Aquaculture and Coastal Habitats Report No. 1

A Baseline Mapping of Aquaculture and Coastal Habitats in Thailand, Cambodia and Vietnam

J. Ronald Eastman, Stefano C. Crema, Florencia Sangermano, Sean Cunningham, Xiao Xiao, Zhuoyue Zhou, Po Hu, Caroline Johnson, Bernadette Arakwiye, Nelson Crone

Clark Labs, Clark University

Abstract

Southeast Asia has seen an enormous growth in aquaculture in recent years, especially for the production of shrimp. In 2013 shrimp production in brackish water ponds accounted for 20% of global production. Unfortunately, this growth has been accompanied by significant impacts on coastal and near-shore environments, especially on mangroves. With a goal of establishing a baseline for monitoring this development, a baseline mapping of aquaculture and coastal habitats was undertaken for the coastal zones of Thailand, Cambodia and Vietnam. In total, 18 land categories and 10 marine categories were mapped using Landsat 8 imagery from 2013-2015. Three were of special focus – pond aquaculture, integrated mangrove-shrimp and mangrove forests, which were mapped with mean accuracies of 90%, 95% and 93%. Pond aquaculture within the coastal zone included all ponds, dry or in active use. Area totals for Thailand, Cambodia and Vietnam were 2080.71, 9.06 and 7711.58 km^2 respectively, with a regional total of 9801.35 km^2. Integrated mangrove-shrimp occurred almost exclusively in Vietnam with an area of 683.45 km^2. Mangroves (not including those in integrated mangrove shrimp) occupied 2570.54, 342.62 and 1464.73 km^2 respectively, with a regional total of 4377.89 km^2. Regionally, pond aquaculture, including integrated mangrove shrimp, covers 8.35% of land areas in the coastal zone while mangroves cover 3.49%.

Introduction

Aquaculture for human consumption has expanded at an enormous rate in the past three decades and now accounts for about half of fisheries' output for human consumption (FAO, 2014). The most valuable product in this sector is shrimp (FAO, 2014), with the major source region currently in Southeast Asia. Shrimp aquaculture in the coastal areas of Thailand, Cambodia and Vietnam accounted for 20% of global production in 2013 (FISHSTAT, 2015). Along with this exceptional growth has been a consequent loss of habitat and ecosystem services. Most notable has been the loss of mangroves and the services they provide for coastal protection, carbon sequestration and fish nurseries (Paez-Osuna, 2001, Alongi, 2012). With the goal of establishing a baseline for monitoring these changes, Clark Labs, in partnership with the Gordon and Betty Moore Foundation, has mapped aquaculture and coastal habitats for the coastal zones of Thailand, Cambodia and Vietnam for the 2013-2015 period. The mapping is based on Landsat 8 Operational Land Imager (OLI) imagery and provides the first regional assessment of aquaculture for Southeast Asia.

Objectives

The primary objective of the study was to provide a baseline mapping of mangroves and shrimp aquaculture, with the intention of repeating the analysis at a later date for assessment of change. A secondary objective of the project was to provide, to the extent possible, a mapping of other habitats and covers within the coastal zone that might affect or be affected by the shrimp industry.

Given this focus on monitoring and the need for continuity both in the future and in the past, the Landsat mission was an attractive option to consider. Landsat 8, launched in 2013, provides moderate resolution (30 m) imagery with a spectral range highly suitable for the mapping of vegetation and a wide range of land covers. Current plans call for maintenance of the operation with the launch of Landsat 9 in 2023 (NASA, 2015), providing more than a half century of coverage. Additionally, the availability of imagery without charge was also an important consideration for a project of this scope. Consequently, a third objective was to develop a protocol that would permit mapping of the primary covers at the generally recognized national-level standard of 85% (Foody, 2002) and to a minimum of 70% (Thomlinson et al., 1999) for the secondary covers.

Study Area

The study area for the mapping was the coastal zone of Thailand, Cambodia and Vietnam. Thailand and Vietnam were chosen because they are among the five largest producers of shrimp worldwide (FAO, 2014). Cambodia has comparatively very little shrimp aquaculture, but has important mangrove resources that face many threats, including destruction for the purpose of farming shrimp (Song, 2004).

Like the European Environment Agency (2006), the coastal zone was initially defined as a zone 10 km on either side of the coastline. Where necessary, the zone was extended to include marine areas <= 30 m based on the GEBCO (2010) bathymetry and land areas <= 5 m as defined by the SRTM (2009) elevation data. The main areas affected by these extensions were the Red and Mekong river deltas in Vietnam and the Chao Phraya river basin in Thailand. Based on information related to salt intrusion in these regions (Anh Duc, 2008; Arli, 2007; Vu and Bui, 2006), a maximum extension of 60 km inland from the coast was allowed. The primary concern was to limit the inland extent to areas where it was likely that pond aquaculture would be dominated by brackish water and thereby have a stronger likelihood of being used for shrimp.

In total, the coastal zone overlapped 42 Landsat 8 images. A list of the specific images classified can be found in Table S1 among the supporting materials at www.clarklabs.org/downloads/TCV_Baseline. The images range from April 2013 until January 2015, primarily from the dry season. For some images, multiple dates needed to be classified to account for large areas of clouds.

Methods

Table 1 indicates the classification scheme that was used in the analysis. The decision to use Landsat 8 imagery was made partly for economic reasons and partly because of the suitability of the Landsat bands for detecting the land cover classes of interest. Early tests showed that pond aquaculture was challenging to classify at a 30 m resolution. Consequently, the decision was made to merge the 15 m panchromatic band information with bands 3, 4 and 5 (blue, green and red respectively). The procedure used was a modified version of the GIHS pan merge algorithm described by Tu et al. (2001). Instead of assuming that the panchromatic band (OLI band 8) was radiometrically equivalent to the summation of the blue, green and red bands (OLI bands 2, 3 and 4), the relationship was established using multiple regression. The resulting coefficients very effectively removed the color distortion normally associated with this technique.

Table 1: The classification scheme used in the mapping

Aquaculture	**Marine Habitats**	**Wetland Habitats**	**Dryland Habitats**	**Barren Habitats**	**Anthropogenic Habitats**	**Missing Data**
Pond Aquaculture	Seagrass	Mangrove	Forest	Sand/Unconsolidated	Sea Salt Production	Obscured by Clouds/Smoke
Cage/Raft Aquaculture	Macroalgae	Swamp	Shrubland	Stabilized Sand	Built Up	Obscured by Turbidity
Macroalgae Aquaculture	Undetermined Aquatic Vegetation	Marsh	Grassland	Rock Outcrop	Cropland	
Integrated Mangrove-Shrimp	Coral	Flat			Quarry/Mine	
Other Aquaculture	Rock Substratum	Open Water				
	Sand Substratum					
	Mud Substratum					
	Undetermined Substratum					

The other bands used in the classification of land features (OLI bands 5-7) were upscaled to match the 15 m apparent resolution of the pan merged bands. For this purpose, a special resampling technique was devised. Because of the co-registration of the panchromatic band with the multispectral bands, every 30 m pixel contains one 15 m pixel at its exact center. This 15 m pixel was estimated using nearest neighbor resampling. All other pixels were determined using a bilinear resampling. This hybrid procedure was quick and ensured a strong correspondence between the original band and its 15 m equivalent.

Using the metadata for each Landsat 8 image, raw Dn were first converted to top-of-atmosphere reflectances. Next a correction was applied for the solar elevation angle. Since classification of the imagery was to be achieved using training samples internal to each image, only a simple 1% dark-object-subtraction haze removal procedure was used (Chavez, 1996).

For the classification of marine features, it was desired to create derivative bands that would minimize the depth and wavelength-dependent attenuation of light by water. The methods described by Lyzenga (1978; 1981) provide an empirical basis for creating depth invariant indices of bottom type. However, they depend on the presence of clear water with uniform optical properties and the ability to sample uniform substrate materials at varying depths. Given the varying levels of turbidity in the region and the difficulty of establishing substrate conditions in many areas, it was decided to work with band ratios in order to minimize the effects of depth-dependent attenuation. Ratios of bands are free of the effects of depth as long as their attenuation coefficients are the same (Lyzenga, 1978). To minimize differences in attenuation by absorption and scattering, ratios were thus created from adjacent OLI bands in the visible wavelengths: band 2/band 1, band 3/band2 and band 4/band3. To re-linearize the ratios, the logarithm of the ratios can be used. Alternatively, a normalized difference ratio achieves the same result. Because band 1 could not be pan merged with the panchromatic, classification of marine features was done at a 30 m resolution.

For classification, several methodologies were used. For most classes, the primary classifier used was a Mahalanobis Typicality classifier (Foody et al., 1992). This classifier is unusual in that it can be used to focus on a single class if desired. The output is in the form of typicality probabilities for each class included in the training process. Typicality probabilities indicate the degree to which a pixel is typical of the data it was trained on. More specifically, the output values express the probability of there being a pixel with a Mahalanobis distance from the class means that is lower than the one found. Thus a pixel with the same spectral response pattern as the class centroid will have a typicality of 1. Figure 1 illustrates this output.

Figure 1: The output from the Mahalanobis Typicality classifier for seagrass in a portion of Van Phong bay in Vietnam. The output has been superimposed on a natural color composite for reference.

The advantage of the Mahalanobis typicality classifier is that it allows the analyst to digitize training data and very quickly compare the soft-classified result with the imagery. Additionally, the analyst can focus on a single class at a time, gradually improving the classification by adding training sites for instances missed in the previous step. To create a hard classification for a single class, the typicalities can be thresholded, typically with a very small value determined by comparison of the typicalities with a color composite.

In the Mekong Delta of Vietnam, pond aquaculture and mangroves are intimately related. Two forms of aquaculture dominate in the region – improved extensive shrimp cultivation and integrated mangrove-shrimp (Shrimp News International, 2015). Both rely on the tidal cycle for the exchange of water as well as stocking of wild shrimp, fish and mud crabs. Inputs are minimal with the exception of supplemental hatchery-raised giant tiger shrimp juveniles. In the former system, mangroves are allowed to grow naturally or are planted in the ponds because they enhance the habitat for cultivated species. This area has many remnant patches of mangroves. Areas with integrated mangrove-shrimp are similar in their production but are designed to maintain a high degree of coastal protection while simultaneously providing farm income from mangroves and pond aquaculture (Ha et al., 2014). In these areas mangroves are mandated to occupy a minimum of 60% of each farm (although farms transitioning into this method will have lower percentages). The Mekong is thus an area with many mixed pixels of water and mangrove and a complex pattern of remnants.

By experiment it was determined that the Mahalanobis Typicality classifier is not a good choice for uncovering mixtures. To facilitate separation of the integrated mangrove-shrimp from extensive pond aquaculture and isolation of remnant mangrove patches, a linear spectral unmixing was undertaken between two end member classes – water and mangroves. Pixels with 75% or greater membership in the mangrove class were designated as mangrove. Mangrove pixels were then spatially aggregated into contiguous groups. Groups with an area greater than 0.5 ha were designated as mangrove stands. From this it was fairly easy to visually determine and manually separate the areas of integrated mangrove shrimp versus the extensive pond aquaculture because of the higher density of mangrove in the former.

The pond aquaculture class was challenging because of the many cover types that comprise this class – pond walls, empty ponds and filled ponds with varying levels of phytoplankton bloom. Consequently, initial classification was followed by a manual cleaning of the result using on-screen digitizing and Google Earth as a check. Care was taken to never include or exclude areas on the basis of Google Earth alone. Rather, we paid special attention to image dates in Google Earth and always sided with the Landsat 8 data when cleaning the result.

After the initial classification, an accuracy assessment was undertaken on the land classes. No assessment was undertaken for the marine classes because of the inability to verify the sample points selected. For the land classes, Google Earth was used as the basis for assessment, again being careful of the Google Earth image dates. The assessment was stratified into two zones: a near-coastal strip <=2.6 km from the coast and a hinterland strip >2.6 km out to the boundary of the coastal zone. This threshold was established on the basis that the median distance of pond aquaculture from the coast was 2.6 km.

Accordingly, within each image, a stratified random sample of 200 points was established in the near-coastal zone and 100 points in the hinterland zone. From this an error matrix was established to allow the determination of errors of omission and commission. After the analysis, some images were re-analyzed for certain classes as will be discussed in the results section.

In a final step, the individual classified images were projected and mosaicked to an Albers Equal Area projection. Supplementary Table S2 provides details about the reference system.

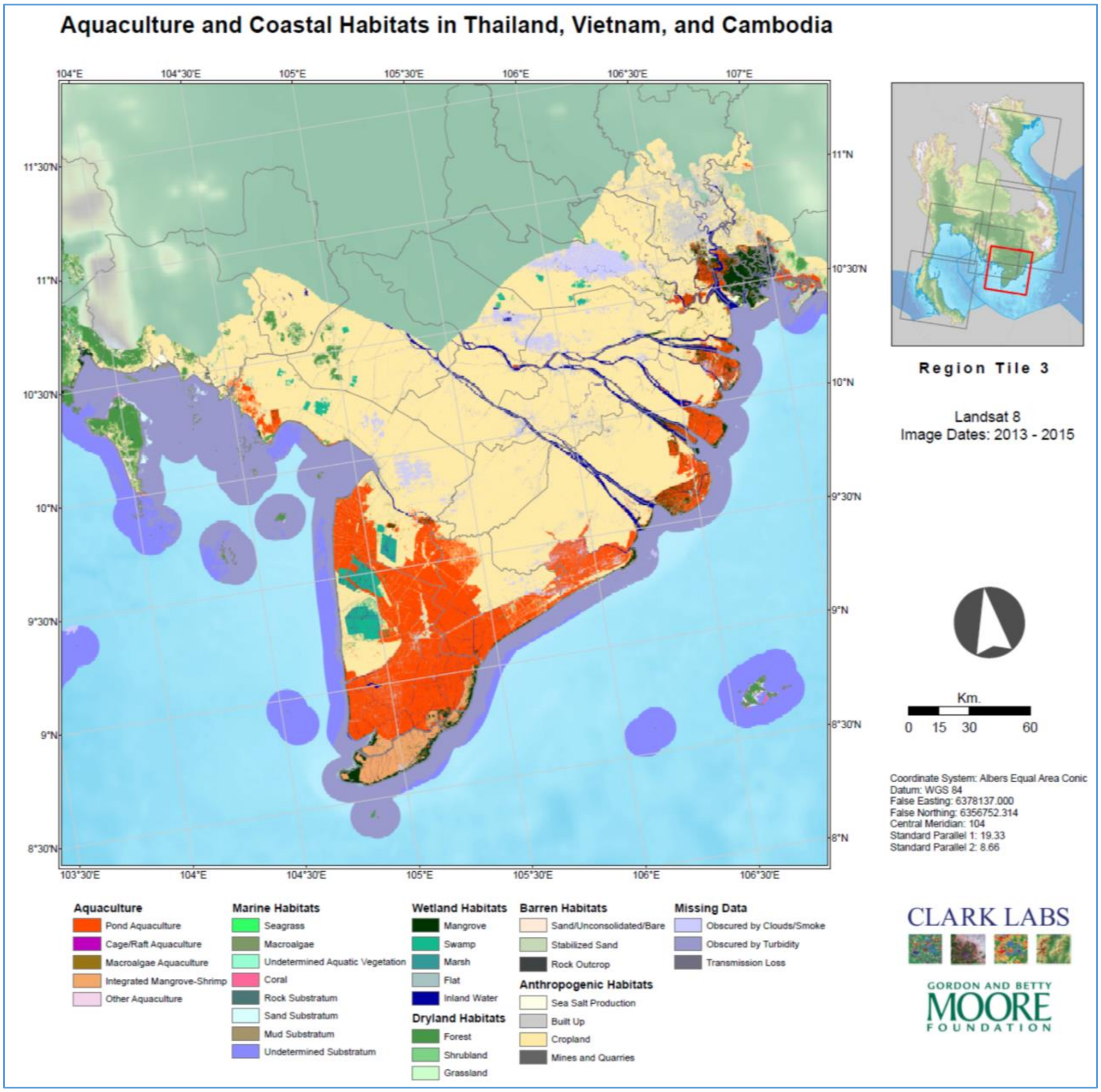

Figure 3: The completed map tile for the Mekong delta region.

Results

Figure 3 shows one of the tiles of the completed map, in this case with detail in the Mekong region of Vietnam. The full resolution data and map compositions are available at www.clarklabs.org/downloads/TCV_CoastalZone. After mosaicing, the coastal zones of Thailand, Cambodia and Vietnam were 86,175.62, 16,037.28 and 119,770.19 km^2, with a combined area of 221,983.09 km^2. Tables 2 shows the area totals of each of the land categories tabulated by province and country. Because an accuracy assessment of the marine categories could not be undertaken, these classes were mapped but not tabulated.

For the accuracy assessment, a total of 9487 locations were assessed. The initial overall accuracy of the map for all categories was 87% which exceeds the 85% standard. Table 2 indicates the user's and producer's accuracy for the land categories for which an adequate statistical sample was achieved. All other classes either had fewer than 30 samples or were not an actual land cover (such as clouds). The user's accuracy is related to errors of commission. It expresses the degree to which a category as found on the map corresponds with that category on the ground. The producer's accuracy is related to errors of omission and expresses the degree to which a land cover category on the ground is correctly represented on the map. Thus, for example, areas of forest on the map might correspond very well with forest on the ground and thus have a high user's accuracy, but may have omitted some areas of forest and thus have a low producer's accuracy.

Table 2. User's and producer's accuracy for the major land categories

Category	User's Accuracy	Producer's Accuracy
Pond aquaculture	94%	86%
Mangrove	94%	92%
Integrated mangrove-shrimp	95% (94%)	76% (96%)
Cropland	87%	93%
Forest	93%	88%
Built-up	81%	83%
Shrubland	85% (87%)	53% (66%)
Sea-salt production	90%	81%
Sand/unconsolidated	67% (80%)	76% (81%)
Stabilized sand	88% (90%)	82% (87%)

Figures in parentheses indicate revised accuracies after reassessment.

The primary categories of focus were pond aquaculture, mangrove and integrated mangrove shrimp. The goal was to attain an 85% accuracy with these classes. The user's accuracy for pond aquaculture was excellent at 94%. The producer's accuracy was somewhat lower (86%) indicating errors of omission. Inspection of the error matrix showed that these errors were most commonly associated with dry ponds being classified as cropland, built-up or sand. Because of the slight imbalance between errors of omission and commission, area tabulations of pond aquaculture are likely to be slightly underestimated, but within the bounds of expected error. User's and producer's accuracy for mangroves are both excellent (94% and 92% respectively) and are essentially balanced. Thus area tabulations should be unbiased. For integrated mangrove-shrimp, however, the initial producer's accuracy (76%) was lower than the 85% target and unbalanced with respect to the users's accuracy (95%). This category is found almost exclusively in the southern Mekong. The problem was with the differentiation between extensive pond aquaculture (which has inclusions of mangrove in this region) and integrated mangrove-shrimp which has a higher proportion of mangrove inclusions. Fortunately, a re-evaluation of this category was possible given that only four images were involved. A color composite of bands 3 (for blue), 7 (for green) and 4 (for red) was found to be very effective for separating pond aquaculture from mangrove, and was thus helpful in a reanalysis of this class. After re-assessment the user's and producer's accuracies were found to be 94% and 96% respectively.

For the non-essential categories the goal was to achieve an accuracy of 70%. All met this goal with the exception of the producer's accuracy for shrubland and the user's accuracy for sand/unconsolidated. Images with substantial amounts of these errors were reanalyzed. After re-assessment, sand/unconsolidated met this goal but the producer's accuracy for shrubland was still low. However, the mean of the user's and producer's accuracy was 77% and given that it was not an essential category, no further change was done.

Table 3 shows a tabulation by country and province of the areas of pond aquaculture, integrated mangrove-shrimp and mangrove.

Table 3: Area (in km^2) for Pond Aquaculture, Integrated Mangrove Shrimp and Mangrove, by Province

Country	Province	Pond Aquaculture	Integrated Mangrove Shrimp	Mangrove
Thailand	Bangkok Metropolis	54.44	0.00	1.28
	Chachoengsao	208.65	0.00	18.04
	Chanthaburi	164.79	0.00	119.77
	Chonburi	61.11	0.00	11.59
	Chumphon	53.53	0.00	60.77
	Krabi	37.82	0.00	372.61
	Nakhon Nayok	6.85	0.00	0.00
	Nakhon Pathom	59.54	0.00	0.00
	Nakhon Si Thammarat	230.15	0.00	135.65
	Narathiwat	0.59	0.00	0.64
	Nonthaburi	0.87	0.00	0.00
	Pathum Thani	9.64	0.00	0.00

	Pattani	19.07	0.00	27.26
	Phang Nga	24.90	0.00	454.51
	Phatthalung	5.38	0.00	4.56
	Phatthalung (Songkhla Lake)	0.15	0.00	2.55
	Phetchaburi	61.73	0.00	51.65
	Phra Nakhon Si Ayutthaya	0.34	0.00	0.00
	Phuket	5.51	0.00	19.55
	Prachin Buri	51.77	0.00	0.00
	Prachuap Khiri Khan	116.01	0.00	1.74
	Ranong	14.21	0.00	249.02
	Ratchaburi	43.06	0.00	0.02
	Rayong	38.32	0.00	16.02
	Samut Prakan	183.36	0.00	18.37
	Samut Sakhon	148.02	0.00	18.65
	Samut Songkhram	95.28	0.00	39.03
	Satun	36.53	0.00	348.50
	Songkhla	91.98	0.00	8.83
	Surat Thani	166.96	0.00	130.44
	Trang	39.66	0.00	341.99
	Trat	49.79	0.00	117.50
	Thailand Total	**2080.71**	**0.00**	**2570.54**
Cambodia	Kampot	7.21	0.00	7.95
	Kep	0.00	0.00	4.59
	Koh Kong	1.80	0.00	265.82
	Preah Sihanouk	0.05	0.10	63.73
	Pursat	0.00	0.00	0.00
	Svay Rieng	0.00	0.00	0.00
	Takeo	0.00	0.00	0.53
	Cambodia Total	**9.06**	**0.10**	**342.62**
Vietnam	An Giang	0.14	0.00	1.23
	Ba Ria - Vung Tau	116.36	0.00	9.01
	Bac Giang	0.00	0.00	0.00
	Bac Lieu	1388.33	0.00	17.02
	Bac Ninh	0.00	0.00	0.00
	Ben Tre	385.20	0.00	114.95
	Binh Dinh	22.20	0.00	0.16
	Binh Duong	0.00	0.00	0.00
	Binh Thuan	18.58	0.00	0.00
	Ca Mau	2697.99	667.03	276.70
	Can Tho	0.01	0.00	0.00
	Da Nang City|Da Nang	2.56	0.00	0.00
	Dong Nai	24.22	0.00	62.28
	Dong Thap	4.31	0.00	0.07

	Ha Nam	0.00	0.00	0.93
	Ha Tay	0.00	0.00	0.00
	Ha Tinh	41.61	0.00	6.74
	Hai Duong	1.05	0.00	0.01
	Hai Phong City|Haiphong	128.75	0.00	26.35
	Hau Giang	0.04	0.00	0.02
	Hoa Binh	0.00	0.00	0.00
	Ho Chi Minh City|Ho Chi Minh	76.21	0.00	414.05
	Hung Yen	0.00	0.00	0.00
	Khanh Hoa	67.14	0.00	0.22
	Kien Giang	1114.84	0.00	61.86
	Long An	110.35	0.00	52.80
	Nam Dinh	70.16	0.00	18.20
	Nghe An	28.11	0.00	7.58
	Ninh Binh	31.49	0.00	4.84
	Ninh Thuan	17.19	0.00	0.06
	Phu Yen	26.61	0.00	0.03
	Quang Binh	25.09	0.00	0.98
	Quang Nam	37.91	0.00	1.27
	Quang Ngai	12.51	0.00	0.80
	Quang Ninh	134.12	0.00	122.74
	Quang Tri	17.23	0.00	0.17
	Soc Trang	518.16	0.00	48.28
	Tay Ninh	0.00	0.00	0.00
	Thai Binh	55.97	0.00	22.03
	Thanh Hoa	56.03	0.00	5.64
	Thua Thien - Hue	58.27	0.00	0.00
	Tien Giang	55.62	0.00	55.03
	Tra Vinh	366.28	16.42	132.65
	Vinh Long	0.94	0.00	0.03
	Vietnam Total	**7711.58**	**683.45**	**1464.73**
SE Asia	Regional Total	**9801.35**	683.55	**4377.89**

Vietnam had the greatest areal extent of pond aquaculture with 7711.58 km^2. Two thirds of this occurs in just three provinces – Ca Mau, Bac Lieu and Kien Giang. Ca Mau is also where 98% of the integrated mangrove-shrimp can be found. Adding the totals for pond aquaculture and integrated pond aquaculture leads to a Vietnam total of 8395.03 km^2 in both forms combined, covering a total of 11.25% of land areas in the Vietnamese coastal zone. Thailand had the next highest areal extent of pond aquaculture at 2080.71 km^2 (representing 4.88% or land in the coastal zone) with almost half of it occuring in the provinces of Nakhon Si Thammarat, Chachoengsao, Samut Prakan, Surat Thani and Chanthaburi. Cambodia had the least pond aquaculture with only 9.06 km^2, almost all of it occuring in Kampot.

Thailand had the largest quantity of mangrove at 2570.54 km^2. Over two-thirds of that occurred in the five provinces of Phangnga, Krabi, Satum, Trang and Ranong. Vietnam had 1464.73 km^2 of mangroves with almost half occuring in just two provinces – Ho Chi Minh (location of the Can Gio Mangrove Biosphere Reserve) and Ca Mau in the Mekong delta, in that order. However, it should also be pointed out that this figure does not include the mangroves in the integrated mangrove-shrimp class. Including the mangroves in that class would undoubtedly make Ca Mau the province with the largest quantity. Finally, Cambodia had 342.62 km^2 of mangrove with 78% occurring in Koh Kong province.

Regionally, 8.35% of land areas in the coastal zone are occupied by pond aquaculture (including integrated mangrove-shrimp), regardless of whether they are in production or not. Meanwhile, 3.49% of coastal land areas are covered in mangrove, excluding integrated mangrove-shrimp.

Discussion and Conclusion

An operational assumption of this project was that by defining the coastal zone in the manner discussed, we could assume that most of what we mapped as pond aquaculture could be interpreted as land used for the purpose of growing shrimp. To provide a check on this, we acquired province level production and area data for Vietnam in 2012 (NSO, 2012). What we found was an excellent correspondence. Regressing the tabulated areas for each province in 2012 against the areas tabulated in this 2013-2015 mapping for pond aquaculture and integrated mangrove-shrimp yielded a nearly perfect linear relationship with a correlation of 0.998. The slope of the regression was 1.22 suggesting a 22% increase in area over that tabulated in 2012. This difference could arise from several sources:

- growth in the area of shrimp production between 2012 and our mapping;
- the presence of ponds not involved in shrimp production within the coastal zone as defined in this study
- The inclusion of ponds in our mapping that are out of production.

We were unable to find area statistics for shrimp aquaculture for the 2013-2015 period. However, from 2012 to 2013 shrimp production increased 18.3% (GSO, 2015). Thus it is plausible that the major part of this discrepancy is related to growth of the industry.

Province-level statistics were also found for 2012 in Thailand (DOF, 2012). However, the statistics only report the area under production while this study includes all ponds regardless of whether they are in use. Thailand has experienced a substantial decline in productivity due to Acute Hepatopancreatic Necrosis Syndrome, also known as Early Mortality Syndrome (EMS). As a result, many ponds were dry in our analysis. In total, the official tally for area under shrimp production was 975.28 km^2 whereas this project mapped 2080.71 km^2 of land currently occupied by ponds (whether in production or not) – a 113% difference.

For mangroves, independent statistics were found for both Thailand and Vietnam. Mangroves for the Future (2011) quotes an area of 2296.2 km^2 for mangroves in Thailand 2011 where this project found 2570.54 km^2 – an 11.9% increase over the period from 2011 to 2013-2015. For mangroves in Vietnam, McEwin and McNally (2014) indicate a total of 1315.2 km^2 while this project found 1464.73 km^2 – a

11.4% difference. Given the high ground-truth accuracy found for this class and the excellent balance between the user's and producer's accuracy (94% and 92% respectively) which should produce unbiased area estimates, these differences may reflect differences related to the method of data acquisition and the precision of remotely sensed data.

The integrated mangrove-shrimp category is a very interesting case. While it can be debated as to the degree to which it provides the same degree of ecosystem services as natural mangrove stands (Bridson, 2013), it is clear that it does offer a substantial degree of coastal protection and is an important ingredient in sustainable shrimp aquaculture (Joffre et al., 2015). The area associated with this category is 683.45 km^2 in Vietnam. Although it is characteristically tabulated with pond aquaculture, the amount of mangrove involved is substantial with a goal of 60% coverage. Adding this to the tabulations of mangrove in Vietnam would substantially increase the total mangrove in that country.

From the accuracy assessment undertaken, it is clear that the OLI instrument on the Landsat 8 platform provides a highly suitable basis for monitoring the status of pond aquaculture and mangroves. Mangrove was captured with high accuracy as were active ponds. Dry ponds were more challenging because of confusion with cropland, built-up land and sand during the dry season. The presence of a co-registered panchromatic band that allowed production of quasi-15 meter band equivalents for Bands 2, 3 and 4 provided important detail for detecting and delineating the ponds. Combining this with the free availability of the data, a highly accessible web archive and the availability of historical imagery for more than 40 years, the Landsat program continues to prove its exceptional value as an observational monitoring platform.

References

Alongi, D. M. (2012). Carbon sequestration in mangrove forests. Carbon Management, 3(3), 313-322.

Anh Duc, N., (2008) *Salt Intrusion, Tides and Mixing in Multi-channel Estuaries*. (Leiden, The Netherlands: Taylor and Francis/Balkema).

Arli, P., (2007) *Numerical Modeling of possible Saltwater Intrusion Mechanisms in the Multiple-Layer Coastal Aquifer System of the Gulf of Thailand*. (Germany: Kassel University Press).

Bridson, P., (2013) Black tiger shrimp: Ca Mau Province of Southern Vietnam and other areas of Southeast Asia, *Monterey Bay Aquarium Seafood Watch*. www.seafoodwatch.org.

Chavez, P. S., (1996) Image-Based Atmospheric Corrections - Revisited and Improved, *Photogrammetric Engineering and Remote Sensing*, 62, 1025-1036.

European Environment Agency. (2006) The changing faces of Europe's coastal areas, EEA Report No. 6.

FAO, (2014). *The State of World Fisheries and Aquaculture*, 2014. (Rome: FAO).

FISHSTAT, (2015) Global Aquaculture Production. *Food and Agriculture Organization of the United Nations, FISHSTAT*.

Foody, G.M., Campbell, N.A., Trodd, N.M., and Wood, T.F., (1992) Derivation and Applications of Probabilistic Measures of Class Membership from the Maximum Likelihood Classification, *Photogrammetric Engineering and Remote Sensing*, 58, 9, 1335-1341.

Foody, G.M., (2002). Status of land cover classification assessment, *Remote Sensing of Environment*, 80, 185-201.

GEBCO (2010) General Bathymetric Chart of the Oceans, (GEBCO_08). http://www.gebco.net.

GSO (2012) General Statistics Office of Viet Nam, Production of Aquaculture, Shrimp, 2012

GSO (2015) General Statistics Office of Viet Nam, Production of Aquaculture, Shrimp, Preliminary 2013, www.gso.gov.vn, accessed 8/24/15

Ha, T.T.P., van Dijk, H., and Visser, L., (2014) Impacts of Changes in Mangrove Forest Management Practices on Forest Accessibility and Livelihood: a Case Study in Mangrove-shrimp Farming, *Land Use Policy*, 36, 89-101.

Olivier M. Joffre, Roel H. Bosma, Arnold K. Bregt, Paul A.M. van Zwieten, Simon R. Bush, and Johan A.J. Verreth (2015) What drives the adoption of integrated shrimp mangrove aquaculture in Vietnam? *Ocean and Coastal Management* 114: 53-63. doi:10.1016/j.ocecoaman.2015.06.015

Lyzenga, D. R., (1978) Passive remote sensing techniques for mapping water depth and bottom features. *Applied Optics*, 17, 379–383.

Lyzenga, D. R., (1981) Remote sensing of bottom reflectance and water attenuation parameters in shallow water using aircraft and Landsat data. *International Journal of Remote Sensing*, 2, 71–82.

Mangroves for the Future, (2011) Thailand National Strategy and Action Plan, 2011-2013.

McEwin, A., and McNally, R., (2014) Organic Shrimp Certification and Carbon Financing: An Assessment for the Mangroves and Markets Project in Cau Mau Province, Vietnam, SNV.

NASA (2015) Landsat 9 is Coming, http://landsat.gsfc.nasa.gov/?p=10391, accessed 8/5/15

DOF (2012) Table 2.4 Number of farms , area under culture and yield by species and province, 2012, Yearbook 2012, Government of Thailand Department of Fisheries

Paez-Osuna, F., (2001) The Environmental Impact of Shrimp Aquaculture: Causes, Effects, and Mitigating Alternatives, *Environmental Management*, 28, 1, 131-140.

Shrimp News International (2015) Vietnam: The Current Status (2014) of the Shrimp Farming Industry, http://www.shrimpnews.com/FreeReportsFolder/FarmReportsFolder/TheStatusOfShrimpFarmingInVietnam2014.html, accessed August 2015.

Song, S.L. (2004). The use of mangroves for aquaculture: Cambodia, in *Promotion of mangrove-friendly shrimp aquaculture in Southeast Asia*, (Tigbauan, Iloilo, Philippines: Aquaculture Department, Southeast Asian Fisheries Development Center), 126-130.

SRTM (2009) Shuttle Radar Topography Mission SRTM3, Version 2.1, http://dds.cr.usgs.gov/srtm/

Thomlinson, J. R., Bolstad, P. V., & Cohen, W. B. (1999). Coordinating methodologies for scaling landcover classifications from site-specific to global: steps toward validating global map products. *Remote Sensing of Environment*, 70, 16–28.

Tu, T. M., Su, S. C., Shyu, H. C., and Huang, P. S. (2001). A new look at IHS-like image fusion methods. *Information Fusion*, *2*(3), 177-186.

Vu M.C., Bui D.D., (2006) Assessment of Saline Water Intrusion into Estuaries of Red-Thai Binh River during Dry Season Having Considered Water Released from Upper Reservoirs and Tidal Fluctuation. Japan - Vietnam Estuary Workshop, the Water Resources University.