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REVIEW

Paradigm changes in freshwater aquaculture practices in China: Moving towards achieving environmental integrity and sustainability

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Abstract Contribution of fisheries and aquaculture to global food security is linked to increased fish consumption. Projections indicate that an additional 30–40 million tonnes of fish will be required by 2030. China leads global aquaculture production accounting for 60% in volume and 45% in value. Many changes in the Chinese aquaculture sector are occurring to strive towards attaining environmental integrity and prudent use of resources. We focus on changes introduced in freshwater aquaculture developments in China, the main source of food fish supplies. We bring forth evidence in support of the contention that Chinese freshwater aquaculture sector has introduced major paradigm changes such as prohibition of fertilisation in large water bodies, introduction of stringent standards on nutrients in effluent and encouragement of practices that strip nutrients among others, which will facilitate long-term sustainability of the sector.

Keywords Chemical usage · Farming systems · Food production · High-valued species · Indigenous species · Paradigm changes

INTRODUCTION

In the wake of the projected population increase to nine billion by year 2050, one of the major concerns confronting the global community is in regard to providing the required food needs. When the challenges of feeding nine billion people are considered, the most commonly raised issues are competition for land, water and energy, as well as maintaining environmental integrity (Godfray et al. 2010; Hanjra and Qureshi 2010). The general consensus is that these issues are likely to be further exacerbated by impending climate change impacts on food production systems including those on fisheries and aquaculture (Cochrane et al. 2009; De Silva and Soto 2009; Leung and Bates 2013; Bell et al. 2016).

It is only in the recent past that the contributions of fisheries and aquaculture to global food security have come to focus (Kawarazuka and Běně 2010; Belton and Thilsted 2014; Youn et al. 2014; Běně et al. 2015, 2016; De Silva 2016). This realisation is also linked to the fact that fish consumption has increased very significantly over the years. The World Bank (2013) estimated that globally the fish consumption per person would increase from 16.8 kg in 2006 to 18.2 kg in 2030. In China, however, the fish consumption per person would increase from 26.6 to 41.0 kg from 2006 to 2030. It is also important to note that fish accounted for approximately 30% of the animal protein requirement for wellbeing, particularly in developing countries (FAO 2014).

It is estimated that even at the current rate of fish consumption the world will require an additional 30–40 million tonnes by 2030 to account for the expected population increase. The global food fish supplies, until recently, were predominantly of a hunted origin based on wild (marine) capture fisheries, and only in the last decade has its predominance come to be based on a farmed supply, like our other staples (De Silva 2012). The situation is further exacerbated as the traditional fish supplies from the marine capture fisheries, at best, have plateaued at around 100 million tonnes, as many of the traditionally fished stocks have reached a dire state (Froese et al. 2012). Only 75% of this tonnage is available for direct human consumption; however, the rest being reduced into fish meal and fish oil.

Aquaculture has continued to provide the additional food fish needs since the plateauing of the supplies from capture fisheries (Subasinghe et al. 2009, 2012). Over the

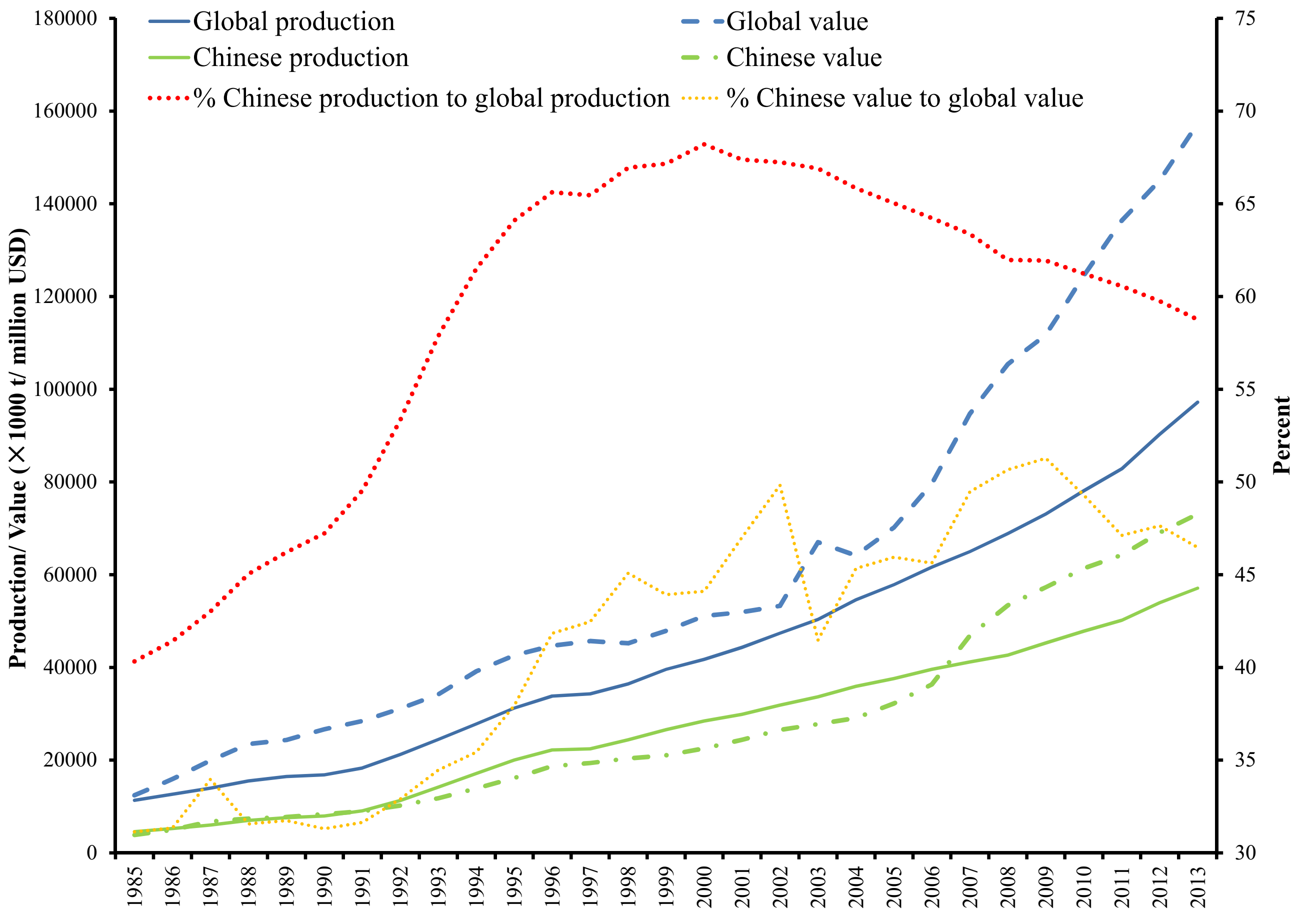

Fig. 1 Trends in global and Chinese aquaculture production (in × 1000 t) and the corresponding value of produce (in × million US $), and the percent contribution from China to global production and value (based on FAO FishStatJ 2016)

last three decades the sector grew at a steady rate of approximately 6% per year, with the main bulk of the global production being in China, accounting for around 60% in volume and 45% in value (Fig. 1).

In the recent past the long-term sustainability of the aquaculture sector has been questioned based primarily on the grounds that feeds for aquatic animals utilise a disproportionate proportion of global fish meal production, which in turn depends on the use of a resource that could be utilised for feeding the needy, directly (Naylor et al. 1998, 2000, 2001; Aldhous 2004). The other concerns and critiques include the impacts of aquaculture on biodiversity and thereby on ecosystem integrity (Moyle and Leidy 1992; Beardmore et al. 1997; Naylor et al. 2001), lack of social responsibility (Primavera 1997, 2005) and negative environmental impacts arising from individual case studies that are too extensive to enumerate here.

Notwithstanding all critiques on aquaculture it has to be conceded that it has become a very important food production sector, benefiting millions and contributing significantly to global food security, a contention that is acknowledged widely (Ahmed and Lorica 2002; World Fish Centre 2011; Subasinghe et al. 2012; Tacon and Metian 2013; Samples 2014; Troell et al. 2014; Běně et al. 2016). However, if aquaculture were to continue its significant contribution to global food security it is imperative that the sector in China, which contributes approximately 60% in volume and 45% in value (Fig. 1) to the sector globally, be sustained.The aquaculture sector in China has also been the subject of numerous critiques. As for the sector globally, such critiques have been on the negative impacts of specific aquaculture practices (Chen 1989; Qin et al. 2007, 2010; Xie and Yu 2007; Guo et al. 2009; Cai et al. 2013; Herbeck et al. 2013; Zeng et al. 2013; Zhou et al. 2016). Notably and more seriously, there also have been critiques on the negative impacts of Chinese aquaculture on the global wild capture fisheries because of its supposedly excessive dependence on fish meal (Chiu et al. 2013; Cao et al. 2015). The latter contention has been refuted strongly; has been provided evidence to demonstrate that the dependence on fish meal in Chinese aquaculture has decreased over the years with greater emphasis on the

Table 1 The average for 5-year periods of total and freshwater aquaculture production (t) and value (in ×1000 USD) in China, and percent contribution of freshwater (FW) aquaculture to total production and value (based on FAO FishStatJ 2016)

Production/value (%)	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010	2011–2013
Production	6 764 977	14 332 305	24 825 054	33 790 371	43 306 443	53 743 080
Value	7 051 372	12 212 851	20 412 590	28 017 100	51 049 502	68 811 124
FW production	3 792 446	6 748 119	12 019 604	15 520 650	20 988 233	26 467 007
FW value	4 286 532	6 857 625	12 088 563	16 760 727	35 387 510	48 279 162
% FW production	56.1	47.4	48.6	45.9	48.4	49.3
% FW value	61.2	56.3	59.3	59.6	68.9	70.2

production of species feeding low in the trophic chain combined with a rational use of fish meal in aquafeeds (Han et al. 2016). It has been demonstrated that the overall trophic level of Chinese aquaculture was 2.25 in 2014 (Tang et al. 2016), and lower than that for aquaculture practices of developed countries or those of other developing countries (Tacon et al. 2010; Olsen 2011).

Beginning in the new millennium, China, following its very rapid economic development has started investing heavily on protecting and restoring natural capital to improve ecosystem services (Ouyang et al. 2016). We are of the view that China has also started addressing issues with regard to environmental impacts, use of primary resources and improving product quality and related aspects leading to long-term sustainability of the aquaculture sector; a major food production sector in the country (Dong 2009, 2015; Wang et al. 2015; Han et al. 2016). These trends will enable it to maintain its contribution to global aquaculture production and hence to food security.

In the above context many paradigm changes have occurred and are occurring in the sector, in particular in some mariculture practices. In respect of molluscs and seaweed mariculture in China much progress has been made in the sequestration of carbon that has resulted in high productive efficiency with low carbon emission that has helped alleviate coastal eutrophication (Dong 2011; Tang and Liu 2016). Here, however, we address the paradigm changes in relation to freshwater aquaculture in view of its relative importance to the sector contributing predominantly to finfish and crustacean culture, as opposed to molluscs and seaweed in mariculture (Wang et al. 2015; Table 1). In doing so, at the outset we will evaluate the major changes that have occurred in the Chinese freshwater aquaculture sector and then address issues on paradigm changes.

DATA SOURCES

For purpose of our evaluation, especially to emphasise the importance of Chinese aquaculture in the global context, we have used the database on fishery statistics of the Food and Agriculture Organisation of the United Nations (FAO 2016). We also used the China Fishery Yearbook (BFMA 2004–2016) to access detailed information on the production levels of individual species as well as areas devoted to different culture practices. The China Seafood Imports and Exports Statistical Yearbook (BFMA 2005–2015) was also used to extract data on volume and value exports to USA and EU from China. In addition, we used many other databases of municipalities, provinces and the central government of China that have the purview to introduce decrees in relation to fish farming practices and environmental management and are in the public domain, and other relevant published materials on aquaculture and fisheries.

CHANGES IN THE FISHERIES SECTOR IN CHINA

Summary of trends of the sector

China, the most populous nation in the world and with an ever increasing middleclass (Kharaz and Gertz 2010) has impacted the world in many ways. The country has become a global economic power and is ranked second in the world. The population and economic changes have also directly and or indirectly reflected in the fisheries sector. Figure 2 depicts the trends for the last three decades in the six main components of the sector viz. capture fisheries production, aquaculture production, export and import volumes and values of fishery products. The most salient features emerging from these data (FAO 2016) can be summarised as follows:

- Capture fisheries production was superseded by aquaculture production in 1984, and the latter continued to grow at the rate of 25.8% per year between 1990 and 2013
- For the period between 1990 and 2013, the export volume and value grew at an annual rate of 39.7 and 58.9% per year, respectively, and

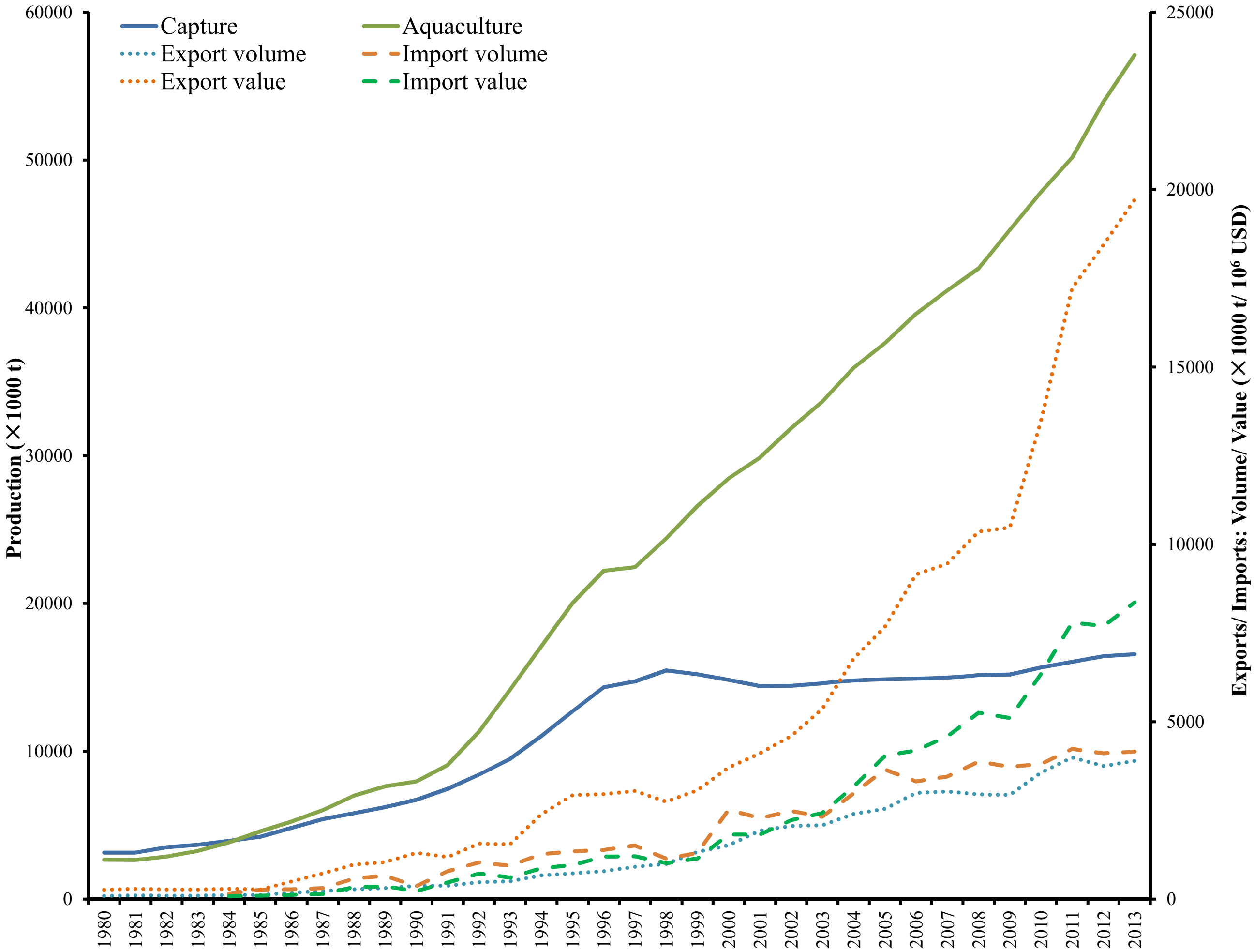

Fig. 2 Trends in capture fisheries and aquaculture production in China together with import and export volumes and values of fishery products to and from China (based on FAO FishStatJ 2016)

- For the same period, import volume and value grew by 43.2 and 151.2% per year, respectively. Of these fish meal imports in 2013 accounted for 23.5% in volume and 20% in value, and throughout was the main imported commodity in volume (Han et al. 2016).

Trends in the aquaculture sector of China

Much has been written about the aquaculture sector in China, particularly in respect of its global dominance (FAO 2014), and relevant facets of it highlighted in different narratives (De Silva 2001; Subasinghe et al. 2012; Wang et al. 2015), and we do not intend to dwell into the details here. However and importantly, one of the major changes being witnessed is the gradual yearly decrease in percent change per year of production volume (total and freshwater aquaculture) but not in the value of the produce as indicated from the detailed fisheries data (FAO 2016). This decreasing comparable trend in global aquaculture production was first alerted at the dawn of this millennium (De Silva 2001), and now has been confirmed more recently (World Bank 2013). As such paradigm changes in Chinese aquaculture are expected to reflect such trends, which in the long-term facilitative sustainability.

PARADIGM CHANGES

In this presentation we consider the paradigm changes relevant to the freshwater aquaculture sector in China to fall under a number of facets which we consider as direct and indirect evidences in support of our contention.

Direct evidence

The following are a summary of paradigm changes that have occurred in the last decades or so in respect of freshwater aquaculture in China that are believed to

Table 2 A summary of municipal, provincial and national decrees issued since year 2000 with a view to combating negative environmental influences that could arise from existing aquaculture practices; the relevant web link is given for each decree

Decree	Scope	Authority
Regulations for Lake protection[a]	Ban on the use of fertiliser for fish culture	Wuhan City, 2002
Regulations for Lake protection[b]	Prohibition on modification of water bodies (e.g. Isolation of bays, side arms with bunds/fences/netting)	Jiangsu Province, 2005
Regulations on the Administration of the Taihu River Basin[c]	Prohibition on modification of water bodies (e.g. Isolation of bays, side arms with bunds/fences/netting)	The State Council of P.R. China, 2011
	Advocate environmental friendly aquaculture practices; reduce pollution	
Regulations for Lake protection[d]	Ban on the use of fertiliser for fish culture;	Hubei province, 2012
	Prohibition on modification of water bodies (e.g. Isolation of bays, side arms with bunds/fences/netting)	
Regulations for Lake protection[e]	Ban on the use of fertiliser/feed for fish culture;	Shandong Province, 2012
	Prohibition on modification of water bodies (e.g. Isolation of bays, side arms with bunds/fences/netting)	
Regulations for water pollution control[f]	Ban on the use of fertiliser for fish culture;	Hubei province, 2014
	Prohibition on modification of water bodies (e.g. Isolation of bays, side arms with bunds/fences/netting)	
Water pollution control action plan[g]	Delimit given areas banning aquaculture in Lake and/or river	The State Council of P.R. China, 2015

[a] http://baike.baidu.com/link?url=PRHvGPNc5QsYEwdf6abTtgSm8UZLMxIORPArv0gJ4gOo6WfaBil-vfn3iOh-YzPnRbbE6MyNWRVrrGRMZ-pYfq (accessed 1 February 2017)

[b] http://baike.baidu.com/view/8142489.htm (accessed 1 February 2017)

[c] http://baike.baidu.com/link?url=cuUp86ueHESePjwRCQTU4MYk5Lb59S_VsVIdyrWkaeuiaP8YE1OTLzwax-e60MMZcpgWqbYNc9q2FIjIP7FrXa (accessed 1 February 2017)

[d] http://baike.baidu.com/view/9393733.htm (accessed 1 February 2017)

[e] http://baike.baidu.com/view/9725408.htm (accessed 1 February 2017)

[f] http://baike.baidu.com/view/13651454.htm (accessed 1 February 2017)

[g] http://www.gov.cn/zhengce/content/2015-04/16/content_9613.htm (accessed 1 February 2017)

contribute to attaining sustainability and environmental integrity in the long term.

- Decreased intensification of culture practices in large water bodies
- Rationalisation of farming systems
- Increasing emphasis on culture of species in conjunction with macrophytes and aquaponics
- Emphasis on the culture of indigenous species and reduced dependence on alien species, and
- Expansion of regulatory measures on fish farming effluent discharge(s) and chemical usage

Decreased intensification of culture practices in large water bodies

It has been the common practice to fertilise lakes and reservoirs in order to increase plankton production that consequently enabled higher rate of stocking of filter-feeding Chinese major carps, silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Aristichthys nobilis*) in particular. Often large water bodies were divided into sections using netting and dykes, and leased to local fisheries organisations (or fisheries bureaus) for promoting fish culture practices. In this manner an average production of nearly 1800 kg ha^{-1} $year^{-1}$ has been obtained through such culture-based fishery practices, a form of stock and capture in China (De Silva 2003; Wang et al. 2015).

However, enhancement practices such as fertilisation and modification of water bodies have resulted in eutrophication, unusual blooms of cyanobacteria and overall deterioration of water quality (Cai et al. 2012, 2013; Zhou et al. 2016). Such occurrences in large lakes have brought about much public concern and outcry (Qin et al. 2010; Zeng et al. 2013). In the above context the Chinese Government banned the use of fertilisers to enhance fish culture in lakes and reservoirs (Table 2), and curtailed the division of large water bodies into suitably sized pens (by netting and/or dam building) for purposes of aquaculture (Fig. 3). The improvements that resulted from these decrees were demonstrated by Lin et al. (2015) in their study on water quality in Wuhu Lake, Yangtze River Basin

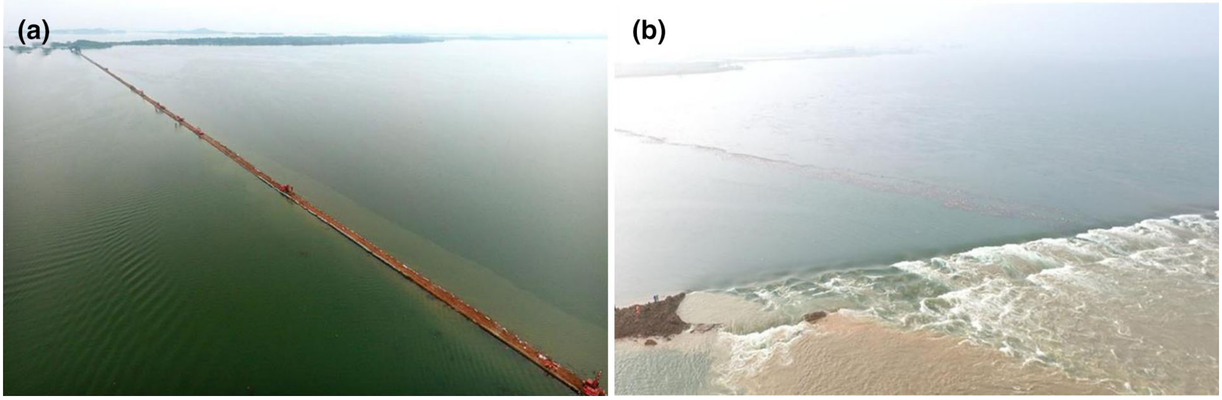

Fig. 3 **a** An example of Liangzi Lake was divided into two parts by a dike built in 1979, for one of the purposes of practicing aquaculture as two manageable units (http://ah.people.com.cn/n2/2016/0714/c227142-28664399-5.html; accessed 1 February 2017); **b** two parts of the lake were connected again by blowing up the dike in 2016 (http://mt.sohu.com/20160714/n459241897.shtml; accessed 1 February 2017)

(Table 3). Also there had been a significant reduction in the pen culture area (in the past these areas were highly fertilised to facilitate plankton production for feed for bighead carp and silver carp) and consequently production (Fig. 4). This is a good example of government intervention to improve environmental integrity at the expense of overall fish production, a distinct paradigm change in freshwater aquaculture practices in China.

It should also be pointed out that the approach to decrease the intensity of culture practices in large water bodies was also accompanied with corresponding changes to the optimisation of fish community structure that commenced as far back as 1998 (Liu and Cai 1998). This approach has been gradually evolving over the years with the aim to develop ecological fisheries in lakes and reservoirs (Liu and Cai 1998; Wang et al. 2006; Jia et al. 2013; Lin et al. 2015). The overall impact of this approach has been recently reviewed by Liu et al. (2017a, b) that emphasises primarily the improvements in water quality, biodiversity, fish quality and economic gains at the expense of total production.

Rationalisation of farming systems

One of the most traditional and long-standing aquaculture practices in China had been the rice–fish culture systems (Li 1988; Liu and Cai 1998; Edwards 2004). This practice is reckoned to be centuries old, and are gradually being adopted by many Asian countries (Hu et al. 2015). Rice–fish culture, now referred to as Integrated Rice Field Aquaculture (IRFA) (Ma et al. 2016) and earlier also referred to as Integrated Aquaculture–Agriculture (IAA), is mooted as an effective means rationalising water usage whilst increasing food production (Ahmed et al. 2014). Rice–fish culture is purported to have synergistic impacts on rice as well as on fish production in that it reduces the quantity of pesticides and fertilisers used for the rice and improves the growth rate of the fish, and reduces nitrogen and phosphorous in the effluent (Miao 2010; Lansing and Kremer 2011; Xie et al. 2011), and offers definitive economic advantages (Berg 2002; Ahmed et al. 2011).

However, in the past the main fish species used were the Chinese major carps (Li 1988). Ma (2016) reviewed the recent changes that have occurred in the IRFA systems in China, in the context of changes of the socio-economic *milieu* of the nation. In this analysis it was pointed out that the species used in rice–fish culture have changed from use of carps to high-valued species such as soft-shelled turtle (*Pelodiscus* spp.), crayfish (*Procambarus clarkii*) and mitten crab (*Eriocheir sinensis*) (Li et al. 2007; Miao 2010; Yan et al. 2014; Wang et al. 2015; Zhang et al. 2016). In addition, the IRFA practices have changed to provide suitable areas such as trenches around the rice paddy-growing area (Fig. 5a), thereby enabling increased production of the high-valued aquatic animals. Often macrophytes are planted in the trenches to encourage food organism for mitten crab and crayfish. For example, the crayfish production and the area of the IRFA in Hubei Province have increased significantly over the past 10 years (Fig. 6). All such changes not only contribute effectively to improving environmental integrity of the farming system(s) but also ensure economic viability. Comparable trends are also occurring in other countries that have adopted the IRFA as an economically viable and an ecologically desirable food production activity (Berg 2002; Ahmed et al. 2011; Hu et al. 2015).

Over the last two decades changes have been introduced into other traditional farming practices particularly in relation to pond aquaculture. For example, increasing emphasis has been laid on methods on reducing the nutrient

Table 3 Changes in water quality parameters from the periods of fish culture practices (mean ± SE) using fertilisers (2006–2007) and after the ban of use of fertilisers (2008–2011) in Wuhu Lake, Yangtze River Basin, China. All the parameters monitored the values in the post-ban period were significantly improved (modified after Lin et al. 2015)

Parameter (unit)	Pre-ban period	Post-ban period	p value
Transparency (cm)	65.8 (± 9)	111.2 (± 9.6)	0.002
TP (mg L^{-1})	0.077 (± 0.01)	0.045 (± 0.005)	0.038
TN (mg L^{-1})	1.14 (± 0.11)	0.84 (± 0.07)	0.004
Chlorophyll *a* (μg L^{-1})	21.45 (± 4.5)	11.58 (± 1.46)	0.025

Fig. 4 Trends in production (in ×1000 t) and farming area (in ×1000 ha) of pen culture practices in freshwater large water bodies in China from 2003 to 2015 (based on data from BFMA 2004–2016)

contents of aquaculture effluent such as through recirculation into artificial wetlands and the like. These aspects have been discussed in detail by Liu et al. (2017a, b), who described the many methods that are been used currently and the relative efficacies of each.

Increasing emphasis on culture of species in conjunction with macrophytes and aquaponics

In the past fish farming integrated with livestock such as pigs, chicken and ducks were common practice in rural China (Li 1987; Cheng et al. 1995). However, in the light of potential health risks and increasing emphasis on product quality related to marketing prospects, integrated fish farming is being gradually phased out (Edwards 2008). Moreover, the effluent discharge from integrated fish and livestock farming is thought to have been largely responsible for deterioration of water quality in some watersheds, such as in the Taihu Lake (119°52′32″ ∼ 120°36′10″E and 30°55′40″ ∼ 31°32′58″N), the third largest inland lake in China (Zhang et al. 2015; Zhou et al. 2016).

With the imposed ban on the use of fertilisers (Table 2) to enhance production in culture-based fisheries (CBF) of plankton feeding Chinese major carps, in particular silver and big head carps, in Lakes and reservoirs, the affected fisheries bureaus that managed these practices had to introduce changes to maintain the economic viability. These changes include the encouragement of adjacent wetlands been used for shallow ponds suitable for mitten crab culture with macrophytes for example in Taihu Lake (Cai et al. 2012, 2013), Hongze Lake (Wang et al. 2016a, b) and Honghu Lake (Feng et al. 2010), which is the third, fourth and seventh largest freshwater lakes in China, respectively. With such strategic changes the economic viability and the employment security of the respective bureau personnel are often assured, and the environmental

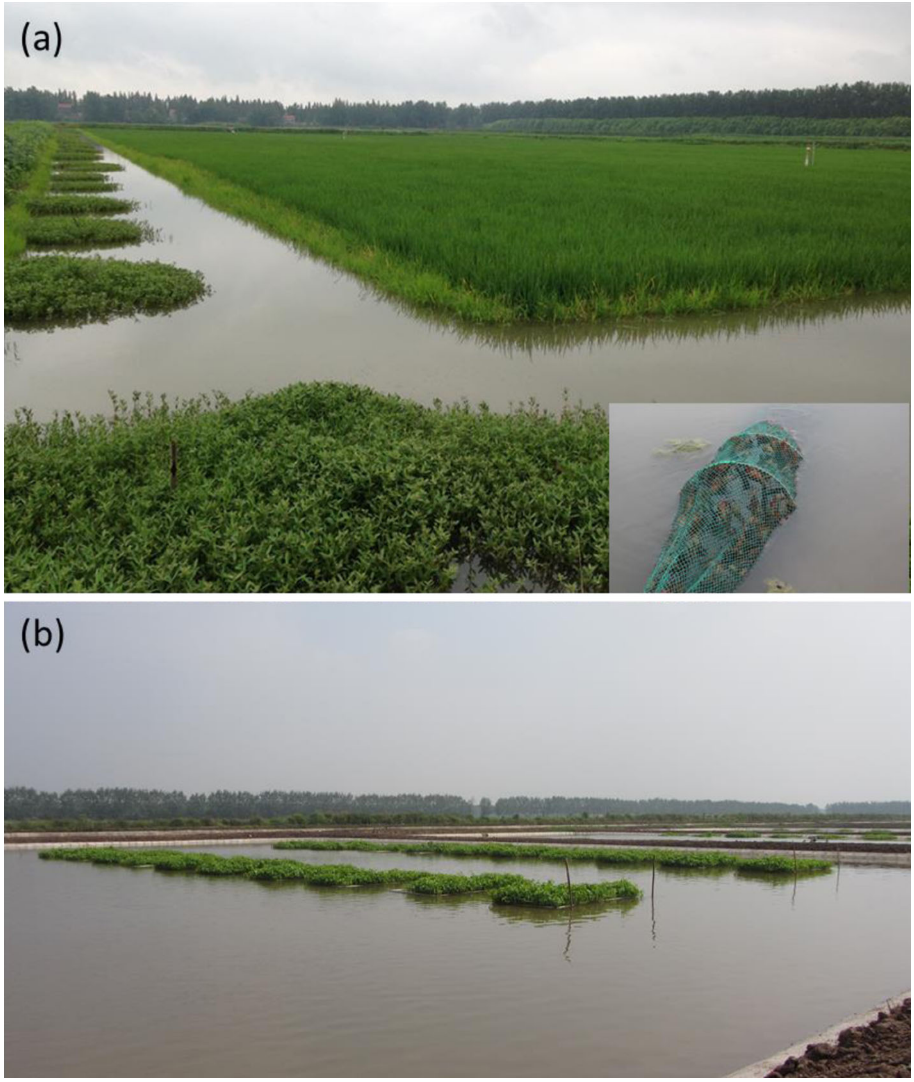

Fig. 5 **a** A typical rice–crayfish/rice–fish farming system outlay in Hubei Province, China; the outer trench maintained around 1 m is used for crayfish/fish/mitten crab aquaculture, the inset shows haul of crayfish, and **b** a model of an aquaponics culture system; the plant beds consist of water spinach and are used in conjunction with the culture of Chinese major carps in Gongan County, Hubei Province, China

integrity of large lake ecosystems is improved, and perhaps over a period of time restored to original status (Feng et al. 2010; Cai et al. 2013; Wang et al. 2016a, b).

There is also an increasing emphasis on the use of aquaponics in aquaculture practices, where beds of floating plants are introduced as a tool for stripping nutrients, which also supplements the profitability (Table 4). It is also evident from Table 4 that the aquaponics model can be used irrespective of the fish species/species group cultured, and is effective with both plankton feeding and carnivorous species. Use of aquaponics models (Fig. 5b) with different plants is becoming popular as it provides a significant income from the harvest of the aquatic plants in addition to the fish and are encouraged by authorities (Chen et al. 2010; Vance 2015).

Emphasis on the culture of indigenous species and reduced dependence on alien species

Aquatic species have been translocated across watersheds and geo-political boundaries for varying purposes, including for aquaculture (Welcomme 1988; DIAS 2004). Aquaculture is often criticised for translocations that are purported to have resulted in loss of biodiversity and thereby brought about ecosystem instability and hence sustainability (Moyle and Leidy 1992; Naylor et al. 2001).

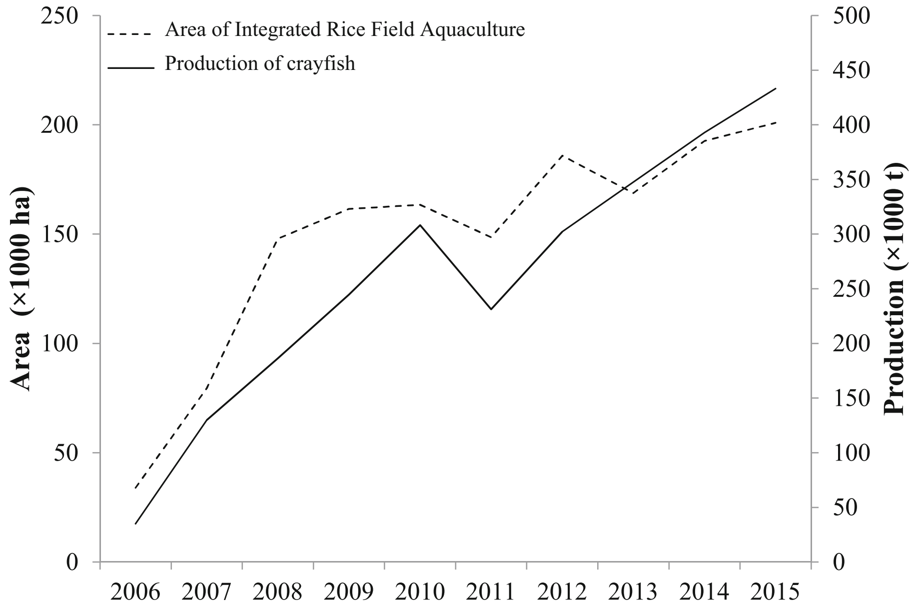

Fig. 6 Trends in the area of Integrated Rice Field Aquaculture and the production of crayfish in Hubei Province, the predominant province for rice–crayfish co-culture in China (based on data from BFMA 2007–2016)

Table 4 A summary of different types of aquaponics systems used in conjunction with pond culture and indication of removal rates of selected nutrients. WS, water spinach (*Ipomoea aquatic*, Convolvulaceae); Lettuce, (*Lactuca sativa*, Asteraceae); GC, Grass carp; C_rC, crucian carp; BHC, bighead carp; PL, Pond loach; LBB, Largemouth black bass; MF, mandarin fish; SC, Silver carp; C_mC, Common carp

Aquaponics system species used		Removal rate (%)		Major province	Authority
Plant	Fish	TN	TP		
WS	GC, C_rC, BHC	9.04–36.56	33.33–45.1	Jiangsu	Chen et al. (2010)
WS	Tilapia	6.82–47.2	43.01–85.59	Jiangsu	Song et al. (2011)
WS	PL	41.25–54.67	32.93–37.80	Zhejiang	Zhang et al. (2012)
Lettuce	LBB, MF, SC, BHC	8.12–36.20	33.33–46.15	Guizhou	Guan et al. (2012)
WS	C_mC	54.7–56.9	91.4–92.6	Shandong	Zhang et al. (2015)

However, such critiques have failed to provide explicit evidence in regard to the negative interactions of exotics in most instances (De Silva et al. 2004) and the fact that in some instances such negativity could be biased by cultural attitudes (De Silva 2012).

China is purported to have a very rich and a diverse finfish fauna (Kang et al. 2014; Xiong et al. 2015). Equally, China is also reputed to have the largest number of alien finfish species, with the great bulk of it introduced through the aquarium trade and or for aquaculture (Xiong et al. 2015). Chinese aquaculture has been much impacted by alien species (Liu and Li 2010). The aquaculture production of some alien species exceeded those in their native countries, such as the Nile tilapia (*Oreochromis niloticus*), largemouth black bass (*Micropterus salmoides*), channel catfish (*Ictalurus punctatus*) and freshwater crayfish (Liu and Li 2010; Lin et al. 2013). However, in the context of the drive towards sustainability and environmental integrity there is a trend to curtail fresh introductions for aquaculture purposes (Fig. 7a) in China, and the introduction of number of alien species has decreased markedly, since the upsurge in the 1980s, the period when there was a push to increase aquaculture production with little concern for environmental consequences (Xiong et al. 2015).

Linked to the above strategy is an increasing realisation for risk management in respect of alien species (Lin et al. 2013), with a view to minimising potential negative impacts on biodiversity. These recent initiatives in Chinese

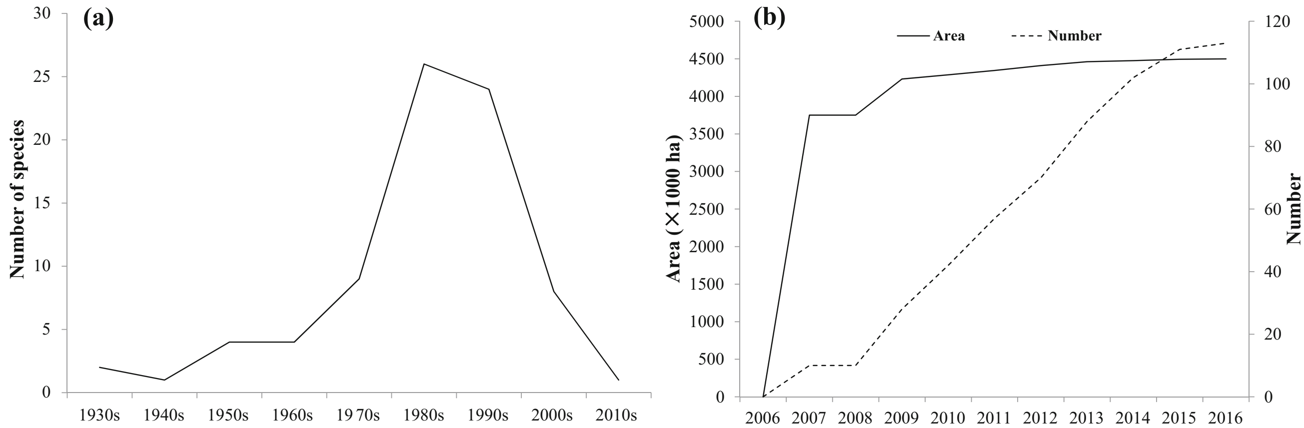

Fig. 7 **a** Trend in number of non-native freshwater fish species introduced into China for aquaculture purposes (updated from Xiong et al. 2015), and **b** trends in the total area (× 1000 ha) and the number of National Aquatic Genetic Resources Reserves (NAGRR) established in freshwater lakes in China from 2006 to 2016

Table 5 Average values (in USD per t) for five high-valued and five low-valued cultured species over the period 2009–2013, cultured in China (based on FAO FishStatJ 2016)

High-valued species	USD t^{-1}	Low-valued species	USD t^{-1}
Yellow catfish	1300	Common carp	1140
Paddy eel	2610	Crucian carp	1090
Mandarin fish	9310	Silver carp	1260
Mitten crab	6960	Bighead carp	1280
Soft-shell turtle	5190	Grass carp	1260

aquaculture, such as an increasing emphasis on indigenous species conforming to the general global trend to minimise and/or to curtail dependence on alien species, are major paradigm changes evident in aquaculture developments in the recent decades. We expect such trends to continue well into foreseeable future in Chinese aquaculture developments.

Since the dawn of the new millennium, with increasing emphasis on environmental integrity and sustainable development globally, freshwater aquaculture in China has made a concerted effort to uplift culture practices on selected, often high-valued, indigenous species. Accordingly, for example there has been a significant upsurge in the production of finfish species such as mandarin fish (*Siniperca chuatsi*), yellow catfish (*Pelteobagrus fulvidraco*) and paddy eel (*Monopterus albus*), and other aquatic species such as the mitten crab and soft-shelled turtle, all relatively high-valued species (Table 5) over the last decade or more. The production of paddy eel, mandarin fish, catfish, mitten crab, soft-shelled turtle have increased from 125 336, 149 886, 54 819, 374 810, 143 816 tonnes in 2003 to 367 547, 298 057, 355 725, 823 259, and 341 588 tonnes in 2015, respectively, corresponding to 1.93, 0.99, 5.49, 1.2 and 1.38 times increase over the 12-year period (BFMA, 2004–2016; Wang et al. 2015). The emphasis on the culture of relatively high-valued species tends to compensate for reduction in culture area of certain practices (see Fig. 4) and associated production volumes to retain economic viability.

The curtailment of introduction of alien species for aquaculture in China, together with increasing emphasis on the culture of indigenous species, in particular high-valued species, has gone hand in hand, with the trend of increasing the number and the total area of National Aquatic Genetic Resources Reserves in freshwater lakes in the country (Fig. 7b). Any form of aquaculture in the reserves is prohibited, but accessibility to germplasm for improving genetic diversity of cultured stocks is permitted. Such paradigm changes in respect of Chinese aquaculture and species conservation often go unnoticed by critiques of the sector.

Expansion of regulatory measures on fish farming effluent discharge(s) and chemical usage

In central Yangtze River basin, freshwater lakes have undergone large-scale reclamation, especially from the 1950s to the late 1970s (Fang et al. 2005), resulting in

Table 6 A summary of maximum permissible limits of selected parameters in aquaculture effluents issued by the Ministry of Agriculture, P. R. China (SC/T 9101-2007); for comparison levels issued by Global Aquaculture Alliance (GAA) and International Finance Corporation (IFC) for the same parameters (Boyd and Gautier 2000)

Parameter	Unit	China, 2007	GAA, 2002		IFC, 1998
		Discharge	Initial	Target	Discharge
TSS	mg L^{-1}	≤ 50	≤ 100	≤ 50	≤ 50
DO	mg L^{-1}	–	≥ 4	≥ 5	–
pH	–	6.0–9.0	6.0–9.5	6.0–9.0	6.0–9.0
COD_{Mn}	mg L^{-1}	≤ 15	–	–	–
BOD_5	mg L^{-1}	≤ 10	≤ 50	≤ 30	≤ 50
Zn	mg L^{-1}	≤ 0.5	–	–	–
Cu	mg L^{-1}	≤ 0.1	–	–	–
TP	mg L^{-1}	≤ 0.5	≤ 0.5	≤ 0.3	–
TN	mg L^{-1}	≤ 3.0	–	–	–
Sulphide	mg L^{-1}	≤ 0.2	–	–	–
Total rest N	mg L^{-1}	≤ 0.1	–	–	–

substantial loss of lakes and wetland areas, and associated ecological consequences such as eutrophication, decline in biodiversity and overall degradation of health of lakes (Jin et al. 2005; Zhao et al. 2005; Fang et al. 2006; Du et al. 2011). Driven by economic interests, large amount of reclaimed areas have been used for pond aquaculture. Effluents from pond aquaculture typically are rich in organic matter and nutrients such as nitrogen and phosphorus and most of them originate from fertilisers and feeds applied to increase production of the cultured species (Cai et al. 2012, 2013). There have been a few studies to document the impacts on different types of water bodies around the world in regard to the environmental impacts of aquafarm effluent on receiving waters and or relevant catchments (Xie et al. 2004; Bartoli et al. 2007; Thomas et al. 2010; Herbeck et al. 2013; Molnar et al. 2013).

In the recent past rather unfortunate events occurred for instance in Taihu Lake, the third largest freshwater lake in China, when unprecedented levels of blue–green algal blooms occurred and impacted on the biota, the usability of the water for domestic purposes and the lake environment as a whole (Qin et al. 2007, 2010). These comparable events in waters elsewhere in China prompted the government to introduce stringent environmental guidelines over last decade, particularly with regard to the use of chemicals in freshwater aquaculture. The major paradigm changes that have been introduced in order to minimise the impacts of aquaculture effluents on watersheds included for example the curtailment on the use of fertilisers to improve plankton production associated with culture-based fisheries and, reduction in the areas devoted to pen culture that was dealt with earlier. Such paradigm changes went hand in hand with the introduction of more stringent regulations on the discharge levels of selected nutrients from aquaculture practices and application of chemicals that are purported to be environmentally harmful.

In Table 6 the permitted discharge values of selected nutrients in Chinese aquaculture are compared with corresponding levels issued by the Global Aquaculture Alliance, a major body that audits aquaculture practices worldwide and the International Finance Corporation which provides financial support for aquaculture development world over. It is evident that aquaculture authorities in China use many parameters and in some instances the former are much more stringent than those used by the other two agencies.

Quantitative data on the use of chemicals in freshwater aquaculture practices in China are relatively difficult to ascertain. It is noteworthy that the authorities in China are expanding the list of prohibited chemicals in aquaculture (Table 7). These increased restrictions are relatively new and also complements that endorses compliance with global certification standards (FAO 2011a) for aquaculture. However, an indirect index that could be deduced from the information available is the percent value of the chemicals used in aquaculture in relation to the value of freshwater aquaculture production (Fig. 8). It is evident from Fig. 8 that there is declining trend from 2007 onwards indicative of the reducing usage of chemicals in Chinese freshwater aquaculture.

Indirect evidences

The primary and major line of indirect evidence comes from an evaluation of exports of cultured products to developed countries, in a climate where the importing-developed countries impose increasingly stringent quality control standards and protocols. Seafood is among the most

Table 7 List of chemicals banned to be used in aquaculture practices in Circular No. 193 as issued by the Ministry of Agriculture, P.R. China, 2002, and list of chemicals that are prohibited for use in aquaculture practices in Professional Standard: NY5071-2002 as issued by the Ministry of Agriculture, P.R. China, 2002

Circular of the Ministry of Agriculture, P.R. China (No. 193): Circular on issuing the detailed list of banning to use veterinary medicine and other chemical compound on animal food commodity	Professional standard of P.R. China (NY5071-2002): Guideline of fisheries chemical usage in producing non-pollution food
Clenbuterol; Salbutamol; Cimaterol; Diethylstilbestrol; Zeranol; Trenbolone; Mengestrol acetate; Chloramphenicol; Chloramphenicol succinate; Dapsone; Furazolidone; Furaltadone; Nifurstyrenate sodium; Sodium nitrophenolate; Nitrovin; Methaqualone; Lindane; Camahechlor; Carbofuran; Chlordimeform; Amitraz; Antimony potassium tartrate; Tryparsamide; Malachite green; Pentachlorophenol sodium; Calomel; Mercurous nitrate; Mercurous acetate; Pyridyl mercurous acetate; Methyltestosterone; Testosterone; Propionate; Nandrolone; Phenylpropionate; Estradiol; Benzoate; Chlorpromazine; Diazepam; Metronidazole; Dimetronidazole	Fonofos; BHC (HCH); Benzene; Hexachloride; Lindane; Gammaxare; Gamma-BHC Gamma-HCH; Camphechlor (ISO); DDT; Calomel; Mercurous nitrate; Mercuric acetate; Carbofuran; Chlordimeform; Anitraz; Cyfluthrin; Flucythrinate; PCP–Na; Malachite green; Tryparsamide; Antimonyl potassium tartrate; Sulfathiazolum ST; Norsultazo; Sulfaguanidine; Furacillinum; Nitrofurazone; Furazolidonum; Nifulidone; Furanace; Nifurpirinol; Chlorampennicol; Erythromycin; Zinc bacitracin premin; Tylosin; Ciprofloxacin (CIPRO); Avoparcin; Olaquindox; Fenbendazole; Diethylstilbestrol; Stilbestrol; Methyltestosterone; Metandren

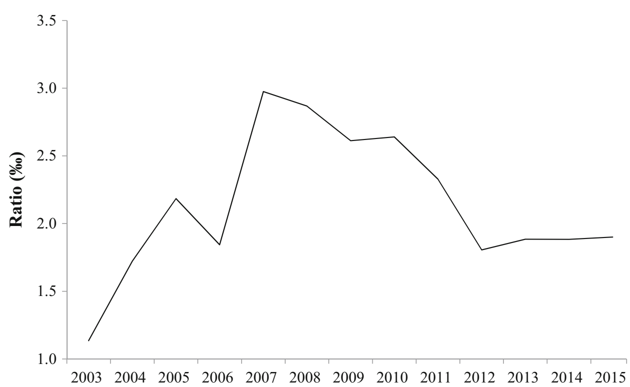

Fig. 8 Trend in the ratio of the value of chemical used in freshwater aquaculture to the value of freshwater aquaculture in China from 2003 to 2015 (based on data from BFMA 2004–2016)

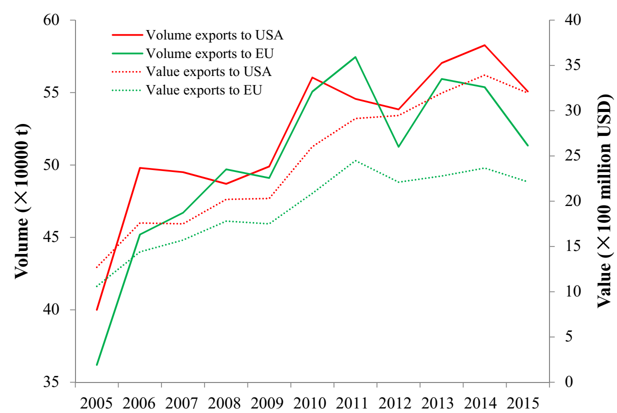

Fig. 9 Trends in the total volume exports to USA and EU, and the corresponding values in US Dollar from 2005 to 2015 (BFMA 2005–2015)

traded commodities globally and in 2010, 38% of all fish produced were exported (FAO 2014). World trade in fish and fish products increased from US$ 8 billion in 1976 to $ 128 billion in 2012 (World Bank 2013). Developing countries are at the forefront of the global seafood trade with more than 54% of fishery exports by value and 60% by live weight equivalent. As evident in Fig. 2 China continues to be a dominant player in both import and export trade of seafood.

The trends in the export volume and value of selected, high-valued, cultured commodities were shown previously. It should be noted that in view of the increasing per capita food fish consumption in China the country is also becoming a major importer of fish (FAO 2014). At present export markets could be sustained only if the production processes and the product quality conform to international standards, such as HACCP, and are traceable and are in compliance with global certification guidelines (FAO 2011a). In this context the changes in the volume and value of exports to two of the most stringent global markets viz. US and the European Union are shown in Fig. 9. Such sustained increase in export volume is indirect evidence that aquaculture practices in China are in compliance with global standards.

CONCLUSIONS

Fish have been an important component of our diet throughout our evolutionary history, and is even thought to have contributed to the development of the human brain, thereby making us what we are (Crawford et al. 1999; Cunnnane and Stewart 2010). In the modern era fish consumption has shown a significant increase, both in the developing world and the developed world, perhaps driven by different entities; in the developing world fish may

provide a more affordable and readily available food item, particularly for rural populations, whilst in the developed world it may be driven by the perceived health benefits fish are known to offer (Sastry 1985; Calder 2004; Siriwardhana et al. 2012). Fish is known to account for nearly 30% of animal protein intake, being significantly higher among rural communities in developing countries (FAO 2011b).

Until just over a decade ago, the predominant fish supply was hunted—i.e. was from the capture fisheries, and its predominance shifted to a farmed origin, like our other staple only a decade and half back (De Silva 2012).

In the wake of plateauing of the fish supplies from the marine capture fisheries, the widening gap between demand and supply was mainly met with aquaculture, which in the last three decades or more registered a mean annual rate of growth of nearly 6%, the highest for any primary production sector globally (Subasinghe et al. 2012). This sustained growth in the sector over these decades was dominated by China, which currently account for nearly 70% of global aquaculture production. However, aquaculture being a newly emerged sector, referred to by some as "the new kid on the blocks" was subjected to a higher degree of scrutiny by the public and was subjected to major critiques on environmental and resource usage grounds (De Silva and Davy 2010). So was the aquaculture sector in China.

As such we encounter the dilemma of meeting a food need and ensuring food security and maintaining environmental integrity and strive towards long-term sustainability of the sector. It is in the latter regard that the aquaculture sector in China, the mainstay of global aquaculture, has endeavoured to make significant paradigm changes in the practices thereof with a view attaining long-term sustainability. In this paper we have attempted to highlight these significant paradigm changes, driven by governmental regulations as well as market forces, but which often go unnoticed by critiques of the sector.

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