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Review

Aquaculture: Relevance, distribution, impacts and spatial assessments – A review

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ABSTRACT

Aquaculture is the fastest-growing animal food production sector worldwide and is becoming the main source of aquatic animal food in human consumption. Depletion of wild fishery stocks, rising global populations, continuing demand for food fish, and international trade has driven aquaculture's tremendous expansion during the last decades – in terms of production volume and value. Farmed aquatic products are among the most widely traded commodities in the world food economy. Aquaculture has mainly been developed in valuable fertile coastal environments and caused large-scale land use changes, destruction and loss of coastal wetlands and pollution of waters and soils. This article presents an overview of the relevance, current status and distribution of aquaculture in global and regional scales and depicts its key environmental impacts. Quantitative assessment of the spatial extent, distribution, and dynamics of aquaculture is of utmost importance for a sustainable management of our planet's land and water resources ensuring human and environmental health. The article points to the potential of remote sensing to detect, map and monitor large-scale aquaculture areas and gives a complementary review of satellite remote sensing studies addressing the observation of aquaculture including site selection, site detection and monitoring of related impacts on the environment.

1. Introduction

Fish is one of the most traded food commodities worldwide (Allison, 2011) and the main source of valuable animal protein in many regions of the world (Béné et al., 2015; Toufique and Belton, 2014). With stagnating global capture fisheries production, growing human population, and continuing demand for food fish, the production of safe and quality aquatic food will be a great concern for global food security in the next years (FAO, 2011; Natale et al., 2012; OECD/FAO, 2013; Toufique and Belton, 2014; UN, 2011). Over the last 30 years, global production of cultivated aquatic food increased rapidly and has driven aquaculture to be one of the fastest-growing animal-food-producing sectors (Allison, 2011; UN, 2011). Today aquaculture accounts for almost half of the fish consumed worldwide (FAO, 2014; Troell et al., 2013). Forecasts on food security indicate that aquaculture has great potential to produce more fish in the future and compensate stagnating supplies from capture fisheries (Natale et al., 2012). The Food and Agriculture Organization of the United Nations (FAO) Director-General José Graziano da Silva declared that the human health and future food security highly depends on how we treat the "blue world" (UN, 2014). Roughly 39 percent of all fishery production being exported are used for human consumption (FAO, 2012). As the fishery sector operates in an increasingly globalized environment (FAO, 2014) it is expected that the share will further expand up to 25 percent in the period 2012–2021 (FAO, 2012). On a global scale, the average per capita apparent fish consumption almost doubled from an average of 9.9 kg in the 1960s to 18.9 kg in 2010 (FAO, 2014) and fish accounts for 17 percent of animal-derived and 6.5 percent of total protein consumption (Troell et al., 2014b). From a human health point of view, future development of aquaculture will be of utmost importance in terms of global protein supply, economic trade, and food security (Beveridge et al., 2013). Statistics from the most updated global capture and aquaculture database from the FAO Fisheries and Aquaculture Department (1950–2013) prove a global trend of rapid aquaculture development. In the period from 1983 to 2013, capture fisheries production increased from 71.1 to 92.6 million tonnes. Aquaculture production meanwhile expanded from 6.2 to 70.2 million tonnes (FAO, 2015, 2012;

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The World Bank, 2013) at an average rate of 8.6 percent per year (FAO, 2014), which exceeded even the rates of poultry (4.6%), pork (2.2%) and beef (1.0%) over the same period (Troell et al., 2014b). From 1980 to 1990, average annual expansion rate was highest at 10.8 percent and slowed down slightly to 9.5 percent in the period from 1990 to 2000 and 6.1 percent for 2000–2013.

More than 600 different animal species (Troell et al., 2014b) are produced in aquaculture systems comprising finfish (e.g. catfish, trout, carp, tilapia, salmon), crustaceans (shrimp, prawn, crabs, freshwater crayfish), and molluscs (e.g. mussels, oysters and clams) (FAO, 2014). Aquatic photosynthetic organisms are also being recorded in the FAO global database on aquaculture production statistics, but mostly listed separately in the global reports. Aquatic photosynthetic organisms are not included in the statistics shown in this paper since the focus is on livestock species only.

Regarding the total amounts of yearly output volumes, world aquaculture production more than doubled from 32.4 million tonnes in 2000 to 70.2 million tonnes in 2013 (FAO, 2014). Aquaculture also contributes an increasing share to the total global fishery production output (Bondad-Reantaso and Subasinghe, 2008). Its share was only 13.4 percent in 1990 but expanded to 25.7 percent in 2000 and received a record of 43.1 percent share of the total 162.8 million tonnes of fish produced worldwide in 2013 (FAO, 2014). Projections by the World Bank for the year 2030 indicate a rise of global fish supply up to 187 million tons with aquaculture equaling global capture production (The World Bank, 2013). The FAO and Organization for Economic Co-operation and Development (OECD) state that capture fisheries output will rise at lower rates with a projected 5 percent growth by 2022 while the output from aquaculture will increase by 35 percent. Thus, it can be foreseen that aquaculture will be the main source of fish for human consumption in the next years (OECD/FAO, 2013; Toufique and Belton, 2014). However, further growth of global aquaculture production will pose a challenge to the sustainable management of our planet's resources and human development. This is a global issue and particularly true for people in rural coastal areas in developing countries (Beveridge et al., 2013; Hossain et al., 2013) where aquaculture provides high nutrition supply potential and is the main income source for poor people (Ahmed and Lorica, 2002).

In the light of a projected increase of world population to 9.6 billion in 2050 (UN, 2013), fish production from aquaculture can make an important contribution to global food security needs and provide human population with valuable protein (Béné et al., 2015; Natale et al., 2012; Naylor et al., 2000). Aquaculture can balance the stagnating production volumes from capture fisheries but also reduce the pressure on the earth's marine resources (Lee and Yoo, 2014). A drawback of aquaculture is its dependence on terrestrial crop and wild fish for feeds (Troell et al., 2014b). As a consequence, growing production output from aquaculture farming has also resulted in a net increase in total demand for fish resources (mainly small trash fish from capture fisheries) being used in aquaculture. Fishmeal and fish oil (mainly produced from small pelagic fish and bycatch) are such sources and widely applied as valuable, complementary or complete nutritional feed. Tacon and Metian (2008a) estimated that 68 percent of global fishmeal and 90 percent of fish oil were utilized by the aquaculture sector.

1.1. Inventory of aquaculture areas

For more than 65 years, the FAO has collected national data on catch and other fishery statistics which are generally submitted by national ministries and institutions. However, the first aquaculture production yearbook was published in the year 2000 and it has only been since 2003 that the FAO carried out a backward revision to provide the first separated capture and aquaculture datasets for the period 1950–2001 (Garibaldi, 2012). Statistical data on aquaculture production is made available by the FAO Fishstat software (FAO, 2015), a global database which allows for the analysis of trends at global, regional and national scales (see Fig. 1). Although there are other attempts to provide valuable database information on fisheries and aquaculture (e.g. the project www.seaaroundus.org), these databases also use previous FAO data as a starting point. Global aquaculture statistic databases should be evaluated with care as there are indications that some data submitted by the FAO member countries are of questionable quality. There are manifold reasons for this, such as over-reporting of production volumes from some countries (Pauly and Froese, 2012), underestimation of aquaculture volume due to large amounts produced by small-scale farmers in Asia and other regions entering domestic and regional markets which are poorly presented in production and trade statistics (Allison, 2011). Inventory and monitoring of aquaculture on a global scale is a challenging task and requires time, effort and significant costs (Marini et al., 2013). Therefore, the question arises which methods and data would be capable to assist or improve present available global statistics on aquaculture production? How can the status and dynamics of aquaculture be observed over large areas around the globe? Since aquaculture has been developed widely around the globe there is an urgent need not only to have global statistics on production volumes and values but more importantly to identify and assess the spatial distribution of aquaculture at local, regional and global scales. Such information is valuable to analyze the increasing pressure on ecosystems and its related environmental impacts.

1.2. Purpose of this paper

This paper starts with a brief background on the diversity of global aquaculture systems status, dynamics and aquaculture at different spatial scales. We discuss the most relevant environmental changes and impacts which can be directly or indirectly associated to aquaculture farming. We then introduce studies that used satellite data and methodologies to detect, monitor and analyze aquaculture areas in different regions around the globe. Through our paper we illuminate the relevance of aquaculture in terms of environmental and human health and the needs to assess spatial information of this fast growing food sector. The purpose of this paper is to:

- give an insight of the main farming environments, practices and main species in global aquaculture
- highlight the current status and dynamics of aquaculture in global and regional scales and its economic relevance in the global food trade system
- summarize the major direct and indirect environmental impacts associated with aquaculture activities
- elucidate the potentials and opportunities of Earth Observation for the application in aquaculture
- provide a comprehensive overview of recent studies which use remote sensing technologies to map or monitor aquaculture areas

2. Global aquaculture systems: environments, practices and main species

The FAO defines aquaculture as the farming of aquatic organisms such as fish, crustaceans, molluscs and aquatic photosynthetic organisms. Aquaculture farming implies individual or corporate ownership of the stock being cultivated and typically involves the enclosure of a species in a secure system (Naylor et al., 2000; Troell et al., 2013). The farming methods are very diverse and generally

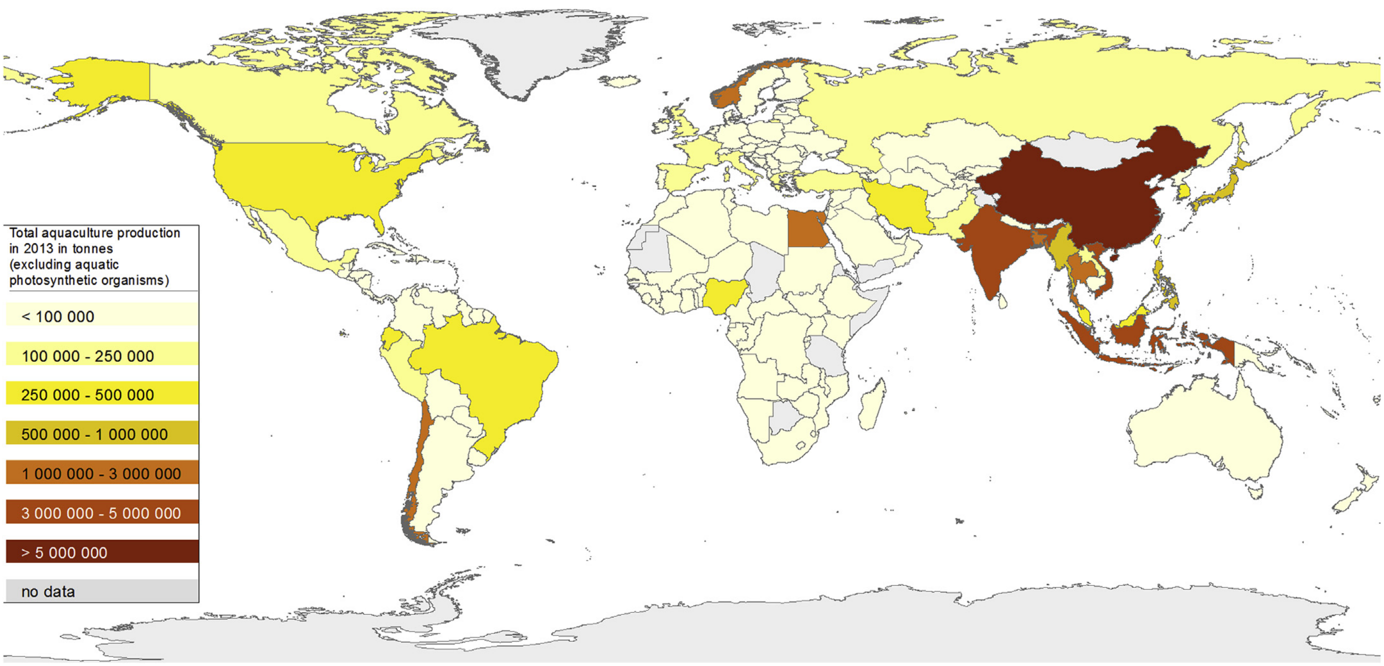

Fig. 1. Map of global aquaculture production in 2013. Data source: FAO (2015).

include interventions such as regular stocking, feeding, and protection from predators (Campbell and Pauly, 2013; FAO, 2002) to enhance production.

2.1. Environments

Aquaculture can be classified into different culture environments that are used for the farming of aquatic organisms (FAO, 2002): (1) Freshwater aquaculture refers to the cultivation in freshwater such as reservoirs, rivers, lakes, canals, and groundwater; (2) Brackish water aquaculture systems are generally installed in estuaries, bays, lagoons and fjords; (3) Mariculture (marine aquaculture) is understood as the cultivation in saltwater/seawater, such as fjords, inshore and open waters and inland seas.

The total production output from aquaculture (excluding aquatic photosynthetic organisms) was 70.2 million tonnes in 2013, of which 43.9 million tonnes were produced in freshwaters, 20.4 million tonnes in marine waters, and 5.9 million tonnes in brackish water (FAO, 2015). Freshwater is by far the main source for the cultivation of aquatic organisms with 63 percent (FAO, 2015) of the world aquaculture production (excluding aquatic photosynthetic organisms) being produced in freshwater systems in 2013 (see Fig. 2).

Only 3 percent of the Earth's water is freshwater and 0.3 percent of that is found in surface waters such as lakes, rivers or swamps (Bostock et al., 2010). Looking at the already scarce global freshwater resources, aquaculture farming has a great impact on future water management since it aggravates freshwater scarcity and water quality deterioration through increased water withdrawal (Verdegem and Bosma, 2009) and pollution (Cao et al., 2007; Peng et al., 2013). This adversely affects human health and natural environments, particularly low lying coastal areas which are the most favorable areas for aquaculture activities (Primavera, 2006) and thus highly affected. However, these areas are already under threats caused by droughts, rising sea levels (Smajgl et al., 2015) and salinization (Tho et al., 2007).

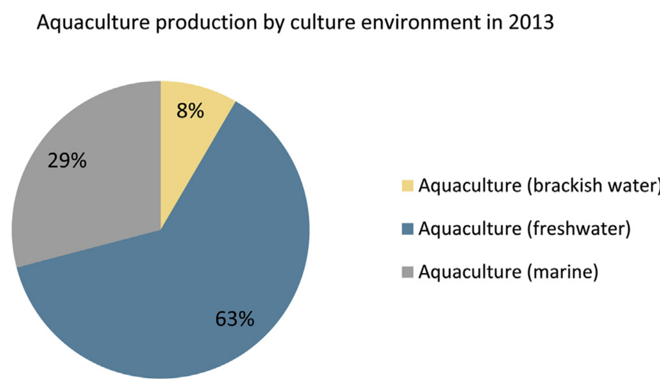

Fig. 2. Different aquaculture environments and its shares to the total global aquaculture production (excluding aquatic photosynthetic organisms) in 2013. Source: FAO (2015).

2.2. Practices

Farming production comprises different types of aqua-ecosystems, including rice fields, ponds, cages and pens, raceways, tanks, and recirculating systems (Bostock et al., 2010; Troell et al., 2014b, 2013). Rice fields are one of the oldest type of aqua-ecosystem (see Fig. 3a) and predominantly developed in seasonally flooded deltas in Asia (Ahmed, 2013; Hambrey et al., 2008). Aquaculture ponds are natural or artificial impoundments forming closed water bodies (see Fig. 3c–f) and mainly used for freshwater (rain-fed, irrigated, flow-through) or brackish water aquaculture (Hambrey et al., 2008; Naylor et al., 2000).

Raceways or tanks (running water ponds) are artificially constructed units (straight-sided or round), often surrounded with concrete sides and bottom, with either running water or water flow systems. Cages or net pens are mostly floating or suspended enclosures and located in natural aquatic systems such as lakes, rivers (see Fig. 3b), ocean or artificial water bodies. The development of various production practices in different regions contributed to the

Fig. 3. Images of different aquaculture systems: (a) mixed rice/shrimp field, (b) Fish net in saline waters of a coastal mangrove area, (c) earthen shrimp pond, (d–f) concrete ponds for intensive shrimp farming. Source: Photos taken from the Mekong Delta (a–c) and Red River Delta in Vietnam (d–e) and the Yellow River Delta (f), Shandong Province, China. Image source: M. Ottinger and M. Wolters. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

large diversity of the aquaculture sector (Lazard et al., 2010), ranging from smallholder ponds in Asia and Africa with low investment requirements to commercial, highly industrialized offshore cage farms in Norway and Chile with immense input of feeds and use of advanced technologies (Bostock et al., 2010). Aquaculture systems also vary among the degree of production intensity and can be categorized into extensive, semi-intensive, and intensive systems. Extensive systems (e.g. mussel farming) are characterized by minimal inputs and offer relatively low yields. With increasing intensification (see Fig. 4), additional feed is required to maintain higher stocking rates (semi-intensive systems: e.g. shrimp farming) or as in the case of intensive aquaculture farming (e.g. salmon or tilapia farming) where systems rely to a large extent or even completely on supply of external inputs and technologies. While extensive systems are very close to natural fisheries, intensified systems are highly resource demanding as they depend on large amounts of supplementary or complete feeds (Folke et al., 1998; Troell et al., 2013). Intensification also implies higher costs for investment and management - be it for the construction of advanced aquaculture technologies (e.g. industrial pond farms, raceways or offshore cage farms) or be it the maintenance (e.g. costs for feed inputs; fuel or electricity for aeration) of such highly stocked systems (Boyd, 1998; Natale et al., 2012; Tacon and Metian, 2008b).

2.3. Main species

The large variety of culture environments, farming intensities and spectrum of cultured species have made aquaculture one of the most complex and diverse food production sectors with a wide range of different systems and technological input. Freshwater fish is the most cultivated aquatic animal group worldwide and account for 56 percent of the total production output from aquaculture (FAO, 2015; Troell et al., 2014b). The second and third largest groups

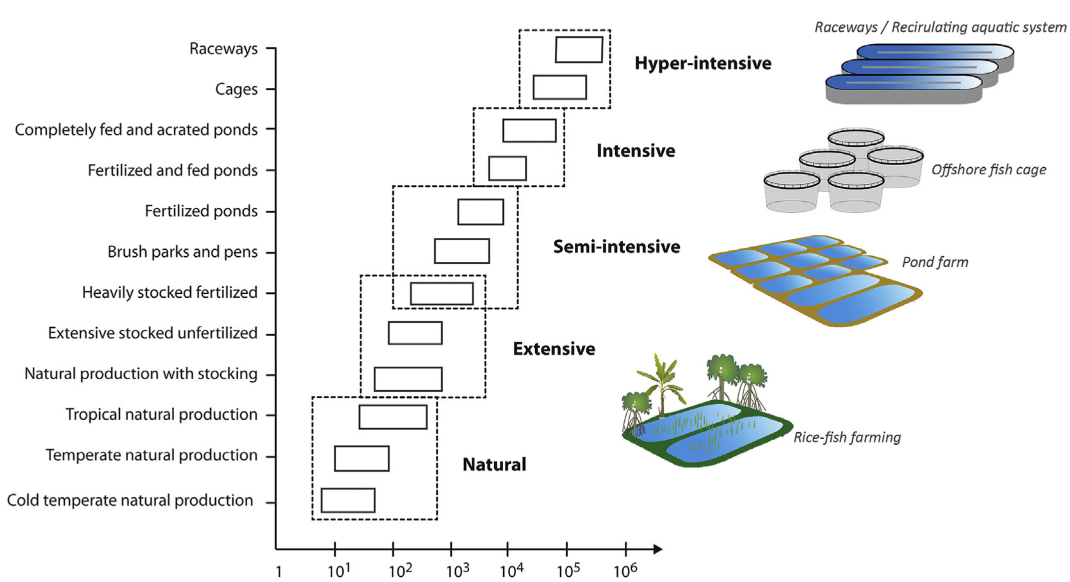

Fig. 4. Production from different aquaculture systems. Figure modified according to Welcomme and Bartley (1998).

are molluscs and crustaceans which contribute 23 percent and 10 percent, respectively, followed by diadromous fish (7 percent) and marine fish (3 percent) (FAO, 2015). Fig. 5 illustrates the geographical distribution of the top 10 aquaculture species which account for around 53 per cent of the total global output volume and 78% by value. Asia and China in particular clearly dominate the production of the 10 most produced aquaculture species.

3. Status and dynamics at global and regional scales

3.1. Global

In 2013, the top 15 aquaculture producers contribute more than 92 percent (65.1 million tonnes) of the total global aquaculture production volume (70.2 million tonnes). China is the world's largest aquaculture producer in all three main groups of species (finfish, crustaceans and mollusks) as listed in Table 1. Moreover, China alone produces 90 percent of carp, 40 percent of tilapia and 50 percent of penaid shrimp globally (Cao et al., 2015). Aquaculture in Norway and Chile consists mainly of export-targeted marine cage culture of Atlantic salmon. These two countries are also the world's largest producers for farmed salmon, which is a high-value species and increasingly popular in the world market (FAO, 2014). In contrast, India, Bangladesh, Egypt, Myanmar, the Philippines and Brazil rely almost exclusively on inland aquaculture of finfish. The farming of marine molluscs accounts for more than half of the aquaculture production in Japan and the Republic of Korea. The rapid increase of aquaculture (see Fig. 6) and the high trade shares of aquatic products has induced positive social and economic changes, mainly caused through the creation of employment opportunities (Chen and Qiu, 2014; Paul and Vogl, 2011; Quansah et al., 2007). Aquaculture has created a huge labor market with more than 23 million people (Valderrama et al., 2010) engaged full-time in fish farming worldwide (Whitmarsh and Palmieri, 2008).

3.2. Regional

Enormous regional differences on continental and country level can be identified in the aquaculture production sector. Nearly 90 percent (see Fig. 7) of the total global aquaculture output in 2013 has been produced in Asia (FAO, 2015). Asia is therefore the most important region for the farming of aquatic foods. Also, the 5 largest aquaculture production countries are all from Asia: China (43.5 million tonnes), India (4.5 million tonnes), Indonesia (3.8 million tonnes), Vietnam (3.2 million tonnes), and Bangladesh (1.8 million tonnes) (see Table 1) (FAO, 2014). Rural and pond-based semi-intensive farming is the main aquaculture type in Asia and generally depends on farm-made feeds. But the intensification of farming practices of species such as shrimp leads to increased demands for high-nutritional complete feeds and is driving the growth of the industrially manufactured aquafeed sector (El-Sayed et al., 2015; FAO, 2011). Most impressive is the total aquaculture output produced in China, which is by far the largest producer of cultured aquatic organisms. According to estimates provided by the FAO, China alone contributes more than 62 percent of the total global aquaculture output in 2013 (see Table 1).

Recent statistics revealed that annual aquaculture production growth during 2000–2012 was fastest in Africa (11.7 percent), Latin America and the Caribbean (10 percent). Africa has a total population of 1.11 billion (UN, 2013) and it is projected that its population will more than double to 2.4 billion by the year 2050 (UN, 2013). Particularly Sub-Saharan Africa's population is rising faster than the rest of the world (UN, 2013) and also lead to increasing food demand. Despite an increasing demand for fish, aquaculture in Sub-Saharan Africa has marginal production due to inefficient technologies and limited access to knowledge which constrained aquaculture development (Lazard et al., 2010). However, the situation is different in Egypt, Africa's largest aquaculture producer (mainly brackish water aquaculture), and major contributor to the higher production volumes reflected by this continent. Egypt even became a million tones producer in 2012 and more people are employed in its national aquaculture sector than in all the other countries of Africa combined (FAO, 2014). Africa, however, has large natural resources that offer great potential for aquaculture development in the coming years (Brummett et al., 2008). Therefore, aquaculture in Africa might further be developed at faster rates than in other regions to support rising demands for protein-rich food sources in the continent's rising population. In African nations fish is still mainly harvested from the wild, but fish output continues to grow at accelerating rates (e.g. Egypt, Nigeria) as aquaculture has become part of many rural agricultural enterprises (Quansah et al., 2007).

3.3. Trade

Increasing international trade of food products and rising global demand for fish has driven aquaculture to a highly globalized sector. Aquaculture products are one of the most widely traded segments of the world food economy, with an estimated total value of US$150.5 billion (see Fig. 8) in 2013 (FAO, 2014). The exports of farmed aquatic products from developing countries even exceeds the overall value of coffee, rubber, cocoa, tea, tobacco, meat and rice (Smith et al., 2010).

Regarding global distribution of imports and exports of aquaculture products it can be seen that there are significant regional differences. Developed countries dominate world imports while developing countries have drastically increased their export shares during the last decades. Europe, North America and Japan together produce just one-tenth of global aquaculture output but consume most of the farmed aquatic products being traded internationally (Naylor et al., 2000).

3.4. Value chain

Like other terrestrial, high-intensive animal production systems, aquaculture interacts with other economic sectors in an increasing globalized and complex value chain ranging from production over distribution to consumption (Deutsch et al., 2007). The transformation of aquaculture towards a highly global traded food business has developed complex networks of input and service suppliers with activities along the value chain from farmers to consumers (Lebel et al., 2002). The aquaculture industry also induced broad socio-economic value in other sectors through income and employment generation, for example in the fields of hatcheries, feed industry, trade, transport and energy (Belton and Little, 2011; Meaden and Aguilar-Manjarrez, 2013) but also in associated processing steps (pre- and post-harvest) from gutting, slicing, cleaning, sorting, quality control to ice-packaging depending on the commodity and market value (Ahmed and Troell, 2010; FAO, 2012).

The global aquaculture market is characterized by large retailers which control the international distribution channels. Within the global marketing systems, shrimp is one of the most traded aquaculture products internationally (Bush et al., 2010) and mainly traded to Japan, the United States of America, and the European Union (EU) - the largest importers of shrimp (Lebel et al., 2002). Outsourcing of processing to reduce production costs has become a global trend and in some cases, even entire industries have been delocalized for some commodities (FAO, 2012; Jackson and Shephard, 2012). Unprocessed aquatic products (e.g. frozen fish)

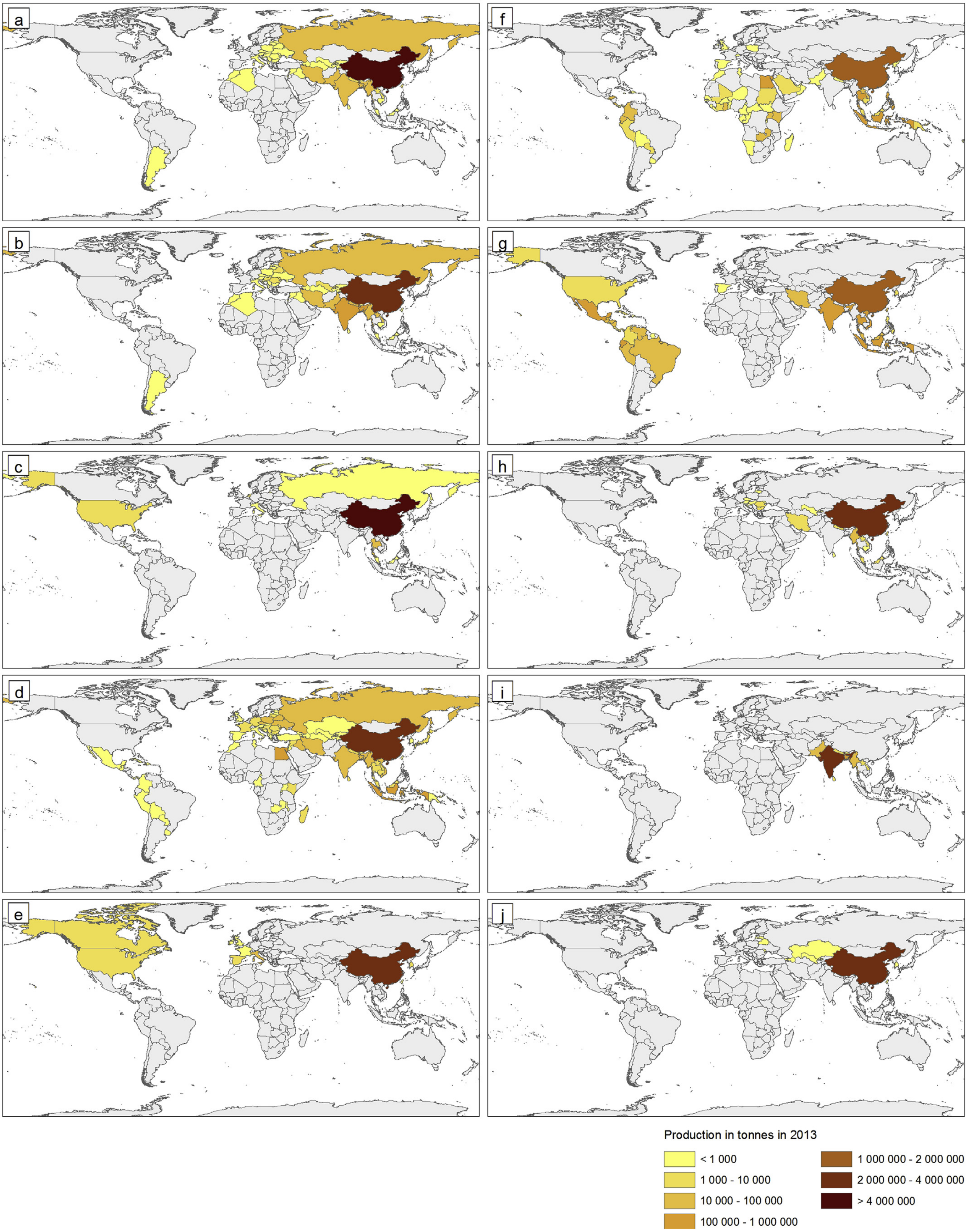

Fig. 5. Geographical distribution of the Top 10 aquaculture species (excluding aquatic photosynthetic organisms) in 2013. a) Grass carp, b) Silver carp, c) Cupped oyster nei, d) Common carp, e) Japanese carpet shell, f) Nile tilapia, g) Whiteleg shrimp, h) Bighead carp, i) Catla, j) Crucian carp. Data source: FAO (2015).

Table 1
Aquaculture production (excluding aquatic photosynthetic organisms) of the Top 15 producer countries and shares of the main aquatic product groups in 2013. Table modified from FAO (2014).

Country	Finfish	Crustaceans	Molluscs	Other species	National total	Share in world total
	tonnes	tonnes	tonnes	tonnes	tonnes	Percentage
China	25,940,887	3,769,655	12,985,785	855,403	43,551,730	62.02
India	4,239,307	297,300	13,000	/	4,549,607	6.48
Indonesia	3,179,963	639,553	29090	215	3,848,823	5.48
Vietnam	2,454,999	558,460	189,867	3847	3,207,200	4.57
Bangladesh	1,719,547	140,261	/	/	1,859,808	2.65
Norway	1,245,502	/	2363	/	1,247,865	1.78
Egypt	1,091,688	5856	/	/	1,097,544	1.56
Thailand	487,599	347,635	217,467	4243	1,056,944	1.51
Chile	780,678	/	252,528	/	1,033,206	1.47
Myanmar	871,353	54,822	/	3005	929,180	1.32
Philippines	694,533	75,511	44,964	/	815,008	1.16
Japan	273,401	1596	332,460	1363	608,820	0.87
Republic of Korea	88,359	3848	293,773	16,161	402,141	0.57
Brazil	388,700	64,769	19,360	600	473,429	0.67
USA	226,430	54,210	160,458	/	441,098	0.63
Top 15 total	43,682,946	6,013,476	14,541,116	884,265	65,122,403	92.74
Rest of the world	3,230,455	635,983	999,426	5288	4,871,152	7.26
World	47,070,533	6,711,678	15,547,993	893,337	70,223,561	100.00

Note:/represents lack of available data or the production volume is regarded as negligibly low.

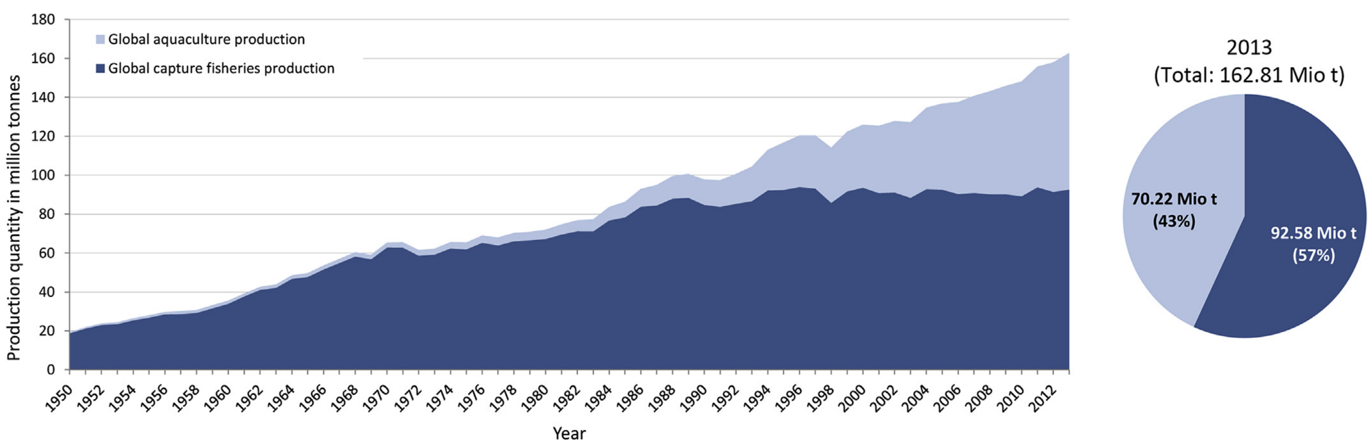

Fig. 6. Global aquaculture (excluding aquatic photosynthetic organisms) and capture fisheries production in million tonnes from 1950 to 2013. Data source: FAO (2015).

are exported from the EU and North America to developing countries for filleting and packaging, and then re-imported (FAO, 2012). Aquaculture expansion resulting from increased demands from national and international markets and technological innovations as seen in Asia and Latin America (Joffre and Bosma, 2009) is not an ubiquitous development around the globe. For example, weak value chain linkages limited sector growth in Africa (Troell et al., 2014b) despite presence of sufficient natural resources. Global food product markets are closely related to each other as reflected by the increasing use of supplementary feeds (crop-based, fishmeal and fish oil) in aquaculture production (El-Sayed et al., 2015). On the negative side, fluctuations of global market price in one commodity can pose risks to another, for example, higher crop prices also raise costs of cultured fish. And the increasing reliance on external feeds may increase risks for future secure production of aquatic products (Troell et al., 2014b).

4. Environmental impacts of aquaculture

Aquaculture can contribute to food security and provides many social and economic benefits like income and employment generation and associated poverty reduction (Paul and Vogl, 2011; Schumann et al., 2011; Slater et al., 2013; Smith et al., 2010). However, the rapid global expansion of aquaculture industry has caused transformation of large areas of valuable coastal and inland environments with subsequent loss of goods and services provided by natural resource systems (Pattanaik and Narendra Prasad, 2011). Although governance of aquaculture has become increasingly important (FAO, 2012), poor environmental regulations and the lack of proper planning and management strategies on national and international policy level (Smith et al., 2010) have led to uncontrolled and uncoordinated development of aquaculture and caused serious environmental degradation over the past decades. As global aquaculture continues to grow at high annual rates, this food sector will also increasingly rely on the natural productivity of adjacent ecosystems. Farming of high-value export-oriented commodities (e.g. shrimp, carp) in developing countries is facing a host of challenges as these systems highly depend on marine and coastal resources and its ecosystem services (Cao et al., 2007; Lebel et al., 2002).

4.1. Footprint of aquaculture in the landscape

Since the mid-1970s, aquaculture production has been expanded and intensified tremendously into coastal areas and

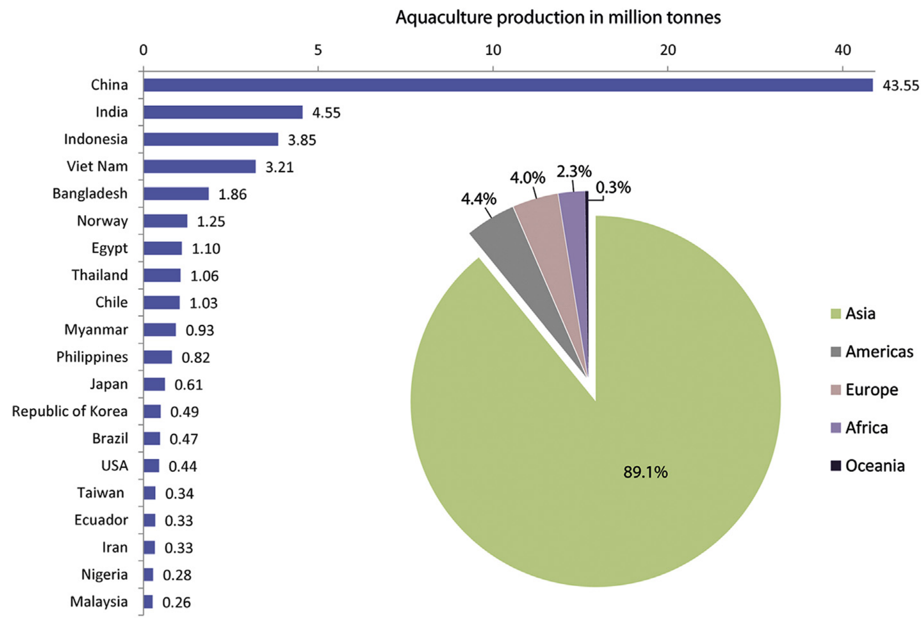

Fig. 7. Global total aquaculture production output (excluding aquatic photosynthetic organisms) in 2013. (1) Bar chart: ranking of the top 20 countries with highest aquaculture production in 2013 (in million tonnes). (2) Pie chart: share of total aquaculture production output among continents in 2013 (in %). Data source: FAO (2015).

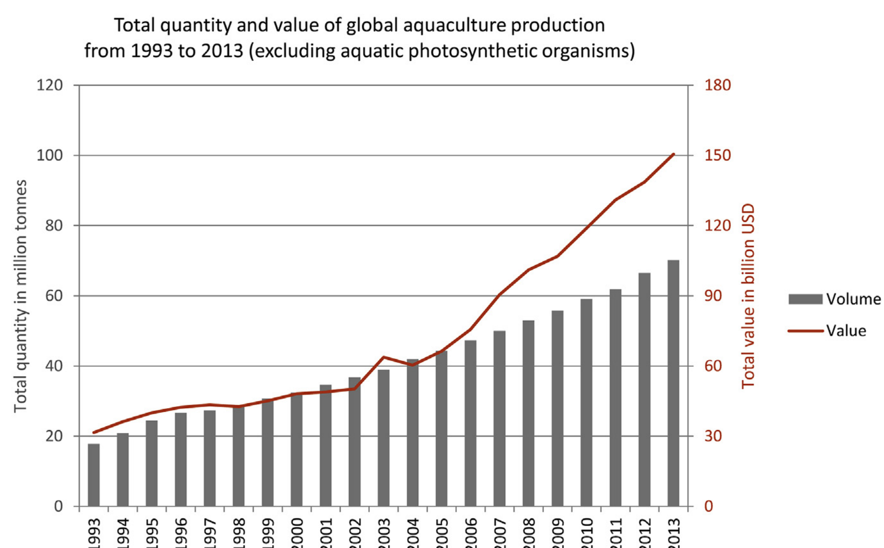

Fig. 8. Total quantity and value of global aquaculture production (excluding aquatic photosynthetic organisms) from 1993 to 2013. Data source: FAO (2015).

induced large-scale conversion of coastal wetlands - mainly mangroves, coastal lakes and lagoons (Bostock et al., 2010; Troell et al., 2013). Fig. 9 illustrates some example locations with predominant aquaculture activities in different regions around the globe (raceways, ponds, cages). Earth observation imagery can demonstrate the large space requirements of different aquaculture (particularly land-based) systems which have caused large-scale transformations in the landscape. In this relation, ponds play a significant role as the main cultivation system for fish and crustaceans. According to estimates from Verdegem and Bosma (2009) there is a total of more than 110.000 square kilometer of aquaculture ponds worldwide, with most ponds used for freshwater production (87,500 square kilometer) followed by brackish water production (23,330 square kilometer) (FAO, 2014). Asia holds the majority of ponds with a share of more than 94 percent of the global pond area (Boyd et al., 2010) where aquaculture systems are predominantly small-scale, family-owned and managed (Lazard et al., 2010; Pant et al., 2014).

Aquaculture has a long tradition in Asia and has undergone tremendous expansion, mainly along the coasts of China and Southeast Asia and major river deltas. These regions are often densely inhabited due to the presence of highly productive arable land and rich marine and freshwater resources (Kuenzer and Renaud, 2012; Renaud et al., 2013) and agriculture (e.g. rice farming) is a main livelihood (Renaud et al., 2014). Rising demands for aquatic products from international markets has driven the rapid expansion of highly export-oriented commodities such as shrimp (Bush et al., 2010) and pangasius catfish (Belton et al., 2011; Genschick, 2011) but also puts pressure on ecosystems since new areas are needed to build more land-based systems (ponds, tanks)

Marine offshore cages (Pacific salmon), Chile

Inland cage aquaculture (Alpine salmon), Southern Alpes, New Zealand

Marine cage aquaculture in Luoyuan Bay, Fujian Province, China

Barrramundi fish farm (raceway system), Australia

Tilapia fish farm (raceway system), Northern Peru

Fish farming in the Yellow River Delta, Shandong Province, China

Tilapia fish farm in Buikwe District, Uganda

Shrimp farm in Baja California Sur, Mexico

Shrimp farm in Terengganu State, Malaysia

Shrimp farming facility in Iran

Shrimp ponds in the Gulf of Guayaquil, Ecuador

Fish farming in Jiangsu Province, China

Shrimp ponds in the Mekong Delta, Vietnam

Shrimp ponds in Trat Province, Thailand

Aquaculture ponds in West Java Province, Indonesia

Fig. 9. Images of different aquaculture production systems (cages, raceways, ponds). Image source: Google Earth.

or water-based systems (fish cages or mussel farms). In many coastal regions land is already a scarce resource forcing aquaculture in an increasing competition with other agricultural activities (Troell et al., 2014b, 2013).

Since semi-intensive and intensive monocultures are highly resource dependent, these systems strongly rely on the natural resource production. High amounts of water are needed in aquaculture systems to support the farmed animals but also to replenish oxygen, balance water loss from evaporation (Bosma et al., 2009; Hambrey et al., 2008; Páez-Osuna et al., 2003; Verdegem and Bosma, 2009) or to remove wastes (Troell et al., 2013). A footprint concept outlined by Larsson et al. (1994) for a study site in Colombia suggest that a semi-intensive shrimp farm requires a spatial ecosystem that is 35–190 times larger than the farm itself while extensive systems only need a support area which is 20 time larger (Folke et al., 1998; Troell et al., 2013). On the other hand, the amount of fish protein (high nutrient pellets) added to feed the farmed species in many intensive and semi-intensive systems is 2–5 times larger than the output gained from the farmed product (Naylor et al., 2000). For these reasons, the ecological footprint of less intensive systems is smaller than that of intensified systems because they are less dependent on resource production and generate relatively low waste (Folke et al., 1998). Although aquaculture supports food supply and gains high income potential, the intensification of farming has increased the need and dependence on external inputs such as feed, energy, and chemicals. While this is an ongoing process around the globe, the aquaculture sector increasingly affects water quality and water quantity, thus having greater impact on aquatic biodiversity and our planet's natural resources in the coming years. The expansion of aquaculture activities lead to increased demand for land, freshwater and other natural resources. Aquaculture, especially in the coastal zone, is in increasing competition with primarily existing agricultural areas and other uses (Bostock et al., 2010; Troell et al., 2014a). Today, half of the global population lives within 100 km from the coast (Primavera, 2006) and with a growing global population, it can be expected that future aquaculture development in coastal areas will be heavily threatened if human exploitation will decline suitable habitats and freshwater availability. Scarce land resources in many coastal areas have already driven aquaculture into marine environments (e.g. offshore cage culture) or suitable terrestrial environments (e.g. aquaculture in inland water bodies) (Troell et al., 2014a).

4.2. Land use change and ecosystem degradation

Coastal ecosystems are highly productive (Seto and Fragkias, 2007) and provide habitat for a large number of fish, shellfish, and shrimp species and serve as important breeding and nursery areas (Afroz and Alam, 2013; Dewalt et al., 1996; Spalding et al., 2014).

The conversion of agriculture to more profitable aquaculture systems and its expansion towards coastal and marine environments has caused tremendous land use changes during the last decades. Along the coast of the South China Sea aquaculture has rapidly expanded and is responsible for large scale loss and fragmentation of wetland habitats through land reclamation and conversion (Peng et al., 2013; Spalding et al., 2014). Inadequate environmental protection and uncontrolled aquaculture development threaten nearby wetlands and substantially impedes a sustainable coexistence of coastal habitat conservation and aquaculture development (Peng et al., 2013). Aquaculture has already changed traditional farming along the coastal areas of Bangladesh, Vietnam and Indonesia, since coastal rice fields and mangrove forests were converted to shrimp ponds (Hazarika et al., 2000; Joffre and Bosma, 2009; Paul and Røskaft, 2013). This has been triggered by liberal government policies (e.g. Doi Moi in Vietnam) which allowed farmers to convert their land from traditional rice farming to more profitable fish and shrimp aquaculture (Ahmed, 2013).

The degradation of important coastal lakes, reefs, mangroves, salt marshes, tidal creeks and lagoons causes serious environmental damage and is undoubtedly one of the most serious threats to coastal ecosystems. Above all, the loss of mangroves and other coastal wetlands alters the natural tidal system, decreases sedimentation rates and affects fisheries decline (Kuenzer et al., 2011). Mangroves are distributed along tropical and subtropical coasts and are among the most threatened ecosystems worldwide (Kuenzer et al., 2011). It is reported that mangrove destruction reaching 50–80 percent regionally and aquaculture expansion appear to be a major factor in this decline (Wolanski et al., 2000). Shrimp farming is an important industry in tropical and subtropical climates (Sohel and Ullah, 2012) and plays a major role in the reduction of mangrove area as exemplified by numerous studies in Asia and South America and Latin America (see Table 2).

4.3. Surface and ground water pollution, water withdrawal

Aquaculture requires large amounts of water and greatly affects the quantity and quality of water resources (Troell et al., 2013). Water pollution has arisen with the development of aquaculture industry causing negative ecological impacts on the surrounding environmental (see Fig. 10). In China, large-scale and intensive aquaculture is listed as one of the major sources of coastal seawater pollution and negative effects to aquatic environment are increasingly recognized (Cao et al., 2007; Peng et al., 2013). Wastewater discharged without treatment into adjacent coastal waters is a key environmental concern in aquaculture and mainly caused by poor managed shrimp and fish farms (Cao et al., 2007). To ensure adequate water quality, discharging water from ponds is a common practice (Burford et al., 2003) and causes subsequent release of high loads of nutrients (nitrogen and phosphorus) and suspended solids into nearby estuaries, lagoons and coastal waters (Islam et al., 2004). High organic matter contents in aquaculture effluents stimulate or exacerbate eutrophication (Carrasquilla-Henao et al., 2013; Wolanski et al., 2000) and algal blooms and cause serious problems for the aquatic ecosystem (Cao et al., 2007; Costanzo et al., 2004; Páez-Osuna et al., 2003). The addition of feed and excessive use of fertilizers and chemicals also enrich waters with nutrients and pollutants (bacteria, viruses and other toxic compounds) (Sohel and Ullah, 2012) and contaminate natural coastal waters if directly discharged. For example, organic waste dispersal from salmon farms causes changes of microflora biodiversity of benthic sediments (Buschmann et al., 2009). Effluent pollution from shrimp farming can be attributed to strong local eutrophication processes and has been reported in coastal lagoons in the Gulf of California, Mexico (Carrasquilla-Henao et al., 2013), Gulf of Fonseca, Honduras (Dewalt et al., 1996), and tidal creeks in Australia (Burford et al., 2003; Costanzo et al., 2004).

Excessive and unrestricted use of antibiotics and chemicals (pesticides, fertilizers) is a general problem in the aquaculture sector, particularly in developing countries. Antibiotics are generally mixed with fish food and applied within semi-intensive and intensive aquaculture systems to prevent bacterial infections or treat disease outbreaks resulting from poor water qualities and dense stocking. There are serious concerns about the uncontrolled use of antibiotics in aquafeeds because it favors the development of (multiple) resistance in bacterial populations which in turn can limit the effectiveness of cultured species' immune system (Cabello, 2006; Primavera, 2006). A survey by Holmström et al. (2003) on

Table 2
List of reviewed studies related to aquaculture activities and coastal wetland degradation.

Global	
	Bush et al. (2010); Giri et al. (2011); Kuenzer et al. (2011); Primavera (2006); Valiela et al. (2001); Whitmarsh and Palmieri (2008)
Asia	
China	Mackinnon et al. (2012); Peng et al. (2013); Yao (2013)
Taiwan	Lee and Yeh (2009)
Vietnam	Béland et al. (2006); Ha et al. (2012); Nguyen (2014); Nguyen et al. (2013); Seto and Fragkias (2007); Thu and Populus (2007); Tien and Yoshino (2013); Tong et al. (2004); Vo et al. (2013)
Indonesia	Fuchs et al. (1998); Rahman et al. (2013)
Malaysia	Olaniyi et al. (2012)
Bangladesh	Hossain et al. (2013); Paul and Vogl (2011)
India	DasGupta and Shaw (2013); Pattanaik and Narendra Prasad (2011); Rajitha et al. (2010); Ramasubramanian et al. (2006); Satapathy et al. (2007); Venkataratnam et al. (1997)
Sri Lanka	Dahdouh-Guebas et al. (2002); Travaglia et al. (1999)
Thailand	Hazarika et al. (2000); Muttitanon and Tripathi (2005); Sremongkontip et al. (2000)
Americas	
Brazil	Queiroz et al. (2013); Santos (2000); Suárez-Abelenda et al. (2014); Zitello (2007)
Peru	Mialhe et al. (2013)
Honduras	Dewalt et al. (1996)
Colombia	Larsson et al. (1994)
Nicaragua	Benessaiah and Sengupta (2014)
Ecuador	Pozo et al. (2012)
Mexico	Berlanga-Robles et al. (2011a, b)
Central America	Son and Chen (2012)
Africa	
Kenya	Kirui et al. (2011)
Oceania	
Australia	Burford et al. (2003); Costanzo et al. (2004); Wolanski et al. (2000)

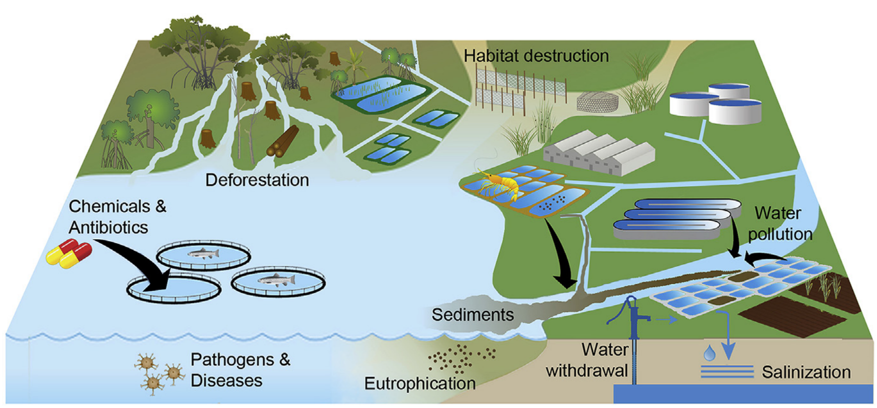

Fig. 10. Aquaculture and the environment - potential pollution sources (several symbols used are adopted or modified according to courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science).

shrimp aquaculture along the coast of Thailand revealed that 74 percent of all interviewed farmers added antibiotics within their production. Rico and Van den Brink (2014) calculated that on average 25 percent of the applied veterinary medicines to aquaculture ponds is released to the environment.

Although saline intrusion is a naturally occurring phenomenon in many coastal regions (e.g. Mekong Delta in Vietnam), the rapid development of aquaculture has exacerbated surface water salinity contents. As described by Páez-Osuna et al. (2003) salinization is also being aggravated due to higher evaporation rates (particularly in tropical regions) and is a major issue in pond systems having 50 percent higher evaporation than natural wetlands. After harvest, hyper-saline waters and wastewaters are often discharged uncontrolled and released to adjacent environments and increase salinity in mangrove and saltmarsh areas. Storing saline water in ponds for shrimp production also leads to percolation of salts into surrounding soils (Afroz and Alam, 2013) altering their physical structure and substantially reducing fertility (Paul and Røskaft, 2013).

Aquaculture is directly dependent on water availability, particularly freshwater for farming of non-marine fish or to establish brackish water conditions in coastal areas. Water availability is a limiting factor and scarce freshwater resources already constrained aquaculture industry in Egypt where water demands for fish farms is mainly compensated by agriculture drainage water (FAO, 2014). Withdrawal of groundwater through pumping (Paul and Vogl, 2011), and high evaporation and infiltration in pond system (Verdegem and Bosma, 2009) causes water loss and considerably exacerbates freshwater quantities in many regions.

4.4. Erosion and land subsidence

Large-scale land use conversions of agricultural fields and natural habitats into coastal aquaculture leads to increased susceptibility to erosion caused by wind or waves (Kuenzer et al., 2014a). Rapid shrimp aquaculture expansion as happened in recent years in the Ganges-Brahmaputra Delta, Mekong Delta, and Godavari Delta has caused extensive mangrove loss and resulted in changed sedimentation patterns and coastal erosion (Nguyen, 2014; Ramasubramanian et al., 2006; Sohel and Ullah, 2012). Erosion also takes place at levees of fish and shrimp ponds and causes inorganic particles to be suspended in waters (Burford et al., 2003). Higher profit margins for aquaculture products (shrimp and prawn) have driven conversion of rice fields to aquaculture, for example in Bangladesh and Vietnam. In the case of Bangladesh, it has become a common practice that farmers illegally built drainage systems through breaching of embankments to obtain necessary saline waters for shrimp cultivation (Shahid et al., 1992). On the negative side, this has led to increased salinity intrusion and reduced productivity of agricultural fields. And the breaching resulted in catastrophic consequences during storm surges (e.g. cyclone Aila in 25th May 2009) since the hinterland was no longer protected by dikes and caused severe flooding with loss of lives and livelihood.

As outlined in Chen and Qiu (2014) it has been demonstrated that aquaculture activities considerably contribute to land subsidence which is a major threat to low lying coastal areas (Kuenzer and Renaud, 2012; Renaud et al., 2013). In Taiwan, aquaculture rapidly developed since the 1980s with high annual production rates and Taiwan was even world's largest producer for white tiger shrimp in 1987. However, aquaculture growth in Taiwan has increased freshwater demand and mainly accompanied by pumping of large volumes of ground water, thus leading to increased land subsidence. Higgins et al. (2013) analyzed interferometric ALOS-Palsar and Envisat-ASAR data of the coastal area of the Yellow River Delta in China, a region that has shown rapid aquaculture development during the last 20 years (Ottinger et al., 2013). Results show that this region has undergone tremendous land subsidence with sinking rates of 250 mm per year which is mainly attributed to increased groundwater extraction as a result of rising freshwater demands in aquaculture. Land subsidence causes considerable economic costs in coastal areas (Chen and Qiu, 2014; Whitmarsh and Palmieri, 2008) and increases the risks for storm surges, flooding, and salinity intrusion and is a major threat as it will aggravate coastal erosion and wetland loss due to rising local sea levels (Nicholls, 2003; Nicholls et al., 1999; Saito et al., 2007; Smajgl et al., 2015; Wassmann et al., 2004).

4.5. Diseases

Global production of animals and plants has diversified and increased in volume and their products are increasingly traded around the globe. Therefore, international trade has increased the potential for the spread and transfer of pathogens from one region to another. Outbreaks of infectious bacterial and viral diseases can cause severe production losses of the industry concerned and constrain aquaculture development. According to Leung and Bates (2013) outbreak severity in terms of cumulative mortality ranges among different climates and is highest in tropical areas (88% at equator) and decreases towards temperate systems (34% at 70°). In the past, diseases have disrupted the production of specific species in many countries and unsustainably affected international trade in terms of import and export restrictions for aquatic products (Bondad-Reantaso and Subasinghe, 2008; Lehane, 2013). These external effects stress aquatic ecosystem and have great impact on human and environmental health and are a major food safety issue.

In Asia, the Whitespot Syndrome Virus and the Yellowhead Virus are among the most dangerous diseases in aquaculture (Walker and Mohan, 2009) and are responsible for catastrophic multimillion dollar crop losses in the shrimp sector in recent years (Primavera, 2006). Bangladesh suffered major damage after an outbreak of the White Spot Syndrome Virus in 1996 that caused a 44.4 percent production loss (Hossain et al., 2013; Mazid and Banu, 2002). Hence, disease outbreaks are considered as one of the biggest obstacles for the development of the shrimp business in Bangladesh (Paul and Vogl, 2011) and other countries. Insufficient regulations and monitoring accelerated the rapid growth of salmon aquaculture industry in Chile but devastating salmon lice outbreaks in 2007 have caused economic costs of 2 billion USD and led to a loss more than 25000 jobs and disrupted the international supply chains (Alvial et al., 2012; Buschmann et al., 2009; Cannon and Beveridge, 2012; Torrissen et al., 2013). Other examples of disease outbreaks have been experienced in Thailand (Verdegem and Bosma, 2009), Vietnam (Joffre and Bosma, 2009), Peru (Mialhe et al., 2013), Nicaragua (Benessaiah and Sengupta, 2014) and Taiwan (Chen and Qiu, 2014).

4.6. Food chain pollution

Fertilizers, disinfectants, pesticides and other feed additives are widely used in aquaculture and applied in large quantities to control organisms, including insects, water weeds and plant diseases (Sabra and Mehana, 2015). The application of such chemical substances may lead to toxicities and cause irreversible damage to cultured species and harm human consumers and wild biota (Holmström et al., 2003; Primavera, 2006). Heavy metals and other residues from domestic wastes and untreated industrial effluents further contribute to the accumulation of toxic residues in aquaculture and the entire food chain in adjacent environments. Contamination of aquaculture products even occurs in post-harvest processing. A case study by Hassan et al. (2012) on post-harvest handling in the shrimp business of Bangladesh revealed that chlorinated water was frequently used in processing facilities to clean floors and handling materials. Also, fluids and substances (such as water or tapioca) were injected into shrimps to increase weight and gain better profit on the markets.

Algal blooms in shallow waters are another environmental threat to aquaculture as algal toxins affect the quality of cultured species and can result in decrease or complete loss of entire harvests. But also oxygen depletion caused by non-toxic algal blooms can create anoxic conditions and greatly affect coastal aquaculture (Bresciani et al., 2014; Burford et al., 2003; Qi et al., 2004; Sabra and Mehana, 2015; Wang et al., 2008).

In the previous sections we addressed several environmental issues relating to the development of aquaculture around the globe and its consequences on the ecosystem and human health. With rising awareness of the environmental impacts of aquaculture it is of great importance to accurately quantify and monitor this land use globally. Global spatial data on aerial extents, distribution and changes of aquaculture can deliver useful information for highlighting existing relations of aquaculture development and environmental pollution and degradation of natural resources. Earth observation can contribute to the quantitative assessment of aquaculture areas and would allow estimating the impacts on water resources and the surrounding environment for large-scale areas. Remote sensing is a cost-effective alternative to extensive field surveys and recordings made by local authorities while it gives an instantaneous overview over large areas of the Earth's surface. Moreover, satellite data can be acquired periodically depending on the sensor's revisit time and cover even very remote regions in rural areas of developing countries where access might be difficult and limited. For these reasons, remote sensing is the perfect tool for the spatial assessment of aquaculture areas at different scales.

5. The potential of earth observation for aquaculture assessment

The increasing importance of aquaculture is recognized by various international authorities such as FAO, World Fish, UN, among others, non-governmental organizations (NGO) and local governments. Earth observation has the potential to support aquaculture management including aquaculture site selection and mapping (past and present observation data for optimal site selection and mapping of aquaculture sites), aquaculture site environmental monitoring (e.g. water quality monitoring), and aquaculture inventory (mapping aquaculture facilities at different scales).

Space-borne multispectral optical sensors (see Table 3) such as Landsat Thematic Mapper (TM), Landsat Enhanced Thematic Mapper Plus (ETM+), Landsat Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Indian Remote Sensing (IRS-P6) - Linear Imaging Self Scanning Sensor (LISS)-III, China–Brazil Earth Resources Satellite (CBERS)-3/4 and Sentinel-2A contain more than 3 spectral bands and are very useful in mapping and monitoring aquaculture. Clear water shows significant absorption in the shortwave and mid infrared wavelengths of the electromagnetic spectrum resulting in low reflectance of water compared to other surface features. For this reason multispectral data is very useful to distinguish between water and non-water surfaces. Despite the potential of earth observation for aquaculture applications there are limitations in the use of remote sensing data which include data availability, data access, and data costs (Kuenzer et al., 2013). Many satellite data are of high costs or limited accessibility but there is an increasing number of free and open access data (e.g. Sentinel-1/2, Landsat fleet) to support effective future aquaculture applications.

For the assessment of aquaculture sites the spatial resolution of satellite sensors is a clear limiting factor for the identification of single aquaculture facilities (e.g. ponds, cages) which have generally quite small, simple geometric forms. For a Landsat 8 image with 30 m ground resolution this means that a pond with a spatial extent of 50 × 50 m will only be covered by approximately four pixels. A larger challenge is the detection of small aquaculture fragments (levees, pond and cage edges) since a pixel in an image of more coarser spatial resolution may cover different surface features (e.g. pond water and levee structure). Very high resolution sensors (<5 m) - both passive optical and active microwave - have the greatest potential for earth observation applications in the field of aquaculture site mapping and monitoring. The highest resolution sensors (e.g. WorldView, Quickbird) are able to monitor the earth's surface at ground resolutions of up to 0.4 m and allow for the detection of even narrow linear aquaculture structures such as levees, dikes around edges of ponds or other aquaculture systems. Upcoming optical and active microwave sensors with very high spatial resolution (e.g. Geoeye-2 0.25 m, CartoSat-3: 0.3 m) will open up a wider spectrum of available satellite data for aquaculture applications. However, these sensors generally have lower swath widths (~20 km for most sensors with spatial resolution less than 2 m; see Table 3) and data is often not available at large areal coverage. But for small-scale investigation areas lower swath widths may not pose a critical criterion. The temporal resolution of satellite sensors comprises the revisit time of a sensor and the monitoring period for which data is available from one sensor (Kuenzer et al., 2014b). Cloud cover limits the timeliness of data acquisition and the availability of time series data from optical sensors and is a major issue in tropical regions which host most of the global aquaculture area. There are an increasing number of high and very high resolution optical and SAR instruments with higher revisit times of 1–7 days enabling the provision of timely data on aquaculture areas which increases the chances of obtaining cloud-free imagery thus improving monitoring capabilities on the ground.

Synthetic Aperture Radar (SAR) instruments provide all-weather capabilities to obtain image data of any sites even with presence of dense cloud coverage. This is a great advantage for aquaculture mapping and monitoring applications particularly for areas located in tropical regions where cloud cover is the major limiting factor for optical data acquisition. Secondly, radar waves interact different with natural surfaces meaning that rough surfaces have a notably higher backscatter than smooth surfaces like water. Radar waves generate higher backscatter response for aquaculture facility components than for enclosed or environed water surfaces (Travaglia et al., 2004) thus enabling identification and separation of aquaculture structures from other natural and man-made structures. The presence of speckle noise due to the inference of return signal in SAR data can obscure fine edges and details and is a limiting factor for the effective detection of various terrain features use (Kushwaha et al., 2000). A large number of advanced synthetic radar imaging instruments with high spatial resolution, large coverage and reliable repetition (e.g. CosmoSkyMed, Radarsat, TerraSar-X, Sentinel-1A) have been launched in recent years (see Table 4) and many more are already scheduled or in planning stage (Kuenzer et al., 2014b). Therefore, SAR data seems to be a promising data source for future aquaculture research.

Hyperspectral space-borne missions were mainly designed for experimental demonstration of hyperspectral technologies. There are only few successful operating space-borne hyperspectral sensors for terrestrial applications such as the Hyperion (aboard NMP-EO-1), Compact High Resolution Imaging Spectrometer (CHRIS, aboard Proba-1) and Hyperspectral Imager (HIS, aboard Huan Jing-1A), but new initiatives like PRISMA and the Environmental Mapping and Analysis Program (EnMAP) are already in planning stage and highly promising due to their high resolution (Staenz and Held, 2012). Hyperspectral data delivers reflectance information in hundreds of bands, enabling in-depth examination and discrimination of material spectra of terrestrial features. This offers new opportunities for estimating water quality parameters such as phosphorus, nitrogen, chlorophyll (Abd-Elrahman et al., 2011), detecting water optical properties (Lesser and Mobley, 2007), seagrass cover (Phinn et al., 2008), macro algae (Vahtmäe et al., 2006), and salinity mapping (Metternicht and Zinck, 2003; Rekha et al., 2012).

Accurate remotely sensed data on aquaculture area extents is very useful for scientists and public authorities to track and evaluate the current status and dynamics of aquaculture and to provide base data for the elaboration of appropriate actions and measures for environmental conservation and natural resource management. Great effort has been directed towards aerial estimation and mapping of aquaculture activities in various investigation areas around the globe. However, comprehensive data on spatial extents of aquaculture in local, regional and global scale does rarely exist. Satellite remote sensing offers great potential for aquaculture management by providing valuable supplementary information and gains considerable opportunity to support decision-makers and policy on national and international level.

6. Earth observation studies contributing to the assessment of aquaculture

Several authors have provided sectorial overviews of the current state and use of remote sensing for different aquaculture applications. More than 20 years ago, Egna (1994) reviewed applications of remote sensing for monitoring water quality and temperature in tropical inland fisheries and aquaculture and presented a brief assessment of new platforms and sensors. Santos (2000) provided a review of the use of airborne and active and passive satellite sensors in fisheries research and operational support and the use of satellite-derived information in the support of fisheries activities. More recently, Quansah et al. (2007) reviewed the current state of

Table 3
List of most relevant optical space-borne instruments for the observation of aquaculture sites.

Platform	Sensor/ Instrument	Agency	Sensor type	Spatial resolution	Minimum local revisit time	Max. Swath width	Launch date	Status
GeoEye-1	GIS	GeoEye	optical	0.41 m–1.65 m	2.1–8.3d	15.2 km	2008	operational
WorldView-1	WV60	Digital Globe	optical	0.5 m–1.8 m	3.7d	17.6 km	2007	operational
WorldView-2/3	WV110	Digital Globe	optical	0.5 m–1.8 m	1.1–3.7d	16.4 km	2009/2014	operational
Kompsat-3A	AEISS-A	KARI	optical	0.5 m–2m	3d	12 km	2015	operational
Quickbird	BGIS-2000	Digital Globe	optical	0.6 m–2.4 m	2.5–5.6d	18 km	2001	operational
Pleiades-1A/1B	HiRI	CNES	optical	0.7 m–2.8 m	2d	20 km –100 km	2011/2012	operational
Kompsat-3	AEISS	KARI	optical	0.7 m–2.8 m	3d	15 km	2012	operational
CartoSat-2/2A/2B	PAN	ISRO	optical	1 m	4d	9.6 km	2007/2008/ 2010	operational
Ikonos	IKONOS	GeoEye	optical	1 m–4m	3d	11 km	1999	operational
KompSat-2	MSC	KARI	optical	1 m–4m	28d	15 km	2006	operational
SPOT-6/7	Naomi	EADS Astrium	optical	2 m–8m	3d; (daily revisit capability SPOT 6&7)	120 km	2012/2014	operational
Formosat-2	RSI	NSPO	optical	2 m–8m	3d	24 km	2004	operational
ZY-3A	HRC (ZY-3A)	CRESDA	optical	2.1 m–3.5 m	5d–59d	52 km	2012	operational
ZY1-02C	HRC (ZY1-02C)	CRESDA	optical	2.36 m	26d	54 km	2011	operational
NigeriaSat-2	VHRI	NASRDA	optical	2.5 m–5m	4 months	20 km –100 km	2011	operational
SPOT-5	SPOT-HRG	EADS Astrium	optical	2.5 m/5 m/ 10 m/20 m	2–3d	60 km	2002	operational
CartoSat-1	Cartosat-1	ISRO	optical	2.5 m	5d	30 km	2005	operational
Rapideye 1/2/3/4/5	REIS	Rapideye	optical	5 m	1d–5.5d	77 km	2008	operational
TH-1/1B	PAN	CAST	optical	5 m	45d	60 km	2010/2012	operational
Resourcesat-1/2/2A	LISS-IV	ISRO	optical	5.8 m	5d	23–70 km	2003/2011/ 2016	operational/planned
ZY1-02C	PAN/MS (ZY1-02C)	CRESDA	optical	5 m–10 m	26d	60 km	2011	operational
CBERS-4	PANMUX	CRESDA/ INPE	optical	5 m–10 m	5d	60 km	2014	operational
ZY-3A	MSC (ZY-3A)	CRESDA	optical	6 m	5d–59d	51 km	2012	operational
NMP EO-1	ALI	NASA	optical	10 m/30 m	16d	37 km	2000	operational
ALOS	AVNIR-2	JAXA	optical	10 m	2d	70 km	2006	operational
TH-1/1B	MS	CAST	optical	10 m	45d	60 km	2010/2012	operational
Sentinel-2A/2B	MSI	ESA	optical	10 m/20 m/ 60 m	10d (5d with 2 sat.)	290 km	2015/2016	operational/planned
Landsat-8	OLI	USGS/ NASA	optical	15 m/30 m	16d	185 km	2013	operational
Landsat-7	ETM+	USGS/ NASA	optical	15 m/30 m	16d	185 km	1999	operational[a]
Terra	ASTER	NASA	optical	15 m/30 m/ 90 m	16d	60 km	1999	operational
VRSS-1	WMC	CAST	optical	16 m	7 d	269 km	2012	operational
CBERS-4	MUXCAM	CRESDA/ INPE	optical	20 m	5d	120 km	2014	operational
Resourcesat-1/2	LISS-III	ISRO	optical	23,5 m	24d	141 km	2003/2011/ 2016	operational/planned
HJ-1A, HJ-1B	WVC	CAST	optical	30 m	4d	700 km	2008	operational
NMP EO-1	Hyperion	NASA	optical	30 m	16d	7.5 km	2000	operational
UK-DMC-1/UK-DMC-2/ NigeriaSat-1/X	SLIM6	BNSC/ NASRDA	optical	32 m	5d	320 km/ 600 km	2003/2009/ 2011/2011	Inactive (2003–2011)/ operational
Resourcesat-1/2/2A	AWiFS	ISRO	optical	56 m	5d	740 km	2003/2011/ 2016	operational/planned
CBERS-4	WFI2	CRESDA/ INPE	optical	64 m	5d	866 km	2014	operational
HJ-1A	HSI	CRESDA	optical	100 m	4d–31d	50 km –500 km	2008	operational
GeoEye-2	GIS-2	GeoEye	optical	0.25 m–1m	4d	n.a.	2015	planned
CARTOSAT-3	PAN	ISRO	optical	0.3 m	7d	6 km	2017	planned
CartoSat-2C/2D	PAN	ISRO	optical	0.65 m	7d	9.6 km	2015/2016	planned
ALOS-3	PSC	JAXA	optical	0.8m–1.24 m	45d	50 km	2015	planned
CartoSat-3	MX	ISRO	optical	1 m	7d	16 km	2017	planned
CartoSat-2C/2D	HRMX	ISRO	optical	2 m	7d	10 km	2015/2016	planned
ALOS-3	HISUI	JAXA	optical	5 m–30 m	30d	90 km	2019	planned
CartoSat-3	HYSI	ISRO	optical	12 m	7d	5 km –405 km	2017	planned

(continued on next page)

Table 3 (*continued*)

Platform	Sensor/ Instrument	Agency	Sensor type	Spatial resolution	Minimum local revisit time	Max. Swath width	Launch date	Status
Orbview-3	OHIRS	GeoEye	optical	1 m–4m	3d	8 km	2003	inactive (since 2007)
Kompsat-1	EOC	KARI	optical	6.6 m	5 months	17 km	1999	inactive (since 2008)
SPOT-1/2/3	SPOT-HRV	EADS Astrium	optical	10 m/20 m	2–3d	60 km	1986/1990/ 1993	inactive (since 2003/ 2009/1996)
SPOT-4	SPOT-HRVIR	EADS Astrium	optical	10 m/20 m	2–3d	60 km	1998	inactive (since 2013)
CBERS-1/2/2B	HR CCD	CRESDA/ INPE	optical	20 m	3d–26d	113 km	1999/2003/ 2007	inactive (since 2003/ 2007/2010)
Landsat-4/5	TM	USGS/ NASA	optical	30 m	16d	185 km	1982/1984	inactive (since 1993/ 2013)

[a] SLC-off since May 2003.

Table 4
List of most relevant radar space-borne instruments for the observation of aquaculture sites.

Platform	Sensor/ Instrument	Agency	Sensor type	Spatial resolution	Minimum local revisit time	Max. Swath width	Launch date	Status
RISAT-2	SAR-X	ISRO	radar	1 m–8m	25d	10 km–650 km	2009	operational
Tandem-X	Tandem-X	DLR	radar	1 m–18 m	11d	10 km–100 km	2010	operational
TerraSAR-X	TerraSAR-X	DLR	radar	1 m–18 m	11d	10 km–100 km	2007	operational
Kompsat-5	COSI	KARI	radar	1 m–20 m	28d	5 km–100 km	2013	operational
Cosmo-SkyMed 1/2/3/4	SAR 2000	ASI	radar	1 m–100 m	5d (0.5d in full constellation)	10 km–200 km	2007/2007 /2008/2010	operational
RISAT-1	SAR-C	ISRO	radar	1 m–50 m	25d	30 km–240 km	2012	operational
ALOS-2	PALSAR-2	JAXA	radar	1 m–100 m	14d	25 km–350 km	2014	operational
Radarsat 2	RadarSat-2	CSA	radar	3 m–100 m	24d	50 km–500 km	2007	operational
HJ-1C	SAR-S	CRESDA	radar	5 m–25 m	4d	40 km–100 km	2012	operational
Sentinel-1A/1B	SAR-C	ESA	radar	5 m–80 m	12d	80 km–400 km	2014/2016	operational/planned
HY-3A/3B/3C	W-SAR	CAST	radar	1 m–10 m	n.a.	40 km–150 km	2017/2018/ 2019	planned
RISAT-1A	SAR-C	ISRO	radar	1 m–50 m	25d	30 km–240 km	2019	planned
Meteor-M N3/Meteor-MP N3	SAR-X	Roscosmos	radar	1 m–500 m	14d	10 km–750 km	2018/2023	planned
RCM-1/RCM-2/RCM-3	SAR RCM	CSA	radar	3 m–100 m	12d (4d with 3 satellites)	20 km–500 km	2018	planned
Radarsat 1	RadarSat-1	CSA	radar	8 m–100 m	24d	45 km–500 km	1995	inactive (since 2003)
ALOS	ALOS-PALSAR	JAXA	radar	10 m–100 m	46d	70 km–350 km	2006	inactive (since 2011)
Envisat	ASAR	ESA	radar	30 m–1000 m	2d–7d	5 km–405 km	2002	inactive (since 2012)
ERS-1/2	AMI-SAR	ESA	radar	30 m–1000 m	35d	100 km	1991/1995	inactive (since 2000/ 2011)

remote sensing applications for sustainable aquaculture, the potential of technology transfer and multi-sensor remote sensing deployment to Africa. Boivin et al. (2004) introduces opportunities of earth observation in the fisheries and aquaculture sector which were established by the New Earth Observation Markets for Fisheries and Aquaculture (NEMA) project. Grant et al. (2008) presented an overview of recent studies that used imagery from various high resolution satellites (Quickbird, Satellite Pour l'Observation de la Terre (SPOT), Landsat and Radarsat) for aquaculture investigations and examined the use of remote sensing in fish and shellfish farming with an emphasis on ocean-color applications. A comprehensive review of Dean and Salim (2013) presents some demonstration remote sensing products and case studies for offshore mariculture at global and regional levels and describes simple options to acquire and process data for incorporation into further analysis. Matthews (2011) reviewed the current state of empirical methods of retrieving various bio-geophysical and optical parameters in inland and transitional waters from space-borne, airborne and in situ remote sensors. There is however no up-to-date publication that provides a holistic overview of application potentials and current and future space-borne optical and radar instruments.

In the following paragraphs, available remote sensing related applications in the field of aquaculture are presented. In order to ensure a good overview, the respective studies were categorized according to the following topics: mono-temporal and multi-temporal imagery analyses of optical and active microwave data and investigations in which aquaculture is the key driver of predominant land use change and adversely impacts the environment.

6.1. Monotemporal investigations

In an earlier study by Wibowo et al. (1994) SPOT XS, Landsat TM and aerial photography has been used to detect suitable locations for aquaculture ponds on the coast of Indonesia. Studies by Gupta et al. (2001) and Karthik et al. (2005) applied visual interpretation of LISS-III data for brackish water aquaculture site selection for coastal tracks in India.

Mapping of aquaculture areas is a crucial task for resource management and environmental monitoring. Attempts to integrate remotely sensed data are described by Fuchs et al. (1998) who assessed the impact of tropical shrimp aquaculture on the environment for a case study in Indonesia using Landsat TM (30 m), SPOT (20 m) and airborne hyper-spectral CASI (Compact Airborne Spectrographic Imager) data to perform a supervised classification of land cover including aquaculture ponds and addressed the use of satellite and airborne data for monitoring aquaculture as a supporting tool. Virdis (2014) used a SPOT-5 panchromatic image (5 m resolution) and WorldView-1 panchromatic image (0.5 m) to classify coastal aquaculture in Tam Giang-Cau Hai Lagoon. In their methodology they applied a RGT segmentation algorithm and ISOSEG classifier for the two very high resolution images to map aquaculture ponds. Sridhar et al. (2008) investigated mapping and classification accuracies of coastal features (such as aquaculture plots) from visible (VIS) and near-infrared (NIR) bands of Landsat TM and LISS-III data and revealed that it is less accurate than for land features due to confusing spatial and spectral characteristics.

Several studies employed simple mapping or change detection approaches that do not provide or use any object features (such as size, shape, homogeneity) which can supply important contour information of aquaculture objects. The processing of reflectance values (optical data) or backscatter intensities (radar data) exclusively makes it difficult to accurately delineate aquaculture areas and to distinguish them from other natural or artificial water surfaces which show similar reflectance response patterns. Since many aquaculture structures (e.g. ponds) have distinct geometries, object-based image analysis (OBIA) can add valuable information and holds great potential to improve accuracies for aquaculture mapping and monitoring campaigns (Blaschke, 2010). Therefore, object-based image analysis promises great potential for the delineation of aquaculture structures due to the distinct linear shape. Zhang et al. (2013) present an automated, object-based region growing integrated edge detection (OBRGIE) method for the extraction and mapping of aquaculture coastlines from Landsat TM (30 m) and SPOT-5 (10 m) data for different aquaculture sites in China. Within this method they proposed a new object feature which demonstrated to be more effective for the separation of water and land than spectral attributes. Zhang et al. (2010) assessed an automatic approach for aquaculture mapping in the coastal zone of East China Sea introducing a multi-scale segmentation/object relationship modeling (MSS/ORM) strategy. They evaluated the effectiveness of the gray level co-occurrence matrix (GLCM) homogeneity texture feature on pond area information extraction and compared the results with a pixel-based maximum likelihood classifier and one-step supervised OBIA with stand nearest neighbor (SNN) strategy. Although the applied pixel-based approach showed good capacity to identify water from land, they failed to identify different water areas only by spectral features. The one step OBIA supervised strategy could identify different water areas but demonstrated to be weak in differentiate reservoirs in land areas from aquaculture and enclosed water area from open seawater area. The applied approach of Zhang et al. (2010) demonstrated that the MSS/ORM OBIA could greatly improve the classification accuracy for automatic pond aquaculture mapping.

Satellite imaging radar (SAR) data are unique in their inherent all-weather capabilities and therefore very important because large parts of global aquaculture activities occur in tropical and subtropical areas. Additionally the backscatter from structure components allows for their identification and separation from other features. Alexandridis et al. (2008) carried out comprehensive, comparative analyses of different earth observation instruments to study the potential for mussel farm mapping (pole farms and long line farms) for a coastal study site in northern Greece. The assessment included test data from three high resolution optical sensors - Quickbird (panchromatic 0.6 m, multispectral 2.4 m), SPOT-5 (multispectral, 10 m), Landsat-7 ETM+ (panchromatic, 15 m) and two active microwave sensors, the Radarsat-1 (HH-polarized, 8 m) and Envisat-ASAR (HH-polarized, 25 m) to examine the level of identification of mussel farms from surrounding open water and the accuracy of mapping for each data source. They concluded that pole farms were identified in all data sources with a spatial resolution higher than 10 m, however, long line mussel farms could not be identified with passive optical sensors and were only identifiable with the SAR image data with declining quality in the presence of waves. Marini et al. (2013) identified fishpond areas in South Sulawesi, Indonesia using SPOT-4 and Advanced Land Observing Satellite (Alos) - Phased Array type L-band Synthetic Aperture Radar (Palsar) data and classified the data with two different methods: maximum likelihood method for the optical image and density slice method for the radar image. The classification results showed that the estimation of fishpond area from Alos-Palsar data was 27 percent less than the estimations from SPOT-4 data. Boivin et al. (2004) analyzed the potential of SAR data to map shrimp ponds in a coastal area in Thailand. They used high resolution Radarsat-1 data to determine the backscatter behavior for pond areas and radar sensivity to water surface roughness and revealed that active aeration devices installed inside ponds caused water surface disturbances which in turn lead to higher mean backscatter for some active ponds.

Other important analyses of aquaculture based on SAR imagery is outlined by Travaglia et al. (2004) who mapped fish ponds in Lingayen Gulf, Philippines based on fine resolution mode Radarsat-1 and European Remote Sensing Satellite (ERS)-2 SAR data with a ground resolution of 6.25 m and 12.5 m, respectively. They consider that the overall mapping accuracy to detect aquaculture and fisheries structures (fish ponds, fish pens, fish cages) with ERS-2 is comparable to the Radarsat-1 data with mapping accuracies ranging from 90 to 100 percent. However, they argue that fish traps were only detectable in the Radarsat-1 data. Szuster et al. (2008) tested the identification of stationary fishing and aquaculture gears and examined the possible automatic signature separation of gear types using four Radarsat-1 satellite images for a coastal study site in the Upper Gulf of Thailand. They obtained four neighboring SAR images at three different incidence angles and performed adaptive filtering, image segmentation and a supervised classification to test the effectiveness of steep and shallow angles for the detection of coastal gears. Their outcomes showed that shallower incidence angles resulted in increased backscatter signal and provided more information so that fishing gear and aquaculture gear were both identifiable in all images. A comprehensive analysis of object features using radar imagery is presented by Chen et al. (2014) who examined how different polarimetric parameters and an object-based approach influence the classification results of various land use/land cover types using fully polarimetric Alos-Palsar data over coastal wetlands in Yancheng, China. Their results indicated that some specific polarimetric parameters greatly improved the classification results and that the shape index was an appropriate feature to distinguish fish ponds and rivers.

An attempt of applying hyper-spectral data for aquaculture research is introduced by Abd-Elrahman et al. (2011) who collected water samples from 14 shallow nutrient-rich aquaculture ponds and evaluated the utility of a ground-based hyper-spectral (HS) imaging sensor for estimating chlorophyll and they concluded that HS images can be successfully used to determine prevailing Chl-a concentrations in eutrophic and hypereutrophic aquaculture ponds.

6.2. Multitemporal investigations

Multi-temporal and multi-sensoral remote sensing approaches have become a useful tool for monitoring and analyzing the impacts of growing aquaculture activities. A wide spectrum of advanced space-borne instruments and products has become available and enables regular surveying of an area which can be used to detect changes of aquaculture over time and to identify specific spatial patterns of aquaculture expansion.

Multi-date satellite imagery for aquaculture site selection has been carried out by Shahid et al. (1992) who used visual and stereoscopic interpretation techniques for black/white aerial photographs, infrared color aerial photographs, Landsat Multispectral Scanner (MSS) and Landsat Thematic Mapper (TM) data to demonstrate the potential of satellite data for locating and measuring shrimp farming areas in Bangladesh. In an earlier bi-temporal study De Graaf et al. (2002) used panchromatic IRS-1D and multispectral SPOT data to demonstrate the capabilities of remote sensing for shrimp pond mapping and highlighted the advantages of image merging for improved pond detection. Hazarika et al. (2000) estimated shrimp farm growth in a coastal district of Chanthaburi province in Thailand from the output image of an applied unsupervised classification of bi-temporal satellite images Landsat TM and ADEOS-AVNIR acquired in 1987 and 1997.

Delineation of aquaculture extents and distributions using multi-temporal remotely sensed images has been outlined by Yang and Yang (2009) who used in situ hyper-spectral observation and multi-temporal satellite images of QuickBird (4 m), CBERS (20 m), and Landsat data (30 m) to retrieve bio-optical models and seagrass distribution and changes in Xincun Bay, China, for the period from 1991 to 2006. They found that chlorophyll-a is a very useful parameter for seagrass detection and used normalized difference vegetation index (NDVI), leaf area index (LAI) and coverage for a subsequent seagrass classification and estimated that its distribution area declined gradually since 1991. Seagrass distribution could only be obtained for the QuickBird data while for Landsat TM and CBERS with their lower resolution it was only able to retrieve seagrass distribution contours. Dwivedi and Kandrika (2005) investigated the feasibility of delineating the type and extent of aquaculture in a coastal part in southern India using multi-temporal Landsat-TM, SPOT-MLA and IRS-1C/- 1D-LISS-III and PAN data. In their approach they detected aquaculture areas based on their spectral response pattern and changes in spectral radiance values and digitized pond boundaries from the PAN-merged LISS-III image to delineate aquaculture areas based on their shape factor.

Multitemporal approaches of SAR data analyses in aquaculture are provided by Travaglia et al. (1999) who processed multi-temporal ERS-1 and ERS-2 SAR data with a spatial resolution of 12.5 m acquired in 1996, 1998 and 1999 to demonstrate the usefulness of high resolution SAR data for the inventory and monitoring of shrimp farms for a case study in Sri Lanka. A non-directional Sobel filter was used to automatically detect edges of aquaculture ponds from the SAR images (dykes surrounding the shrimp farms) and proximity analysis was applied to examine the boundaries of water bodies obtained from the classification. Liu et al. (2010) introduced an object-oriented method to detect the changes of fishpond area in South China with three temporal HH-polarization SAR images acquired from the RADARSAT-1 sensor in 2006. They found that the SAR data with short time interval were suitable to identify the change of fish pond since the backscatter and texture characteristics can provide efficient information for change detection.

Time series data analyses have great potential to reveal long term dynamics of the earth's surface and promise potential for the monitoring of aquaculture structures, area extents and ecological parameters (Kuenzer et al., 2015). By today time series analyses of remote sensing data for aquaculture purposes however rarely exist. An example is the work of Saitoh et al. (2011) who derived sea surface temperature from 297 Moderate Resolution Imaging Spectroradiometer (MODIS) images and suspended solid concentrations from daily SeaWiFS data to determine the impact of climate change on site suitability for scallop aquaculture in southern Hokkaido, Japan. A related approach for the same study area was carried out by Radiarta et al. (2011) who also used MODIS and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) data and additional bathymetric data to determine potential areas for the cultivation of Japanese Kelp. Higgins et al. (2013) carried out comprehensive differential SAR interferometry (DInSAR) analyses using Alos (Advanced Land Observation Satellite)-Palsar (Phased Array L-Band Synthetic Aperture Radar) and Envisat (Environmental Satellite) Advanced SAR data (ASAR) to retrieve land subsidence for the coastal aquaculture areas of the Yellow River Delta in China. The results from the DInSAR technique showed tremendous subsidence occurred at aquaculture facilities with rates up to 250 mm per year and they concluded that subsidence in this region can be mainly attributed to increased groundwater pumping. Rahman et al. (2013) mapped and quantified the destruction of mangroves and identified the drivers of deforestation in order to develop successful mitigation/adaptation strategies. In their study they used a new and improved quality-assured time series of 'high-fidelity' MODIS imagery, a simple yet robust statistical method of change detection, and a mixed-pixel analysis method, to reconstruct 11 years of deforestation history of mangrove areas in the Mahakam Delta at consistent temporal and spatial scales. The results show that a total of about 21,000 ha of mangrove land in the Mahakam Delta were deforested and converted to shrimp ponds in 11 years.

6.3. Land use change, degradation

As depicted in chapter 4, aquaculture has caused tremendous land use changes in many coastal environments and often indicates removal or destruction of wetlands. Land cover/land use change gives us a clearer picture of what has been displaced by the development or expansion of new aquaculture areas and how these change affect the landscape. A number of studies analyzed land cover/land use changes in coastal and marine areas and derived aquaculture area, its extent and expansion over time, and are presented below.

Berlanga-Robles et al. (2011a) analyzed the impact of shrimp aquaculture on coastal wetlands on the northern coast of Sinaloa, Mexico using Landsat MSS (1986), TM (1992 and 2005), and ETM+ (2000) images and performed a land cover and land use change detection analyses. In combination with a digital elevation model and land use vector data they used the output images to build a decision tree to derive a six class map. Shrimp farm polygons were digitized from the Landsat images and in a second step they analyzed patch-size distribution and evaluated the changes in the spatial structure of the wetlands using landscape metrics. Their results from the change-detection matrix, patch-size distributions and landscape metrics indicated that although mangrove systems have been altered by shrimp aquaculture, saltmarshes are the most affected wetland type. Tong et al. (2004) assessed the impact of shrimp aquaculture in two provinces of the Mekong Delta in Vietnam on mangrove ecosystems using four SPOT-4 HRVIR scenes and identified and delineated five ecologically distinct landscape classes that indicated that about 30 percent of mangrove ecosystems have been lost in Ca Mau Province since 1965.

Mialhe et al. (2013) combined ground surveys and interviews with multi-temporal inventory of land resources obtained by an image data set from the sensors Landsat MSS, TM, ETM+, SPOT and aerial photographs covering a period of 45 years to study the impacts of shrimp farming in the Tumbes river delta in northern Peru. Principal component analysis (PCA) was first performed on each image in order to convert possibly correlated spectral data into a set of linearly uncorrelated variables. Then they quantified the areas over which aquaculture-related land use has expanded at the expense of mangrove and found out that aquaculture has also developed over land cover categories initially detected as bare soil, dry forest, and savanna. Yao (2013) classified aquaculture farms and other land uses in the coastal zone of Nantong (China) based on Landsat TM and ETM images to analyze spatial patterns using land use mapping and the corresponding statistical data. They applied a supervised classification approach using the support vector machine classifier to extract all land use types from the pre-processed images. It was found that the classification method alone was not able to effectively distinguish between the aquaculture farms on land and the shallow sea, and between the reclaiming regions and the rivers flowing into the sea. Rajitha et al. (2010) quantified land cover changes in the coastal stretches of the East Godavari delta in India using five multi-temporal images from the IRS-LISS II and IRS-LISS III sensors acquired in 1990, 1994, 1997, 1999, and 2005. The change detection was based on normalized difference vegetation index image differencing. Their study revealed that aquaculture ponds more than doubled within the 15 years investigation period. Pattanaik and Narendra Prasad (2011) assessed the impact of aquaculture on mangroves in Mahanadi delta of Orissa, East coast of India which is famous for its distinctive mangrove ecosystem. Satellite data from Landsat MSS (80 m) of 1973, Landsat TM (30 m) of 1990 and IRS-LISS III (23.5 m) of 2006 were used. The satellite data were classified and it was found that there was a loss of mangrove areas and increase of aquaculture area. Zitello (2007) analyzed landscape changes in coastal Northeast Brazil between 1990 and 2006 resulting from increased shrimp pond development. In this study land cover maps were generated from Landsat TM, ETM+ and ASTER imagery at three separate time periods (1990, 2000, 2006) which indicated a substantial growth of shrimp aquaculture facilities. Contrary to literature regarding shrimp aquaculture impacts in other regions of the world, their study revealed that mangroves were least likely locations to site new shrimp pond development and did not show great losses due to displacement by culture ponds. Shrimp aquaculture rather developed in tidal salt flats that lie behind the mangrove forests and experienced greatest destruction.

Muttitanon and Tripathi (2005) used Landsat 5 TM composites of 1990, 1993, 1996 and 1999 of a coastal area in southern Thailand and applied a supervised classification with a maximum likelihood classifier to generate land use maps and used image differencing to detect changes from one land cover to another based on NDVI composite classification, which were found suitable for delineating the development of shrimp farms and land use changes in Ban Don Bay. This study illustrated an increasing trend of shrimp farms, forest/mangrove and urban areas with a decreasing trend of agricultural and wasteland areas.

Nagabhatla et al. (2009) investigates the complexity of an inland freshwater wetland system of Lake Kolleru in India through mapping and monitoring dynamics acquired from multi-temporal image analyses of Landsat MSS, TM, ETM and IRS-LISS III and proved declining wetland agriculture and an increase of aquaculture. For the same site, Jayanthi et al. (2006) also assessed the impact of aquaculture on Lake Kolleru, India with IRS 1D, LISS III and Survey of India topographic maps from 1967 to 2004 and revealed a total loss of lake area of 109.02 km^2 between 1967 and 2004, in which aquaculture was developed in 99.74 km^2.

It can be seen that aquaculture development in mangrove areas is a hot topic and is reflected by the majority of reviewed publications indicating that there is a clear linkage between destruction of mangrove and other wetland types and predominant aquaculture development. Although aquaculture is not always the central objective in many studies it is however directly or indirectly investigated and becomes increasingly important, offering great potential for further analyses with advanced remote sensing techniques.

Mangrove deforestation in the course of shrimp and prawn farming intensification and expansion is outlined in a multi-temporal analysis by Almeida-Guerra (2002) who used 20 m SPOT data to detect land use change in a study areas at the Colombian Caribbean Coast. They argue that the increase of aquaculture activities in this area has resulted in the construction of new ponds and could be closely related to deforestation of mangroves. Santos et al. (2014) assessed and mapped anthropogenic activities on the mangroves in the São Francisco River Estuary, Brazil Northeast using SPOT 5 and CBERS-2B images in order to draw up guidelines for a local management plan. Their results indicated that shrimp farming is the main anthropogenic activity, occupying the highest area and occurring within the tallest *Rhizophora* mangrove forests. Satapathy et al. (2007) used IRS-LISS III data to detect mangrove changes in the Godavari delta from 1992 to 2004. Both supervised and unsupervised signature extraction techniques were used to classify the imageries and carried out change detection analysis subsequent to land use/land cover classification. Their results show that mangrove area was destroyed by aquaculture and tree falling. Seto and Fragkias (2007) present a methodology to operationalize the use of satellite imagery to assess the impact of the Ramsar Convention on Wetlands in the Red River Delta, Vietnam. To identify aquaculture development and mangrove extent, they used artificial neural networks to classify multi-temporal Landsat MSS and TM images acquired from 1975 to 2002. The approach uses time series analysis of landscape pattern metrics of total mangrove extent, mangrove fragmentation, mangrove density, and aquaculture extent to assess land cover conditions before and after designation of Ramsar status to monitor compliance with the Convention.

Many other studies used remotely sensed optical and radar data for land use change mapping in areas where aquaculture tends to be a main economic basis for supporting livelihood of local farmers. Binh et al. (2005), Nguyen et al. (2013) and Lam-Dao et al. (2011) carried out spatial-temporal change detection of mangrove extents and adjacent land use in coastal areas of the Mekong Delta revealing that shrimp farming became the dominant land use while mangrove area declined drastically during the past decades. Moreover, mangrove conversion to shrimp, prawn or mussel farming are also described for coastal case studies in Thailand (Sremongkontip et al., 2000), India (Ramasubramanian et al., 2006; Venkataratnam et al., 1997), Vietnam (Béland et al., 2006) and Brazil (Guimarães et al., 2010).

7. Conclusion

The rapid growth of aquaculture production has outpaced capture fisheries and it is foreseen that aquaculture will be the main source of aquatic animal food in the next years. Aquaculture already gained great value as a primary source of animal protein in many countries and has great potential to improve global food security. However, global climate change is a major challenge to the sustainability of coastal aquaculture. Climate change impacts such as global warming, sea level rise, saline intrusion and extreme weather events (floods, droughts, storms) could have severe effects on future aquaculture. Potential increased pressure on water resources (shortages in freshwater availability) and water quality (eutrophication) could lead to declining aquaculture production and affect food security and export earnings with negative consequences for the economy in high export-oriented aquaculture production countries.

While providing economic benefits, aquaculture causes a number of environmental problems and affects sustainable use of natural resources. Continuing rise of global aquaculture will entail increasing loss of valuable coastal habitats, environmental degradation and water and soil pollution which will also increase the vulnerability of ecosystems and threaten environmental health. For this reason it is important to spatially assess aquaculture in order to deduce potential effects and to develop appropriate measures to protect the environment. Earth observation is a perfect tool for standardized inventory to obtain a local, national, regional or even global picture of the current status of aquaculture.

The reviewed published research demonstrated advantages and opportunities of earth observation applications for the assessment and monitoring of aquaculture sites. A total of 21 different satellite sensors were counted during the review of the literature - the most frequently applied optical sensors were Landsat, SPOT, IRS-LISS III, and Radarsat-1, ERS-1/2 and Alos-Palsar for Synthetic Aperture Radar (SAR) sensors. Many new earth observation instruments with very high spatial resolution and shorter revisit times have been recently launched or are scheduled and will extend the possibilities of detailed delineation, tracking and monitoring of aquaculture sites. Data costs are a significant concern and constrain access and use of advanced remotely sensed data, particularly in developing countries. However, more and more high resolution data from optical and radar satellites can now be downloaded by everyone free of charge. Since 2008 the U.S. Geological Survey (USGS) started to provide free access to its decade-long Landsat data archives with large amounts of image data from the Landsat instruments MSS, TM, ETM+ and OLI/TIRS. Within the free and open data policy of the Copernicus program of the European Space Agency (ESA) the high resolution Sentinel-1A/B radar satellites and the optical Sentinel-2A/B sensors will facilitate advanced remote sensing studies for accurate inventory and monitoring of aquaculture.

Many of the environmental factors that influence the sustainable development of aquaculture can be measured by remote sensing. Earth observation can effectively support the planning and management of aquaculture practices and the implementation of adequate regulations and protection measures. Here, it will be a challenge to bring together experts from various fields of research with different background and viewpoints and to integrate and supply remote sensing as a useful tool for sustainable aquaculture research. There are fisheries experts, biologists, ecologists and remote sensing experts involved – all with very different spatial perspectives ranging from in depth field surveys and measurements on micro-level to mapping and monitoring of large-scale areas on local, regional and global level. Area-wide assessments of aquaculture and visualization of such valuable data would add great value to support and convince stakeholders, politicians, and conservationists in all urgent matters to protect our planet's natural resources and enable sustainable further development in the aquaculture sector.

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