EVALUATING THE INFLUENCE OF POLICY AND TECHNOLOGY IN DRIVING AQUACULTURE LAND USE PATTERNS IN THAILAND, 1990-2013

by

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THESIS ABSTRACT

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Since the 1980's shrimp aquaculture has been one of Thailand's largest industries and has created cultivation ponds as a dominant feature on the landscape. While shrimp farming has been economically successful, it has received criticism for being environmentally harmful, most notably because of farms replacing mangrove forests. Legislation regulating aquaculture development and technological responses to disease outbreak have had a large influence on the land use of the Thai coast. The objective of this research is to provide a systematic examination of how regulation and technology development have influenced land use in this region. To accomplish this, Landsat derived data were analyzed at the national and provincial scale to determine how Thai coastal land use systems change over time. I found that interrelated changes in technology and legislation have had complex influences on the landscape, which encourage both the restriction and expansion of aquaculture growth depending on time and location.

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TABLE OF CONTENTS

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Shrimp farming has become one of the most important industries in Thailand over the past twenty-five years. It is a major component of the national economy, as it maintains 380,000 jobs and produces one of the country's largest exports (FAO, 2014). In 2010, Thailand exported 600,000 tons of shrimp valued at over 2 billion USD, and while production has decreased in recent years due to disease, it remains one of the top producers of shrimp in the world, exporting heavily to the United States and Canada (Giap, Garden, & Lebel, 2010).

The shrimp industry's success has had a profound impact on the landscape of Thailand. Shrimp are farmed in large earthen ponds. Pond densities range from single farms in remote areas to high densities that extend along the coast where they are interrupted only by access roads. These farms have traditionally been built near the ocean, where they are able to fill with seawater before shrimp are added, and expel used water once the crop has been harvested. While many of these farms are not active today as they have been abandoned temporarily or permanently for a variety of reasons, few are converted to other uses and so remain a dominant feature along the coast.

Despite being vehicles for economic success, these ponds have been critiqued for their negative effect on the environment, especially for their role in destroying and degrading mangrove forests (Barbier & Sathirathai, 2004). Mangroves are a particularly sensitive and important ecosystem as they serve as nursery to much ocean wildlife, including a large portion of animals caught in commercial fisheries. Existing in the intertidal zone, mangroves constitute an interface between land-based and aquatic habitats where they provide ecosystem services such as wave attenuation and storm surge protection (See Figure 1). The areal reduction of mangroves has led to severe environmental degradation as effluent from ponds that contain fertilizers, antibiotics, and disease, are no longer filtered by the natural landscape. Instead, these pollutants are allowed to run directly into the ocean waters along the coast. As a result, multiple national policies were enacted over recent decades in an attempt to protect mangrove forests. Hence, regulation coming from Thailand's highly centralized national government has had major influence on shrimp farm development, especially in relation to mangrove forests (McNally, Uchida, & Gold, 2011). Thailand has had inconsistent regulation and enforcement of how development has been allowed to proceed in mangroves, which has led to variation in how the shrimp farm industry has influenced land use change patterns across the country.

During the same time period, technological innovations were influencing land use change in a different manner. The large increase in the number of shrimp farms in recent decades was facilitated by large agribusinesses, such as Charoen Pokphand Foods (CP) – the largest agribusiness firm in Thailand, which impacts virtually all parts of the shrimp production chain in order to increase production. However, high production rates and increasing densities of shrimp farms led to widespread disease in farms across the country. The presence of disease in farmed shrimp has been a large obstacle for farmers since the advent of intensive shrimp aquaculture. Flegel et al. (2008) estimate that disease resulted in international losses of approximately 15 billion USD between 1990 and 2000. In response to this, farmers implement a number of strategies to prevent infection. When a pond becomes infected, it is a common practice to abandon the farm and build new

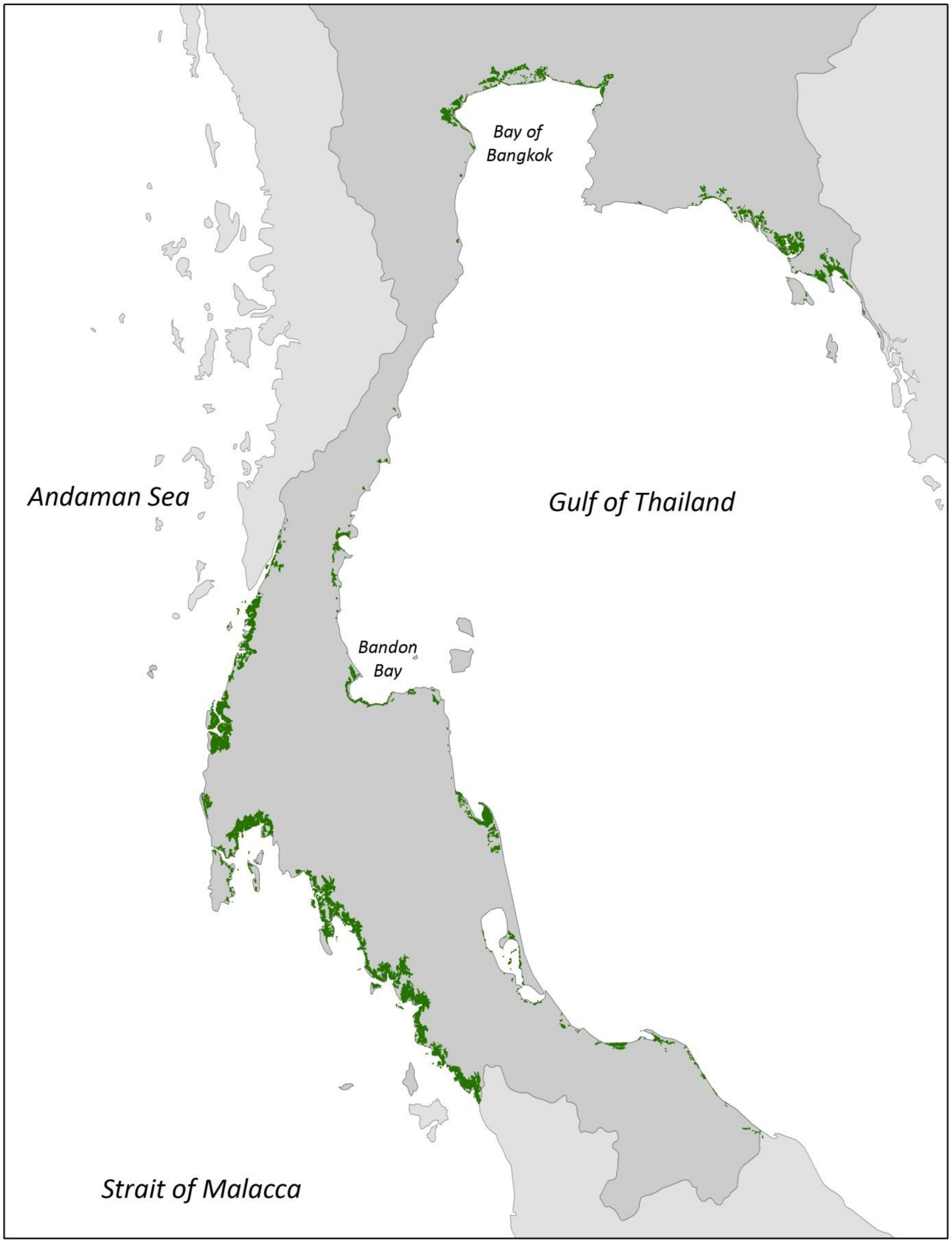

Figure 1 – Mangroves (Green) in Thailand, 2013

ponds elsewhere. Abandoned ponds might be reused again after a number of years, but often continue to be left vacant (Kautsky, Rönnbäck, Tedengren, & Troell, 2000). Such disease management practices coupled with the use of disease resistant shrimp have had a significant impact on land use patterns in Thailand.

The reasons for observed land use change patterns resulting from the shrimp farming industry in Thailand are evidently complex. Decisions regarding when and where shrimp farms are developed or abandoned are made at the level of the individual farmer who is influenced by technology (Ahsan, 2011, Le, Seidl, & Scholz, 2012), yet these same decisions are governed at a larger scale by corporate, national, and international bodies (Lebel et al., 2008). Numerous studies have examined the processes by which land use and land cover have changed in and near mangrove forests at the local scale. Several case studies have compared the development of shrimp farms, alongside other land uses, in one or several communities (Dewan & Yamaguchi, 2009, Giap, Yi, & Yakupitiyage, 2005, Muttitanon & Tripathi, 2005, Béland, Goïta, Bonn, & Pham, 2006). Other studies have analyzed the benefits of building shrimp farms in mangroves given environmental costs (Barbier, 2012), and built complex systems models to understand system dynamics of mangrove related land cover change (Chen et al., 2013). At a national and international scale, there has been much effort into understanding both how the shrimp industry has grown and how it has affected the environment by using historical data and ecosystem modeling (Kuenzer, Bluemel, Gebhardt, Quoc, & Dech, 2011). These studies find that in Thailand and other tropical communities, shrimp aquaculture has had a drastic effect on the landscape, replacing a variety of other land covers including rice farming, mangroves, and salt marshes. In some studies, mangroves were found to be replaced by both aquaculture and agriculture (Kuenzer et al., 2011), while other studies have shown evidence of more mangrove reestablishment (Muttitanon & Tripathi, 2005). However, what is lacking is a systematic investigation that examines how land use change patterns are influenced by technology and innovation versus policies resulting from environmental degradation.

The goal of this paper is to evaluate how policy and technology have influenced land use change in coastal Thailand relating to the shrimp farming industry. To do this, I utilize Landsat data from multiple time periods to classify forest mangroves in coastal Thailand and to digitize approximately 100,000 shrimp farms over a 25-year period. I then examine the spatial distribution of shrimp farm growth and decline at both the national and provincial scales for selected provinces. While a national scale analysis reveals general patterns of land use change, a provincial scale analysis helps us understand sub-regional variability in the timing and land use change patterns resulting from policies and technology. Digitizing individual shrimp farms across multiple time periods and analyzing the results at both national and provincial scales provides a novel contribution to the literature on the shrimp farm industry, and, more broadly, the geography of land use change patterns.

In the next section, I discuss the history of shrimp farm development in the context of land use regulation and technology in Thailand. I then examine the historical expansion of shrimp farms by mapping each aquaculture pond in Thailand during three separate time windows over the past 25 years. Next, I present the analysis of how the quantity and spatial distribution of shrimp farms has changed during this 25-year period. I then discuss in detail how observed land use change patterns have been influenced by policies versus technology. I conclude by providing insight into future work concerning the examination of land use change and shrimp farming in Thailand and beyond. The significance of this research rests in the fact that, while shrimp farms arguably exert greatest impact on mangroves, they also impact tourism, local communities that use coastal resources, urban structure, the international food market, and agriculture systems.

CHAPTER II

BACKGROUND

2.1. History of Shrimp Farm Development

Two types of aquaculture have defined shrimp farming in Thailand over the past eighty years: *extensive* and *intensive* shrimp farming. Extensive shrimp farming dates back to the 1930's when it was introduced by Chinese immigrants who facilitated the spread of aquaculture technology throughout the region (Szuster, 2006). In extensive aquaculture, a farmer receives seawater into a rice paddy during high tide. The water brings with it shrimp, along with many other organisms, which becomes trapped there until they were harvested before it is time to plant rice. Yields are generally low and the farms are relatively large. Shrimp production usually supplements food and income during the dry season when rice cannot be grown.

Until the 1970's, shrimp farming had little impact on the extent of mangrove forests. Mangroves existed on a large portion of Thailand's 3,200 km coastline, covering a total area of approximately 3500 km^2 (Blasco, Aizpuru, & Gers, 2001) Mangroves were used for resources such as firewood and food by local communities. In the early 1970's the establishment of Exclusive Economic Zones, areas of production in which taxes were heavily reduced or exempt caused Thailand to lose over 700,000 km^2 of its fishing grounds, which was around the same time that demand for shrimp in the US, Japan, and Europe began to rise (Ruyabhorn & Phantumvanit, 1988). To replace income lost from fishing, many chose to engage in semi-intensive shrimp farmin*g* in which farms were generally smaller than in extensive shrimp farming. The farms would stock shrimp larvae instead of catching them, causing the number of shrimp grown in each farm to be much higher. Many of these farms were built directly on mangrove forests, which were ideal locations because of their flat topography, their access to ocean water, and because they were not being used for agricultural production. It was then that farms began replacing mangrove forests, and by the mid 1980's there was just over 2000 km^2 of mangroves remaining (Blasco et al., 2001).

Intensive shrimp farming became popularized in Taiwan in the mid-1980's when new specialized aquaculture technologies were introduced. In this type of farming, shrimp are raised from larvae that are produced in a factory, and antibiotics, processed food, and chemical water treatment practices are applied to increase yields. Taiwan quickly became one the world's leading producers of shrimp, exporting over 37 million pounds in 1987. Rice farming at the time was the predominant cash crop in the region. By farming shrimp instead of rice with an intensive system, one could earn up to sixty times the amount of money (Levallee, 1997). In 1988, the Taiwanese shrimp farming industry collapsed due to disease, producing just over 3 million pounds by 1990. Thailand quickly began to adopt the practice, and because of their absence of disease and improved production practices, soon became the world's leading shrimp producer. During the next decade, Thailand's shrimp industry expanded exponentially, as the number of extensive and semi-intensive farms grew five-fold between 1985 and 1995. By this time, over 80% of farms utilized intensive methods (Huitric, Folke, & Kautsky, 2002). In the mid-1990's, Thailand was annually producing almost 300,000 tons of shrimp with an export value of over $1.5 billion (FAO, 2014).

Extensive farming began in Thailand on the Gulf of Thailand near Bangkok. This location was near the largest market and close to research centers that were researching aquaculture-related technology. Farms quickly expanded around the Gulf of Thailand and later began appearing on the southern coast and the Andaman Sea. By 1993, the total area of mangroves was reduced to almost 1,500 km^2. The most intensely farmed areas lost over 85% of their coastal forests, and by the mid 1990's there was little room for further expansion on the east coast (Szuster, 2006).

In the late 1990's, the production of shrimp in Thailand began to decline due to the rise of disease among the predominantly farmed species of shrimp - the giant tiger prawn. Until this time, this species was virtually the only exported shrimp, accounting for over 96% of production by weight in 1998 (FAO, 2014). The viral disease known as white spot syndrome (WSS) spread quickly throughout the region, likely due to the spatial density of ponds, poor pond management, and the cultivation of only one species (De Schryver, Defoirdt, & Sorgeloos, 2014). Although overall production declined for a few years after the initial outbreak of white spot syndrome, by 2003 Thailand was again setting export records (See Figure 2). Thai farmers built new ponds to avoid disease and increased use of pesticides. Shrimp farming also became more popular inland, as seawater would be shipped to farms in central Thailand for initial stocking, reducing the risk of becoming contaminated from using water that might have been discharged by a neighboring farm.

Thailand was able to recover from WSS because they converted from harvesting giant tiger prawn to harvesting pacific whiteleg shrimp. This exotic species was more resistant to disease, and eventually Specific Pathogen Free (SPF) strains of the shrimp allowed for further protection from infection. SPF shrimp are genetically engineered shrimp which are resistant to certain types of disease. SPF strains have since become the predominant type of shrimp grown across Thailand (Walker & Mohan, 2009). These innovations have allowed the industry to remain stable for most of the past decade. In 2010, Thailand exported about 600,000 tons of shrimp valued at over 2 billion USD. The patterns of mangrove have changed since the late 1990's as well. The transition of farms inland and stricter land use laws (discussed in section 2.2) caused the conversion of mangroves to shrimp farms to decrease. The area covered by mangroves increased in the late 1990's because of efforts to replant mangroves on abandon farms.

While Thailand is no longer the world's leading producer of shrimp (a title that China gained in the mid-2000's), it continues to produce a vast amount of food for export each year. The threat of disease has resurfaced again, as a disease called Early Mortality syndrome (EMS), also known as Acute Hepatopancratic Necrosis Disease, has emerged. Discovered first in 2010, EMS affects post-larval shrimp before they are fully grown, and causes up to 100% mortality per pond. The effect of EMS on the industry is large, with shrimp production estimates for 2014 expected to be about half the 2012 totals across Thailand (Seaman, 2014). While some say that better pond management can help the problem (Seaman, 2014), others point to pond disinfection as a cause (De Schryver et al., 2014).

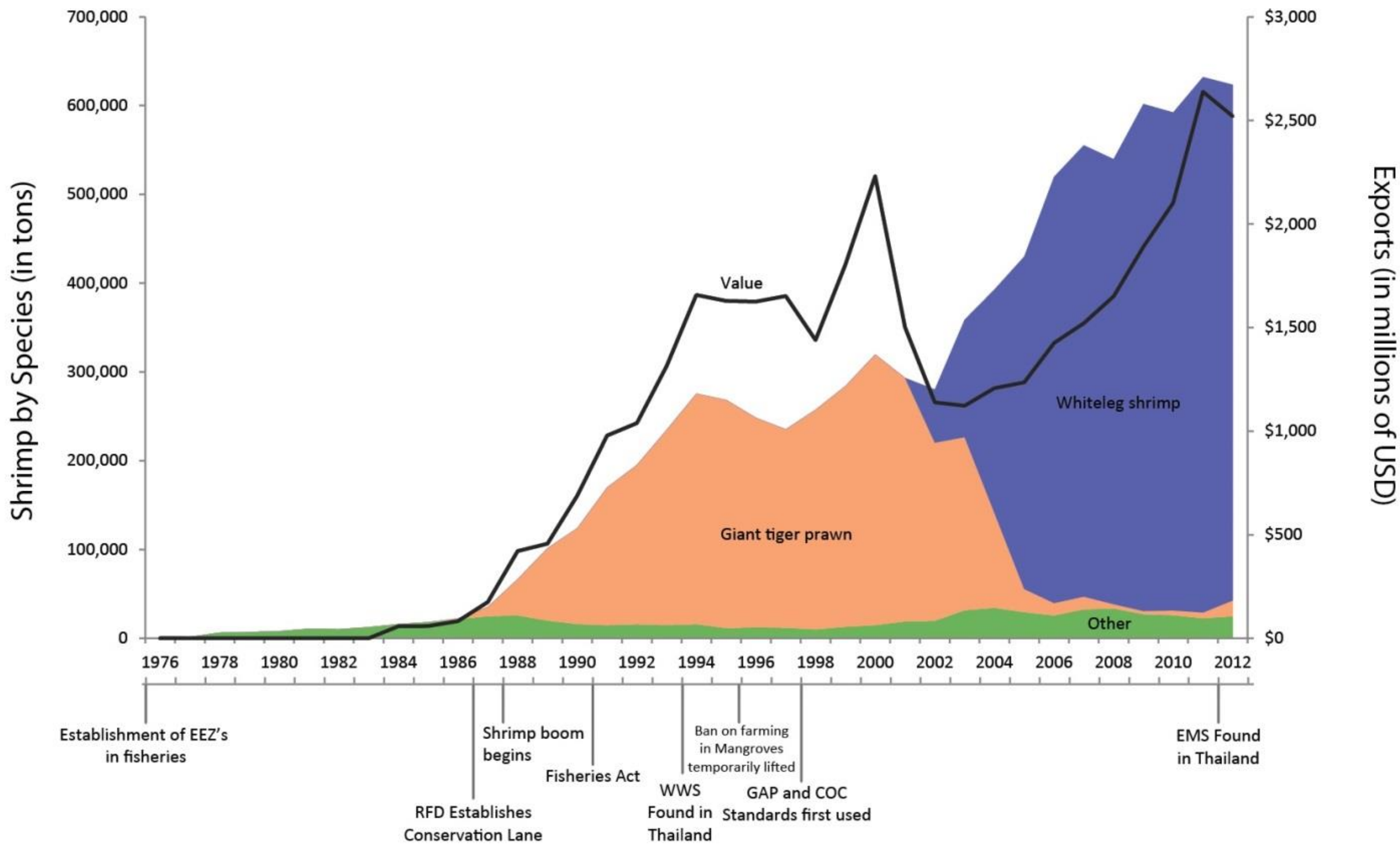

Figure 2 - Shrimp Production 1976-2012
(FAO 2014)

The Thai shrimp industry's current crisis with Early Mortality Syndrome will present interesting challenges as it tries to recover. Zavolloni et al. (2014) found that EMS might have proliferated because current methods kill competing 'good' bacteria in ponds. While it is as of yet unclear whether EMS infected ponds will require abandonment, it is possible that the construction of many new ponds might be necessary to reach previous levels.

2.2. Regulation

The national government has jurisdiction on the development and management of mangrove forests in Thailand. The highly centralized structure of the Thai government allows it to make decisions on land use and aquacultural policies at local levels around the country. The two main departments in the Thai government responsible for regulations regarding aquaculture and the use of mangroves are the Department of Fisheries and the Royal Forestry Department (RFD), respectively. The role of the Department of Fisheries (DoF) is particularly illustrative of how the structure of the Thai government has contributed to the patterns of land use change in coastal areas. The DoF is responsible for both the promotion of the industry as well as its regulation. This can lead to conflicting interests, as the DoF's success is based on how much money is produced by the industry as well as the enforcement of potentially economically limiting regulations, such as those focused on mangrove conversion.

Before the introduction of semi-intensive shrimp farming in the 1980's, there was very little regulation in the shrimp farming industry. A notable legislation example is the Fisheries Act of 1947, (which still governs much of what is allowed today) in which the only regulation of cultivation ponds is that the farmer needs permission from the government to construct a pond on land that belongs to the State.

In Thailand, mangroves are traditionally owned by national government (and managed by the Royal Forestry Department). Land owned by the Thai government is classified as Crownland, Treasure Land, or Wasteland (Huitric et al., 2002). Until recently, all mangroves owned by the government were classified as Wasteland, which is the only nationally owned land that can be purchased from the government (Barbier & Sathirathai, 2004). In 1954, the Land Code of Thailand was passed that, among other things, standardized how land was transferred from the government to private ownership. An occupier could apply for ownership of the land after a seven to fifteen year concession, costing as little as four dollars per year. Often shrimp farmers would buy concessions from loggers after the area had been cleared.

The first major regulation in mangrove management came in 1987, when the RFD became interested in land use planning. This plan segmented the mangroves into different use zones, some of which were designated as conservation land and thus closed to shrimp farming. However, enforcement was weak and much of the protected land was still used by shrimp farmers. In 1991, the Department of Fisheries enacted its first major regulation, the Fisheries Act and Ministerial Regulations. In these measures, shrimp farms were banned from using mangrove forests, and the Bank of Thailand would no longer make loans to farms in mangroves. Many of the other regulations only applied to very large farms, of which there were very few (Huitric et al., 2002).

Aside from regulating the industry, the DoF was also responsible for promoting the expansion of shrimp farming. While it is possible for the same department to perform both tasks, the DoF did not have the institutional framework that allowed these two components to complement each other. Instead, throughout the next decade there were a number of policies and incentives that contradicted previous environmental protections. For example, in 1996 the DoF lifted its ban on shrimp farming in mangroves to promote the industry, while only one year later another law was passed by the Thai government stated that only 10% of the remaining mangroves could be used for aquaculture (Ridmontri, 1996).

A similar occurrence happened when inland farms began to show negative environmental impacts. After the collapse of the Gulf of Thailand's giant tiger prawn populations, many farms moved inland to central Thailand to begin low-salinity shrimp farming. After worries that inland shrimp farming would cause salinization and contamination of rice fields, among other environmental impacts, the practice of building farms away from the coast was banned in 1997 (Flaherty, Szuster, & Miller, 2000). However, inland shrimp farming continued to expand throughout the 2000's, and many of these farms were subsidized by the government. A large amount of inland farms continue to exist today.

Thai property rights also have a strong influence on how the landscape is shaped, and consequentially, have helped shrimp farming expand into mangroves. Private property rights are guaranteed by the constitution and personal property can be used in any way an owner decides. This has made it difficult to pass legislation that includes environmental protections, because protection-based legislation is often superseded by the constitution (Huitric et al., 2002). Additionally the Thai legal system lacks case law, making it difficult to set environmental harm as precedent.

Near the beginning of the "shrimp boom" when semi-intensive aquaculture became popular in the late 1980's, acquiring land in mangroves was easy, and once owned, private property laws made it difficult to regulate. Most farms at this time were abandoned after five years due to disease or contamination (Rivera-Ferre, 2009). This process led to the quick acquisition of land, use of it, and abandonment for unused soil.

Recently Thai government has been relatively more successful in creating and enforcing laws that limit environmental impacts. The most notable of these regulations was the adoption of the Good Aquacultural Practices (GAP) and Code of Conduct (CoC) certification schemes. These certifications attempt to help increase sanitation, quality of product, and environmental and social sustainability. These standards were initially adopted in 1998, and were last changed in 2009 (Giap, Garden, & Lebel, 2010).

Since they were first instated in 1998, all farms in Thailand have been required to meet GAP standards. These standards require that farms not be located in illegal areas, and have strict regulations regarding the treatment of effluent to prevent the spread of disease and pollution. Aside from complying with existing laws, there is no regulation in GAP that accounts for the location of the farm. The CoC standard is much stricter, and in theory GAP standards should help farmers eventually achieve CoC standards. These standards aim to regulate the entire production line, rather than just the shrimp farm. However, the incentive to gain CoC certification is unclear, and participation is low (Vandergeest, 2007). For every farm that gained CoC certification in 2012, 132 gained GAP certification ("Database of Certified Aquaculture Farms," 2014).

Regulation of shrimp aquaculture in Thailand during the industry's growth period was erratically enforced and was filled with mixed incentives. The Department of

Fisheries had a strong interest in the financial success of shrimp production, which is evident in the significant financial support it provided to the industry (Giap et al., 2010). This support conflicted with the DoF's responsibility to regulate aquaculture's conversion of mangroves, which resulted in inconsistent and confusing legislation. The resultant law's influence on the landscape was mixed, allowing farms to replace mangroves in some areas and some not, depending on the time the farms were built and the strength of enforcement in the region.

CHAPTER III

METHODS

3.1. Study Area

Areas covered in this study include all of coastal Thailand as identified in Figure 3. To the east, Thailand borders the Pacific Ocean at the Gulf of Thailand, which includes the Gulf of Thailand to the north and Bandon Bay to the west. The west coast of Thailand borders the Indian Ocean at the Andaman Sea and Strait of Malacca. All aquaculture ponds and mangroves in each district (known as an *Amphoe*) that borders the ocean were surveyed. The study area was deemed appropriate for this study because the vast majority of all coastal aquaculture farms in Thailand in addition to all mangrove forests exist in this area. While there are inland aquaculture ponds outside of this area, they were not included in this study because they differ in their reliance and effect on the surrounding ecosystem. In all, 114 districts in 27 provinces were included in the study area.

To measure change in mangroves and aquaculture ponds, the coast was surveyed utilizing remote sensing imagery from three time periods, each approximately one decade apart. Landsat Thematic Mapper imagery was used from Landsat satellites 4, 5, 7 and 8, depending on the most suitable available image near the survey date. Each period used 14 Landsat images to cover all of coastal Thailand. For time periods 1 and 2, imagery from Landsat's Global Land Surveys for GLS1990 and GLS2000 were used, unless images with a clear view of coastal districts closer to 1990 or 2000, respectively. Time period 1 had imagery from between March 1988 and March 1992, except for two scenes in 1994. Time period 2 consisted of imagery taken between December 1999 and March 2002.

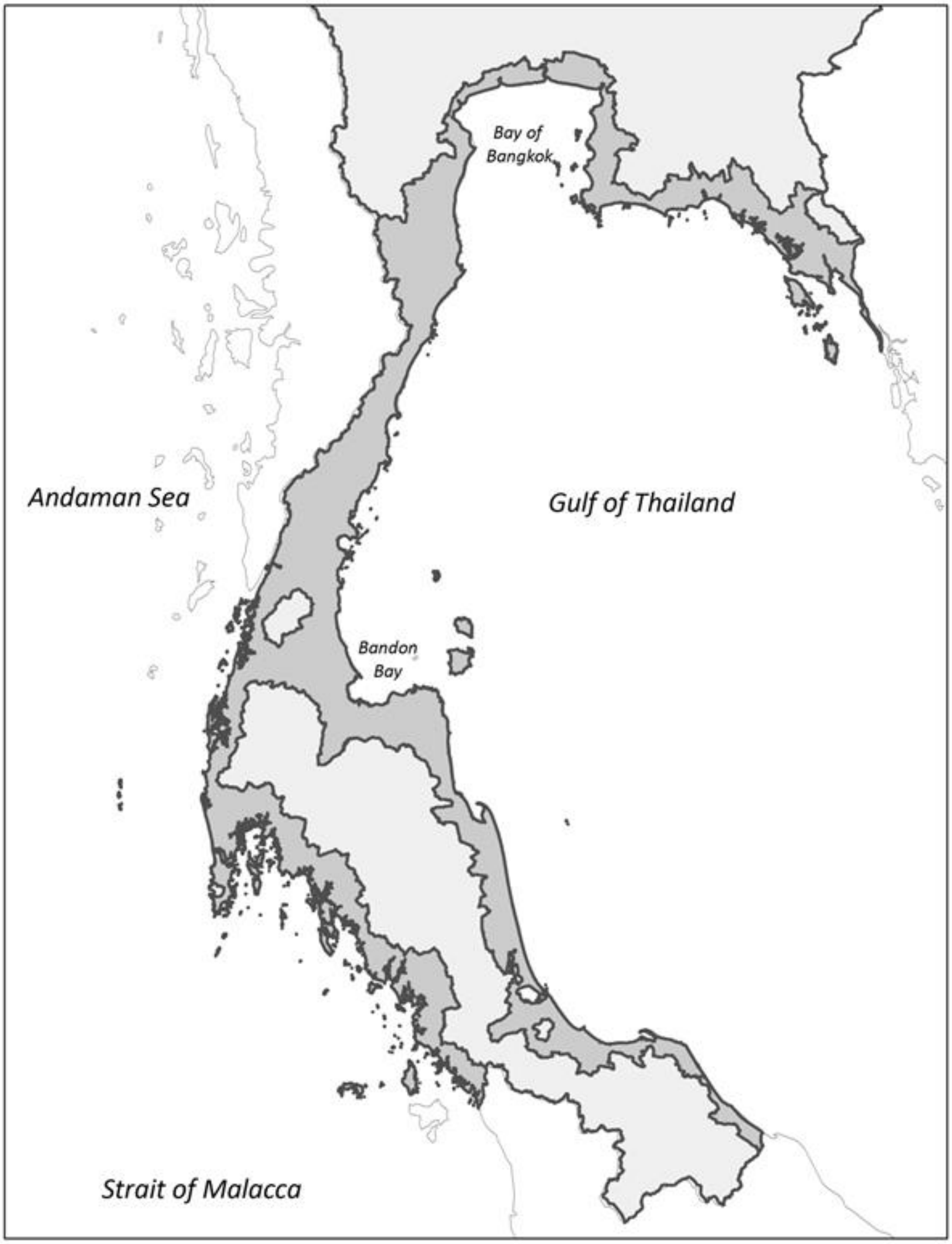

Figure 3 – Study Area in Dark Grey

Landsat 8 data imagery from between April 2013 and February 2014 were used for time period 3.

3.2. Data Classification

Data classification was performed on the remote sensing imagery in order to identify areas of mangrove stands. The satellite images were radiometrically calibrated for radiance. Atmospheric correction was then preformed using Fast Line-of-sight Atmospheric Analysis of Hypercubes (FLAASH) methodology, with a tropical atmospheric model. To identify areas of mangrove forests, a supervised classification was executed using maximum likelihood classification on all available raster bands.

After classification, many smaller mangrove stands were eliminated from analysis. This was done to identify areas of mangroves that were healthy and provided a reasonable amount of ecosystem services. Koch et al. (2009) demonstrate that wave attenuation by mangrove forests is significant with mangroves extending 100 m from the seaward boundary, while wave attenuation declines exponentially after 100 m. Small mangrove stands may still exists after land use conversion, but would fail to provide this and other important ecosystem services (Barbier, 2012). Only stands greater than 15,000 m^2 were kept for analysis.

3.3. Digitization

Aquaculture ponds were manually digitized from the Landsat imagery by drawing the approximate area covered by each pond. The near-infrared band was used to identify areas of water, and subsequently the geometric structure of these ponds. Landsat imagery is available at 30 m resolution, an area roughly the same size as smaller aquaculture ponds. (The average size is 1.6 ha (Kongkeo & Davy, 2010)). Therefore, some of the smallest ponds may have been omitted, or multiple small ponds in close proximity to one another may have been grouped together. Only the smallest of shrimp farms would be missed in this way, and their marginal impact on land use change would be very small.

Shrimp ponds were only digitized if they were observed to be active (i.e., filled with water). Ponds might be temporarily inactive, for example if they were abandoned due to disease only to be used again years later, permanently abandoned, or converted to another land use. Because temporarily inactive ponds were much more difficult to identify, they were not included as aquaculture ponds in this study. If a pond was initially identified as active and in a later time period was inactive, it kept is designation as an aquaculture pond unless it had been converted to another land use. This conversion was apparent as it would include easy-to-identify vegetation of either agriculture or mangrove stands.

3.4. Analysis

In order to address the research questions, the quantity and location of coastal shrimp farms, along with the extent of mangrove forests, were compared between time periods and between locations. I examined how the growth of aquaculture farms changed nationally between 1990 and 2014.

I then examined three provinces, Nakhon Si Thammarat, Chanthaburi, and Trang. These provinces have distinct physical and cultural geographies, and show very different patterns of aquaculture development and mangrove change. I looked at the changes in these provinces to help discover how policy and technology have shaped local land use change differently, and what this in turn might say about Thailand’s shrimp industry as a whole.

CHAPTER IV

RESULTS

4.1. National Scale Analysis of Aquaculture Growth

In the 1990s, there were 29,629 aquaculture ponds identified in coastal Thailand (See Figures 4 and 5). The majority of farms then existed in the Gulf of Thailand, with the majority along the northern shore of the Bay of Bangkok. The five provinces along this part of the coast contained 11,886 ponds that covered an area of approximately 260 km^2. This region has historically been home to much extensive shrimp farming, where ponds are much bigger. Ponds in the province Samut Sakhon, for example, have a mean size of 23,352 m^2, while the national average size of 15,830 m^2.

Two other regions were home to high numbers of shrimp farms. The southwest coast of the gulf had 7,238 ponds between the provinces of Nakhon Si Thammarat and Surat Thani, and Chanthaburi in far southeast Thailand included 3,567 ponds. In contrast provinces in on the Andaman coast, home to the country's most extensive mangrove forests, had only 45 shrimp ponds between them. These three hotspots (the north and southwest coasts of the Gulf of Thailand and Chanthaburi) held 77% of the countries shrimp farms at the time.

By 2000, the growing industry spread out to available land along almost the entire coast. At this time, Thailand was home to 67,995 aquaculture ponds, which now existed in each of its 23 coastal provinces, covering approximately 607 km^2. Ponds built during the 1990's were considerably smaller than those built before, with an average size of 4,895 m^2, while those built by 1990 had a mean size of 15,833 m^2. Of the ponds that existed in 1990, 25,398 still existed in 2000. The remaining 4,147 ponds were either

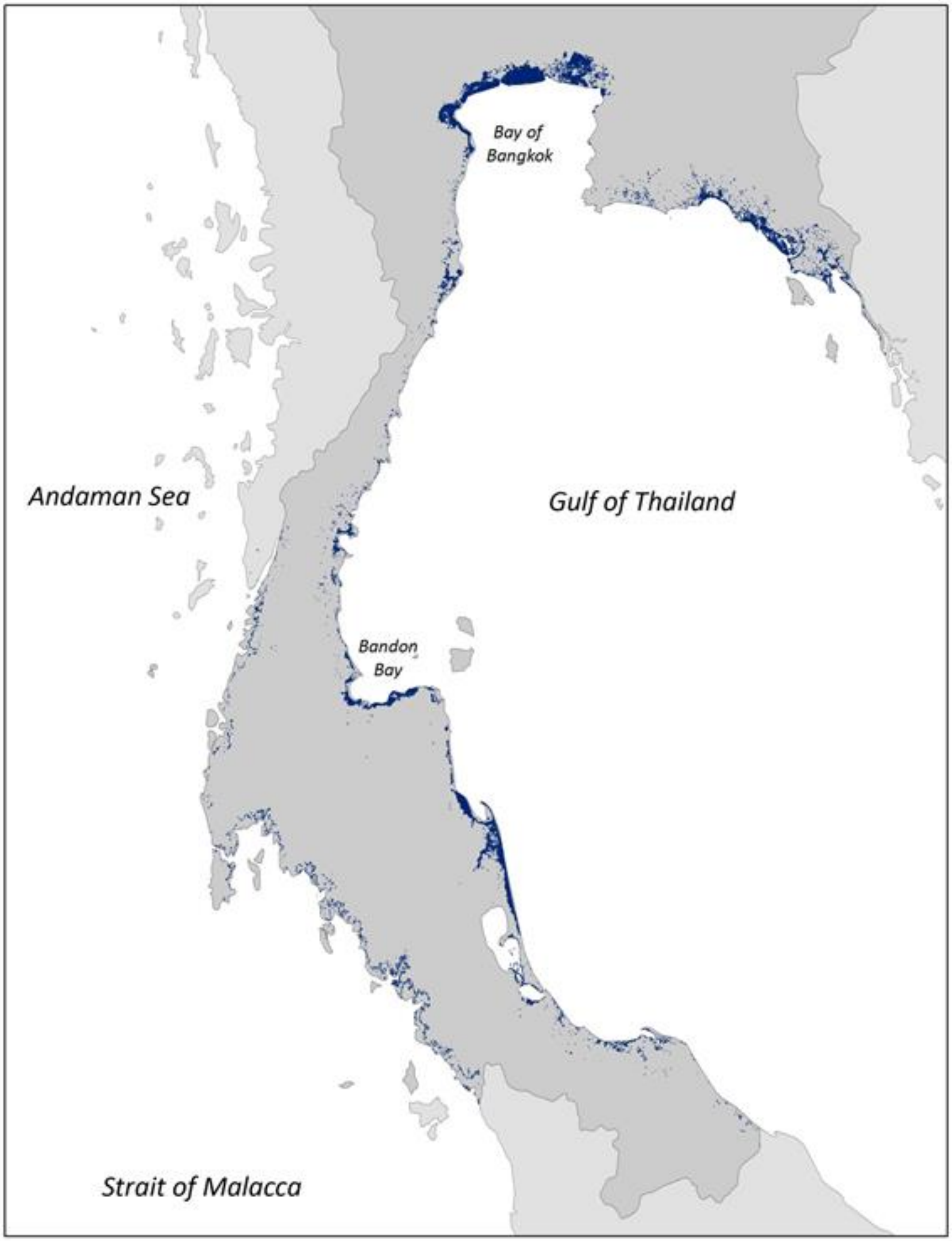

Figure 4 – Shrimp Farms (blue) in Thailand, 2013

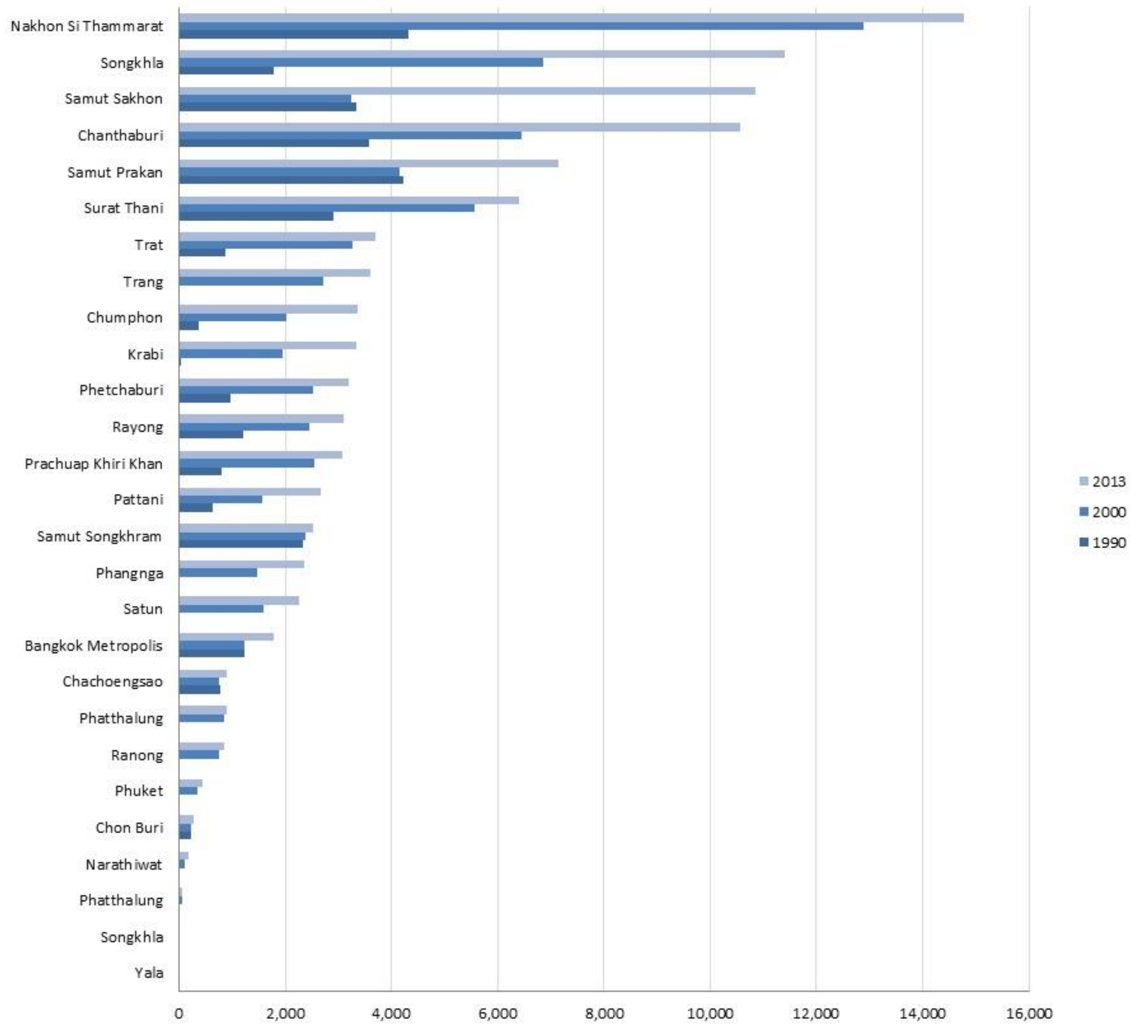

Figure 5 - Shrimp farm growth by province

converted to another use, abandoned, were reforested, or were spatially reconfigured into other ponds. Most of these were smaller, intensive ponds far from Bangkok. There were 1,382 of these in Chanthaburi Province alone. Regions of high concentration of ponds were maintained between the two periods. The two provinces with the highest number of ponds held 29.0% of ponds in 1990 and 29.8% in 2000. (Nikhon Si Thammarat and Samut Prakan, and Nikhon Si Thammarat and Songkhla, respectively). The region with the largest change was the Andaman coast, where the number of ponds increased from 45 to 8,834. Ponds in this area were notably small, averaging only 3870 m^2.

The region with the least change was the western coast of the Bay of Bangkok, which was one of the areas with the highest concentration in 1990. This area had only an 11% increase in the number of farms, while the other high activity areas from the previous decade grew by 223%.

The number of farms continued to increase between 2000 and 2013 even with more stringent regulation on the industry, as by 2013 there were 99,743 ponds in Thailand. All provinces continued to experience an increase in the number of shrimp farms, even as the number of abandoned ponds increased. The abandonment and conversion of ponds continued to be highest in the Bay of Bangkok. Here, 14% of ponds that were active in 2000 were not present in 2013. Another five percent had been reconfigured into new ponds, most of which were extensive ponds being segmented into multiple intensive ponds.

Provinces with the most aquaculture growth during this period was Surat Thani, which increased by 5,283 ponds, and Samut Sakhon, in the Gulf of Thailand with 7,618, and Chanthaburi with 4,116 new ponds. These provinces were in areas with high production in the previous study periods, showing that while the industry is expanding geographically, it is expanding more in already established areas.

4.2. National Scale Analysis of Mangrove Decline

In 1990, Thailand was home to 2049 km^2 of mangrove forests. By this time, the majority of mangroves along the Bay of Bangkok had already been lost, with only 3.5 km^2 remaining. The vast majority of mangroves were along the Andaman coast, which held 82.2% of the area of mangrove forests in the country. This was also the region that had the largest mangrove stands. Contiguous mangrove stands along the Andaman had an average size of 1.30 km^2, while all other stands in Thailand had an average area of .40 km^2. Notable areas of mangrove stands outside the Andaman coast were located in Pattini, Nakhon Si Thammarat, Chumphon, and Trat. Additionally, relatively high concentration of mangroves were present in Chanthaburi and Surat Thani, but were highly fragmented due to aquacultural and agricultural production.

By 2000, the total area of Thailand's mangrove forests had been reduced to 1749 km^2. Most of this loss was on the Andaman coast that at the time retained the greatest area of contiguous forest. Generally, lost mangrove area occurred on the landward edge of the forests. There were only 2,888 aquaculture ponds that were built between 1990 and 2000 that occupied areas where mangroves were lost in the same period. While the total area of these ponds was only 14.6 km^2, necessary infrastructure for these ponds was also built in mangrove areas. While Thailand had a net loss of mangroves between 1990 and 2000, it did gain 2,294 km^2 in new mangrove area. Much of this was marginal forest growth on the landward edge of pervious forests, but large stand growth did occur in Satun, Surat Thani, Chumphon, and Samut Songkram provinces.

Between 2000 and 2013, the size of Thailand's mangrove loss was considerably smaller, losing only 51 km^2 of forest. A number of regions had a net increase in mangrove forests, such as the coast along Phetchaburi where the forests size increased by 30%. Even though there were fewer total ponds built between 2000 and 2013 than the previous period, there were more new ponds built in existing mangroves forests.

4.3. Provincial Scale Analysis

This section examines shrimp farm development in a select set of diverse provinces to understand how this type of land use change differs regionally and locally in Thailand. The provinces of Trang, Sakhon Si Thammarat, and Chanthaburi were chosen as they were geographically distinct and illustrative of the variety of land-use patterns displayed across the country. Trang is a province in southwest Thailand on the Andaman Sea (Figures 6 and 7). It has an area of 4,917 km^2 with a population of 626,708 as of a 2011 census (National Statistical Office, 2011). The majority of the Trang coast is lined with mangrove forests, which covered an area of 375.3 km^2 in 1990 and 370.0 km^2 in 2000. In 1990, Trang contained no identified aquaculture farms. By 2000, however, the industry had expanded to the region and 2,706 shrimp farms had been built. While only 52 of these ponds had displaced any mangrove forests, nearly all farms relied on mangroves, they can be resources for shrimp production. Over 98% of newly built shrimp farms in this region were developed within one kilometer of mangrove forests. Shrimp farms in Trang averaged 297 m^2 in size, well below the national average. Trang experienced more growth in aquaculture between 2000 and 2013. It added an additional 925 ponds for a total of 3,607. Only nine of these new ponds were built in existing mangrove forests. Trang did lose roughly 1 km^2 of mangrove between 2000 and 2013, with only a small percentage of that because of aquaculture.

Nakhon Si Thammarat is a province on the southwest coast of the Gulf of Thailand, and is a prominent area in intensive Thai aquaculture (Figures 8). With an area of 9,943 square km, this province included one of the country's largest contiguous mangrove forests at 92 km^2 as of 1990, located on the Talumphuk peninsula at the mouth

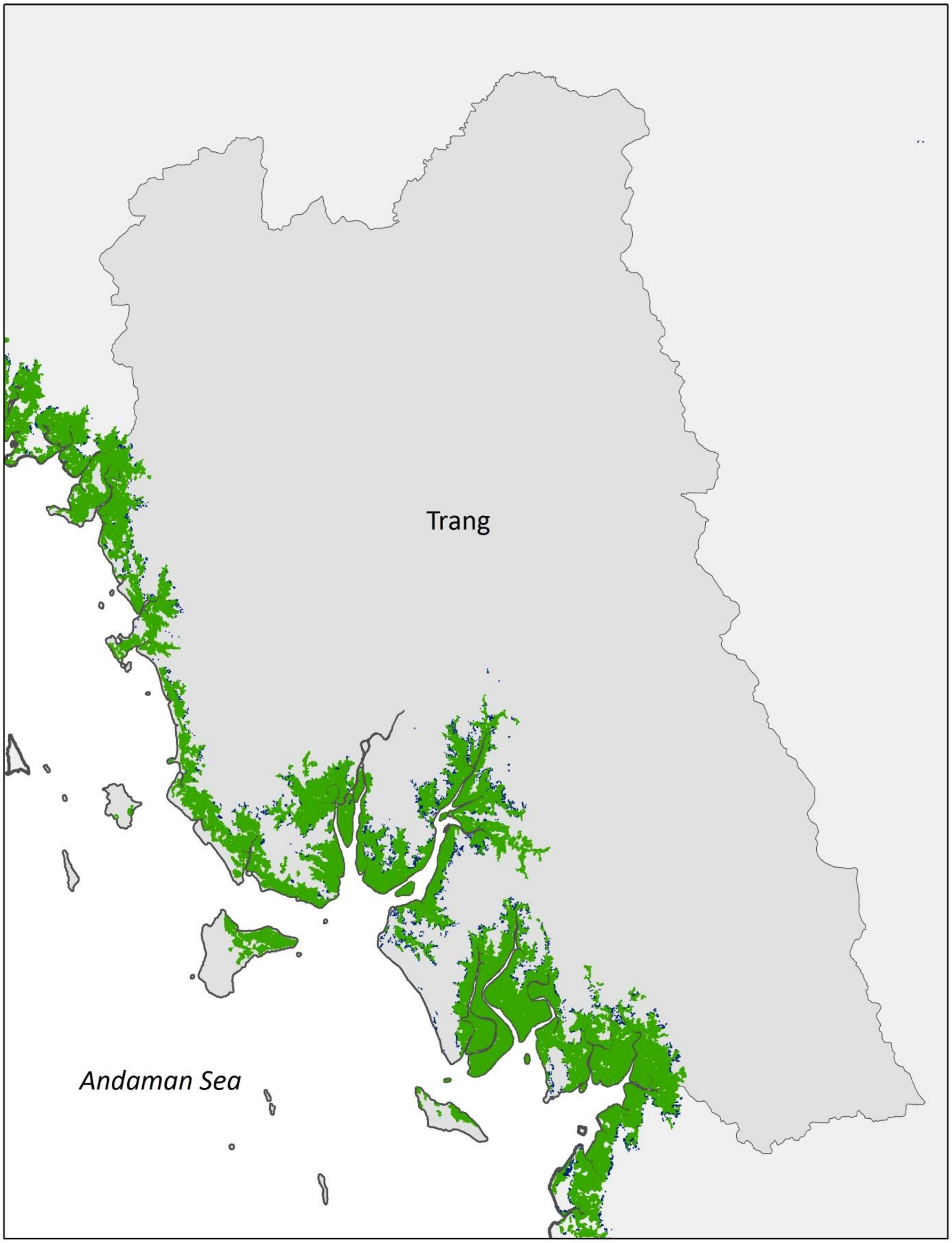

Figure 6 - Shrimp farms (Blue) and Mangroves (Green) in Trang

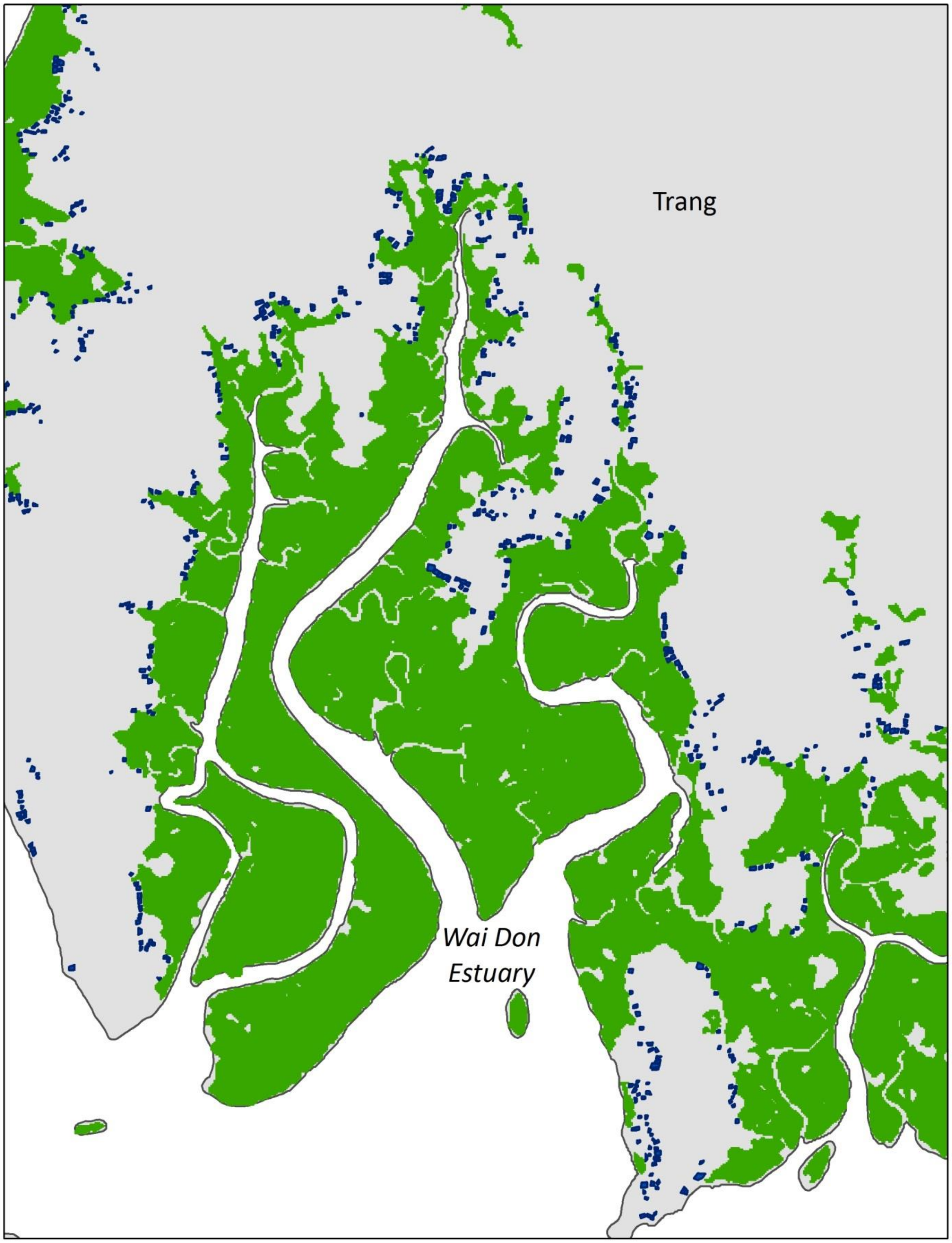

Figure 7 - Shrimp farms (Blue) and Mangroves (Green) in Wai Don Estuary

of the Pak Phanang River. In 1990, the province had a total of 4,319 aquaculture ponds covering an area of 57.8 92 km^2. By 2000, the number had increased to 12,883 ponds covering an area of 92.6 km^2. There were 9,365 ponds built during the decade, with most of the expansion on the south eastern shore of the province. A total of 215 ponds had been abandoned or converted into another land use. Another 586 ponds had been reconfigured into new ponds. Nakhon Si Thammarat had a relatively high loss of mangroves due directly to aquaculture pond construction. Shrimp farms during this time were built to extend along the entire eastern shore of Talumphuk peninsula, resulting in 82 farms that were built on previously existing mangroves. Additionally, 1,407 ponds were located within 1 km of a mangrove stand. In total, the area of mangrove in this province was reduced from 94.8 km^2 in 1990 to 76.5 km^2 in 2000. Most of this was not due to shrimp farm construction, although most of the lost area was adjacent to aquculture ponds on the east coast central tidal streams of Talumphuk peninsula.

Between 2000 and 2013, Nakhon Si Thammarat saw only a modest increase in the number of shrimp ponds, totaling at 14,777. This is unlike other areas that had been centers of the aquaculture industry that continued to increase in ponds at a high pace. This is like due to two reasons, the first being that it had so much of its coast populated by aquaculture ponds by 2000, there was little room to expand, especially on the southeast coast. Secondly a large number of ponds, 580, had been abandoned. These were almost all ponds that had been built by 2000. Mangroves in this province also grew marginally during this period, increasing their area to 80.5 km^2. There were 18 new ponds built on mangroves during this period, although most were in small stands of segmented mangroves, none of which in the forest on Thalumphuk peninsula.

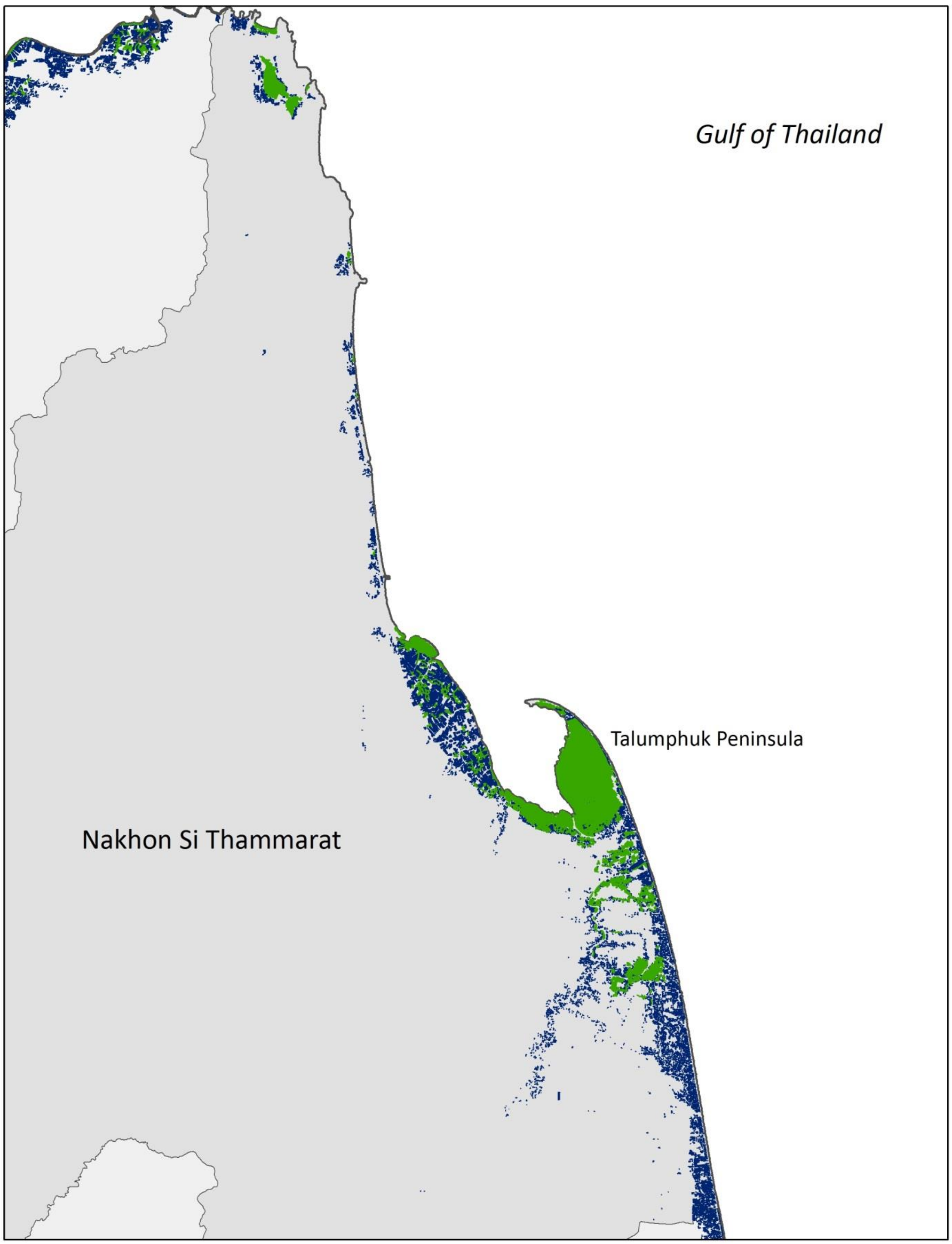

Figure 8 - Shrimp Farms (Blue) and Mangroves (Green) in Nakhon Si Thammarat

Chanthaburi province is in southeast Thailand, with Cambodia bordering to the east and the Gulf of Thailand to the west, it separates the province of Trat from the rest of the country (Figure 9). Since 1990, Chanthaburi, this province has included virtually of the country's shrimp farms east of the Bay of Bangkok. These ponds are largely located in the estuaries of the Welu and Chathaburi rivers, which are the dominant features on the coast of the province.

By 1990, the quickly growing industry already had a strong presence in this province. While there were a number of large, extensive ponds in the southeast coast of the Gulf of Thailand, the majority of ponds are smaller, intensive ponds that dominate the estuaries in what was previously mostly mangrove and mudflats. In all, there were 3,567 aquaculture ponds in the province built by this time. All but approximately 400 of these were small, intensive ponds. Aquaculture continued to grow quickly in Chanthaburi during the next decade, as by 2000, the number of ponds had nearly doubled to 6,461. At this time, there was an aquaculture presence along the entire coastline of the province. While the overall amount of shrimp ponds had larger growth, there were a number of ponds that had been abandoned early enough in the decade where mangroves were already reestablishing by 2000. Many of these were expensive ponds on the southeast coast and Welu estuary. These trends continued between 2000 and 2013. Growth in the number of ponds continued, although moderately slowed, to arrive at a total of 10,577 by 2013. Growth occurred along the entire coast of the province, but was largely concentrated on the central coastline between the two estuaries, where large farms with up to 150 ponds each had established. Abandonment of ponds also continued, as large

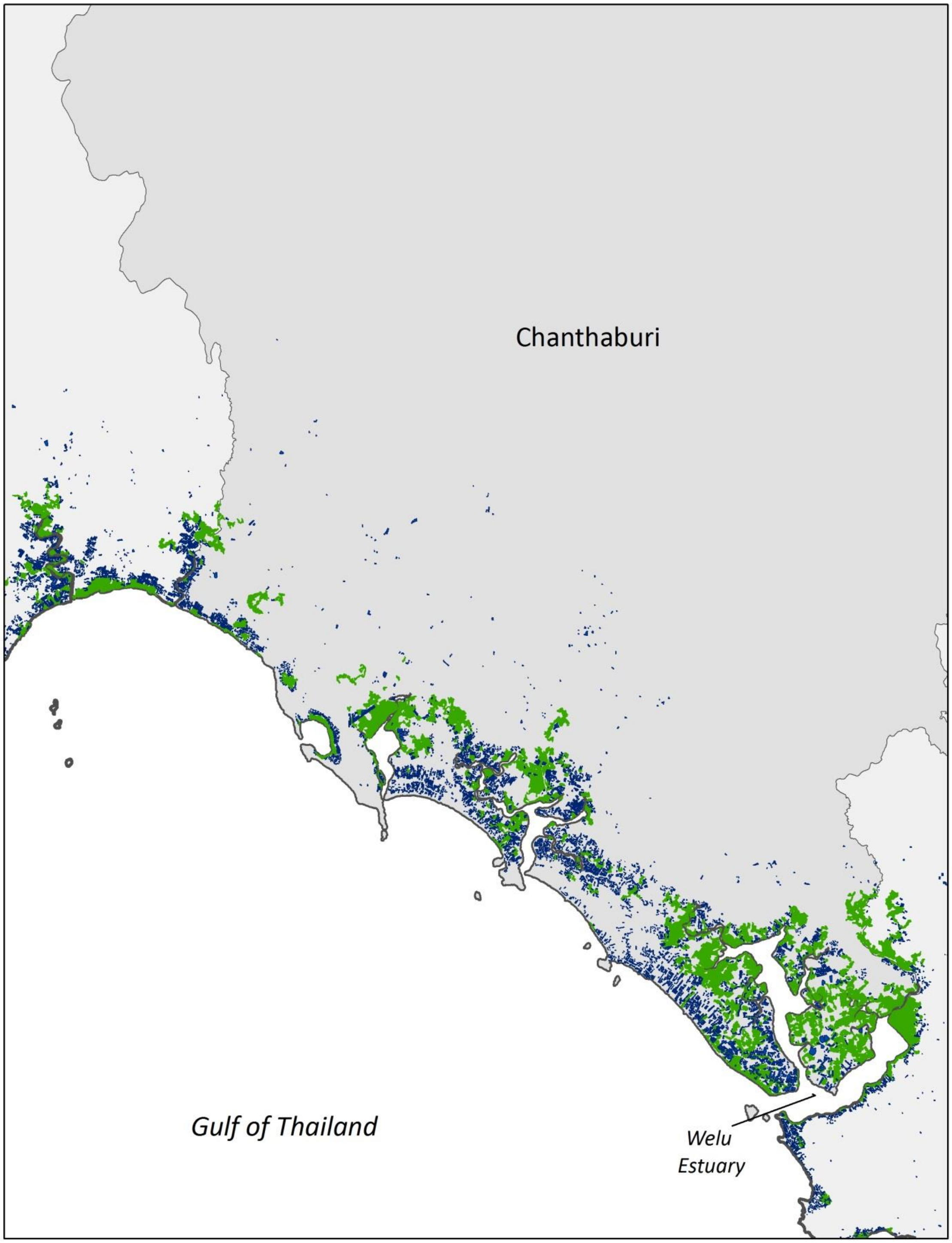

Figure 9 - Shrimp farms (Blue) and Mangroves (Green) in Chanthaburi

portions of the peninsula to the southwest of Welu estuary are returning to mangrove cover, although many ponds still remain.

As mentioned, by 1990 the industry had already been established in Chanthaburi province, and many of the ponds built by that time were in historic, pre-1970 mangrove areas. While mangrove forests did remain, many were segmented and continued to be over the next twenty-three years. By 1990, approximately 94 km^2 of mangrove remained the province, and by 2010 increased to 105 km^2. A large part of this increase was due to abandonment of aquaculture and surrounding infrastructure.

CHAPTER V

DISCUSSION

The objective of this research is to show the importance of understanding how policy and technology can affect land use by specifically documenting shrimp farm growth in Thailand at a resolution not yet performed at a national scale. Our analysis reveals the diversity in the way shrimp farms developed across different regions of Thailand. This diversity was produced by the timing of the arrival industry to these regions. The technology available and the laws governing land use played an important role in the spatial patterns in different locations, both when shrimp farming arrived and how it developed afterwards.

Technology influenced land use change patterns resulting from shrimp farming in two major ways. The first relates to the technology that facilitated the transition from extensive to intensive farming.. A large portion of ponds which exist in historic mangrove areas were already established at the beginning of the shrimp boom at the end of the 1980's, and are mostly large, extensive shrimp ponds. In this sense, the development of intensive shrimp farming methods allowed the industry to experience geographic and economic growth while keeping new farms out of mangrove forests. Intensive aquaculture relies less on the tide to bring wild shrimp in or replenish water supply, and can be built further inland. This was evident in our analysis. In some areas on the Andaman coast, which had no aquaculture ponds before 1990, virtually every pond was built off the edge of mangrove forests on the landward side. This was especially true during 1990-2000. This observation is likely due to the development of intensive aquaculture technologies. Shrimp farms were new to the area at this time, and as they did not rely on the tide to replenish pond water, farmers were able to build infrastructure outside of the mangroves. These farms still relied on the mangroves for water exchange, but could be built further inland and thus avoid replacing mangroves to a large degree.

Farms on the Andaman coast arrived later and were more likely to be small and intensive farms. The large, mangrove lined estuaries and rugged landscape with striking karst features allowed for small groups of ponds at the border of the intertidal zone. Elsewhere in Thailand, regions with high numbers of shrimp farms in 1990 continued to lead the country in growth over the next quarter century. The Nahkon Si Thammarat province on the southwest coast of the Gulf of Thailand is one such place. Here, farms were more likely to be grouped together in large grids, extending inland from the coast about one kilometer. Pond expansion was generally adjacent to existing ponds. Mangroves in this region, while being as expansive as some areas on Andaman, were replaced much more frequently by shrimp ponds. Some of these were established by 1990, but a number more were built between 1990 and 2000. Chanthaburi province exhibited different spatial patterns of ponds yet. Most early ponds were large, extensive ponds built amid mangroves in estuaries of the province which fragmented the forests considerably. New ponds built in the upcoming decades were built in high density areas along the remainder of the coast, as well as continuing to be built in mangrove areas. Many small, intensive ponds directly replaced the larger, extensive ponds. While there were areas of mangrove loss in 2000 and 2013, there were also large areas of mangrove growth, generally in abandoned extensive farms. Many farms which had been abandoned due to disease across the country have been candidates for reestablishment of mangroves, both naturally and intentionally, and it seems likely this was the case here.

The second way in which technology influenced land use change patterns resulting from the shrimp farm industry is through response to disease. While technological advances and new policies facilitated successful growth of the shrimp farm industry, it also led to the prevalence of disease that has influenced the spatial distribution of shrimp farms. While there are many factors that influence why and where shrimp farms are built, two general competing factors can be considered. First, farmers who encounter disease would often abandoned their farm and rebuild a pond elsewhere, a process which would repeat itself as often as every two years during the early 1990's (Walker & Mohan, 2009). Advancements in shrimp pond growing methods, such as the development of SPF shrimp and better water treatment, would allow ponds to operate for longer periods of time and not need to be replaced as often. However, it is likely the increased profitability of a pond due to these same technologies would allow farmers to expand production to other ponds. The relationship between these two forces is poorly understood, especially when considering geographic variability in pond construction patterns. Our methodology likely underestimates ponds that are abandoned for the long term or permanently, and cannot address this question adequately. However, it does agree with previous research that finds abandoned ponds as good candidates for reestablished mangrove forests, especially extensive ponds that usually exist in intertidal zones. This can be seen especially well in the Chanthaburi example. Data in this province provide an example of the industry's struggle with and response to disease. Here intensive ponds were growing at an increasing rate by 2013. While many abandoned extensive ponds are being slowly repopulated by mangrove forests, others were replaced by dense arrangements of intensive aquaculture. These industrial farms reflect the success and expansion of the industry.

The most evident impacts of government policies on land use change patterns resulting from the shrimp farm industry is the amount of mangrove forest lost to shrimp farms. The data from the 1990 survey revealed a large number of shrimp farms in mangroves, most notably in the Bay of Bankok. The number of new farms in mangroves declined in the 2000 survey in response to national policy aimed to reduce mangrove loss, even though this policy was not fully enforced and was repealed for one year during 1996. There was minimal change in the number of new farms in mangroves in the 2013 survey, exhibiting that conversation policies were likely effective. This observation counters previous findings in the literature that signals an emphasized role of aquaculture in the loss of mangrove forests, with some estimates citing that worldwide shrimp farming is responsible for to 50% of forest loss (Kuenzer et al., 2011), and 40% of forest loss in Thailand (Giri et al., 2008).

In addition to influencing the location of new shrimp farm development, government policy most likely facilitated the increase in the number of new shrimp farms that occurred between the 1990 and 2000 survey by changing the definition of what constitutes legal shrimp production in Thailand. This policy, coupled with tax incentives and other measures aimed at growing the industry, helped to fuel the expansion of farms across the country and to maintain a resilient industry that could efficiently address disease outbreaks.

These observations lead to the finding that the influences of policy and technology on land use change patterns resulting from the shrimp farm industry in

Thailand are inherently intertwined. Unraveling how policy and technology drive land use change cannot be accomplished separately as policies are often developed as responses to technological innovations, such as the curbing of mangrove loss when the number of shrimp farms increased due to intensification, or broadening the legal definition of harvestable shrimp. If Thailand wants to protect mangroves as a natural resource, it must respond quickly legislatively to new technologies and outbreaks of disease, as well as learn from its land use history. With the emergence of EMS, Thailand must evaluate how land use change is likely to occur, and what it can do to curb unnecessary new pond growth into environmentally sensitive areas. Encouraging sustainable shrimp aquaculture, such as those discussed by Giap et al. (2010) and Matsui et al. (2014) would be advantageous in curbing disease outbreak while protecting environmentally sensitive areas.

CHAPTER VI

CONCLUSION

The shrimp farm industry is, and will continue to be, a large part of the Thai economy. The tradeoffs between environmental degradation and industry growth will persistently drive where shrimp farms are developed and the quantity of new farms over time. A sustainable shrimp farm industry is able to balance the needs of economic growth with protecting and Thailand's most valuable environmental services. The contributions of this research were facilitated by the fine scale data produced by the digitization of all shrimp farms in Thailand during three time periods. Previous studies in this region have examined how land use changes by area, rather than by individual pond. By using individual farm data I was able to uncover how government policies and technology influenced land use change over the past twenty-five years. Future work in this area should focus efforts on how the recent outbreak of EMS has impacted land use on the Thai coast, and how this change differs from previous disease occurrences, especially that of white spot syndrome. Learning how different disease management techniques and responses influence the landscape can help Thailand prepare for future land use plans.

Furthermore, this study provides novel analysis that includes coastal shrimp farms that exist away from mangroves. Although these areas are often understudied in the literature, they are crucial to the shrimp industry as over 90% of ponds on the Gulf of Thailand are more than two kilometers from a coastal mangrove forest. These farms are not absent of ecological concern, however. Shrimp farms outside of mangroves can still be responsible for the spread of disease to both other farmed shrimp and wild shrimp, and can contaminate nearby ocean water with pesticides, fertilizer, and antibiotics added during the rearing process if effluent is not properly treated. Salinization of land is also an often cited concern (Flaherty et al., 2000), as it can be difficult to convert ponds to an agricultural land use. Furthermore, shrimp farm development far from mangroves can still affect how mangroves are destroyed or preserved. For example, emergence of disease in one area of the country might encourage the construction of new farms in previously untouched areas like the large mangroves along the Andaman Sea.

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