and aquaculture production*. FAO Fisheries and Aquaculture Technical Paper No. 541. Rome, FAO. 63 pp.

Romana-Eguia, M.R.R., Laron, M.A. & Catacutan, M.R. 2013. On-farm feed management practices for Nile tilapia (*Oreochromis niloticus*) in the Philippines. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 131–158. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Santiago, C.B. & Laron, M.A. 2002. Growth and fry production of Nile tilapia, *Oreochromis niloticus* (L.), on different feeding schedules. *Aquaculture Research*, 33: 129–136.

Sarder, M.R.I. 2013. On-farm feed management practices for three Indian major carp species (rohu *Labeo rohita*, mrigal *Cirrhinus cirrhosus* and catla *Catla catla*) in Bangladesh: a case study. *In* M.R. Hasan & M.B. New, eds. *On-farm feeding and feed management in aquaculture*, pp. 213–239. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome, FAO. 585 pp.

Srikanth, G.K., Nandeesha, M.C., Kesavanath, P., Varghese, T.J., Shetty, H.P.C. &, Basavaraja, N. 1989. On the applicability of a mixed feeding schedule for common carp, *Cyprinus carpio* var. *communis*. *In* E.A. Huisman, N. Zonneveld & A.H.M. Bouwmans, eds. *Aquacultural research in Asia: management techniques and nutrition. Proceedings of the Asian Seminar on Aquaculture, Malang, Indonesia, 14–18 November 1988.* pp. 254–260. Wageningen, Pudoc. 271 pp.

Tacon, A.G.J., Hasan, M.R. & Metian, M. 2011. Demand and supply of feed ingredients for farmed fish and crustaceans: trends and prospects. *FAO Fisheries and Aquaculture Technical Paper.* No. 564. Rome, FAO. 87 pp.