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Opportunities and Challenges for the Estimation of Aquaculture Production Based on Earth Observation Data

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Abstract: Aquaculture makes a crucial contribution to global food security and protein intake and is a basis for many livelihoods. Every second fish consumed today is produced in aquaculture systems, mainly in land-based water ponds situated along the coastal areas. Satellite remote sensing enables high-resolution mapping of pond aquaculture, facilitating inventory analyses to support sustainable development of the planet's valuable coastal ecosystems. Free, full and open data from the Copernicus earth observation missions opens up new potential for the detection and monitoring of aquaculture from space. High-resolution time series data acquired by active microwave instruments aboard the Sentinel-1 satellites and fully automated, object-based image analysis allow the identification of aquaculture ponds. In view of the diversity and complexity in the production of aquaculture products, yield and production varies greatly among species. Although national statistics on aquaculture production exist, there is a large gap of pond-specific aquaculture production quantities. In this regard, earth observation-based mapping and monitoring of pond aquaculture can be used to estimate production and has great potential for global production projections. For the deltas of the Mekong River, Red River, Pearl River, and Yellow River, as one of the world's most significant aquaculture production regions, we detected aquaculture ponds from high spatial resolution Sentinel-1 Synthetic Aperture Radar (SAR) data. We collected aquaculture production and yield statistics at national, regional and local levels to link earth observation-based findings to the size, number and distribution of aquaculture ponds with production estimation. With the SAR derived mapping product, it is possible for the first time to assess aquaculture on single pond level at a regional scale and use that information for spatial analyses and production estimation.

Keywords: aquaculture; sentinel-1; coastal zone; earth observation; food security

1. Introduction

1.1. Relevance of Aquaculture for Global Food Security

Rising global demand for aquatic protein, such as fish, crustaceans and mollusks, high income and substantial profit potentials made a key contribution to the almost fivefold increase in global aquaculture production from 13 million tons in 1990 to 76 million tons in 2015 (see Figure 1) valued at USD 158.1 billion [1]. Over the same period, the contribution of aquaculture to the global fish production has increased from about 13 percent to 45 percent. With an average annual growth rate of 6.7 percent [1], aquaculture became the world's fastest growing animal food production sector; a major source of essential fatty acids and animal protein [2,3]. Aquaculture is gaining increased international attention in matters of future nutrition and food security of the world population [4–6]. Worldwide average fish consumption (see Figure 2) per capita almost doubled from 10 kg in the 1960s to 19 kg in 2013 [7,8] and an increasingly large share of fish and other aquatic organisms entering global markets stems from farming in ponds, cages, and net systems [2,6]. Aquaculture, therefore, had a mitigating effect on the declining availability of capture fisheries [9] and has the potential to substantially grow the supply of farmed fish in coming decades [10,11].

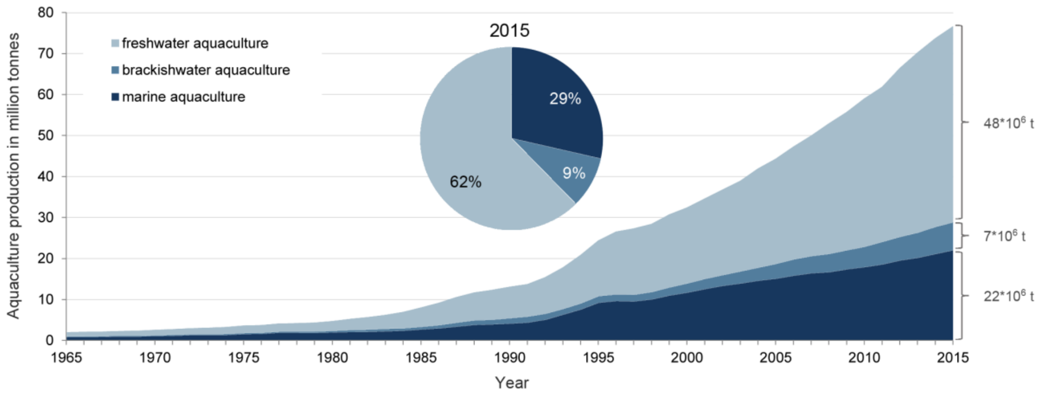

Figure 1. Global aquaculture production (excluding photosynthetic organisms) in freshwater, brackish water and marine culture systems. Data source: [1].

The rapid growth of aquaculture had positive economic and social impacts in many countries, contributing to the generation of income and employment for millions of people. On the other hand, aquaculture caused significant environmental degradation in the coastal zone around the globe. Aquaculture needs space and is a main driver of deforestation [12–14] and water pollution [15,16]. The input of external feeds and antibiotics leads to the destruction of ecosystems [7,17,18] and adversely impacts the health of our planet's coastal ecosystems. Mangroves, tidal flats, and creeks are most affected. This primarily includes all low-lying coastal areas and river deltas around the world and, in particular, in the tropical and sub-tropical regions of Asia where the majority of species farmed are grown in ponds [19,20]. In 2015 freshwater aquaculture accounted for about 62 percent of global production quantity (see Figure 1). Within freshwater aquaculture, land-based ponds are the predominant culture systems in fish and shrimp farming in Asia [19,21].

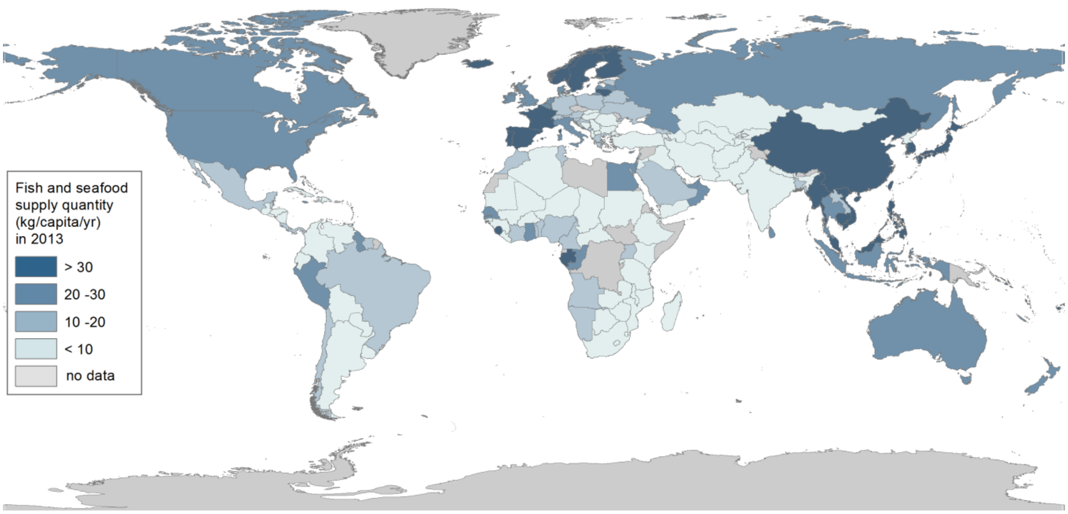

Figure 2. Consumption of fish and fishery products per country. Data source: [22].

Food security is a major policy priority across governments, non-governmental institutions, and international organizations such as the Food and Agriculture Organization (FAO) and the World Food Programme (WFP) of the United Nations, The World Bank (WB), or the International Fund for Agricultural Development (IFAD) [23]. Globally, fish and other aquatic food products provide more than 17 percent of all animal protein to the planet's population [23–25]. Maintaining production and supply of aquatic food is crucial to meet rising global demands for protein-rich fish and seafood for the next decades [10].

1.2. Sustainability and Challenges in the Context of Global Change

The global human population is expected to exceed 9 billion by 2050 [26] and will increase the pressure on the food sectors to increase production [10]. Meeting the food and nutrition needs of a growing global population will create greater competition for land, water, and energy resources [11,27]. However, maintaining supplies of resources for aquatic products is a major challenge particularly in the face of global climate change [25]. World aquaculture production will be increasingly vulnerable to global warming and its impacts: sea level rise, a changed water balance and freshwater supply, increased frequency of extreme weather events (floods, droughts, storms) and disease outbreaks are major challenges to the sustainability of future aquaculture [7,28,29].

In estuarine and marine environments, nutrient pollution, disease spread, and the use of capture fish in feed threaten the economic stability and environmental sustainability of aquaculture [30]. The expansion of aquaculture has already limited land availability in low topography coastal areas leading to increased land-use competition for urban areas, wetlands and freshwater resources [31]. In this context, the FAO expressed concern for the future growth of inland aquaculture given higher demand on land availability, freshwater resources, and urbanization [32]. However, continued sustainable development of aquaculture is necessary to meet future demands for fish [33]. The FAO promotes the "Blue Growth" initiative, a concept conceived at the United Nations Conference on Sustainable Development in 2012 (Rio+20 summit). The goals of the Blue Growth Initiative are closely aligned to the 2030 Agenda for Sustainable Development and its Sustainable Development Goals (SDGs) and aim to better address the need for sustainable and socio-economic management of natural aquatic resources, with an emphasis on efficient resource use in capture fisheries and aquaculture [31,32].

Advances in hatchery production, grow-out technology, feeds, and feed-delivery systems could increase output. Future gains may also come from better stock selection, larger-scale production technologies, aquaculture in larger inland water bodies, and the culture of a wider range of species [27]. On the downside, intensification and higher stocking rates increase risks of disease outbreak and intensify the consequences of an outbreak [34].

1.3. Characteristics of Aquaculture Pond Systems

In this paper, we focus on pond systems used for the farming of aquatic animals (excluding photosynthetic organisms, e.g., aquatic plants) for four selected study areas distributed along the coasts of China and Vietnam. Aquaculture ponds are permanently water-filled surfaces surrounded by dams, levees, or dikes, constructed of soil or other impervious surfaces. They are typically shallow, no deeper than 2 m [35], as aquaculture farmers need to be able to wade in the water for the application of feed, medicine, repair, maintenance, servicing and harvesting. Although the pond system can be used to grow aquatic plants (e.g., algae), the vast majority of ponds are utilized to cultivate a wide range of aquatic animals such as fish, crustaceans, and mollusks [35]. Ponds usually have a rectangular shape (see Figure 3) and their sizes vary among facilities and farmed species [35] ranging from small-scale and subsistence-oriented aquaculture [36–38] to large-scale commercial or industrial aquaculture [19]. External input including feed, fertilizers, water, and energy [39] is used to increase yields and profitability and differs according to the degree of farming intensity. With their predominantly rectangular shape, ponds can be detected and identified with high-resolution satellite data and image segmentation methods [40–44].

Figure 3. Photos of shrimp ponds with aeration systems from Soc Trang Province and Tien Giang Province, Mekong Delta, Vietnam (Source: DeltAdapt project, 2017).

1.4. Yields and Statistical Data

Crop yields in pond aquaculture vary depending on the culture intensity for different aquaculture production systems. According to Tucker and Hargreaves [35], yields in ponds vary by at least two orders of magnitude, from 200 kg per hectare in lightly fertilized fish ponds to over 20 tons per hectare in intensively managed crops with feeding and continuous ventilation. Therefore, it is difficult to estimate the total annual aquaculture yield.

The FAO is assembling, harmonizing and archiving global reported statistics provided by FAO member countries [45]. Campbell and Pauly [46] state that only one-sixth of lower-value, domestically-traded and small-scale aquaculture production is officially reported, therefore having great impact on the accuracy of the aquaculture status. Many countries and national agencies lack the means to directly collect fishery data. However, robust estimates of current and potential yields are essential for informing effective food security and environmental conservation efforts by governments as well as by international aid, development and conservation groups such as the UN and non-governmental organizations [24]. In view of challenges with regard to on-the-ground data collection for inland fisheries the FAO concludes in its latest report [24] that there is a need for broad-scale assessment tools to inform national and international policy.

1.5. Potential of Earth Observation

Remote sensing of aquaculture exploits the fact that active ponds are permanently water covered year-round. Temporally dense high-resolution earth observation time series data [47] allows distinguishing aquaculture from other rectangular, water covered surfaces, which look identical to aquaculture in mono-temporal imagery, but are not water covered year-round. These are for example rice fields [48], salt production brine ponds or other square fields [49]. The availability of free and open data through the newest Sentinel missions of the European Copernicus programme has brought large potential to map aquaculture in the tropics and sub-tropics where cloud coverage is limiting the availability of dense optical time series data. Optical sensors have the disadvantage that they are not able to penetrate clouds, which is a major problem in coastal regions where frequent cloud cover affects the quality of the time series. Reliable detection of aquaculture ponds from space requires the analysis of dense satellite image time series to identify temporal profiles of pond water. Radar satellites, such as Sentinel-1, on the other hand, have the ability to capture the continuously water covered aquaculture independent of daylight and cloud cover [50]. Figure 4 illustrates the appearance of aquaculture ponds in radar (Figure 4a–c) and optical (Figure 4d–f) imagery acquired with different sensors.

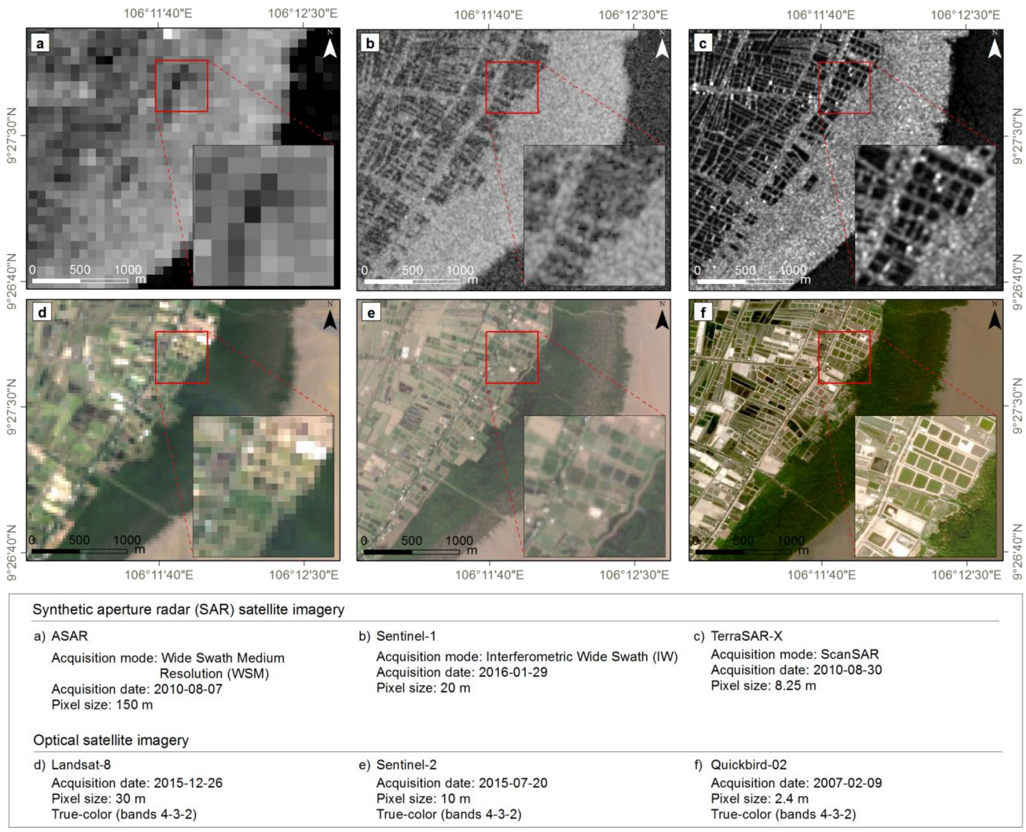

Figure 4. Appearance of shrimp pond system in Synthetic Aperture Radar (SAR) and optical satellite data. Example spot is located in Soc Trang Province, Mekong Delta, Vietnam.

This study highlights the opportunities of earth observation for the estimation of aquaculture yield and production, based on time series data processing. Within the developed framework, that integrates satellite remote sensing data and aquaculture statistics, we elucidate the potential and challenges for the calculation of an appropriate estimate of pond production. For comparison, the area analyzed exceeds that of the country of Iceland.

2. Study Area

We focus on four river deltas–the Mekong River Delta (MRD) and Red River Delta (RRD) in Vietnam and the Pearl River Delta (PRD) and the Yellow River Delta (YRD) in China. In the past 30 years, these deltas have experienced rapid socio-economic transformation resulting in urbanization, industrialization, population growth, and agricultural intensification [49,51–54]. Deregulation policies and growing demand for aquatic food products caused unrestrained expansion of aquaculture in the coastal zone within its suitable environments: lagoons, estuaries, and river deltas.

With the exclusion of aquatic plants from production estimates, Asia contributes 90 percent to the global aquaculture production. China clearly dominates the aquaculture market, producing more than 47 million tons in 2015, accounting for 62 percent of the total global aquaculture volume and 48 percent in terms of value. The Chinese provinces Shandong and Guangdong contributed the highest shares to the national aquaculture volume (see Figure 5) and include the Pearl River Delta and Yellow River Delta respectively. Along with Vietnam which ranks fourth in the world, these two Asian countries are responsible for two-thirds of the world's total aquaculture production in 2015 [40].

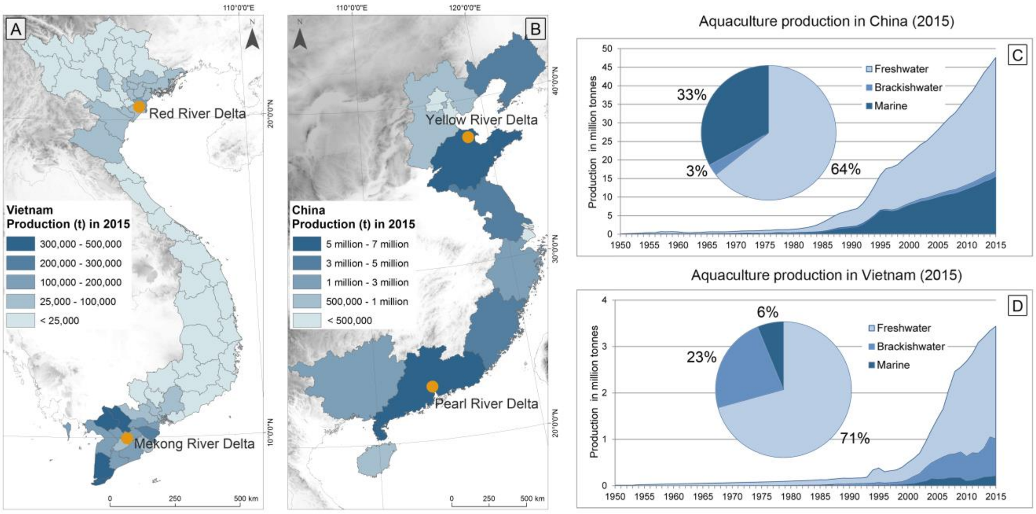

Figure 5. Statistical data on aquaculture production (excluding aquatic photosynthetic organisms) in Vietnam and China (coastal provinces) at province level in 2015 (**A**,**D**) and classified according to different culture systems (**B**,**C**). Data source: [1].

3. Earth Observation-Based Derivation of Pond Aquaculture

3.1. Earth Observation Data

We used VH-polarized Sentinel-1 C-band synthetic aperture radar (SAR) data in the Interferometric Wide Swath Mode (IW) and GRDH format with a resolution 10 m pixel spacing (after 5 $\times$ 1 multi-looking). A total of over 500 Sentinel-1A/B scenes for a two-year period (September 2014 to September 2016) were collected: 192 for the Mekong Delta, 83 for the Red River Delta, 174 for the Pearl River Delta and 66 scenes for the Yellow River Delta. Figure 6 shows the data volume of all available Sentinel-1A/B GRDH scenes (in ascending and descending orbit) along the coastal zone of China and Vietnam from launch up to October 2017, indicating that data coverage considerably varies among regions.

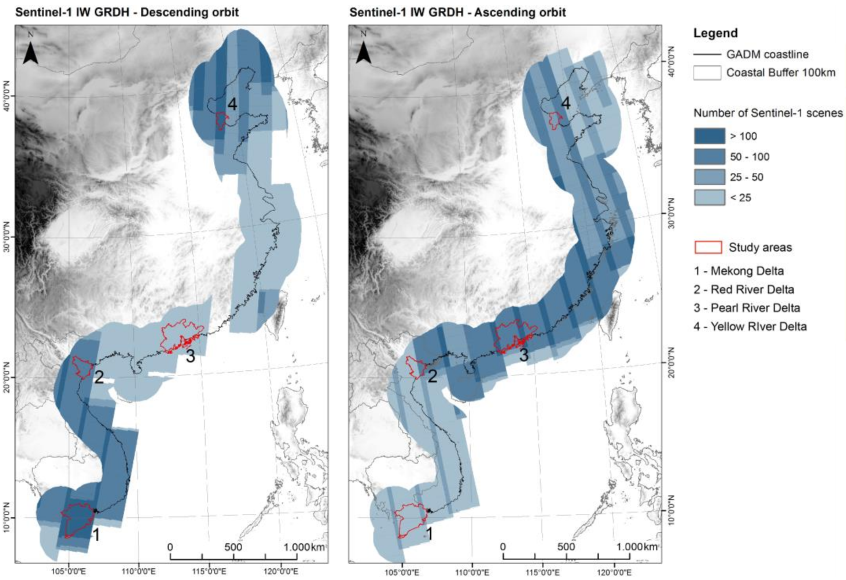

Figure 6. Coverage frequency of dual-polarized Sentinel-1 scenes (September 2014–October 2017) for the coastal zone of China and Vietnam acquired in descending (**left**) and ascending (**right**) orbit.

3.2. Aquaculture Assessment Framework

We developed a reliable, object-based mapping workflow for mapping aquaculture ponds (see workflow described in Figure 7) as described in detail in Ref. [40]. We used Sentinel-1 time series data provided by the Google Earth Engine team (https://earthengine.google.com/, [55]) which is globally available and preprocessed using the free and open source Sentinel Application Platform (SNAP) software. The preprocessing comprised the application of an orbit file using restituted orbits, removal of thermal noise, and radiometric calibration to convert intensity values to the backscatter coefficient sigma naught. In a next step terrain correction was performed with the Shuttle Radar Topography Mission (SRTM) 30 m resolution data to correct for layover and foreshortening effects. Depending on the total number of available acquisitions in the respective orbit directions data in either ascending or descending mode was selected and transformed into a data cube for the subsequent analysis. We processed more than 500 Sentinel-1A scenes for a two-year period (September 2014 to September 2016) with a data volume of more than 700 GB. In a next step, the pixel-wise median was calculated for the time series data cube to identify permanent and stable low scatterers (pond water) from the dense and long temporal time series. The median of the temporal image stack (data cube) enabled a reduction of speckle noise, which affects SAR intensity data, improving the appearance and detection of aquaculture ponds with its narrow, elongated line structures (such as dams and levees).

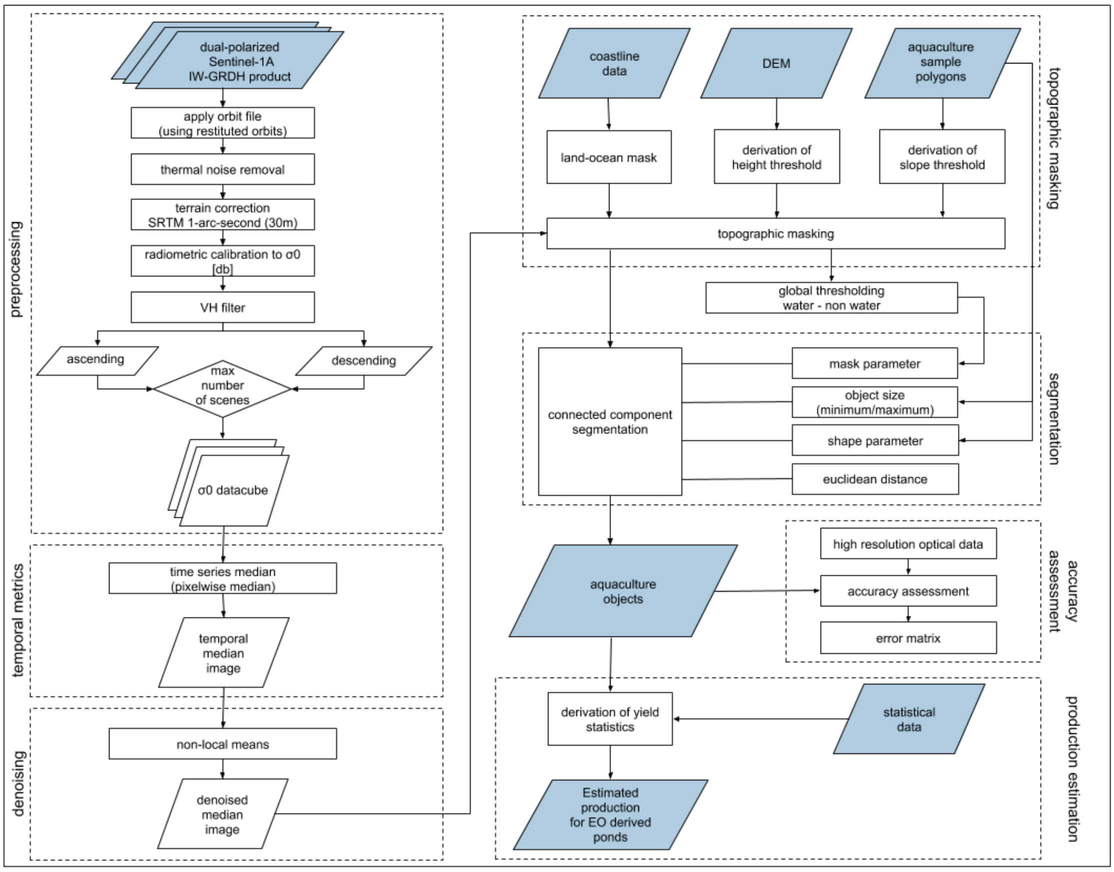

Figure 7. Workflow of the aquaculture mapping framework, modified according to Ottinger et al. [40].

Terrain information based on digital elevation model (DEM) derived topographic features (elevation and slope) and coastline data provided by the Institute of Geographic Sciences and Natural Resources Research (IGSNRR), Chinese Academy of Sciences [56,57], was used to extract potential low-lying coastal regions that are suitable for coastal pond aquaculture and exclude other water bodies which are most likely to be confused with aquaculture ponds.

As a preliminary step of the subsequent segmentation, a clustering-based image thresholding method is applied to automatically discriminate water and land area and to generate binary water masks for the separation of pond water surfaces and surrounding land area. For the detection of aquaculture on single pond level, an object-based pond classification of the Sentinel-1 image data cubes is performed using a connected component segmentation algorithm provided within the Orfeo Toolbox (OTB) (see Appendix A). The algorithm applies Euclidian intensity pixel distance criterion, object and shape properties [40].

For each study site, we performed accuracy assessment based on stratified random sampling, distributed 100 samples per stratum (aquaculture and non-aquaculture) [40]. The proposed approach achieved overall accuracies ranging from 0.80 in the Yellow River Delta, 0.83 in the Mekong Delta, 0.84 in the Red River Delta, to 0.88 in the Pearl River Delta, with a mean overall accuracy of 0.84. The Pearl River Delta has a higher coverage of Sentinel-1 data than the Red and Yellow River Delta and also shows a higher accuracy. The vast pond area required for fish and shrimp farming becomes visible in Figure 8, illustrating the mapping results for the four large-scale delta regions located along the Chinese and Vietnamese coasts. 3.3. Spatial Pattern of Aquaculture Ponds in the Coastal Study Sites

To enable a viable representation of the results for the complete study sites, we summarized the pond features over a hexagonal grid and calculated the number of ponds (Figure 9A,C,E,G) and pond area (Figure 9B,D,F,H). In Figure 9 we can identify areas with high pond density in the hexagon plots. In the Mekong Delta and Yellow River Delta, aquaculture is mainly concentrated near the coast, while in the Pearl River Delta (and to lesser extent also the Red River Delta) the ponds form no distinct spatial pattern. In the Pearl River Delta, many ponds are located along the main river and its tributaries which can be attributed with the flat relief in this area. We found a highly significant positive correlation between pond area and pond number, indicating that as the pond area per unit increases, the number of ponds also increases.

We calculated the number of aquaculture ponds (see Figure 10) and aquaculture pond area (see Figure 11) for buffer rings along the coastline for each study site. The two profiles in Figure 10. Figure 11 illustrate that the highest shares of aquaculture are concentrated in close proximity to the coast (15 km distance to the coastline) of the respective study area. Information on the spatial distribution of aquaculture is necessary for spatial planning and development in the coastal zone at local and regional levels. Aquaculture is in conflict with other existing or foreseeable land uses, e.g., urban development, tourism, and traffic infrastructure, among others. The coastal zone provides large resources for millions of people and sustainable management is essential for future development. The construction of pond facilities, freshwater management (groundwater withdrawal) and waste discharge within aquaculture production induces coastal erosion [58,59], subsidence [60], and salinization [17,61] and has great impact on the environmental degradation of coastal ecosystems [12,62–64].

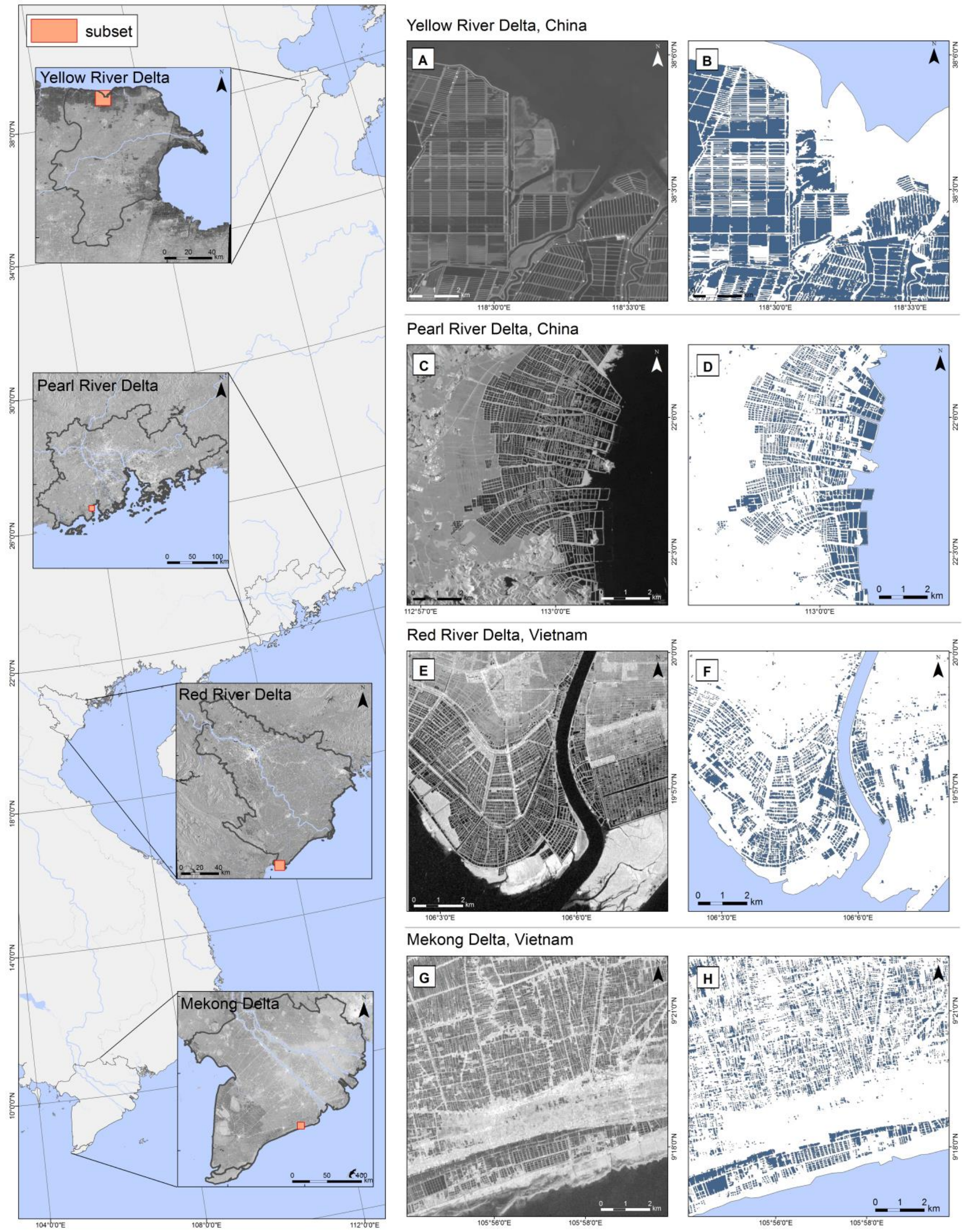

Figure 8. Map of the study areas along the coast of China and Vietnam (**left**). Smoothed Sentinel-1 time series and corresponding aquaculture mapping result for subsets of the Mekong Delta (**G**,**H**), Red River Delta (**E**,**F**), Pearl River Delta (**C**,**D**), and the Yellow River Delta (**A**,**B**).

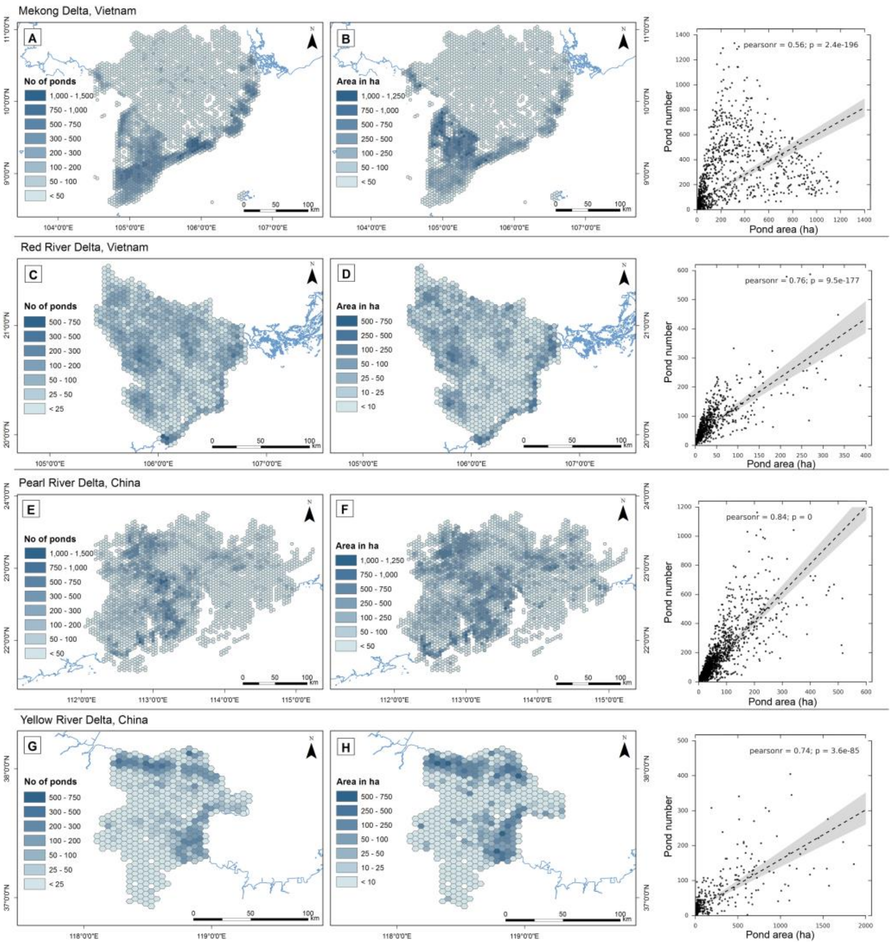

Figure 9. Number of ponds (**A**,**C**,**E**,**G**) and pond area in hectare (**B**,**D**,**F**,**H**) for the study areas. The earth observation derived aquaculture object dataset has been generalized into a hexagon grid map (hexagons with a side length of 5 km).

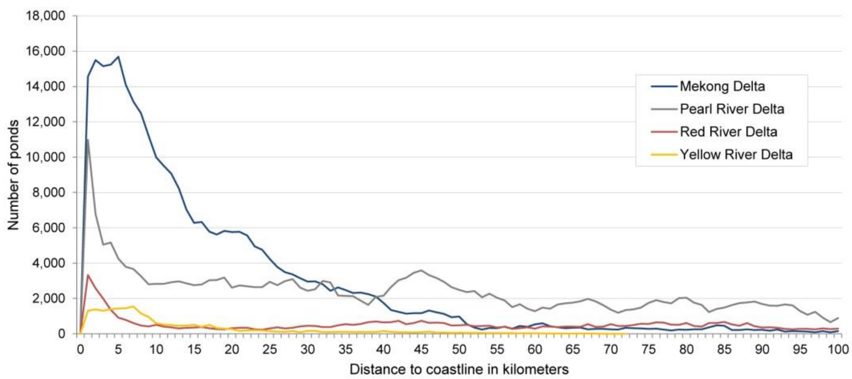

Figure 10. Amount of earth observation derived aquaculture ponds in relation to distance to the coastline.

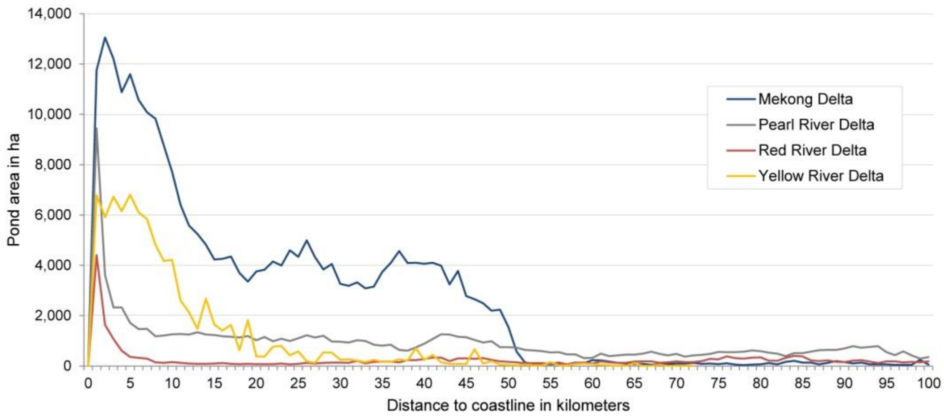

Figure 11. Area of earth observation derived aquaculture ponds with different distance to the coastline.

4. The Potential of Earth Observation Data for Aquaculture Production Estimation

In view of the great potential of aquaculture to contribute to global food security, the estimation of pond production quantities is an essential research objective for the coming years. Statistical data (e.g., provided by the FAO for most countries) are available at national and sub-national levels, though generally in limited detail, providing statistics on total aquaculture quantities. However, detailed data on aquaculture regional statistics, its expansion and localization barely exist but is of utmost interest.

With the approach outlined in the previous chapter, we derived the number of aquaculture ponds and aquaculture pond area for four large-scale study areas. We collected annual statistics of aquaculture production for all study areas at province, district and municipality levels depending on availability. Based on the statistical information collected we matched statistical and earth observation derived data in order to detect quantitative indicators and correlations. Using aquaculture production and yield statistics, we estimated aquaculture production amounts for the earth observation derived fish and shrimp ponds. With the SAR-derived product, it is possible for the first time to assess aquaculture on single pond level at regional scale and use that information for spatial analyses and production estimation.

4.1. Available Datasets

4.1.1. Global Aquaculture Production Database

The FAO Fisheries and Aquaculture Department compiles and disseminates fishery data, structured within its data collections on capture and aquaculture statistics at a national scale (see Table 1). Information on aquaculture production is collected annually and standardized from relevant national offices by FAO's Statistics and Information Service (FIPS). Data reported to the FAO are mainly based on official government reports, supplemented by verifiable information from other sources, including academic reviews, consultants reports and other specialist literature [65,66]. The FAO database includes statistical datasets on annual production of capture fisheries and aquaculture since the year 1950 for most countries, providing complete global coverage [24].

Table 1. Aquaculture production * in Vietnam, China and global. Data source: FAO (2017).

	Total (All Species)		Fish			Crustaceans			Mollusks		
	Tons	**% WT**	**Tons**	**% NT**	**% WT**	**Tons**	**% NT**	**% WT**	**Tons**	**% NT**	**% WT**
Vietnam	3,438,378	4.5	2,606,272	75.8	5.0	612,038	17.8	3.7	21,562	0.6	0.3
China **	47,615,734	62.1	28,791,920	55.5	55.5	13,848,424	29.1	18.1	4,125,538	8.7	56.1
Global	76,641,026	100.0	51,907,471		100.0	16,473,112		100.0	7,351,349		100.0

* excluding photosynthetic aquatic organisms (e.g., aquatic plants); ** including Hong Kong SAR; NT = national total; WT = world total.

4.1.2. National Aquaculture Production Statistics

China

Aquaculture statistical data at national and sub-national levels for China can be obtained from the National Bureau of Statistics of China (NBS). This data is made available on a highly aggregated level depicting information on total aquaculture production volumes and aquaculture area. The database provides total production figures for the entire aquaculture sector in which all available species (and culture systems) are compiled. On a lower administrative level statistical data are freely available from the district statistics offices. These offices provide aggregated aquaculture production statistics on a district level and on a more detailed level for the respective municipalities. For China we collected statistical data on sub-district level for all municipalities that are part of the Pearl River Delta and Yellow River Delta regions.

Vietnam

Vietnam provides statistical data on aquaculture production for fish and shrimp at national and provincial levels via the Vietnamese General Statistics Office (GSO). Aquaculture production statistics at district or municipality level are not publicly available but can be purchased directly from yearbooks published by the respective administrative offices. We collected province statistical yearbooks from all 13 province statistics offices of the Mekong Delta. The province yearbooks data cover a 5-year period and the data was translated, encoded and standardized for further use.

4.1.3. Literature

Literature is another important source of aquaculture yield estimates. Numerous publications estimate aquaculture production and yields in local and small-scale studies, which cover a small number of ponds. A large share of these publications incorporates shrimp or freshwater species. We searched, summarized and standardized the most important and meaningful sources which refer to yield estimates in various regions and present them in Table 2.

The average yield values per species shown in Table 2 have a spread that is smaller than the difference in between the species. In this context, yield of aquaculture pond systems in Vietnam have been comprehensively analyzed and documented. For fish (carp, tilapia) culture in pond systems yield ranges between 3–15 t/ha/year. In extreme case, intensive catfish pond culture in the Mekong Delta can produce 370 up to 700 t fish per hectare per year. The yield for shrimp ponds ranges from to 6–8 t/ha/year in intensive systems, 0.4–2 t for semi-intensive systems, and less than 0.4 t for extensive systems.

Table 2. Yield at different aquaculture pond systems, species and regions.

Region	Environment	Species	Yield *	Source
Global	general	general	0.2–20 t/ha/yr	[35]
Global	fertilized polyculture ponds	carp	3.6–14.6 t/ha/yr	[35,67]
Global	fertilized ponds	herbivorous or omnivorous fish	3–10 t/ha/crop	[35,67]
Tropics	fertilized ponds	nile tilapia	3.6–7.3 t/ha/yr	[35]
China	pond culture	-	6.8 t/ha/yr	[68]
Honduras	semi-intensive	shrimps	0.4–2 t/ha/yr	[69]
Thailand	-	shrimps	7–8 t/ha/yr	[69,70]
Vietnam	-	pangasius catfish	370 t/ha/crop	[71]
Mekong Delta	intensive culture	black tiger shrimps	7 t/ha/crop	[15]
Mekong Delta	brackish water polyculture	mud crab	0.044 t/ha/yr	[72]
Mekong Delta	brackish water polyculture	fish	0.096 t/ha/yr	[72]
Mekong Delta	rice–shrimp farms	fish	0.116 t/ha/yr	[72]
Mekong Delta	intensive	pangasius catfish	300–400 t/ha/crop	[73]
Mekong Delta	extensive farming	penaeus shrimp	0.077–0.24 t/ha/yr	[72]
Mekong Delta	semi-intensive or intensive systems	penaeus shrimp	1.3–6.2 t/ha/yr	[72]
Mekong Delta	inland pond	pangasius catfish	370 t/ha	[74]
Mekong Delta	intensively, in deep ponds	catfish	450 t/ha/crop	[75]

* Abbreviations: t = tons; ha = hectare; yr = year.

4.2. Regression Analysis

The production quantity in pond aquaculture mainly depends on following factors:

- Pond size
- Pond depth
- Cultured species
- Stocking density
- External inputs (degree of intensification)

Challenges for an accurate estimation of production for aquaculture ponds arise from the diversity of species, production systems, yield range, harvest frequency, and intensification degree in the aquaculture sector. There is a large number of different species (e.g., shrimp, fish, mussels) produced in various culture systems: earthen ponds, concrete ponds, recirculating aquaculture systems (RAS), open net-pens, raceways, offshore cages. A geographical independent correlation of the average pond size has been identified between three of the four Delta regions. While average pond size in the Mekong, Red River and Pearl River deltas is within the range of 0.4–0.6 ha, it is many times greater in the Yellow River Delta with 3.5 ha (see Table 3). The differences of pond size are displayed by boxplots in Figure 12, showing the median, interquartile range and outliers of the individual variables. Aquaculture along the coast of Northeast China (Yellow River Delta) is predominantly cultivated in much larger ponds as compared to South China and Southeast Asia.

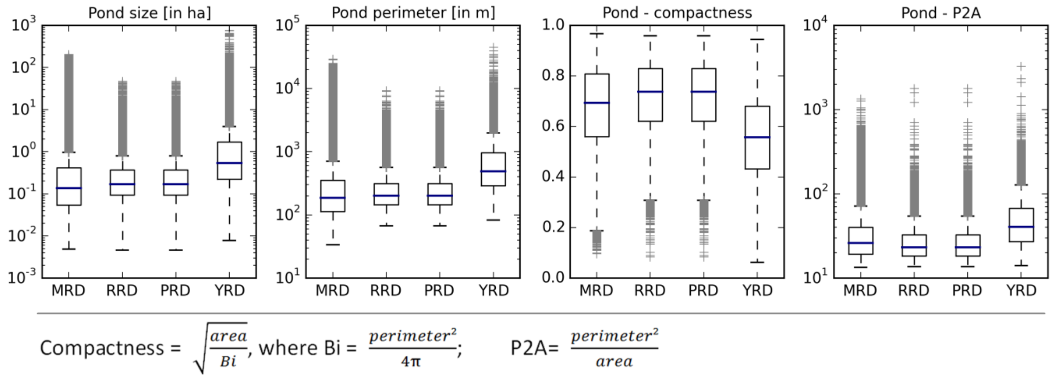

Figure 12. Boxplots of pond object properties for the four study areas. From left to right: area in ha, perimeter in meter, compactness and P2A.

Table 3. Characteristics of earth observation-derived aquaculture ponds in the study areas.

	Study Area (in km^2)	**Earth Observation-Derived Ponds–Characteristics**			
		Number of Ponds *	**Pond Area * (in ha)**	**Share of Pond Area to Study Area * (in %)**	**Average Pond Size * (in ha)**
Mekong Delta	39,385	299,820	265,943	6.7	**0.52**
Red River Delta	15,541	62,289	29,940	1.9	**0.56**
Pearl River Delta	42,378	264,863	105,070	2.5	**0.41**
Yellow River Delta	7435	20,671	86,371	11.6	**3.55**

* Aquaculture pond object dataset derived from Sentinel-1 time series data (see Section 3.2).

Table 4 shows the total aquaculture production for the reference year 2015 which we collected from public statistics offices. For the Mekong Delta we collected district level data from the province statistics offices and province level data from the databases of the General Statistics Office of Vietnam for the Red River Delta. Statistics for China were obtained at county level for the respective districts of the Pearl River Delta and the Dongying District covering the Yellow River Delta. The yield was calculated on the basis of the official aquaculture production and earth observation derived pond area for the respective study areas (see Table 4). The average yield is 27.0 tons per hectare for the Pearl River Delta and 19.4 tons per hectare Red River Delta. For the Mekong Delta and Yellow River Delta the yield accounts for 9.3 and 4.9 tons per hectare, respectively. The Pearl River Delta is one of the most rapidly industrialized and urbanized economic regions in China [52] and has the highest yield value of all four study sites. The relative low yield rate of the Yellow River Delta can be attributed with less developed capabilities and investment to establish intensive aquaculture as this region is still undergoing rapid transformation transition from rural agricultural area to industry structure [51]. The relative difference of the calculated yield values indicates a correlation between pond productivity and the region's levels of economic and social development as identified by the relative difference of the yield values shown in Table 4.

The official aquaculture production statistics were collected at district level and province level for Vietnam and China, respectively. A positive correlation was found between the official production statistics and the earth observation derived pond number (see Figure 13A) and pond area (Figure 13B), determined by Spearman's coefficient of 0.57 and 0.62. This is a close and solid correlation that confirms the potential using the outlined earth observation-based pond aquaculture assessment approach for the approximation of production estimates.

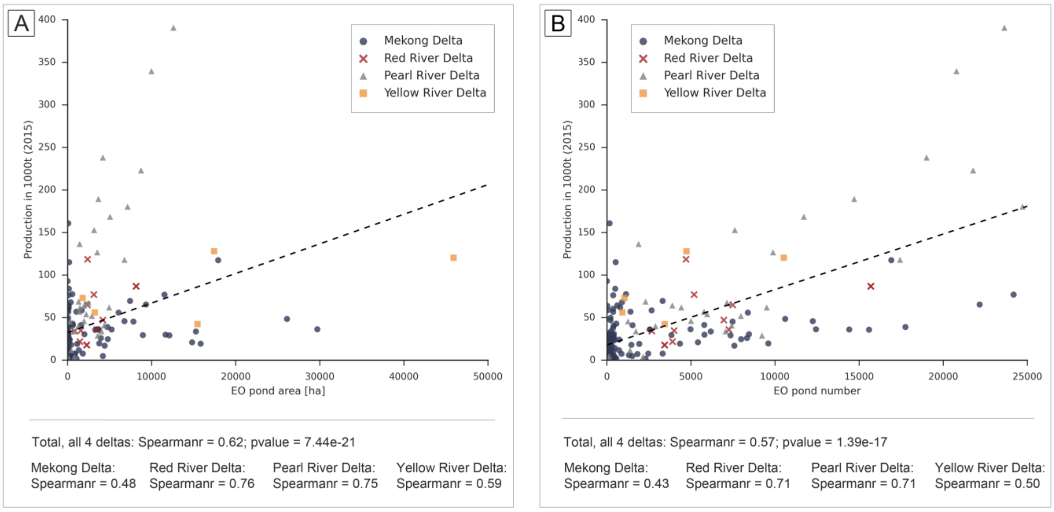

Figure 13. Scatterplots correlating official aquaculture production statistics (for the year 2015; Source: official statistics authorities, see Section 4.1.2) with the number of earth observation derived ponds (**A**) and with the total area of earth observation derived ponds (**B**). Spearmanr = Spearman rho; pvalue = propability value.

Table 4. Aquaculture production statistics from official authorities and derived yield for the study areas.

	Study Area (in km^2)	Official Aquaculture Production * (in t)	Derived Yield (in t */ha **)
Mekong Delta	39,385	2,471,327	9.3
Red River Delta	15,541	580,915	19.4
Pearl River Delta	42,378	2,836,970	27.0
Yellow River Delta	7435	419,516	4.9

* Sub-national production statistics for 2015. Data sources: province statistical yearbooks (books, Mekong Delta), General Statistics Office of Vietnam (Red River Delta), district statistical yearbooks (online, Pearl River Delta and Yellow River Delta). ** Earth observation derived pond area.

4.3. Best "Guesstimate" Approximation

For regions where reliable required statistical data are not available we can use empirical yield values to estimate production for the earth observation derived pond areas. There is an appropriate match between the mapped pond product (Figure 14A) and the official aquaculture production statistics (Figure 14B), indicating a strong positive correlation. If no reliable statistical data exist or relevant official statistics are unavailable, the earth observation pond product can be used to "guesstimate" the aquaculture production. Yield estimates from literature are assumed to principally correspond to the regions specific production values. By applying assumed yield values we approximated the pond production for the respective administrative units of the study areas (district and county). Tucker and Hargreaves [35] provide a plausible range of global yield values (production in tons per hectare) for pond aquaculture production estimates. Within the limits of this value range we determined yield values for the minimum, maximum, mean, the 25th, and 75th percentile and used as a basis to calculate a potential pond production range for the respective study areas (see Table 5).

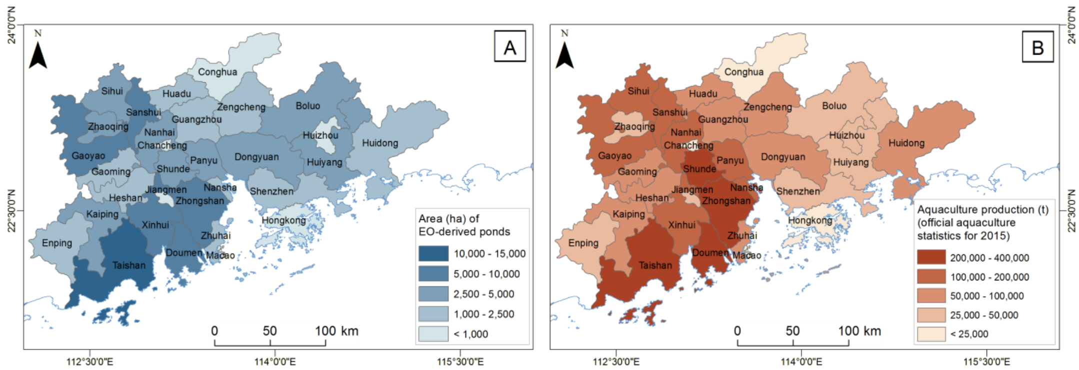

Figure 14. Visual comparison of (**A**) Eaerth Observation (EO)-derived pond area and (**B**) aquaculture production statistics for the districts of the Pearl River Delta, China.

Table 5. Estimation of production for the earth observation derived ponds based on global yield values.

	Pond Area * (in ha)	Potential Pond Production Range (in t)				
		Yield Values (t/ha)				
		Min **	25th Perc	Mean	75th Perc	Max **
		0.2 t	**5.2 t**	**10.1 t**	**15.1 t**	**20.0 t**
Mekong Delta	265,943	53,189	1,369,606	**2,686,024**	4,002,442	5,318,860
Red River Delta	29,940	5988	154,191	302,394	**450,597**	598,800
Pearl River Delta	105,070	21,014	541,111	1,061,207	1,581,304	**2,101,400**
Yellow River Delta	86,371	17,274	**444,811**	872,347	1,299,884	1,727,420

* Earth observation derived pond area; ** Global yield values; Source: Tucker and Hargreaves [35].

According to the county, district, and provincial administration boundaries, we estimated pond aquaculture production based on earth observation derived pond area and a selected yield value (see Table 5) for the four study regions. The results could also be compared (if available) with relevant statistics from the national statistics (see Figure 15). Figure 16 shows the earth observation derived pond production at district level (Vietnam) and county level (China) and the earth observation derived pond area for the respective study areas.

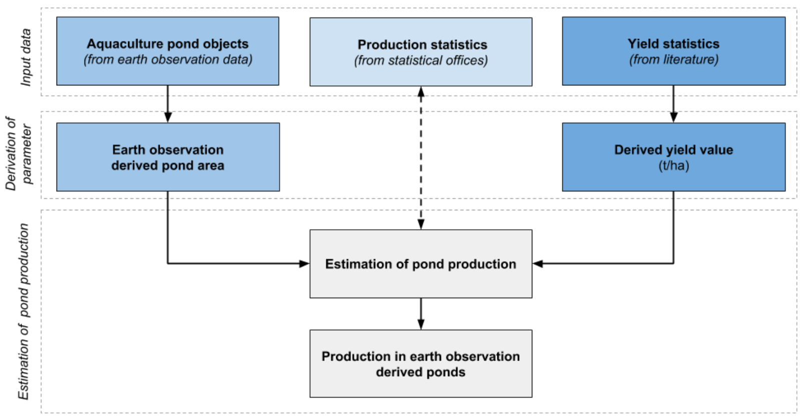

Figure 15. Scheme for the estimation of aquaculture production in EO derived ponds.

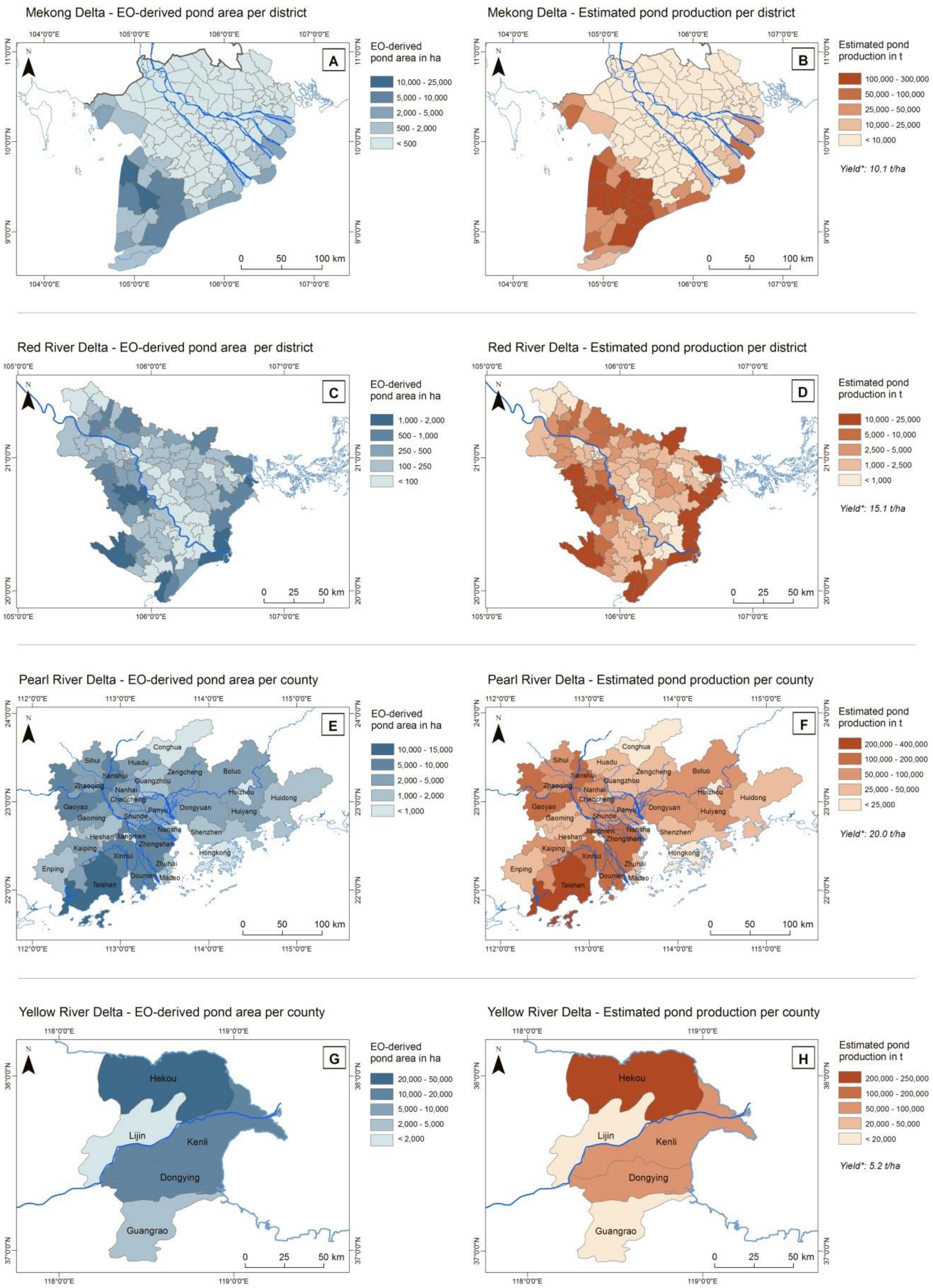

Figure 16. (1) Area of earth observation derived ponds and (2) Estimated pond aquaculture production for the Mekong Delta (**A**,**B**), Red River Delta (**C**,**D**), Pearl River Delta (**E**,**F**), and the Yellow River Delta (**G**,**H**). * Selected yield value according to Table 5.

5. Discussion

Knowledge on the areal extent of aquaculture is important for a better conservation and sustainable management of our planet's coastal ecosystems and can be utilized for the derivation of aquaculture yield and production to support food security information. With the outlined approach we are capable to accurately map aquaculture ponds with Synthetic Aperture Radar data and estimate pond production based on remote sensing techniques and statistical data. Radar remote sensing is appropriate for mapping aquaculture ponds because of the SAR specific weather-independent monitoring capabilities, which is an advantage for cloud-prone coastal areas where aquaculture is predominantly cultivated. In this study, we focused on active aquaculture ponds which are predominantly water-covered all-year. Dry active ponds are difficult to determine since we do not know whether the pond has been abandoned recently or drained on a temporary basis for restoration, repair, or harvest. We utilized time series of satellite remote sensing imagery acquired by advanced high-resolution SAR sensors of the Copernicus Sentinel-1 mission and achieved a mean overall accuracy of 0.84 for the earth observation-based pond mapping. The proposed approach can be extended in space and time, is easily transferable to other geographic regions and holds the potential for continental and global mapping.

We found that a higher temporal coverage of Sentinel-1 data for a given location can enhance the appearance of narrow, linear pond structures (such as dams, levees, and dikes) and therefore improve the detection of ponds from the SAR median image. The range of different pond sizes for aquaculture identified within the study areas refers, on the one hand, to the diversity of pond systems. On the other hand, depending on the study area, outlines of ponds may not be completely detected if the enclosing dams, dikes, or levees are smaller than the spatial resolution which leads to the effect that neighboring ponds form larger connected pond objects.

For the study sites, we identified relevant commonalities in terms of average pond size and a clear positive correlation was found between the earth observation derived pond area and pond number with official aquaculture production statistics. We calculated the Spearman's correlation coefficient between the production and pond area for each study region which ranges from 0.46 for the Mekong Delta to 0.76 for the Red River Delta. The correlation between the pond number and the production ranges from 0.43 for the Mekong Delta and to 0.71 for the Red and Pearl River deltas. The lower correlation of the pond number and pond area in the Mekong Delta may be related to the rather small sized and irregular shaped ponds which are harder to detect compared to the larger and more regular ponds in the other deltas. The higher correlation for the Red and Pearl River deltas could indicate that the specific appearance of aquaculture ponds in these regions (size and shape) enables a better detection of pond aquaculture with our method. This relationship is helpful in order to support relevant statistical data collections on aquaculture production more effectively. The availability, completeness, and quality of annual statistical data are based on the reporting in the individual countries and their statistical offices.

But how to proceed if such information is not available? Is it possible to estimate production for regions where no statistical data is collected and provided? We estimated a spectrum of production ranges for the earth observation derived pond area based on assumed yield values. Since a clear correlation between the area and official production statistics exists, a reasonable and reliable estimate within a range of reasonable production estimates can be made. For this purpose, simplifications and approximations for determining best and reasonable estimates are based on the experience, knowledge, and findings from studies published in other regions.

When statistical data are available, it can be used as a reference for comparing the officially recorded production volumes with estimated production. Statistical data provides a sound basis for estimating production volumes for the earth observation derived pond aquaculture and assessing the reasonability of these estimates. The FAO provides a valuable, fully-documented data collection on national aquaculture production statistics for most countries. At sub-national level (regional or local) some countries provide detailed production figures for different species, culture systems, and years. There is often no consistent collection of aquaculture statistics, and data are often not standardized and thus not readily comparable with another. Other countries publish aggregated aquaculture statistics [76] from all possible production systems (including inland pond culture, net and pen aquaculture, and even offshore aquaculture) and do not fully reflect the diversity. Comprehensive in-situ data can be used complementary to the statistical data released by public authorities and provide representative yield values.

We know that the yield has a lower and upper boundary per species which we can use to estimate the possible range of production. The species diversity in the aquaculture sector is a challenge for the selection of appropriate yield values for the approximation of aquaculture production. In most cases, however, the majority of national aquaculture production accounts for only a relatively small number of species. For instance, the aquaculture sector in Norway and Chile is clearly dominated by salmon farming and accounts for more than 80 and 92 percent of the total national aquaculture production [1]. The aquaculture market in the Mekong Delta of Vietnam is mainly concentrated on shrimp and intensive pangasius catfish farming [77].

In this research, we focused on the land-based ponds, which is the most important culture system and accounts for the largest share of total global aquaculture production and makes a significant contribution to food and *nutrition* security in Asian countries. The approach could be advanced and extended to detect also other aquaculture systems, e.g., marine offshore aquaculture which plays an increasingly important role in the aquaculture industry in terms of trade and production. For the mapping of (offshore) cage systems data from earth observation satellites with very high-resolution is needed to detect the cages, visible fine net, or cage components at the water surface.

Space-based earth observation data and products have a particular potential to assist reporting organizations and governments by providing additional, independent information for the evaluation and assessment of statistical data to improve their estimates and thus the validity of global reported aquaculture production volumes. Availability and comparability of aquaculture production statistics is sometimes restricted by lack of data or limited access to existing data for some regions. In regions for which no (reliable) statistical data are reported and/or available, earth observation has opportunity to derive spatial aquaculture information and can fill the gap to estimate aquaculture production volumes for non-reporting or incomplete-reporting countries.

The Copernicus Sentinel missions enable high spatial and temporal resolution mapping and monitoring of pond aquaculture and offer high potential for the derivation of pond production estimates. The development of new sensors with higher spatial resolution data and advanced edge-detection and object-based methodologies can help to improve pond mapping accuracy, leading to more precise aquaculture production estimates in the future. The synergetic use of radar and optical earth observation data is recommended to achieve a much denser time series of satellite earth observation data. Combining space-borne high-spatial resolution data (e.g., from the recently launched sensors of the Sentinel-1 and Sentinel-2 missions) can provide temporally dense time series and holds the potential to enhance the contrast of aquaculture features (e.g., dams, levees, dikes) and improve the detection accuracy of land-based pond aquaculture and offshore cage culture systems.

Aquaculture observation from space allows identifying and mapping typical aquaculture structures and can assist aquaculture producing countries by enabling improved estimation and forecasting, particularly for non-reporting regions. The presented approach of production estimation based on remote sensing derived pond data and collected statistical data can be regarded as a first attempt for further research. Further application opportunities and potentials could arise in following fields:

- Set up of a production estimation framework for future predictions on food security
- Create new maps, and update existing databases with new results and information
- Aquaculture pond characterization based on high-resolution optical and thermal data (algae bloom, sediment content, water temperature)
- Assessment of ecosystem service losses due to aquaculture expansion
- Harvest loss estimation in case of disease outbreaks

6. Conclusions

We present the first production estimation of aquaculture ponds in the coastal zone based on earth observation data. This novel approach includes a large-scale assessment of land-based pond systems, regression analysis, and pond production estimates based on remote sensing techniques and statistical data. Using more than 500 Sentinel-1 scenes, open source tools and software, we developed an object-based image processing chain to detect aquaculture ponds from smoothed time series stacks. The radar satellite remote sensing data were processed by means of topographic masking and *temporal* filtering, and aquaculture statistics at a detailed administrative level were collected, translated, encoded and standardized. The free, full and open data policy adopted for the Copernicus Sentinel satellites has greatly expanded earth observation opportunities for the assessment of aquaculture. Several terrabytes of new data is added every day, extending the volume of earth observation imagery for comprehensive satellite time series analysis in future. The presented examples reveal the potential of SAR time series data with high temporal resolution. Statistical data on production volumes at sub-national administrative units and pond yield statistics derived from literature were utilized to estimate production. In combination with additional, more detailed statistical information species-specific production estimates could be assessed. The approach can be transferred to data obtained with other high-resolution data from imaging radar instruments such as TerraSAR-X, TanDEM-X, Radarsat-2.

Data on spatial-temporal dynamics and detailed (regional) statistics of the aquaculture sector barely exist but are essential for sustainable natural resource management. Aquaculture is a major policy priority across governmental and non-governmental institutions. Considering increasing intensification in the aquaculture sector with higher use of pesticides and antibiotics, the protection of coastal ecosystems and their resources becomes a global challenge. In view of the growing world population and rising demand for fish and seafood, aquaculture has potential to meet the needs for a secure food production and to provide global food security for the next generations. The assessment of the entire aquaculture sector would require a comprehensive concept towards the development of advanced methodologies capable of mapping culture systems other than ponds. Future research should focus on the detection on net and cage-based aquaculture systems. A global estimation of aquaculture production holds a large potential for a broad range of geoscientific analyses and applications.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Software packages used for reading and processing the spatial and statistical data:

- Python 2.7.11
- Scipy 0.17.0
- GDAL 1.11.2
- pandas 0.17.0

- seaborn 0.7.0
- Turf.js 2.0.0
- Orfeo Toolbox 5.4.0

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