Article

Remote Sensing-Based Assessment of the Long-Term Expansion of Shrimp Ponds Along the Coastal and Protected Areas of the Gulf of California

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Abstract: Shrimp farming has expanded over coastal areas in Mexico, particularly in the protected regions of Sonora and Sinaloa. Over the past 30 years, the economic activity associated with these farms has grown so much that the amount of shrimp produced in these ponds now exceeds that harvested from traditional shrimp fisheries. Establishing shrimp ponds has led to significant land changes. The construction of these ponds has fragmented local ecosystems, resulting in permanent alterations to areas such as flood-plains, mangrove forests, and dunes, many of which are protected zones. This study aimed to investigate the long-term growth of shrimp farms from 1993 to 2022 and their impact on land-use changes in surrounding ecosystems, focusing on protected areas in the Sinaloa and Sonora coastal regions. We analyzed Landsat images using the Google Earth Engine platform. Our findings indicate that shrimp farm development over the past three decades has been extensive, with protected areas experiencing fragmentation and changes. Remote sensing and platforms like Google Earth Engine enable the effective monitoring of these spatiotemporal changes and their impacts, helping to identify the most affected areas.

Keywords: Ramsar sites; biosphere reserves; land cover change; remote sensing; Google Earth Engine

1. Introduction

Shrimp farms in the Gulf of California currently occupy a significant portion of the Mexican coastal areas in Sonora and Sinaloa. During the last few decades (1993 to 2022), this economic activity has surpassed that of the shrimp fisheries in these regions [1–28]. Several authors [29–32] have already determined the impacts of shrimp ponds on coastal ecosystems to various environmental issues, including water pollution from organic matter, heavy metals, bacteria, and viruses. The contaminants enter the coastal ecosystem through the farm's water exchange. Crop cycles and the periodicity of water exchange regulate the volume and timing of these discharges. Additionally, the farms' latitudes influence the water exchange; those in the northern region experience greater evaporation and more significant water exchange than those in the southern region [33]. Although Mexican environmental legislation prohibits the expansion of shrimp farms due to the

resulting extensive loss of natural habitats, the impact on natural vegetation, and the pollution of coastal and marine habitats, it has been observed even in protected areas along the Gulf of California.

Remote sensing is a powerful tool for analyzing changes in different types of land cover, including shrimp farms [34,35]. Furthermore, remote sensing can help evaluate the entry of contaminants, such as nitrogen and phosphorus, in farming activities [36]. It can also help monitor the effects of farm growth in coastal zones, particularly in areas without field measurements, such as the Gulf of California.
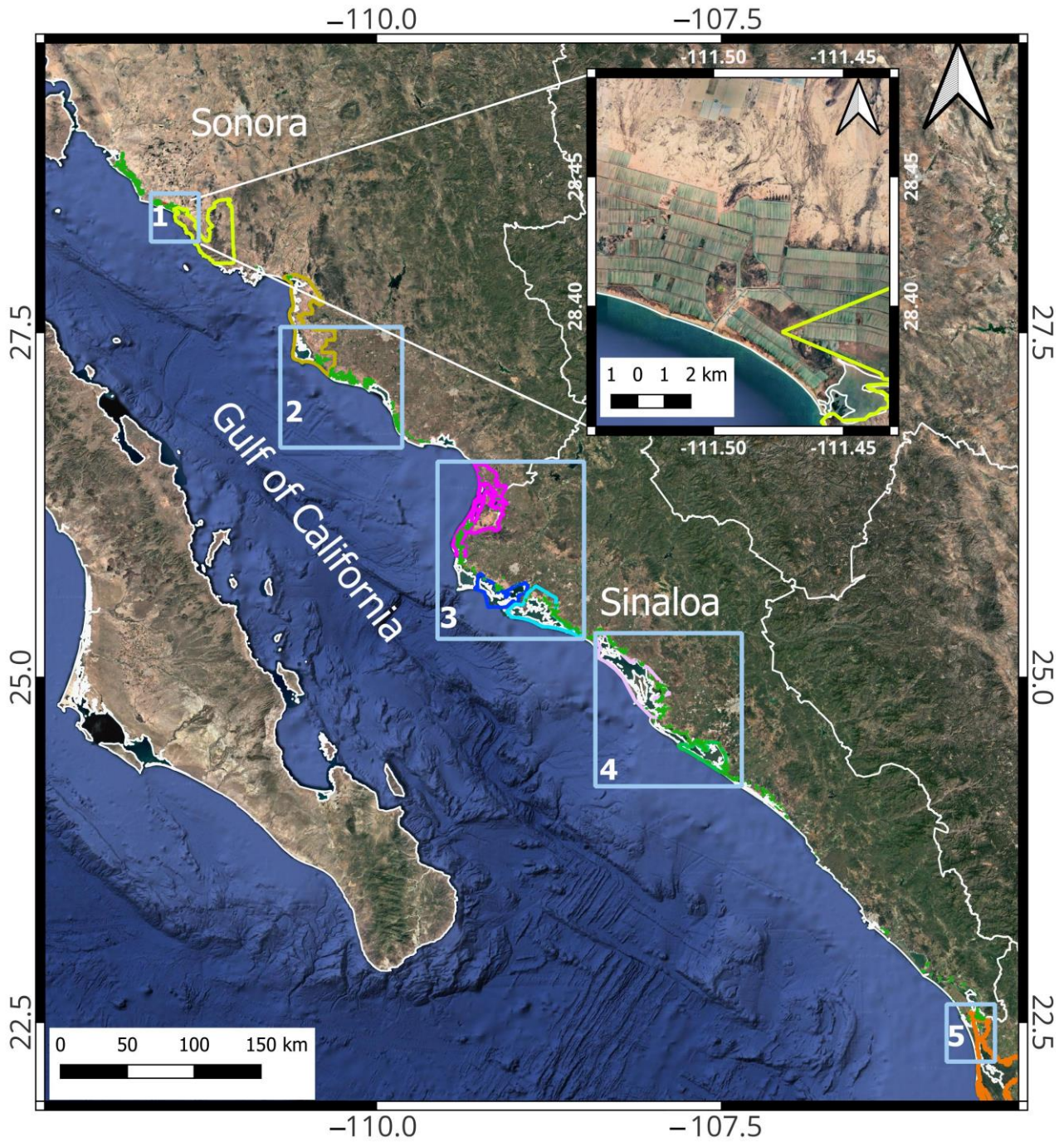
This manuscript addresses aquaculture development over areas cataloged as Biosphere Reserves or Ramsar sites. The objective of this study was to investigate the long-term growth of shrimp farms (from 1993 to 2022), their impact on land-use changes generated in the surrounding ecosystems located in the coastal and protected areas of the Gulf of California, and how researchers and decision-makers can apply tools such as Google Earth Engine [37] for quick estimation and knowledge of farm activities and their effects.

2. Materials and Methods

2.1. Study Area

Located east of the Gulf of California (northeastern Mexico), the study area (Figure 1) comprised the coastal areas of Sonora and Sinaloa. These states have a coastline of 1848 km [38]. The area's extreme coordinates are 31.559° N, 115° W and 23.6° N, 106.61° W. Our study analyzed the expansion of shrimp farms inside and outside the Biosphere Reserves Cajón del Diablo (box 1 in Figure 1) and Marismas Nacionales (box 2 in Figure 1). Marismas Nacionales was decreed in 2010 [39] and is also a Ramsar site. Its management program divided the reserve into ten areas within two core zones. The area near Sinaloa, named the "subzone of human settlement El Roblito" allows for different human activities, including aquaculture. The Biosphere Reserve Cajón del Diablo in the Sonora State was decreed in 1937 [40] and does not have a management program. Currently, the limits and polygons of this Biosphere Reserve do not appear in the data catalog or the list of Biosphere Reserves published by the Mexican Commission for the Knowledge and Use of Biodiversity [41]. However, in 2000, it was part of Mexico's Priority Regions Project [42].

Our study also included the following Ramsar zones experiencing aquaculture expansion inside and outside their limits: Complejo Lagunar Bahía Guásimas–Estero Lobos (box 3 in Figure 1) in the Sonora State; Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo, along the border of Sonora and Sinaloa; and Lagunas de Santa María–Topolobampo–Ohuira (box 4 in Figure 1), Sistema Lagunar San Ignacio–Navachiste–Macapule, Laguna Playa Colorada Santa Maria Reforma, and Ensenada Pabellones (box 5 in Figure 1) in the Sinaloa State.

Figure 1. Study area. The numbers in the boxes represent the order in which we present the results for the Ramsar sites or Biosphere Reserves where we analyzed pond expansion. Boxes 1 to 3 do not cover the entire protected area, as we focus solely on the sections that contain shrimp ponds. The figure provides a close-up view of the pond areas surrounding the Biosphere Reserve Cajón del Diablo.

2.2. Satellite Data Processing

We selected images from May to October for each classified year between 1993 and 2022, concentrating on the active periods of the farms. This approach allowed us to identify the ponds that were in use without considering when they were constructed. The image processing (definition of training points by category, selection of Landsat image by date, selection of bands for training, selection of classification algorithm, and downloading of the classified image) was performed in Google Earth Engine. For the 1993 to 2010 land cover classifications, we used the averaged reflectance of Landsat 5 Surface Reflectance Tier 1, which was atmospherically corrected using the Landsat Ecosystem Disturbance Adaptive Processing System with clouds, shadows, water, and snow masks. For the 2003, 2004, 2011, and 2012 land cover classifications, we used the averaged reflectance of Landsat 7 Surface Reflectance Tier 1. For the 2013 to 2021 classifications, we used Landsat 8 Atmospherically Corrected Surface Reflectance Tier 1 using the 1 Land Surface Reflectance Code. For the 2022 classification, we used the Landsat 9 Collection 2 Tier 1 Top of Atmosphere Reflectance. Because of extreme cloudiness in certain areas, we could not estimate most of the shrimp pond areas in 2012. For this year, we obtained the areas using the equation for shrimp pond area estimation as a function of time (in years), published in [43]. This equation is the result of a linear regression (a = −7,374,695 + 3703 t, r^2 = 0.936). As shown in [43], the trend of the pond area, represented by the equation, was a continuous growth from 1993 to 2021.

We trained an algorithm based on the random forest classification [41,42] to obtain water, soil, and vegetation classes. Random forest classification implements a combination of tree predictors in such a way that each one depends on the values of a random vector sampled independently and with the same distribution for all trees in the forest, generating an effective tool for prediction. The random forest classification algorithm did not work on the pixels corresponding to areas that we masked out using the non-pond water bodies layer (coastal lagoons and permanent water bodies). We generated this mask using QGIS version 3.16 software [44]. The mask had a maximum width of 5 km from the sea to the continent, covering the shrimp farm locations. The land classification area covered an average of 1,482,936 ha. We applied another mask each year to the random forest classification to filter out temporary water bodies mixed into the farms' ecosystems and to ensure high accuracy when assessing the total shrimp pond area. A Google Earth Engine example script is linked here: https://code.earthengine.google.com/82b0944f4e414bec0b376fb2b34526ec (accessed on 28 January 2025).

We applied the methodology proposed by Olofsson et al. [45] to assess the accuracy and validate the classification results. As we did not have other reference images for the accuracy assessment, we validated the Landsat classification by taking true color and infrared composites of the same image as references. As [44] pointed out, validating the classification of Landsat images against other products of the same Landsat images is possible when no other reference images are available. As we studied the farm's expansion in the past 30 years (from 1993 to 2022), it was impossible to perform the ground-truthing. Following [44], we calculated the sample size and assigned it to the classified categories, called the sample allocation to strata by these authors. They propose to use the estimated lowest standard errors as criteria for selecting sample allocation, which can be equal, proportional, or an allocation that gives more sample units to the rare class stratum. According to these criteria, the allocation that took the class ponds as a rare class (with at least 120 sample units for it) was the most selected in the present study. The ponds class was taken as the rare class, as it had the smallest area among the three categories. Table A3 in the Appendix Section lists the standard errors of the selected sample allocation by class. We used a standard error of the selected estimated overall accuracy S(ÔN) of 0.15. The sample consisted of 400 points divided into three classes (pond, soil, and vegetation) and

distributed randomly within their polygons. As proposed in [44], we obtained the estimated area by multiplying the estimated area proportions by the total map area. Estimations of the area confidence intervals were obtained by multiplying the standard error for the estimated area (S(Ûp), the total map area, and the confidence interval error margin (1.96).

3. Results

Table 1 shows the commission and omission errors for the class ponds and the overall accuracy of the classifications. On average, we obtained 2%, 1%, and 94%, respectively, which indicates good performance. Figure 2 shows the assessed area value in the center of the 95 percent confidence intervals for each classified year (gray bars). Figure 2 also shows that the overall accuracy of the classifications by year was mostly above 90% (light brown bars). We estimated 6741 ha of active shrimp farms in 1993, whereas by 2022, the total active area of the shrimp farms was more than 102,906 ha. We observed peaks of pond area for the years 1997, 2011, 2013, and 2014, indicating an increase of more than 100% and a decrease of less than 25% for 1998 and 2010, respectively. During the studied period, the pond area increased at an annual average of 19.5% compared to the prior year. Thus, the entire area of shrimp farms grew by more than 1400% during the studied period compared to the 1993 value (see Figure 2). These results highlight the significant development of shrimp ponds over the thirty years considered in the study.

Table 1. Commission and omission errors of the pond class and overall accuracy of the land cover classification from 1993 to 2020.

Year	Ponds Class		Overall Accuracy (%)
	Commission (%)	Omission (%)	
1993	0	0	94
1994	0	0.71	96.6
1995	0	4	95.7
1996	0	0	95.3
1997	0	0.67	95.6
1998	0	1.67	95.9
1999	0	2.67	95.1
2000	0	4.23	96.8
2001	11.46	0.67	95
2002	0	0.71	95.4
2003	0	0.83	90.9
2004	0	0	89.3
2005	11.2	2	95.4
2006	15.6	5	93.5
2007	0	2	96.8
2008	0	0	94.7
2009	0	1	90
2010	0	4	94.2
2011	0	1	91.3
2012	Na	Na	Na
2013	7.5	2	89.1
2014	0	0	95.1
2015	6.3	2	96.1
2016	0	0	92
2017	0	1	94.5
2018	0	0	94.3

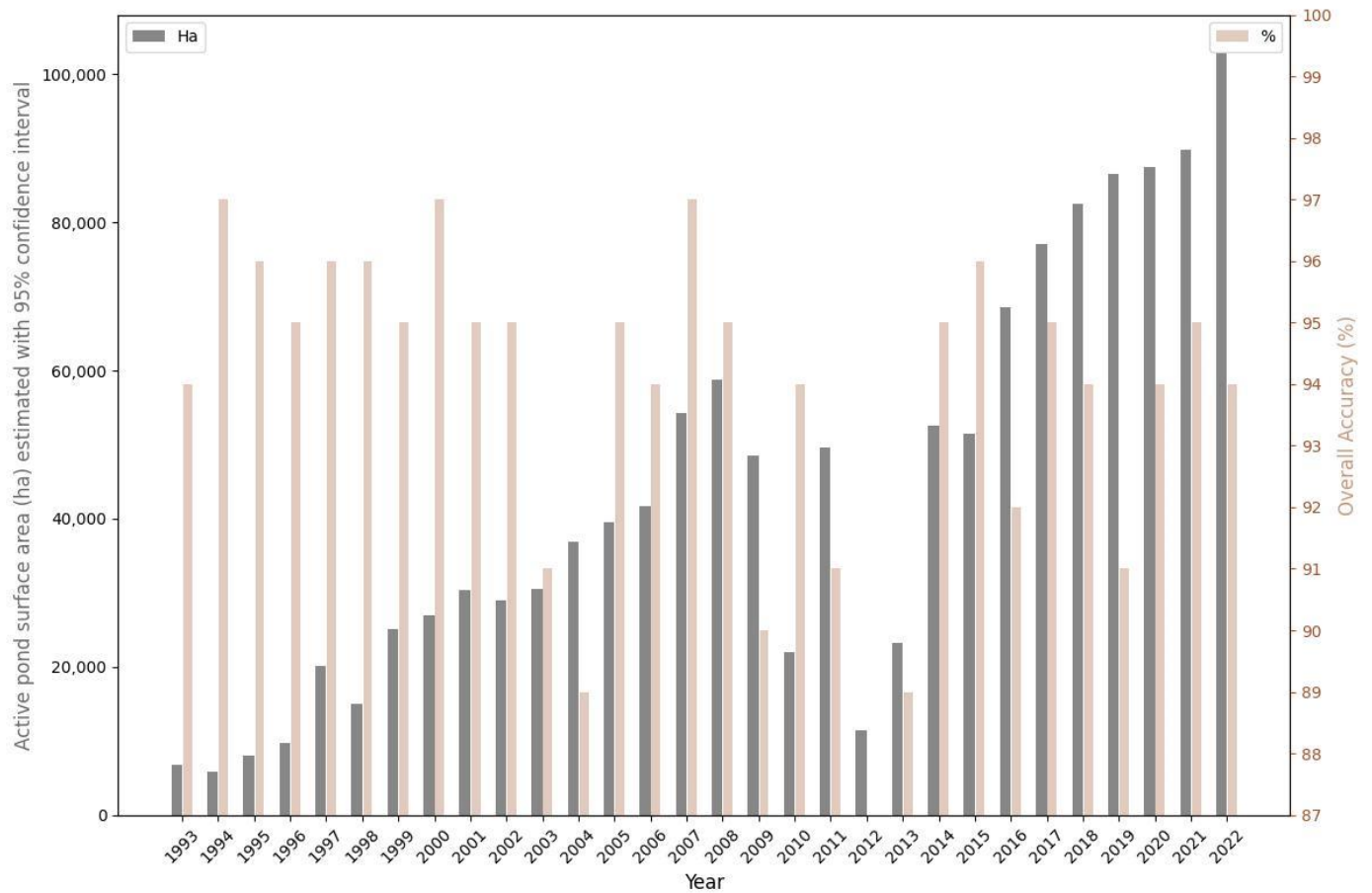|			
2019	0	0	91.1
2020	0	0	93.9
2021	0	0	94.5
2022	0	4	93.7
Average	2	1	94

Figure 2. Expansion of the shrimp pond area from 1993 to 2022 along the Gulf of California. The plot shows bars with the total area in Ha per year of the ponds in the region and overall accuracy bars in %.

Shrimp Pond Expansion from 1993 to 2022 in the Coastal and Protected Areas

Figure 3 shows the long-term invasion of shrimp farms in the Biosphere Reserve Marismas Nacionales. We did not detect ponds inside this Biosphere Reserve in 1993. In this case, the expansion of ponds began in 2000. For this year, we detected approximately 15 ha (see Table A2 in the Appendix Section, which shows the annual growth of farms in ha for reserves and Ramsar sites inside and on the outer limits of their polygons). According to our results, twenty-two years later, the construction of ponds inside the reserve reached more than 473 ha, representing a growth of 3128% compared to 2000.

Figure 4 shows the same process for the Biosphere Reserve Cajón del Diablo. Farms first appeared inside the reserve in 2004 with the development of approximately 4 ha. By 2005, we detected the construction of 816 ha, indicating a massive increase of 21658% regarding the previously constructed ponds (see Table A2). By 2022, we detected the construction of 1236 ha inside the reserve (see Table A2).

Figure 5 shows the process for the Complejo Lagunar Bahía Guásimas–Estero Lobos. In the case of this Ramsar zone and its periphery, we observed different moments of non-intensive growth inside the Ramsar zone during the years 1996, 2000, 2004, 2009, and 2016.

In terms of newly constructed ponds inside the site, the corresponding areas for these years were 390, 799, 1022, 2142, and 2727 ha (see Table A2).

Figure 6 shows the results of the pond expansion for the Ramsar sites Lagunas de Santa María–Topolobampo–Ohuira, Sistema Lagunar San Ignacio–Navachiste–Macapule, and Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo. We observed two main periods of explosive growth for these sites from 1995 to 1999. In the Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo, we estimated 471 ha of ponds in 1994. In 1997, we detected the highest growth, with 2106 ha (a 113% increase in the maximum development compared to previous years). Sistema Lagunar San Ignacio–Navachiste–Macapule behaved similarly. In 1995, we estimated the pond area inside the Ramsar site to be 363 ha; by 1997, this value was 1265 ha (a 248% increase in the maximum development compared to previous years). Meanwhile, for the Lagunas de Santa María–Topolobampo–Ohuira Ramsar site, we observed an increase of 34 ha of newly constructed ponds in 2014. By 2017, this value was 107 ha, representing a 200% growth. The shrimp ponds within the Ramsar site continued growing until 2022, when the area reached more than 940 ha. (see Tables 2, A2, and A3).

Shrimp farm development has steadily increased across all studied areas (see Figures 3–7 and Tables A1 and A2). Notably, in specific years, the construction of new farms surged, with new pond areas exceeding the previous maximums by over 100%. For instance, in the Ramsar area Laguna Playa Colorada Santa Maria Reforma (shown in Figure 7), the shrimp pond area was 363 ha in 1996; by the following year, it grew to 1422 ha, representing a 291% increase (see Table 2).

The growth rate observed in the study area, which includes all protected regions, was nearly 20 percent higher than the previous year (see Tables A1 and A2 in the Appendix Section). Furthermore, we identified peak growth periods across the protected areas studied, taking the highest values from prior years as a reference. For instance, Biosphere Reserve Marismas Nacionales grew by 840% in 2009, Cajón del Diablo by 21,658% in 2009, Complejo Lagunar Bahía Guásimas–Estero Lobos by 105% in 2000, Lagunas de Santa María–Topolobampo–Ohuira by 696% in 2006, Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo by 100% in 1994, Sistema Lagunar San Ignacio–Navachiste–Macapule by 248% in 1997, Ensenada Pabellones by 49% in 2005, and Laguna Playa Colorada Santa Maria Reforma by 291% in 1997 (see Table 2).

Figure 3. The long-term expansion of the shrimp ponds in the Biosphere Reserve Marismas Nacionales. The arrows indicate the locations of the new ponds constructed in the indicated year.

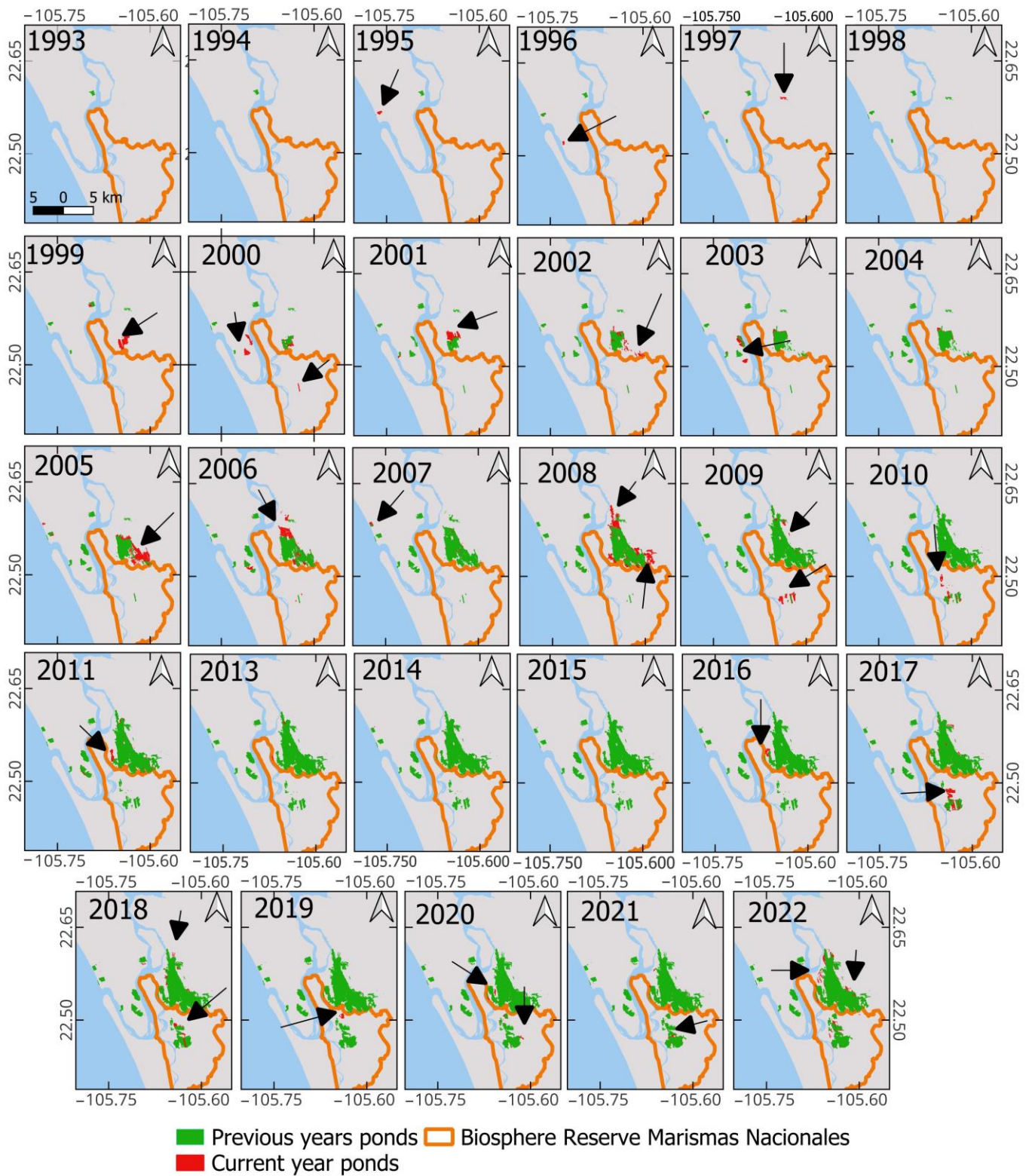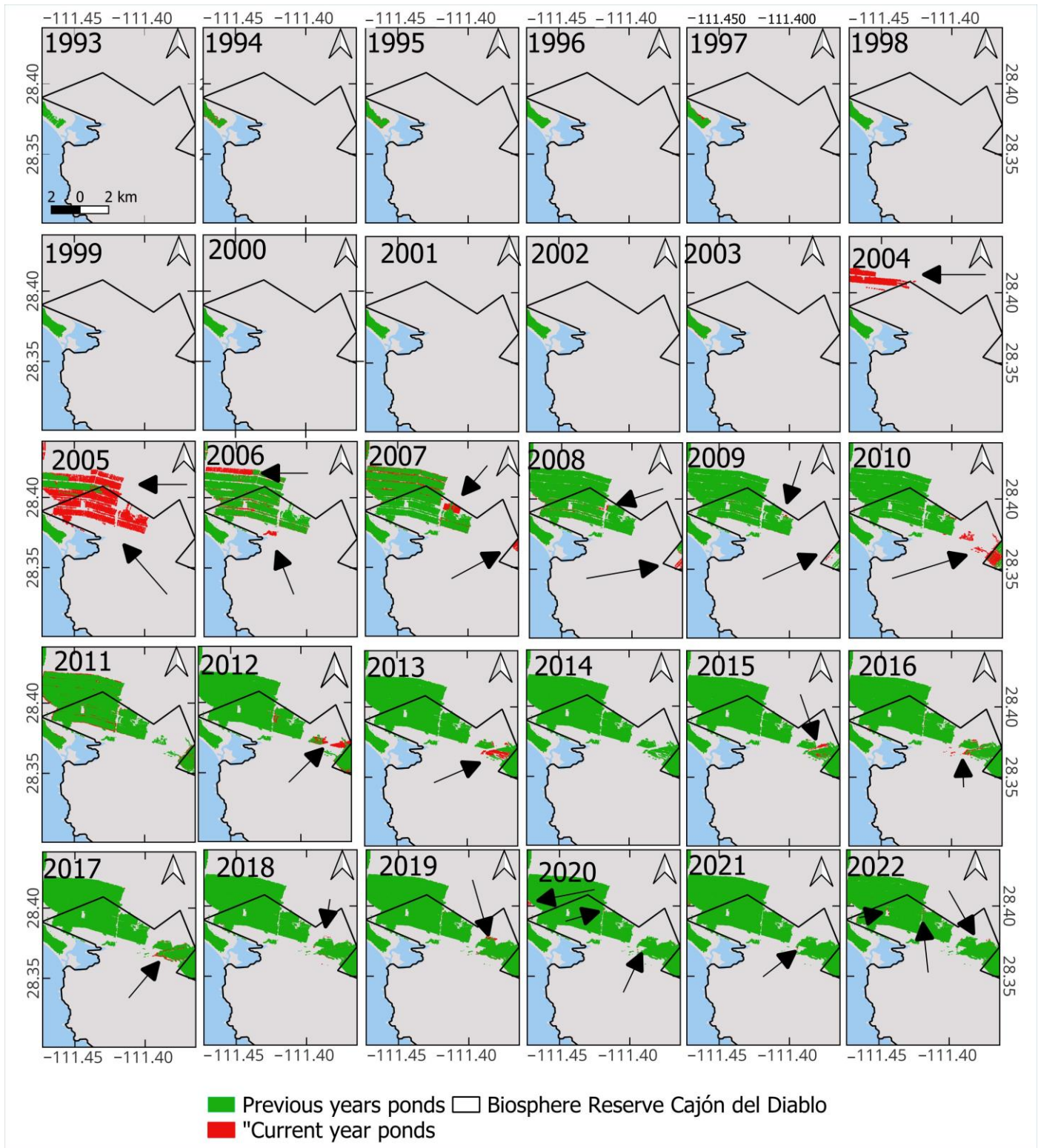**Figure 4.** The long-term expansion of shrimp ponds in the Biosphere Reserve Cajón del Diablo. The arrows indicate the locations of the new ponds constructed in the indicated year.
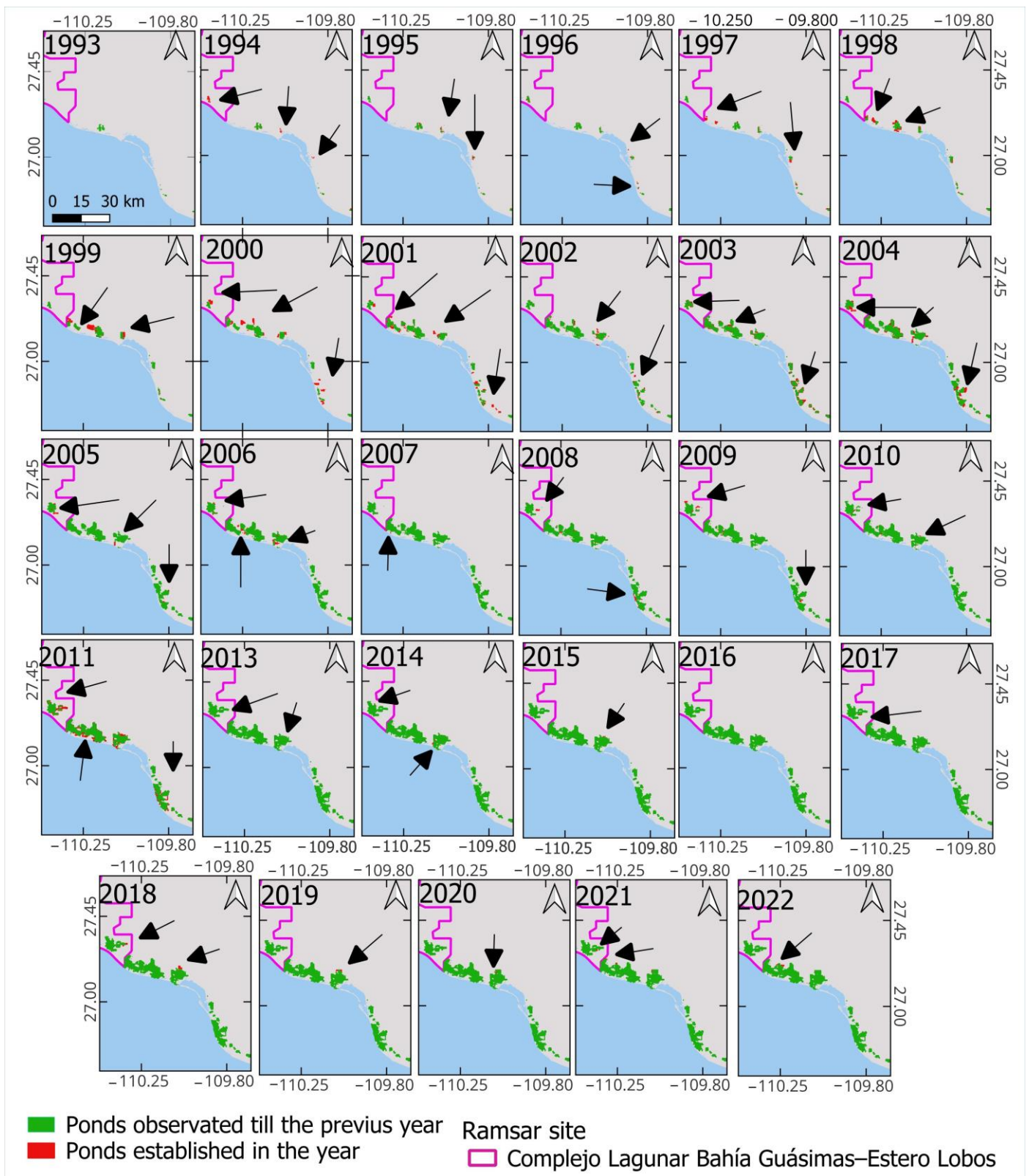
Figure 5. The long-term expansion of shrimp ponds in the Complejo Lagunar Bahía Guásimas–Estero Lobos. The arrows indicate the locations of the new ponds constructed in the indicated year.
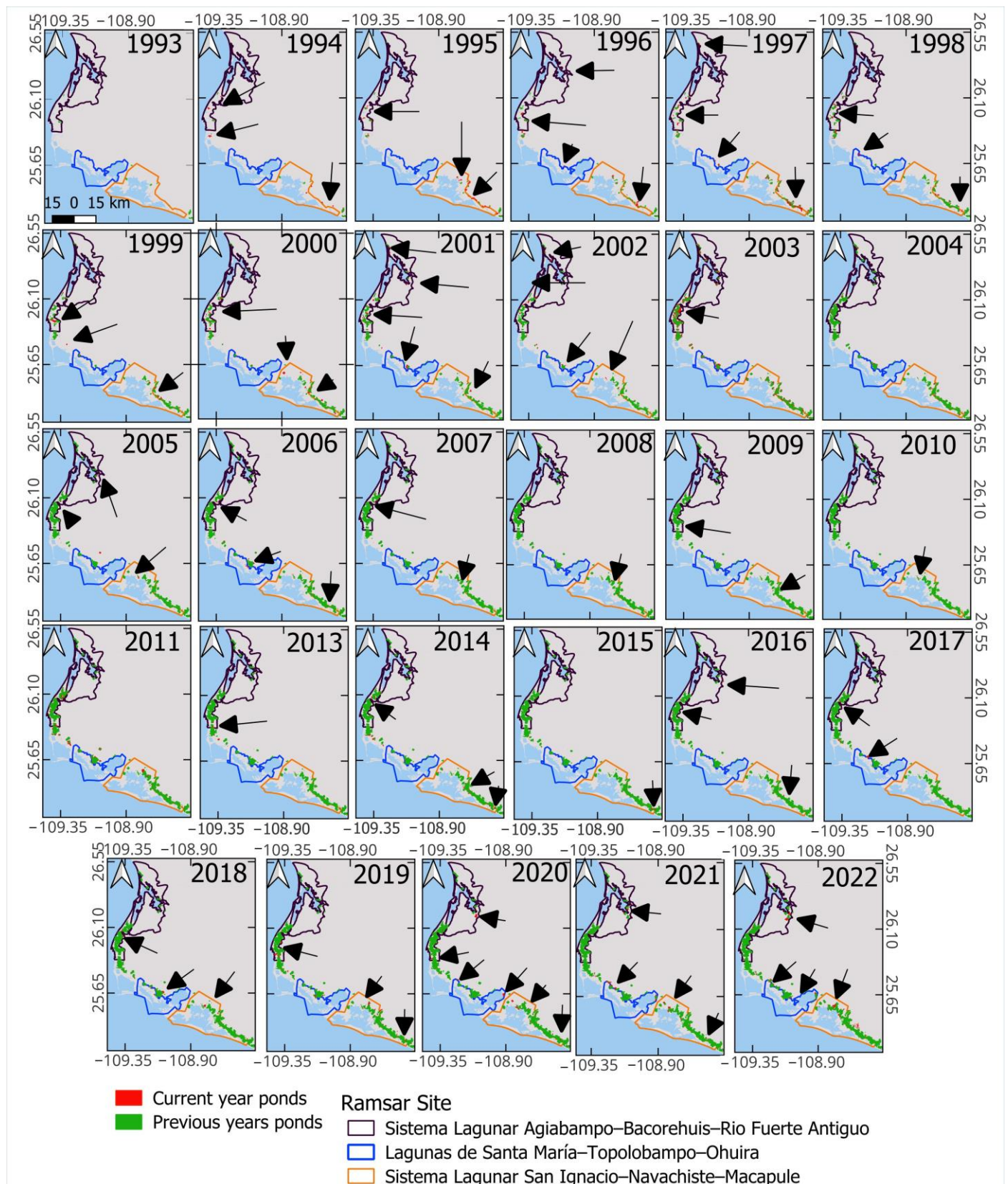
Figure 6. The long-term expansion of shrimp ponds within the sites of Sistema Lagunar Agia-bampo–Bacorehuis–Rio Fuerte Antiguo, Lagunas de Santa María–Topolobampo–Ohuira, and Sistema Lagunar San Ignacio–Navachiste–Macapule. The arrows indicate the locations of the new ponds constructed in the indicated year.

Figure 7. The long-term expansion of shrimp ponds within the sites Laguna Playa Colorada Santa Maria Reforma and Ensenada Pabellones. The arrows indicate the locations of the new ponds constructed in the indicated year.

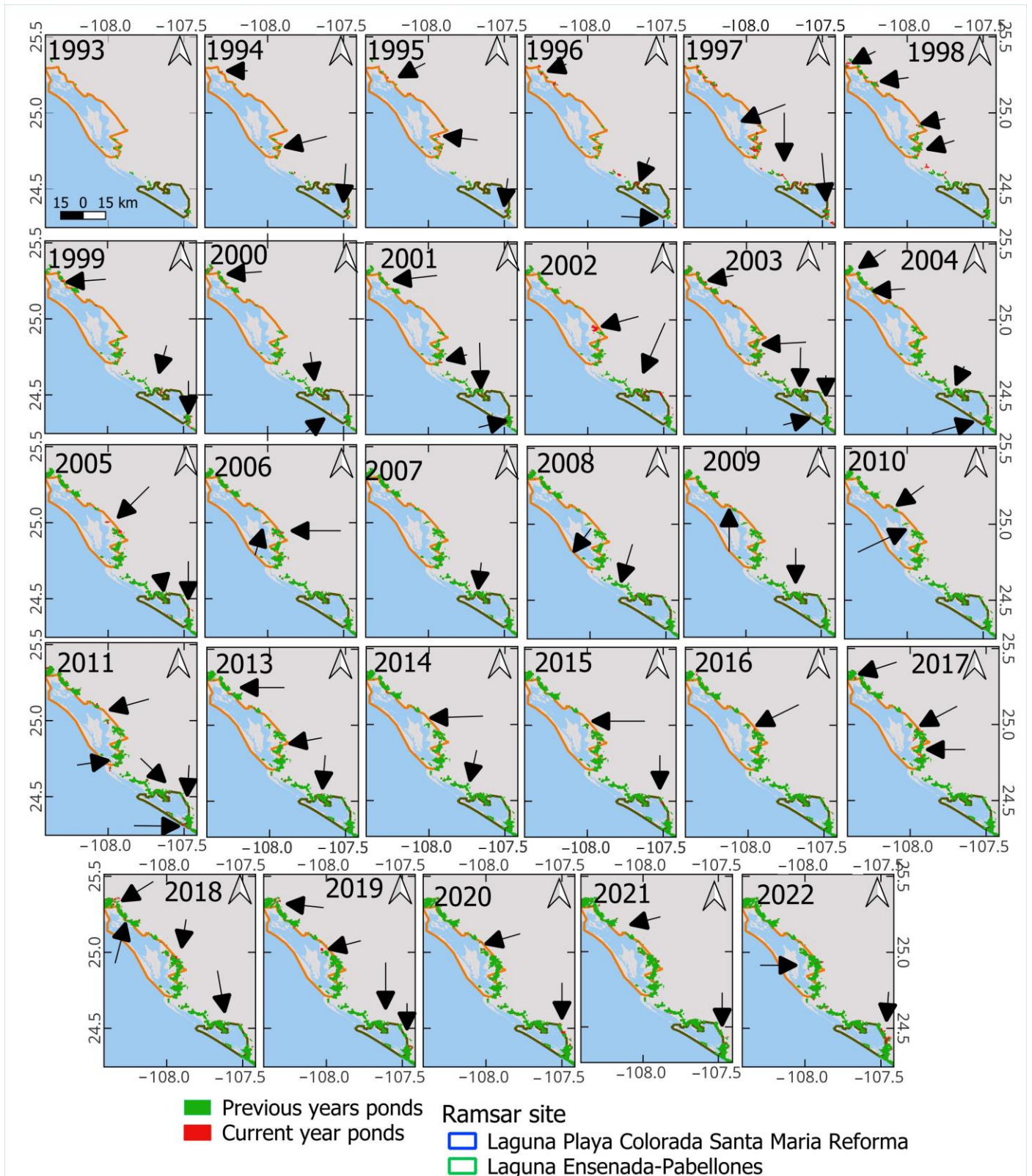**Table 2.** Years of intensive growth in the maximum development of previous years for the Biosphere Reserves and Ramsar sites. Bold numbers indicate growth higher than the previous maximum growth.

Name	Year	
	Inside	Surrounding
Biosphere Reserve Marismas Nacionales	**2009**, 2010, 2017	**1997**, 1999, 2002, **2008**
Biosphere Reserve Cajón del Diablo	**2005**, 2016	2004, **2005**, 2007, 2016
Complejo Lagunar Bahía Guásimas–Estero Lobos	1996, **2000**, 2004, **2009**, 2016	1997, **1998**, **1999**, 2001
Lagunas de Santa María–Topolobampo–Ohuira	**2006**, **2017**, **2018**, **2019**, 2021, 2022	1997, **1998**, **1999**, **2001**, 2006
Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo	**1994**, **1996**, 1997, **1998**, 1999, 2001, 2003, 2017	1995, **1996**, **1998**, 2014, 2016
Sistema Lagunar San Ignacio–Navachiste–Macapule	1995, 1996, **1997**, 2007, 2019, 2022	1994, **1995**, **1997**, **2007**, 2016
Ensenada Pabellones	1997, **2005**, 2015, **2018**	**2005**, 2015, **2018**
Laguna Playa Colorada Santa Maria Reforma	**1997**, **2002**, **2015**, 2017, 2021	**1997**, 2016, 2018

4. Discussion

We studied the long-term growth of shrimp farms from 1993 to 2022 and their impact on land change generated in the protected areas located in the coastal areas of the Gulf of California. In the next paragraphs, we discuss aspects related to the following topics: image classification and accuracy assessment, shrimp farm expansion and its effects on protected areas, and the use of Google Earth Engine in similar studies.

The confidence intervals of the shrimp pond areas estimated using the methodology of Olofsson et al. [45] applied to the classified Landsat images could be affected by temporary water bodies that vary each year. Data were missing (NA in Table A2 in the Appendix Section) due to cloud cover for specific periods, such as 2013, 2015, and 2022. Because we could not find suitable images for 2012, we estimated the area using an equation of area as a function of time, proposed in [43]; we additionally confirmed the values of area by comparing it against the official records of shrimp production [9]. We confirmed that 2012 had low production values, which indicates that the area obtained using the equation is correct. The results of our assessment, specifically an overall agreement of 0.9 or higher (s. Figure 2) and obtained applying the Oloffson et al. [44] method, confirmed the accuracy of our estimated long-term expansion from 1993 to 2022.

The rapid growth of aquaculture farms over protected areas has attracted our attention. The total area of shrimp farms has continuously increased. In particular, the total area of shrimp ponds increased significantly in 1997, 2001, 2008, 2016, and 2022. The area obtained for 2022 in our work exceeded the value estimated in [43]. This difference can be explained by various factors, such as the effect of white spot disease and other diseases that cause the inactivation of ponds [46] or the masking of ponds by clouds in the satellite classification, which could generate noise in our estimates.

One of the main concerns of shrimp pond development is the debris entering the water column of the lagoons and marine areas through the water exchange and pond cleaning, which generates and increases nutrients, organic matter, and sediments in these ecosystems [31,33,47–49]. Concurrently, with these nutrient increases in water bodies, other sources of nutrients must be considered, such as agriculture, livestock, urban zones, and other types of industries in the region [50]. Researchers [31,33,51,52] have observed different compounds and biomass discharged into the surrounding ecosystems from the ponds during the study period, as well as increases in organic matter, nutrients, heavy metals, and water with different salinities. In addition, it is worth noting that some of the soil excavated to create the ponds could increase sediments, which enter the water column

instead of being swept away by rain or wind. Another key concern is the introduction of new pathogens into the surrounding ecosystems.

The 2022 shrimp pond area we detected in the coastal lagoons of Sinaloa comprises 81% of the total estimated shrimp pond area in Sinaloa and Sonora. In Sinaloa, almost 55% of the shrimp ponds are located near a Ramsar site, and in Sonora, this value is 26%, indicating that most shrimp farm development has taken place along the coastal lagoons of Sinaloa. Our image classification results indicated a significant decrease in active ponds detected from 2009 to 2013 compared to previous years. Some authors [43,53,54] attribute this decrease to the presence of diseases such as early mortality syndrome.

The development of aquaculture in protected areas such as the Biosphere Reserve Marismas Nacionales affects mangroves, coastal vegetation, and coastal water bodies. In the case of this Biosphere Reserve, shrimp farm development began in 2009 and continued to grow until 2022. The decree and the management program do not specify whether the construction of new ponds is allowed after the year of the decree [39]; however, the management program stipulates that it is not permitted to "Interrupt, fill, drain or divert hydraulic flows, and modify the natural conditions of aquifers, hydrological basins, natural stream channels, springs, riverbanks, and basins" [55]. This regulation needs to be implemented, given the observed development of aquaculture farms, which could modify the conditions of the aquifer and fragment the environment.

Shrimp pond development in the Biosphere Reserve Cajón del Diablo began in 2005 and continued until 2014. The situation of this reserve is critical because, as previously mentioned, it does not have a management program, and its limits and polygons need to be precisely defined and well managed. According to [56], "the reserve does not receive attention or management for prolonged periods, the limits have been lost, and it is difficult to locate it precisely".

Another example of land change due to shrimp ponds in Sinaloa is the coastal lagoon Ensenada Pabellones. The shrimp ponds have altered the peripheral ecosystems near this complex lagoon, leading to the development of overflood areas and vegetation such as mangles, bushes, and marshes, which partially contribute to the fragmentation of these ecosystems. References [47] and [57] have reported related land changes due to aquaculture farms.

It is worth noting that farms grew explosively within the protected areas studied and in their peripheries. For example, in 2009, new ponds were created within the Biosphere Reserve Marismas Nacionales polygon; these ponds represent a peak of more than 800% of what was previously built, i.e., during 2008. That year, there were about 16 ha of shrimp ponds, and by 2009, there was an increase of more than 157 ha.

Regarding Ramsar zones, farms occupied areas around Lagunas de Santa María–Topolobampo–Ohuira from 1997 to 2001. In 2006, the construction of ponds within the Ramsar site reached its first peak, and the construction of new shrimp ponds continued from 2017 to 2022. In the case of Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo and Sistema Lagunar San Ignacio–Navachiste–Macapule, the development of ponds began in 1994 and continued until the early 2000s.

As discussed, shrimp farms have expanded along the east coast of the Gulf of California over subtropical and desertic zones and into several coastal lagoons, cataloged as Ramsar sites. We observed the construction of new farms inside Ramsar areas and in their margins. This expansion implies that these areas must be managed appropriately as naturally protected areas, and management plans should be established for each site, as pointed out in [58]. These wetlands function as carbon sinks, fish nurseries, passages for migratory birds [59], and refuges for endangered species, such as the jaguar [60].

The legacy of Landsat 5, 8, and 9 on the Google Earth Engine platform allowed us to quickly assess the expansion of this economic activity in the coastal zone of the Gulf of

California [61]. Although we could not estimate the areas for some in 2012 because of a lack of images or cloudiness, land change near and inside the coastal protected areas was detected. Regarding our results, it is possible to monitor the growth and effects of this industry on coastal ecosystems (including protected areas) using remote sensing platforms such as Google Earth Engine. However, combining the information obtained with remote sensing analyses with field data about water quality measurements, pollutants, and bioindicators is necessary to understand environmental and ecological problems better. Local and scientific communities, institutions, and government offices in charge of verifying compliance with environmental regulations should be involved in implementing projects concerning the change in location of old shrimp farms and the construction of new ponds. Determining the environmental effects of these activities and regulating waste from shrimp farms are indispensable for the sustainable management of this economic activity, which is already widely distributed throughout the Gulf of California, invading protected areas.

5. Conclusions

Despite the Mexican environmental legislation forbidding the extensive loss of natural habitats due to the impact on natural vegetation in protected areas, vast shrimp farm development has occurred over the last 30 years. Aquaculture farms were continuously developed and expanded by almost 1400% along the Gulf of California between 1993 and 2022. Consequently, different ecosystems have been reduced, fragmented, or altered, even in protected areas. In addition, this type of aquaculture generates the entry of various compounds and pathogens into the ecosystems supporting these ponds. Remote sensing and new platforms, such as Google Earth Engine, allow us to monitor these changes and identify where ecosystems are threatened and require more supervision. These tools can help improve, at a low cost, the understanding of these economic activities and other factors affecting ecosystems.

The establishment of shrimp ponds within Ramsar areas and Biosphere Reserves is clear. There is a need for greater control over the areas where these activities can occur and their impact on the surrounding ecosystems. Using remote sensing, we have proved the long-term growth of shrimp ponds within Ramsar sites and Biosphere Reserves. This expansion highlights the urgent need for stronger regulations concerning the locations where these activities can take place and their impact on surrounding ecosystems. Remote sensing provides an effective means to monitor this growth. However, it is also crucial to develop ecological approaches integrating remote sensing with field data to understand the effects on coastal ecosystems comprehensively.

Author Contributions: D.A.G.-R.: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, and environmental analysis. A.O.-R.: supervision, conceptualization, legislative research, and environmental analysis;.. F.-O.T.-S.: writing, supervision, conceptualization, methodology, software, validation, formal analysis, and investigation. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: The original data presented in the study are openly available in 'Shirmp_Farms' at https://github.com/Dagriva/Shirmp_Farms.

Conflicts of Interest: authors declare no conflicts of interest.

Appendix A

Table A1. Area by year and percentage growth compared to the previous year.

Year	Area (ha)	Percentage Concerning 1993	Percentage Concerning Last Year
1993	6741.9	NA	NA
1994	5852.3	−13.2	−13.2
1995	7950.5	17.9	35.9
1996	9665.2	43.4	21.6
1997	20,117.6	198.4	108.1
1998	15,026.6	122.9	−25.3
1999	25,094.6	272.2	67.0
2000	26,993.5	300.4	7.6
2001	30,436.5	351.5	12.8
2002	29,002.4	330.2	−4.7
2003	30,535.4	352.9	5.3
2004	36,849.4	446.6	20.7
2005	39,531.7	486.4	7.3
2006	41,655.5	517.9	5.4
2007	54,283.9	705.2	30.3
2008	58,794.6	772.1	8.3
2009	48,570.4	620.4	−17.4
2010	22,067.3	227.3	−54.6
2011	49,642.5	636.3	125.0
2012	11,438.4	69.7	−77.0
2013	23,187.2	243.9	102.7
2014	52,628.7	680.6	127.0
2015	51,433.7	662.9	−2.3
2016	68,478.0	915.7	33.1
2017	77,129.7	1044.0	12.6
2018	82,563.5	1124.6	7.0
2019	86,573.7	1184.1	4.9
2020	87,550.3	1198.6	1.1
2021	89,747.3	1231.2	2.5
2022	102,906.0	1426.4	14.7
Average	44,334.7	NA	19.5

Table A2. Estimated area of shrimp ponds per year inside and outside Biosphere Reserves and Ramsar sites.

Year	Biosphere Reserve Marismas Nacionales		Biosphere Reserve Cajón del Diablo		Complejo Lagunar Bahía Guásimas–Estero Lobos L		Sistema Lagunar Agiabampo–Bacorehuis–Rio Fuerte Antiguo		Lagunas de Santa María–Topolobampo–Ohuira		Sistema Lagunar San Ignacio–Navachiste–Macapule		Laguna Playa Colorada Santa Maria Reforma		Ensenada Pabellones	
	FLIL*	FLOL**	FLIL	FLOL	FLIL	FLOL	FLIL	FLOL	FLIL	FLOL	FLIL	FLOL	FLIL	FLOL	FLIL	FLOL
1993	0	433.66	0	197.17	NA	575	235	NA	NA	41	227	351	354	1558	NA	959
1994	0	213.16	0	219.62	287	580	471	142	NA	45	56	478	210	1155	43	474
1995	0	178.15	0	235.16	NA	657	824	190	NA	NA	293	989	245	1237	49	995
1996	0	146.29	0	260.7	390	672	990	463	0	53	363	624	363	1779	177	581
1997	0	718.79	0	249.89	NA	973	2106	484	NA	135	1265	1998	1422	3863	304	2967
1998	0	NA	0	267.02	NA	2263	2656	790	1	274	468	1705	1045	3801	NA	NA
1999	0	932.84	0	291.16	362	4080	3543	826	1	387	592	2037	1043	2954	285	3040
2000	14.67	700.71	0	151.8	799	3860	3908	691	1	428	1155	2360	1223	4535	354	2864
2001	NA	769.69	0	281.14	576	5343	5410	988	1	626	999	2006	1056	4054	213	2322
2002	8.31	1166.32	0	225.22	633	3446	3455	1049	4	577	850	1405	1791	3398	361	2582
2003	NA	829.82	NA	341.57	493	2293	7910	1128	1	651	1074	2093	1169	5177	152	1211
2004	NA	580.99	3.75	508.59	1022	4739	7833	719	1	712	689	2271	1033	4758	393	1937
2005	2.28	1753.1	816.35	1423.94	1223	4312	3297	778	1	637	1183	2252	1813	3652	586	3191
2006	14.13	2156.15	740.83	1585.99	1374	5529	4980	959	29	971	1191	2331	1927	4266	418	3134
2007	NA	1064.73	471.6	2072.36	1254	6083	8785	1196	2	1159	1524	3456	1152	6021	500	5085
2008	16.79	3180.68	851.09	1956.38	1298	6501	7201	1282	2	1344	1690	3609	1301	5951	608	4396
2009	157.92	1930.4	648.62	1007.14	2142	6439	6744	1213	8	1261	1360	3426	1831	4838	654	4883
2010	233.15	2235.13	743.87	1525.94	1326	2586	2082	259	5	804	1133	1084	512	980	70	904
2011	3.95	1261.89	777.26	1746.83	2124	6022	6160	1122	12	1410	1240	2227	1391	4830	387	3594
2012	NA	NA	913.24	1536.66	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2013	5.69	541.38	448.51	162.74	1160	1333	1690	652	22	648	981	1604	1368	3087	394	3467
2014	NA	781.57	383.44	1272.26	1925	5203	8291	1540	34	1126	1907	3934	1665	6062	618	5289
2015	NA	NA	735.8	2006.16	1986	4493	7056	1477	8	1128	1806	3761	3044	5881	905	5740
2016	NA	712.75	1099.12	2792.82	2727	6115	9089	1864	14	1653	2222	4618	3263	7386	722	6051
2017	449.59	1414.77	1213.26	2911.3	2427	6578	11,489	2145	102	1820	2558	4764	4871	8889	944	5877
2018	234.03	1591.85	1075.79	3020.02	2723	6319	11,317	1955	204	2098	2723	5201	5410	10,179	1353	7477
2019	91.62	988.25	1190.68	3435.02	2883	6828	12,069	2144	368	2142	3449	5665	5866	10,752	1433	8149
2020	417.93	953.4	1147.85	3532.06	2771	6459	13,811	2358	611	2271	4052	5679	5197	10,367	1554	8368
2021	418.37	1311.88	1083.53	3337.83	2538	6169	13,408	2139	787	2383	4660	6015	6280	11,362	1750	8721
2022	473.35	2513.87	1236.77	3696.79	2748	6699	15,241	2266	944	2439	5702	6876	6648	12,683	1954	10,484

Table A3. Estimated standard errors S(ÔSa) of the selected allocations for each classified year and the estimated commission errors for each class, with S(Ûp) for shrimp pond, S(Ûs) for soil, and S(Ûv) for vegetation.

Year	S(Ôa)	S(Ûp)	S(Ûs)	S(Ûv)
1993	0.0185327	0.027501	0.0254457	0.0254457
1994	0.0186531	0.0254457	0.024577	0.0287348
1995	0.0193838	0.024577	0.0224231	0.0361158
1996	0.0178544	0.027501	0.0212664	0.0337526
1997	0.0190717	0.024577	0.0224231	0.0361158
1998	0.0183226	0.027501	0.0254457	0.0254457
1999	0.0188459	0.024577	0.0224231	0.0361158
2000	0.0183717	0.0254457	0.0254457	0.027501
2001	0.019122	0.024577	0.0224231	0.0361158
2002	0.0182602	0.0254457	0.024577	0.0287348
2005	0.0181647	0.0254457	0.024577	0.0287348
2006	0.0192668	0.024577	0.0224231	0.0361158
2007	0.0173769	0.027501	0.0212664	0.0337526
2008	0.0185983	0.024577	0.0224231	0.0361158
2009	0.0179573	0.0254457	0.0254457	0.027501
2010	0.0187727	0.0254457	0.024577	0.0287348

2013	0.0185095	0.0254457	0.024577	0.0287348
2014	0.0188619	0.024577	0.0224231	0.0361158
2015	0.0181858	0.0254457	0.024577	0.0287348
2016	0.0173426	0.027501	0.0212664	0.0337526
2017	0.0172606	0.027501	0.0212664	0.0337526
2018	0.017472	0.0254457	0.024577	0.0287348
2019	0.0169542	0.027501	0.0212664	0.0337526
2020	0.0174175	0.0254457	0.024577	0.0287348
2021	0.0174555	0.0254457	0.024577	0.0287348
2022	0.0174022	0.0254457	0.024577	0.0287348

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