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The Expansion of Shrimp Farms in the Gulf of California and Potential for Restoration to Support Migratory Waterbirds

Miles Scheuering
University of Montana, miles.scheuering@umontana.edu

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Miles Scheuering, Wildlife Biology Program (Senior), Avian Science Center, W.A. Franke College of Forestry and Conservation, University of Montana, 32 Campus Drive, Missoula, MT, 59812, USA.
E-Mail: miles.scheuering@umontana.edu

Abstract

Wintering and stopover areas provide crucial habitat for migratory birds yet are often understudied. The estuaries of Sonora and Sinaloa on the Gulf of California in Mexico provide critical wintering and stopover sites for migratory waterbirds in the Pacific Flyway. Shrimp farms are the greatest threat to these areas and their full impact is not well understood but they provide poor habitat for waterbirds. A significant portion of existing farms may be abandoned based on a disparity between active area reported by the Sonora and Sinaloa state commissions and observed area based on remote sensing. Abandoned farms represent potential area for restoration. This project seeks to understand the area abandoned to estimate area available for restoration. To quantify the area of shrimp farms I digitized and classified them by wetland characteristics using recent satellite imagery. I then used imagery from 1984 to present to determine when farms were constructed. I modeled monthly water extent in shrimp farms using spectral mixture analysis in Google Earth Engine. Shrimp farm area has increased steadily since 1990 with an average growth rate of 10% per year. Despite this increase, abandoned area has stayed stable at ~8% of total farm area. This level of abandonment means restoration will not be cost-effective, thus increasing the threat to waterbirds. If similar loss of wintering habitat occurs throughout the flyway, waterbird populations will be severely impacted. Promoting sustainable development and identifying sites where protection and restoration has the greatest effect will be necessary to maintain healthy waterbird populations in the future.

Introduction

Migratory birds spend most of their time on breeding and wintering areas, but their entire range also includes the area they use to move between breeding and wintering areas. The geographic area for a group of related species from their breeding to wintering areas, including sites where they rest and forage (i.e., stopover areas) is a flyway (Boere and Stroud 2006). A flyway can exist at the continental or multi-continental scale. Delineations of flyways exist worldwide (Boere and Stroud 2006) based on generalized overlaps of multiple migratory birds. Management and conservation efforts correspond to these flyway delineations to focus on individual or similar populations. For many migratory species, information on the breeding areas has received the most research attention. However, areas used during non-breeding periods can have similar impacts on population trends.

Wintering habitat plays a significant part in the annual life cycles of migrating birds (Marra et al. 1998, Norris et al. 2004, Sherry et al. 2005). The theoretical foundation is the Winter-Food Limitation Hypothesis (WFLH) that states winter habitat quality and availability drive population demographics in migratory birds (Sherry et al. 2005). For example, waterfowl body condition correlates with winter habitat conditions in many species (Heitmeyer 1988, Lovvorn 1994, Thomas 2004, Moon et al. 2007, Reinecke 2017). In turn, body condition affects survival, leading to cascading effects across the life cycle (Bergan and Smith 1993, Moon and Haukos 2006).

In the Pacific Flyway, the northwestern coast of Mexico serves as an important winter and stopover area for migratory waterbirds. Estuaries in this region are highly productive wetland resources that support the energetic demands of wintering waterbirds. They hold 35% of all wintering waterfowl and 59% of all wintering shorebirds present in Mexico (USFWS 2006, Morrison and Ross 2009). During droughts in the western United States, the relevance of these estuaries increases because they provide stable habitat conditions and serve as refugia for numerous species. These estuaries contain a diversity of vegetation and wetland types such as mangroves, saltmarshes, mudflats, freshwater wetlands, shallow lagoons, and deep bays. Mangroves are small trees or shrubs that grow in coastal saline water and form extensive groves in the intertidal zone. They are foundational species within estuarine systems because they influence various ecosystem processes, including hydrology, food webs, and nutrient cycles (Ellison et al. 2005). Saltmarshes are areas of dense, salt-resistant forbs and grasses that are regularly flooded by tides. They have high productivity and export nutrients to adjacent habitats (Valiela et al. 2002), while directly providing areas for feeding and roosting (Hughes 2004). Mudflats are areas of sediment exposed by tides and are heavily used by shorebirds. Freshwater wetlands occur on the edge of estuaries, in areas with freshwater input from rivers or agriculture. Shallow lagoons separate intertidal areas from deeper bays and provide habitat for wading bird. These vegetation and wetland types form heterogeneous systems that provide habitat for many species of waterbirds. Large estuaries in this region are classified as priority sites by at least one organization. For instance, eight estuaries are designated as being of international important by the Ramsar Convention. Four of these sites, and one additional site, are designated by the Western Hemisphere Shorebird Reserves Network (WHSRN).

Because estuaries are driven primarily by tidal fluxes, shifts in temperature or precipitation resulting from climate change will have less impact than anthropogenic development. Shrimp farming is an anthropogenic development that threatens estuaries. In Mexico, shrimp farming began in the 1980s with extensive development in the 1990s. The Gulf of California is estimated to have 97% of the shrimp farms in Mexico (Páez-Osuna et al. 2003). Of shrimp farms present, most are semi-extensive, with each pond 1-5 ha up to 30 ha, or extensive, with larger, more irregularly shaped ponds (Briggs n.d.). Shrimp production cycles are four to five months, with one to two completed each year (Briggs n.d.). Individual ponds are drained between production cycles to sanitize ponds, reducing disease risk (Briggs n.d., Cuellar-Anjel et al. 2010).

Shrimp farms most often replace salt marshes and mudflats. These natural heterogenous estuaries driven by tidal fluxes are altered to a series of shallow, monotypic saltwater ponds. They differ greatly from the salt marshes and mudflats they replace, and do not provide suitable habitat for waterbirds. The construction of shrimp farms is often completed within a year, allowing rapid expansion, and preventing birds from adapting to habitat changes. The infrastructure, such as roads, further fragments and leads to habitat loss for waterbirds. In terms of impacts to ecological processes, water pollution from shrimp food and antibiotics is the most significant threat of shrimp farms (Páez-Osuna et al. 1997, DeWalt 2000, Barraza-Guardado et al. 2013).

Less known is the impact of the abandonment of farms. Farms cease operation when they reach the end of their operating lifespan, lack financial support, or experience disease outbreaks. Farms are left as permanently flooded or dry. The area of abandon farms is expected to increase as well, because farms will naturally reach the end of their operating lifespan.

In the Gulf of California, the potential area for shrimp farm development is 236,000 ha (De la Lanza-Espino et al. 1993). As of 2020, there is ~122,000 ha of shrimp farms, suggesting that the area of farms could double. Identifying restoration activities is critical to maintaining the wetlands for migratory waterbirds, given the potential for continued anthropogenic development.

This project aims to quantify the present area of active and abandoned shrimp farms in the Gulf of California. In addition, this project seeks to quantify the spread of shrimp farms over time, including the date of new farms. I predict that the area of abandoned farms increases proportionally with the construction of new farms.

Methods

My study area included coastal estuarine systems in the states of Sonora and Sinaloa, Mexico (Figure 1). The estuaries include mangrove, saltmarsh, mudflats, shallow lagoons, deep bays, adjacent freshwater wetlands, and brackish water areas, which support a large abundance of waterbirds within the Pacific Flyway. Sonora and Sinaloa support up to half of all wintering shorebirds in the Pacific Flyway, with Ensenada de Pabellones and Bahía de Santa María accounting for one-third (Engilis et al. 1998). This area holds 78% of wintering shorebirds in Mexico (Morrison and Ross 2009). Ensenada de Pabellones also supports 10% of all waterfowl wintering in Mexico (Ducks Unlimited 2001), including 1.5 million northern pintail (*Anas acuta*). Of the five WHSRN sites, one is classified as hemispheric importance (Bahía de Santa María), two of international importance (Bahía de Tóbari and Ensenada de Pabellones), and two of regional importance (Playa Ceuta and Bahía de Lobos). The high waterbird diversity and the high density of shrimp farms provide the framework to understand how active and abandoned shrimp farms influence waterbirds.

I developed a spatial inventory of water features within estuaries from Estero Lobos in Sonora to Bahia de Ceuta in Sinaloa during Fall 2020 (Figure 1). I used wetland classes: tidal, shrimp, wet agriculture, freshwater wetland, and mangrove to categorize features based on the satellite imagery. Areas were classified as wet agriculture if there were wetland features in the field and for agricultural runoff. Tidal is a combination of mudflats and salt marshes. I used 2020 Google and Bing imagery tiles in QGIS because they differed in the timing of the imagery as well as contrast, which affected the visibility of water.

I classified the year that each portion of a shrimp farm was constructed using satellite imagery from Landsat 5 Thematic Mapper (1984-2011) and Landsat 8 Operational Land Imager (2013-2020). Landsat coverage for Mexico before 1990 was limited. Thus, I only classified one year prior to 1990. I took the median value for each pixel for each year and used the resulting image as the base layer. I then delineated within the existing shrimp farm polygons and assigned the year to a new attribute. When water was first visible in the imagery, I classified this year as the initial date of the shrimp farm.

I monitored shrimp farm activity by calculating seasonal surface water from 1990 to 2019 using satellite imagery from Landsat 5 Thematic Mapper (1984-2011) and Landsat 8 Operational Land Imager (2013-2020). There is a gap in satellite imagery in 2012, preventing surface water calculation for that year. Based on an approach from Donnelly et al. (2019), I calculated surface water extent with constrained spectral mixture analysis (B Adams and R Gillespie 2006) that provides proportional estimates of water within a 30 m x 30 m pixel grid (Jin et al. 2017). The approach allows an accurate depiction of water extent when part of the grid cell has visible surface water due to obfuscation from vegetation (Devries et al. 2017), common in shallow wetlands in arid regions (Jolly et al. 2008). Parts of the image containing cloud, cloud shadow, snow, and ice were masked out with the Landsat CFMask band (Foga et al. 2017). All unmasked visible, near infrared, and short-wave infrared pixels from Landsat 30 m were included except for the Landsat 8 coastal aerosol band.

I extracted unique spectral endmembers for each satellite image classified to serve as training points. Training site locations were selected from areas of homogenous water, wetland vegetation, upland, shrub, and soil land cover types. Spectral endmembers were collected for water based on image masks created from 99th percentile normalized difference water index values (Mcfeeters 1996). Mask extents were within adjacent areas of ocean. Wetland vegetation endmembers were collected with a similar approach, using normalized difference vegetation indices (Box et al. 1989). Because spectral mixture analysis requires minimal training data (B Adams and R Gillespie 2006), upland, shrub, and soil endmembers were generated from a few static plots. Upland plots contained dry areas with grass or forbs covering most of the ground. Soil plots were in dry areas with minimal vegetation. Shrub plots used areas of dense brushy vegetation with low vegetative productivity and high soil exposure.

Surface water extent was calculated for all months of the year for a rolling five-year period. Based on the five-year mean, a reducer was applied to count the number of months that each pixel was wet. This count was averaged by polygon, resulting in a mean number of months each polygon was wet. Shrimp farm activity was classified based on the length of production cycles, with a period of 4-10 wet months being considered active (based on a cycle length of 4-5 months and 1-2 cycles per year). Farms that did not meet the active criteria were considered inactive. I obtained annual hectares (ha) of shrimp farm activity reported by the state commissions of Sonora and Sinaloa (COSAES 2019, CESASIN 2020). I then compared the state commission values to the area I calculated from satellite imagery.

Results

The total area of shrimp farms in Sonora and Sinaloa Mexico that I classified is 122,447 ha (Figure 2). The reported area for Sonora and Sinaloa by the state commissions is 77,222 ha (Figure 2). This leaves 44,225 ha of shrimp farms not classified as active by the state commissions. Within the study area, there are 97,856 ha of farms. In priority areas there are 66,918 ha, or 15% of total wetland area (Figure 3).

Shrimp farms production started ~1990 in both states (Figure 4, Figure 5). In Sinaloa there was a steep increase in shrimp farms from 1990 to 2000, followed by a stable level over the next ten years, with a steady increase after 2010 and a steep rise in the last few years (Figure 4). In Sonora there was a steady increase initially, followed by a steep increase from the late 1990s to the mid-2000s, and another steady increase (Figure 5). The average growth rate across the study area is 10% per year.

For most years, the proportion of abandoned shrimp farms has been low (Figure 6, Figure 7). From 1990 to 2000 in Sinaloa, the area of abandoned farms was high in relation to overall area at 5000 to 7000 ha abandoned compared to 7500 to 13,500 ha in total. The average area abandoned during this period was 28% of the total. Abandoned area subsequently declined to around 2000 ha and stayed stable, while active area increased (Figure 6). From 2000 to 2019, abandoned area was 8% of the toal. In Sonora, the area abandoned started around 500 ha or less, before increasing to roughly 1800 ha, and staying stable. Average area abandoned was 7%.

Discussion

The total area of shrimp farms accounts for a significant portion of estuaries in the sates of Sinaloa and Sonora in Mexico. Within priority areas shrimp farms are comparable in hectares to freshwater and tidal wetlands (Figure 3), both important habitats for waterbirds. Priority areas are the most important for waterbirds and should receive the most protection, yet they contain

55% of shrimp farms. The potential area for shrimp farms in this region has been estimated at 236,000 ha (De la Lanza-Espino et al. 1993), meaning the current area of farms could double. Further, my prediction that abandoned area would increase in proportion to overall area was false. Abandoned area was variable throughout but from 2000 onward, it was near or below 10% and was 8% on average across the study area.

Shrimp farms provide minimal habitat for waterbirds and do not represent a viable food resource except when they are harvested at the end of production cycles. However, this only results in conflict between waterbirds and farmers trying to protect their harvest. Because they do not provide suitable habitat, the development of farms is correlated with a decline in waterbird abundance in the Gulf of California (USFWS 2006). The proportion of shrimp farms in priority areas threatens waterbirds because they are the most important areas of habitat. Continued degradation of these sites will cause population level declines in waterbirds if there are no suitable sites elsewhere. The northwest coast of Mexico already serves as a refuge for waterbirds during drought years in the western United States. As shortages and variability in availability of water becomes more common due to climate change, wintering areas in the United States may cease to be viable, putting more pressure on estuaries in Mexico. With the potential for the area of shrimp farms to double, waterbirds may not find suitable wintering habitat in northwestern Mexico or the southwestern United States, leading to population declines across the flyway through direct mortality or decreases in reproductive rates.

The higher than expected number of active farms means pollution and water quality are still significant issues. Even abandoned shrimp farms may have some passive release of pollutants. Therefore, shrimp farms can disrupt or deteriorate nearby habitats. More research is needed to understand the area of effect for pollution from shrimp farms and the impact it has on waterbirds.

While the area abandoned is low, there is still a significant disparity between the active area reported by state commissions and the observed area from satellite imagery. While the reported area is from 2018 and 2019, and the observed area is from 2020, this difference would not account for the full 45,225 ha because the highest growth per year is ~5000 ha. It is possible that states report only the ponds of the shrimp farms and not associated infrastructure. It is also possible that there is a disconnect in the reporting system, with either farms or commissions not fully reporting active area. As a result, more farms may be abandoned than estimated by this study, or there may be widespread corruption within the reporting system.

Restoration or protection is needed in these areas. There is potential to restore abandoned shrimp farms based on how they have responded to dikes being breached. When this occurs through storm damage, or wear over time, tidal connectivity is reestablished, and vegetation can recolonize. This means that area abandoned acts as an indicator for areas where there is potential for restoration. Organized restoration efforts could restore estuarine habitat using dike removal, provided there is suitable abandoned area. However, the current area abandoned is low, and ponds are widely distributed, making restoration unlikely to succeed. While restoring ponds may improve habitat in small areas, it would not be cost effective because restored areas would be fragmented, and the total restored area would remain low.

Regulation of future development shows more promise. Shrimp farming is a profitable and growing industry, so limiting construction of new farms requires economic considerations. However, research has indicated that super-intensive techniques are viable (Briggs n.d.). Super-intensive farms are equivalent to fish hatcheries and have higher production rates, without water exchange, and with a much smaller footprint. If this type of production can be incentivized, then the demand would be met while limiting destruction of estuaries.

Protecting waterbirds in this region will require an understanding of the relative importance of each site, and the viability for restoration and protection. Areas that are the most important to waterbirds may not be easy to conserve, so understanding both will allow action in the areas that can provide the greatest benefit for the effort involved.

Estuaries in Sonora and Sinaloa are a critical component of wintering habitat for waterbirds in the Pacific Flyway. In addition to existing shorebird and waterfowl populations that winter in this region, it provides a refuge from drought for birds wintering in the southwestern United States. Shrimp farms cause significant issues through pollution and habitat destruction, and with only half of the viable area in this region developed, the area of farms will continue to grow. Regardless of the viability of shrimp farm restoration, this region must continue to receive protection. Such will require international collaboration and continued research to understand possibilities for conservation.

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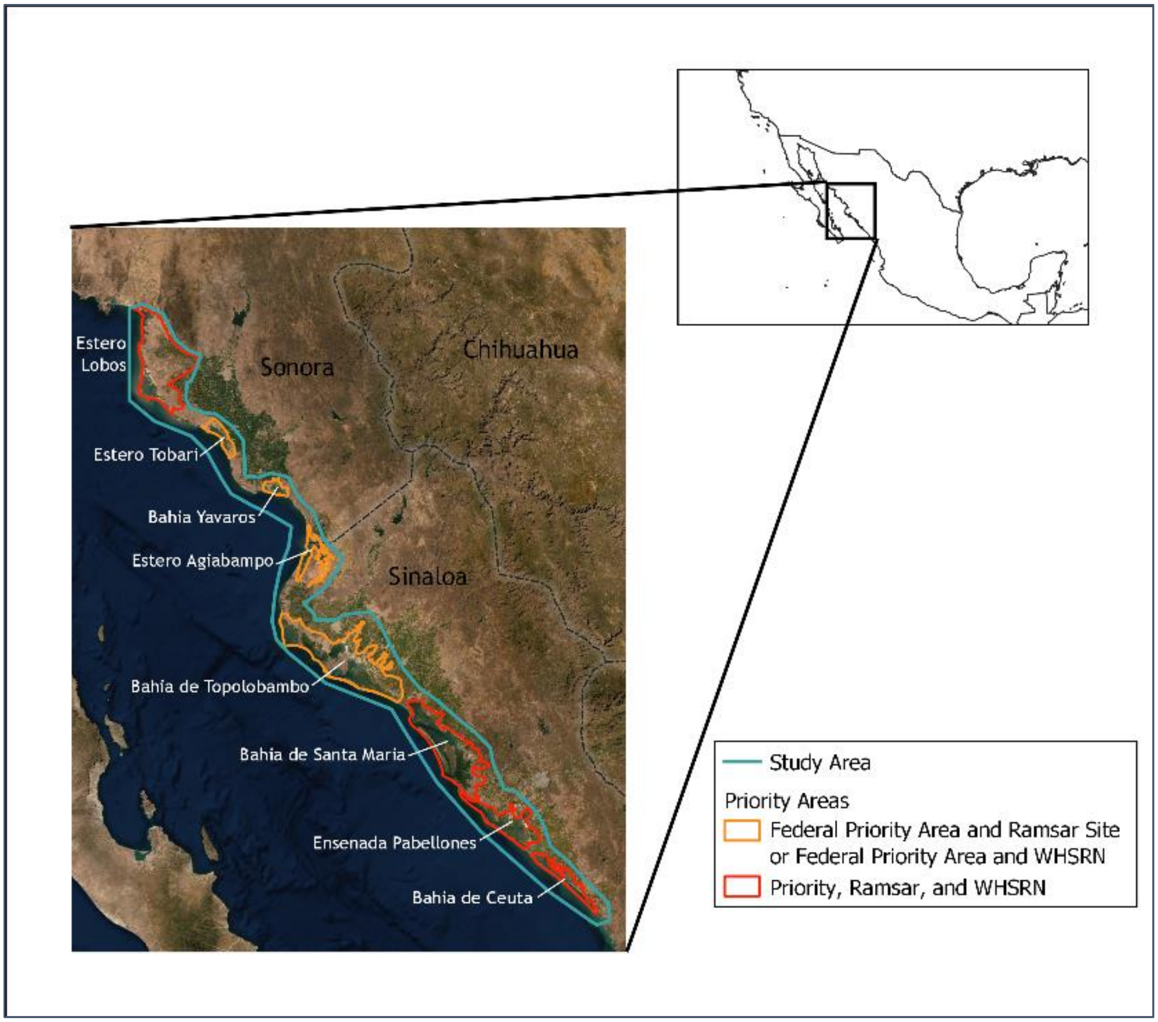

Figure 1. Priority Sites in study area.

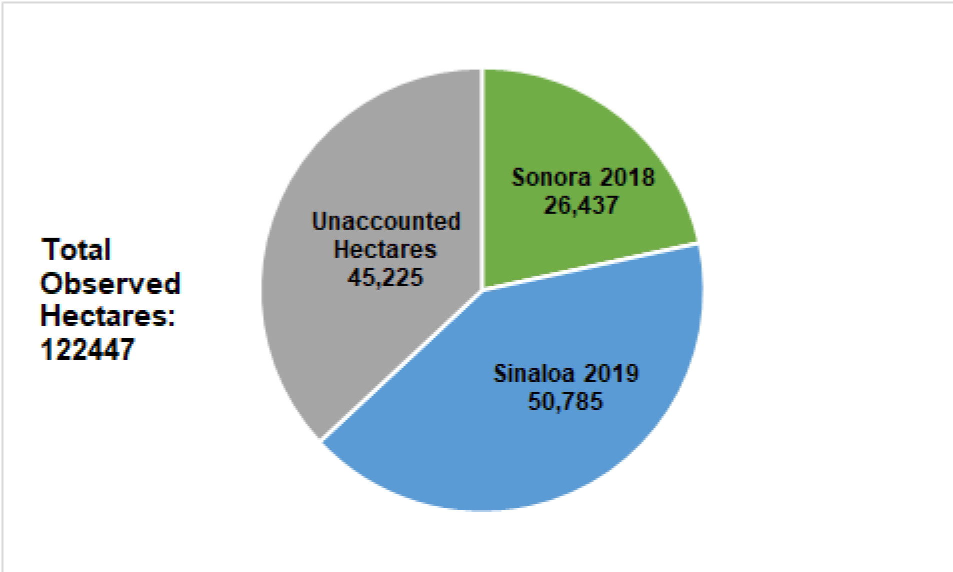

Figure 2. The proportion of shrimp farms reported by the Sonora and Sinaloa state commissions compared to shrimp farms I classified.

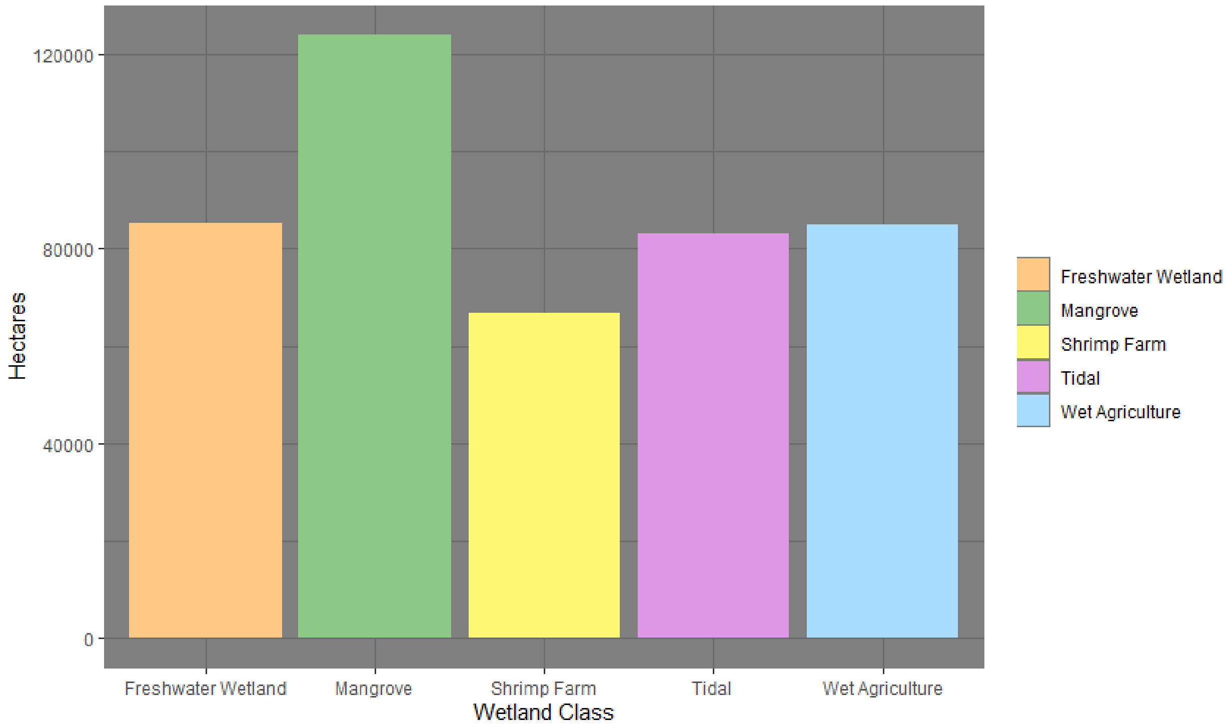

Figure 3. Area of wetland classes in priority sites in study area.

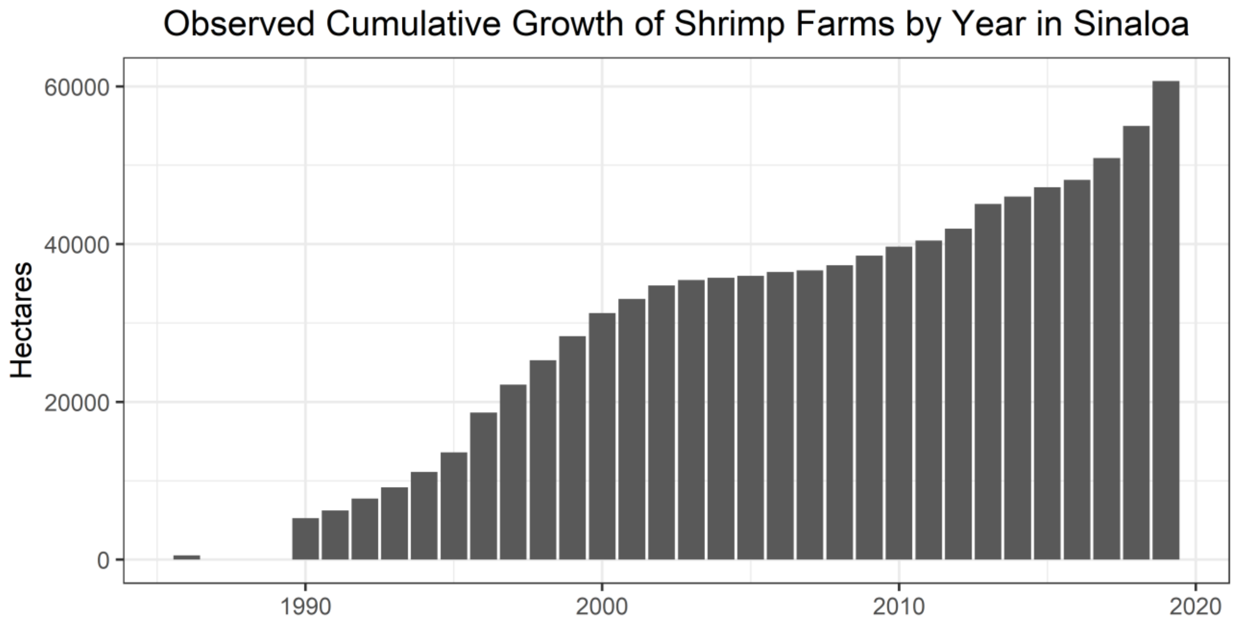

Figure 4. Cumulative growth in hectares of shrimp farms in Sinaloa from 1990 to 2019.

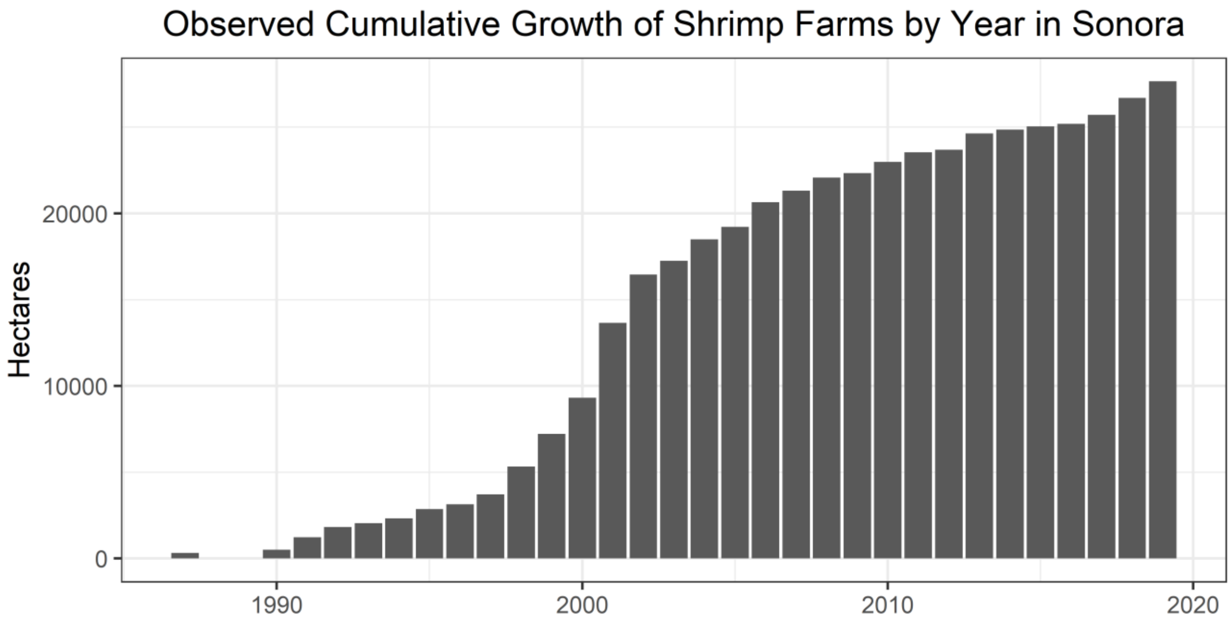

Figure 5. Cumulative growth in hectares of shrimp farms in Sonora from 1990 to 2019.

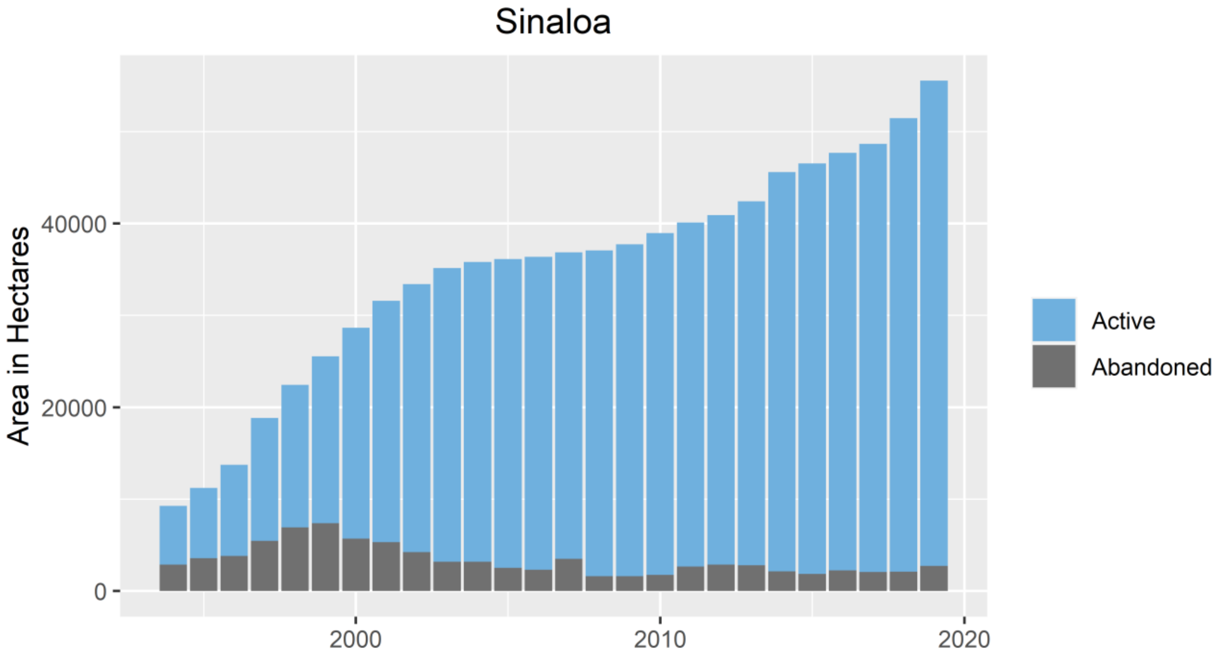

Figure 6. Area of abandoned shrimps as a proportion of total shrimp farm area in Sinaloa from 1990 to 2019.

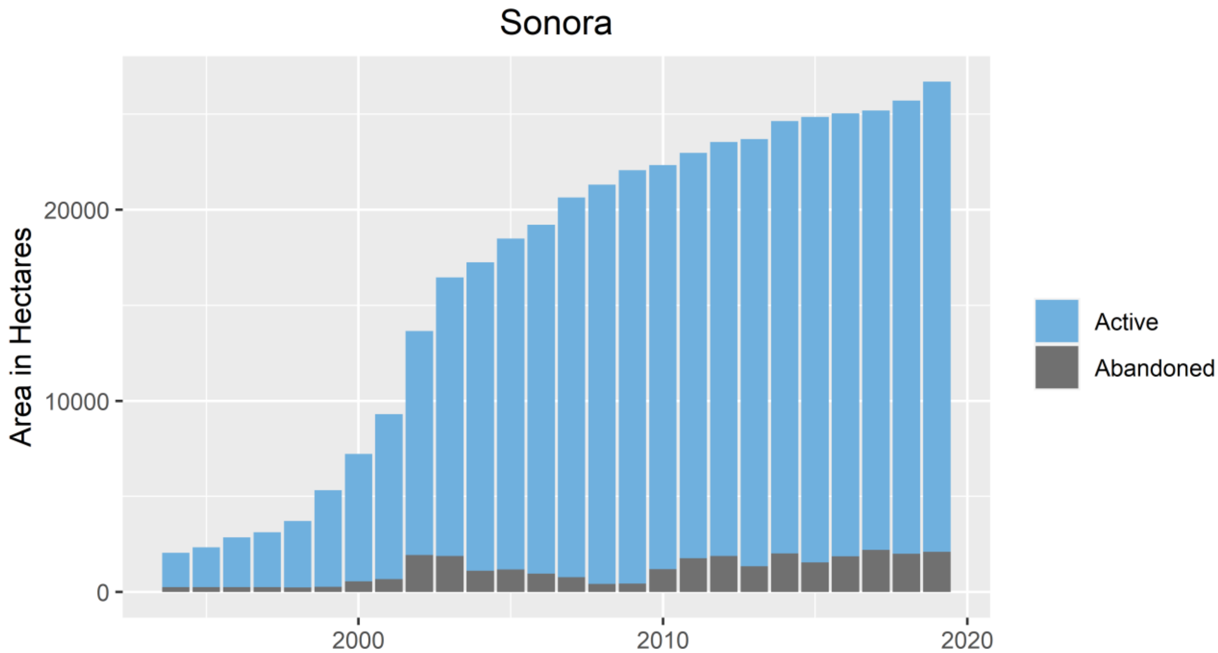

Figure 7. Area of abandoned shrimps as a proportion of total shrimp farm area in Sonora from 1990 to 2019.