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Research Article

Pacific white shrimp (*Penaeus vannamei*) stock enhancement with aquaculture recruits: a case study in the coastal lagoons of southern Sinaloa, Mexico (2019-2020)

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ABSTRACT. Laboratory-reared Pacific white shrimp (*Penaeus vannamei*) postlarvae were released into the Huizache-Caimanero and Cerritos lagoon system (Sinaloa, Mexico) using a stock enhancement approach to improve production and preserve the wild spawning stock. Fifty-two point three million postlarvae were sown, and the system was monitored between June 28 and November 29, 2019. A total of 3844 shrimp ranging from 27 to 170 mm in total length (TL) and 0.2 to 41.2 g in total weight were obtained. Individuals were classified in 5-mm size classes to estimate the length at first maturity ($TL_{50\%}$: 110 mm) as a proxy of the length (age) at which they become part of the breeding stock. The associated relative age (based on the mean postlarvae length) was 80 days, with most of the sampled specimens ranging from 60 to 100 days in age. Molecular analysis of genomic expression was performed to compare the genetic profiles of samples obtained in June 2019, October 2019, and 2012 (reference) and detect possible genetic admixture between hatchery and wild specimens. The catch obtained at the end of the fishing season was >220 t, clearly above the average of the last five fishing seasons. As it was impossible to replicate the study, the results must be taken cautiously. At least one follow-up study is required to confirm the results and discard the possibility that the increase in production was due to natural environmental or biological variability.

Keywords: *Penaeus vannamei*; hatchery postlarvae; fisheries management; stock enhancement; stock recovery; coastal lagoon

INTRODUCTION

Worldwide, nearly 60% of fish and invertebrate stocks are caught at volumes near their maximum sustainable yield, notably impacting ocean ecosystems, marine biodiversity, and food security (FAO 2020). It has been estimated that underfished stocks accounted for only 6.2% of all stocks in 2017, and the number of overfished stocks has continued to grow since then (FAO 2020). Given the increasing demand for fisheries products that support food security in many world regions, effective management tools and strategies are needed to safeguard marine ecosystems and their resources.

The United Nations (UN) has declared 2021-2030 the Decade of Ocean Science for Sustainable Development (UNESCO 2021) to provide a common framework for research and decision-making. Moreover, the UN has declared 2022 the International Year of Artisanal Fisheries and Aquaculture (FAO 2022) to emphasize the importance of these activities for food security across all organizational levels. Indeed, small-scale fisheries are critical players in global food security and poverty alleviation. Although current analytical methods may be used for inland and marine ecosystems, inland fisheries worldwide have been scarcely assessed, hindering effective decision-making (Lorenzen et al. 2016), which is troubling since artisa-

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nal or small-scale fisheries directly employ around 39 million people (including women and men), most of whom participate in inland fisheries in developing countries (FAO 2020).

Given this context and additional social, economic, and environmental issues, coastal countries must work to restore and recover their overexploited fisheries. In particular, efforts to restore fisheries resources are needed to satisfy the growing demand for food, which has increased from 10 kg of fisheries products per capita per year in 1960 to 13.5 kg in 1995 and 20.5 kg in 2018 (FAO 2020). This demand was expected to increase by ~1.5% in 2020. However, there is no available data to corroborate this estimate, which was also contingent on price (Delgado et al. 2003) and the impacts of the COVID-19 pandemic (Ruiz-Salmón et al. 2021).

In countries where inland and coastal fisheries have declined, aquaculture restocking or enhancement practices may help affected stocks recover by adding hatchery recruits to natural populations to stabilize or improve yields. Considering the needs of local fishers, these practices may help to protect wild populations and preserve biodiversity (Bartley & Bell 2008, Bell et al. 2008). Potential recruits can be produced through aquaculture methods, or they may be obtained by catching and reallocating wild postlarvae with low probabilities of survival, which may help avoid the Ryman-Laikre effect. This effect arises when a few captive parents produce large numbers of offspring, resulting in an increase in inbreeding and a reduction in total population size in the mid-and long term (Ryman & Laikre 1991, Waples et al. 2016). Thus, the goals of stock enhancement programs include increasing the productivity of a fishery in terms of organism growth and overall harvest volumes by ensuring that the added recruits contribute to the biomass of the fishery.

Only two previous initiatives have integrated aquaculture efforts in Mexico to restock wild marine populations. On the west coast of the Baja California peninsula, aquaculture farming of abalone (*Haliotis* spp.) is being conducted, while aquaculture efforts aimed at conserving the endangered totoaba (*Totoaba macdonaldi*) in the Gulf of California are also underway (Searcy-Bernal et al. 2013, Juarez et al. 2016). However, a pilot program has recently been proposed for the protected waters of the coastal ecosystems of the state of Sinaloa in northwestern Mexico to improve the production of the Pacific white shrimp (*Penaeus vannamei*) fishery.

The experimental program Assisted Recruitment to Repopulate Pacific White Shrimp (*Penaeus vannamei*) in the Huizache-Caimanero lagoon system was designed to enhance shrimp recruitment. The program aimed to determine if adding aquaculture recruits would benefit the wild broodstock and protect it from decline by evaluating the effects of restocking on the productivity of the Pacific white shrimp fishery. This project was spearheaded by the National Commission for Fishing and Aquaculture (CONAPESCA, by its Spanish acronym) and researchers interested in recovering this important fishery resource. The program was based on previous agreements with local fishers and regional shrimp larvae producers, and its results, particularly those related to white shrimp population dynamics and fishery production, are presented here.

The shrimp industry in Sinaloa is well-developed. This productive industry generates jobs, economic resources, and food products while forming a fishing system that has fostered technical innovation and furthered scientific knowledge, which has proved useful for managing other fisheries resources (Dubay et al. 2010). Shrimp yields have traditionally been high in the Huizache-Caimanero and Cerritos lagoon systems (HCCLS), which is located in southern Sinaloa. However, over the last 30 years, production has undergone a dramatic decline, falling from ~1000 t in an average season between 1970-1987 (De la Lanza-Espino & García-Calderón 1991, Del Valle & Martín 1995) to less than 250 t on average per season in the last 10 years. This decline has negatively affected the welfare and livelihoods of coastal communities that depend on this resource.

Although it has been reported that some individuals have escaped from shrimp aquaculture ponds while others have been unsystematically and deliberately released into natural systems, no program to create a supply of recruits reared for restocking purposes has been implemented until now. Thus, this study aimed to increase the average postlarvae density to the natural maximum estimated capacity of 5-6 ind m^{-3} for the HCCLS by adding aquaculture recruits to the wild population to identify the impact of the addition of recruits on shrimp growth, recruitment, and yield. The existing shrimp population was monitored before and after the release of reared postlarvae recruits until the conclusion of the fishing season.

The results of this study will contribute technical information that may be used at the public policy level to restock recruit programs in specific locations and to create local management proposals. Potential restocking sites should meet pre-established requirements to minimize the potential negative environmental impacts derived from the release of hatchery larvae into the wild. The results of this study may be used to determine the extent to which technical interventions can benefit the natural production of a fisheries resource without negatively affecting the environment or the genetic diversity of the resource in question. The results of this study will likewise contribute to meeting the global demand for seafood while improving the well-being of local communities.

MATERIALS AND METHODS

This study consisted of two sequential phases to evaluate the success of introducing postlarvae to the HCCLS to enhance local shrimp production without damaging the existing reproductive stock, namely seeding and monitoring, which is described in the subsequent sections.

Study area

The HCCLS in southern Sinaloa is located between 22°48' to 23°07'N and 105°54' to 106°17'W. The total surface area of the water bodies within the HCCLS is ~140 km^2. However, this varies seasonally and mostly corresponds to the Huizache-Caimanero lagoon system, with the small Cerritos lagoon located to the south (Fig. 1). The HCCLS connects with the Presidio River to the north and the Baluarte River to the south. Both rivers flow into the Gulf of California through estuarine and mangrove channels. Changes to the surrounding landscape that are mostly related to agricultural practices and the construction of shrimp culture facilities inside the lagoon systems have reduced the size of the basin and increased the siltation rates, which has affected the average depth of the HCCLS and its water quality (Ruiz-Luna & Berlanga-Robles 1999, Berlanga-Robles & Ruiz-Luna 2002).

Nursery site installation and seeding of aquaculture shrimp postlarvae

The empirical knowledge of the local fishers was used to select five sites that were adapted as nurseries to guarantee a minimum level of environmental quality (salinity < 15 ppt, dissolved O_2 > 5 mg L^{-1}, and minimum depth ≥ 70 cm) and sources of organic matter in the field. Three sites (Pozo del Caimán, Candelones, and El Violín) were located along the Huizache estuarine channels. In contrast, one site (Pozo de la Hacienda) was located in the Caimanero lagoon, and the final site (El Puyeque) was located in the Cerritos Lagoon.

All of these sites are semi-isolated from the rest of the lagoon system due to the installation of Tapos, a traditional fixed fishing gear made of concrete or logs arranged across the estuaries (~20 to 250 m in width). Tapos close off aquatic ecosystems and prevent shrimp from escaping while allowing water to circulate (Pedini 1981). These fishing gears are open part of the year and usually close in either July or August following the massive entrance of shrimp postlarvae and subadults. After closing, the Tapos resemble an extensive culture system that allows for shrimp growth and fishing, which usually begins in September.

Before releasing the postlarvae, potential predators (mainly fish and crabs) were removed from the nursery sites using fishing nets before the rainy season, when the system naturally floods. Afterward, the nursery area was closed off and protected with plastic or fiberglass nets (mesh size 1.5 mm) that allowed for water flow but limited the reintroduction of predators (Fig. 2). This allowed for the postlarvae to remain isolated under natural developmental conditions until their release after the Tapos were closed.

Considering the average amount of water within the HCCLS per year, it was estimated that ~75 million nursery postlarvae would be needed to reach a density near the maximum natural recruitment estimated for the area (4-6 ind m^{-3}, De la Lanza-Espino & García-Calderón 1991). Commercial hatcheries provided the postlarvae with their genetic lines, which were developed from wild broodstock, as wild seeds have not been used in Latin America since the late 1990s (FAO 2006). The final number of postlarvae ultimately depended on the environmental conditions (e.g. water availability), local productivity, and natural survival rates. Nonetheless, aiming for a density of 4-6 ind m^{-3} in the HCCLS would likely result in a high yield at harvest. After HCCLS flooding and Tapos closure, the nursery-reared postlarvae (settled at the PL12 stage) were released to join the natural stock. However, their release depended on local environmental conditions.

Monitoring

Biological sampling was performed once or twice monthly in the study area from June 2019 (before postlarvae seeding) until November 2019, when lab-reared postlarvae had completely integrated into the stock. Artisanal cast nets were thrown 3-5 times per sampling visit in the five nursery sites of the HCCLS. Shrimp were separated from the catch, and the number of shrimp (n), individual total wet weight (TW) to the nearest 0.1 g, total length (TL) to the nearest mm, and sex were recorded. Growth was estimated using the following equation from Haddon (2001):

$Wt = a\ Lt^b$, where b is the allometric growth parameter, and a is a constant.

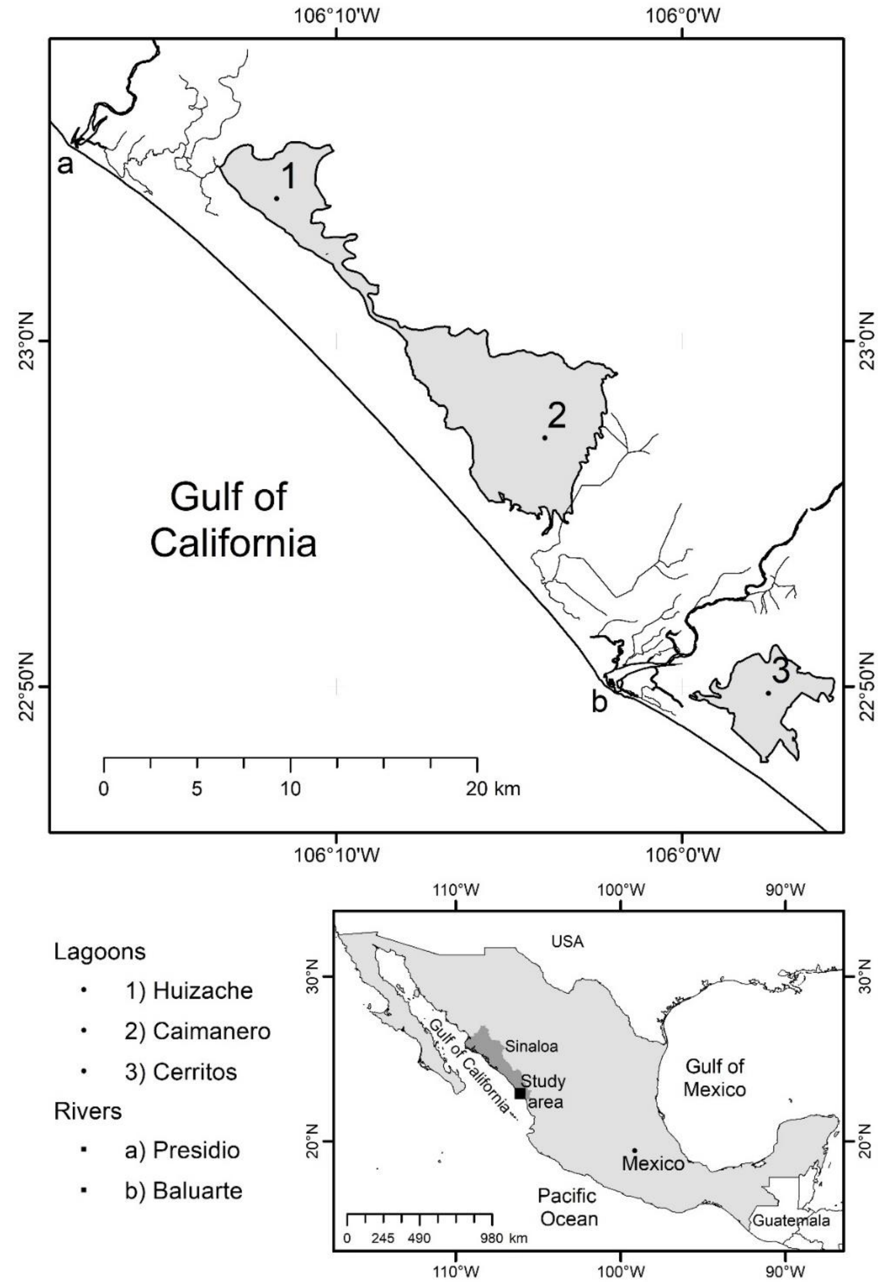

Figure 1. Study area. Huizache-Caimanero and Cerritos lagoon system (HCCLS) in southern Sinaloa, Mexico.

Shrimp sizes (mm) by sample were arranged into frequency histograms to estimate central tendency measures and model the growth rate based on modal groups or cohort distributions. Cumulative relative frequencies were analyzed to estimate the length at which 50% of the shrimp had reached maturity ($TL_{50\%}$) as a proxy of the length at first maturity and the size at which individuals become part of the reproductive stock (Aragón-Noriega 2016). Relative age (days) was associated with the length groups considering an average 30-day period of larval marine drift before migration into the estuarine systems, which mostly occurs at the postlarvae stage (4-6 mm length) and lasts between 30-35 days up to the juvenile stage (Goytortua 2023). Considering this and assuming that Tapos allow the entrance of PL up to 12 mm length (~ 40-45 days old), a 60-day relative age was associated with the 25-mm length class, acknowledging that growth rates vary between 0.42-1.5 mm d^{-1} and depend on environmental conditions and population density (De la Lanza-Espino

Figure 2. Traditional fishing gears (Tapos) and nursery sites in the Huizache-Caimanero and Cerritos lagoon systems in southern Sinaloa, Mexico.

& García-Calderón 1991). Further age at length values were obtained based on the findings of Aragón-Noriega (2016).

Genetic diversity and lab-reared postlarvae introduction

A composition and genetic diversity analysis was conducted to evaluate the impact of adding nursery-reared postlarvae on the wild stock. For this, samples obtained in the study area in June and October 2019 were compared with a reference sample of wild *P. vannamei* collected in 2012 in Teacapán, located 30 km south of the study area. Fresh tissue samples were collected, preserved in alcohol, and sent to the Center for Aquaculture Technologies (San Diego, CA, USA) for DNA extraction and genotyping using 192 single nucleotide polymorphism (SNP) markers. Individual data profiles were depurated (those in which more than a third of the loci did not amplify were eliminated) and codified for analysis with GenAlEx (Peakall & Smouse 2012) and Arlequin v.3.5 (Excoffier et al. 2005).

Hardy-Weinberg equilibrium (HWE) was determined for each sample, and genetic diversity was assessed by estimating the number of alleles per locus (n_a), the effective number of alleles per locus (n_e), and expected (H_e) and observed heterozygosity (H_o). Student t-tests were used to evaluate significant sample differences (Pérez-Enríquez 2020). Additionally, to identify genetic profiles that were different from those of the wild population, a principal component analysis (PCA) was performed with the 'Adegenet' package (Jombart 2008) in R (R Core Team 2020). Finally, to evaluate the impact of postlarvae seeding on local shrimp production, a simple comparison was conducted with central tendency measures estimated from the annual production data obtained from different sources and dates (De la Lanza-Espino & García-Calderón 1991, Del Valle & Martín 1995, CONAPESCA 2020).

RESULTS

Only 52.3 million postlarvae were introduced into the HCCLS at the PL12 stage (~30 days old), which is the recommended stage for stocking based on the degree of maturity and the costs of maintaining postlarvae in hatcheries. Due to weather conditions that delayed flooding in the lagoon systems, this amount was 30% less than originally projected. Four regional laboratories collaborating within the Genetic Unit of Biosecure Massal Selection of Mexican Aquaculture Genetics (GENAMEX) system provided the hatchery recruits (Table 1). Before seeding, the postlarvae were acclimated to the existing environmental conditions and gradually released into the nurseries between July 15 and August 3, 2019. Approximately 1-2 ind m^{-2} of hatchery recruits were effectively added to the natural lagoon stock.

During the monitoring phase, 3780 individuals were collected during 10 sampling campaigns that were conducted over 1-2 days in 2019. A minimum and maximum of 67 and 1118 individuals were collected in June and September 2019, respectively. The TL and TW of the shrimp ranged from 27-170 mm and 0.2-41.2 g, respectively. The highest average values were observed in June, at the beginning of the study, and in September. The sex ratio was generally skewed in favor of females throughout the study (<5:1). However, it was much more balanced from September to November, with nearly 1.5 females for each male when all individuals were included (Table 2).

The parameter values of the weight-length relationship were estimated for the total number of pooled individuals. In all cases, a strong correlation ($R^2 = 0.91$) was observed with a mean allometric coefficient or growth rate (*b*) of 2.86, which ranged between 2.7 and 3.3. The estimated value for this coefficient was not significantly different from 3.0 ($P > 0.05$), indicating isometric growth (Table 3). Relative frequency histograms based on 5-mm length classes were used to detect age groups or cohorts. The relative assigned age (days) ranged from 60 (27 mm) to >100 days (>145 mm). Considering the cumulative relative length frequencies, the $TL_{50\%}$ was estimated to be ~110 mm (age >80 days).

Regarding the modal length assembly by sample, the addition of new cohorts to the shrimp population was apparent after the release of the reared postlarvae into the nurseries and perceptible in the samples collected on July 31, 2019, when the Tapos were still open and wild organisms could enter. This sample set contained the smallest shrimp length classes of the entire study, given that these samples were probably composed of pre-adult hatchery shrimp (Fig. 3). It is also important to note that a large fraction of the sampled population (54.5%) was composed of individuals ≥106 mm (110-mm class) and that 14.6% of the sampled population exhibited sizes ≥140 mm, indicating that these individuals were close to maturity and therefore able to migrate to the open sea to reproduce. This migration generally takes place in June and September.

The Huizache lagoon system displayed a relatively more homogenous length distribution, with most samples measuring between 60 (65 days) and 150 mm (100 days). On the other hand, the individuals from Caimanero were dominated by sizes larger than those found in Huizache. In Caimanero, the sizes of shrimp monotonically increased from the 75-mm size class to 160 mm, with a modal class of ~130 mm (90 days). A similar pattern was observed in the Cerritos Lagoon, with most of the sampled population measuring between 90 and 150 mm and more than 55% of the specimens reaching sizes greater than the $TL_{50\%}$ (Fig. 4).

To conclude the monitoring phase, three samples (190 individuals) were collected and processed for molecular analysis. The first sample (n = 66) was taken before postlarvae seeding (June 2019), while the second and largest sample (n = 122) was taken in October 2019. A wild *P. vannamei* sample (n = 22) from 2012 was obtained and included as a reference. Only 172 individuals had more than 127 successfully amplified loci (>66.6%) and were selected for further analysis.

The HWE analysis results indicated that deviations were present in four loci. Individuals were eliminated to avoid bias, and the sample size was reduced to 168 specimens for the three samples, with a total of 156 loci. The estimated values for the number of alleles per locus (n_a), the effective number of alleles per locus (n_e), and expected (H_e) and observed heterozygosity (H_o) were different among samples (Table 4), although these

Table 1. Data of *Penaeus vannamei* postlarvae released into five nursery sites in the Huizache-Caimanero and Cerritos lagoon systems.

Date	Commercial Lab supplier	Postlarve realesed (ind×10^6)	Release site (nursery)	Lagoon system
July 20, 21	Prolamar	16.3	Pozo del Caimán	Huizache
July 22	Biomarina	10.0	Candelones	Huizache
July 23	Biomarina	5.0	El Violín	Huizache
July 15, 22	Fitmar/Acuain	11.0	Pozo de la Hacienda	Caimanero
August 2, 3	Fitmar	5.0	Pozo de la Hacienda	Caimanero
July 20	Fitmar	5.0	El Puyeque	Cerritos
Total		52.3		

Table 2. Sample size by date (n), total length, total weight, and female:male sex ratio (F:M). Min: minimum, Avg: average, Max: maximum.

Date	n	F:M	Total length (mm)			Total weight (g)		
			Min	Avg	Max	Min	Avg	Max
18/06/2019	67	4:1	93	135.2	166	3.7	14.5	25.8
29/06/2019	170	3:1	73	105.8	147	3.0	9.9	27.8
18/07/2019	167	2:1	61	108.0	147	1.6	11.8	28.2
31/07/2019	276	5:1	27	88.7	150	0.2	7.0	24.0
21/08/2019	254	4:1	42	86.6	156	0.5	6.6	31.8
13/09/2019	1118	2:1	52	123.6	170	0.9	14.2	35.8
27/09/2019	389	1:1	75	117.2	165	2.2	12.1	25.6
09/10/2019	868	2:1	30	102.1	167	0.2	8.8	41.2
30/10/2019	253	1:1	32	71.2	116	0.2	3.2	12.9
29/11/2019	218	1:1	40	99.0	135	0.5	7.9	19.2
Total	3780	1.5:1	27	106.8	170	0.2	10.3	41.2

Table 3. Estimated growth and weight relationship parameters in the *Penaeus vannamei*. *b*: allometric growth parameter, *a*: constant.

Date	n	*b*	*a*	*exp a*	R^2
18/06/2019	67	3.1	-12.720	2.9907E-06	0.96
29/06/2019	170	3.3	-13.028	2.1979E-06	0.98
18/07/2019	167	3.2	-12.744	2.9198E-06	0.99
31/07/2019	276	2.9	-11.254	1.2955E-05	0.98
21/08/2019	254	3.2	-12.540	3.5805E-06	0.99
13/09/2019	1118	2.7	-10.378	3.1109E-05	0.93
27/09/2019	389	3.1	-12.476	3.8172E-06	0.92
09/10/2019	868	2.8	-10.985	1.6954E-05	0.96
30/10/2019	253	3.1	-12.325	4.4394E-06	0.98
29/11/2019	218	3.0	-11.629	8.9041E-06	0.97

differences were not statistically significant (Student t-test; $P > 0.05$), except for the HC-Nov-Teacapán comparison, which showed a significant difference in n_a ($P = 0.032$). Moreover, differences among samples were also not significant, given the global *Fst* value of 0.0022 ($P > 0.05$) of the analysis of molecular variance (AMOVA). Additionally, the PCA results did not indicate differences among samples, even when some individuals were graphed away from the center of the plot. No defined groups or structures were identified (Fig. 5).

Based on the data reported by De la Lanza-Espino & García-Calderón (1991), Del Valle & Martin (1995), and CONAPESCA (2020), a 1969/70-2018/19-time series of shrimp catches in the study area was reconstructed, with a data gap between 1988 to 1994. The average annual production during this time was deemed to be ~690 t. However, it nearly reached 1000 t during the period of 1969/70 to 1986/87 before falling to 355 t between 1994/95 and 2018/2019 (Fig. 6). The catch data displayed a monotonic reduction from the early 1990s to the present that dramatically culminated in an average of ~200 t during the 2014/2015 to 2018/2019 seasons (which includes the 30% estimated to be underreported by fishers). This value increased to ~230 t after the restocking program (CONAPESCA 2020), which was adjusted to ~330 t when the underreported 30% was added to the total.

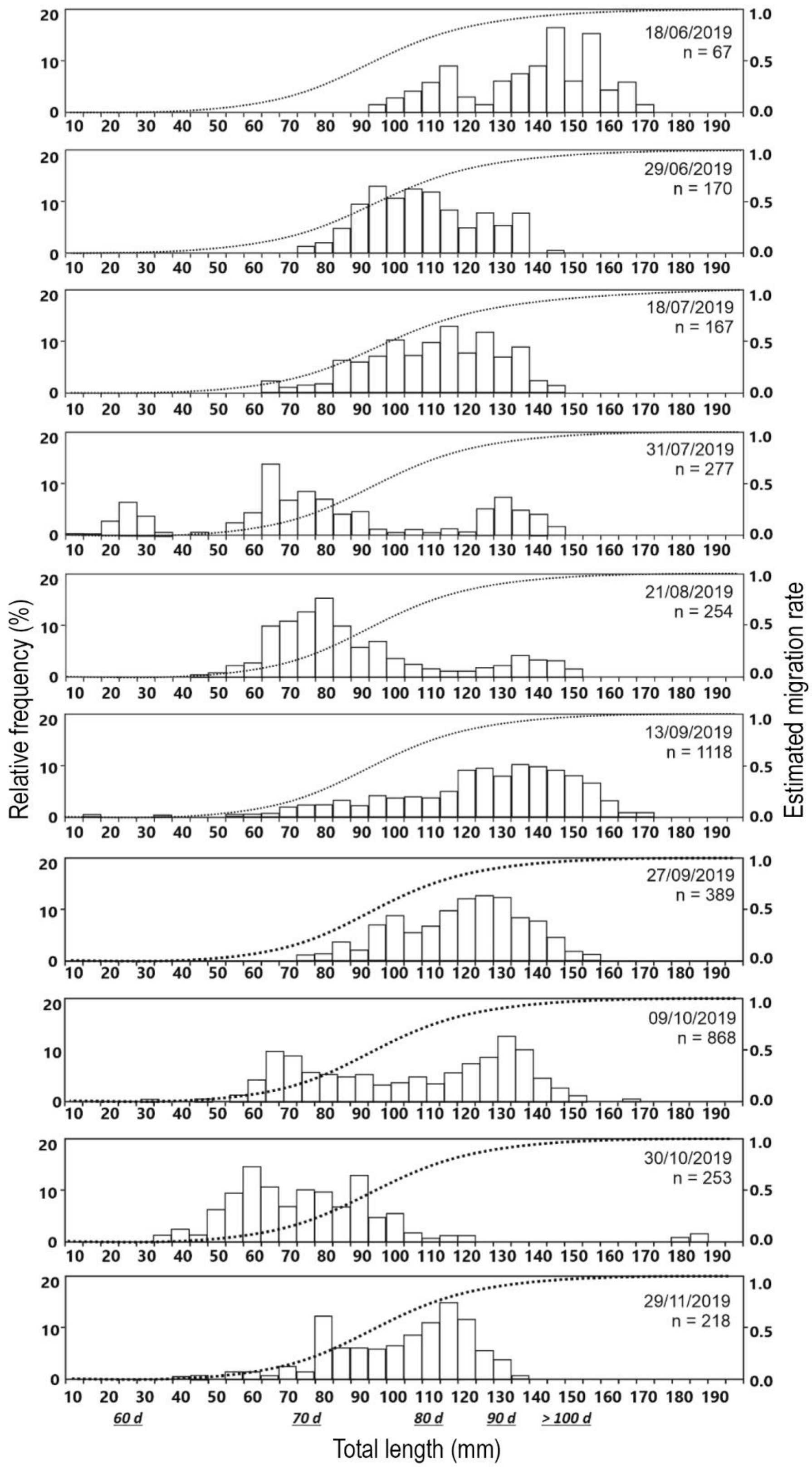

Figure 3. Total length distribution for *Penaeus vannamei* in samples obtained from June to November 2019 in lagoons in southern Sinaloa, Mexico. The *S*-curve symbolizes the total migration rate. Bold and underlined numbers on the x-axis represent the relative age in days.

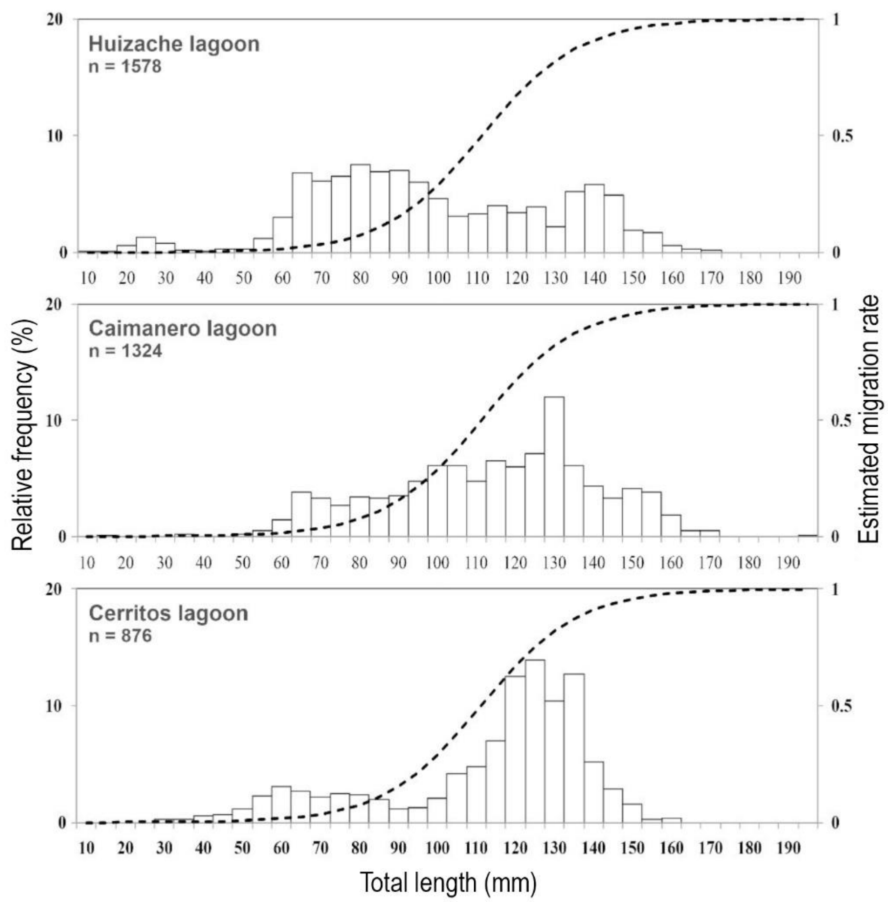

Figure 4. Total length distribution for *Penaeus vannamei* by lagoon system in southern Sinaloa, Mexico. The dashed line represents the total migration rate.

Table 4. Comparative genetic diversity among shrimp samples obtained in June 2019 (Huizache-Caimanero lagoon system; HC-Jun 2019), November 2019 (HC-Nov 2019), and 2012 (Teacapán 2012). Estimated values for the number of alleles per locus (n_a), effective number of alleles per locus (n_e), and expected (H_e) and observed heterozygosity (H_o).

Sample	n_a	n_e	H_o	H_e
HC-Jun 2019	1.982	1.612	0.367	0.344
HC-Nov 2019	1.996	1.629	0.348	0.357
Teacapán 2012	1.958	1.598	0.332	0.340

DISCUSSION

There is worldwide concern regarding the growing human population and its needs, particularly those related to food security. The proportion of the global population that is undernourished has also increased in recent years, which is partially due to the inequities among countries that have been exacerbated by unequal economic recovery to the COVID-19 pandemic (FAO et al. 2022). Global food production systems have developed strategies to reduce hunger and provide the elements needed for healthy diets, including supporting agriculture, poultry, and livestock production. Releasing reared individuals into natural populations has become a common strategy to maintain fishing, hunting, and logging practices. Although these practices carry economic and social benefits, they pose potential risks to wild populations, including the loss of genetic variation (Laikre et al. 2010), especially when these practices are improperly conducted.

A recent analysis by Kitada (2018) revealed that at least 187 aquatic species were released between 2011 and 2016 in 20 countries, with Japan releasing the most (72). Nearly all these animals were fish and mollusks, with salmonids being the most commonly released (reared and released by ten countries). Nonetheless, the majority of these releases were conducted without the support of proper studies to assess their effectiveness and the benefits to production in terms of the increase in fishery biomass derived from the interventions.

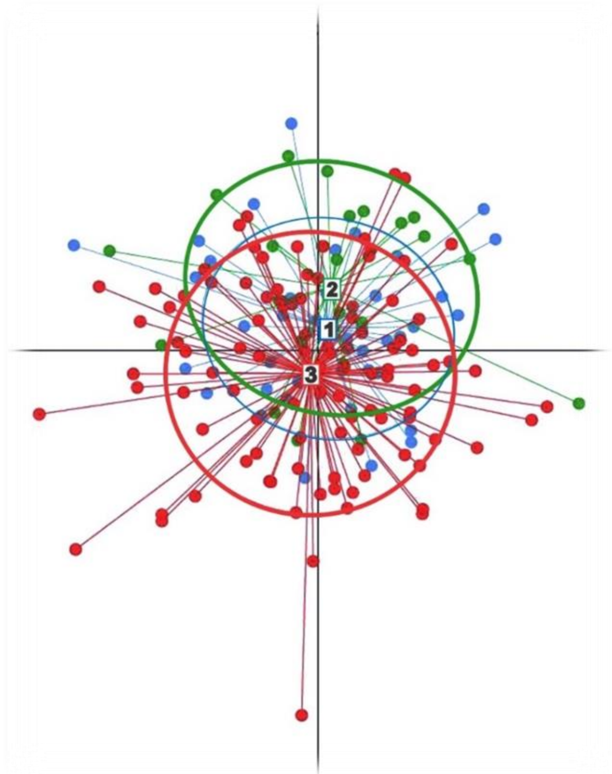

Figure 5. Principal component analysis (PCA, axis 1 and 2) for the genetic profiles of three *Penaeus vannamei* samples. 1) Huizache-Caimanero and Cerritos lagoon systems (HCCLS), June (blue); 2) reference sample, 2012 (green); and 3) HCCLS, November (red).

In Mexico, stock enhancements, mariculture, or restocking practices are limited or nonexistent. The efforts of this study are the first to document the release of reared shrimp larvae into a natural system to enhance fishing production in the country. These efforts resulted from collaborations on behalf of the government, fishers, the aquaculture industry, researchers, and other interested sectors. Despite our efforts, this study did not fulfill some expected conditions. For example, an unexpected delay in the rainy season and the reduction in the estimated supply of postlarvae resulted in the experiment beginning under a different scenario than the one planned. Nonetheless, the production obtained at the end of the fishing season was satisfactory. It constituted a near doubling of the average production of the previous five fishing seasons, according to official data from CONAPESCA (CONAPESCA 2020).

Although the results of this study were not sufficiently robust to definitively conclude that the increase in fishery production was only due to the release of postlarvae, it is important to highlight that the 52.3 million postlarvae that were released into the nurseries increased the density of the population to ~1-2 postlarvae per unit area, which may have been sufficient to overcome possible recruitment limitations and benefit production. Therefore, it is essential to repeat and improve this study to ensure that the results, which favorably increased the catch above the average value of the last five years, were not randomly obtained.

It is worth mentioning that the satisfactory results of this study may have been due in part to favorable environmental conditions within the HCCLS ecosystem that allowed for good water quality and high natural productivity to support the growing shrimp population throughout the experiment. This conclusion is supported by the estimated growth rate values of the samples, which were close to the isometric growth value (3.0) associated with healthy individuals. Also, the modal class analysis indicated that continuous recruitment occurs in the lagoons. Thus it is necessary to systematize monitoring efforts to gain experience, generate reliable data, and adequately manage the entry of postlarvae into the HCCLS. Moreover, it is necessary to catch and sow postlarvae in areas predefined as permanent nursery areas to reduce the need for postlarvae from hatcheries that could impact the genetic structure of the wild population. Therefore, an adaptive and responsible management scheme should be developed and followed.

According to De la Lanza-Espino & García-Calderón (1991), two maximum recruitment peaks for *P. vannamei* occur every year in the Huizache-Caimanero lagoon system in July and December, with the July peak contributing the most to sustain the fishery. However, the same authors point out that previous recruitment data is heterogeneous due to weather and hydrological conditions. These inconsistencies have been documented for many small-scale fisheries in Latin America and have contributed to the inadequacy of the existing data and information systems (Bermudez & Agüero 1994).

Despite the information gaps, our results confirm those from previous studies, such as those from Menz (1976), who reported that the sizes of shrimp in the Huizache lagoon are smaller on average than those in Caimanero despite both systems being connected. It is also remarkable that despite illegal and unreported catches, which have conservatively been estimated to be close to one-third of the reported total, most of the sampled individuals reached sizes near the $TL_{50\%}$ (~110 mm and 9.4 g). In contrast, 15% of individuals reached sizes that indicated they were near sexual maturity and thus could join the wild broodstock.

Another factor that contributed to the successful shrimp production in this study was the use of Tapos, a

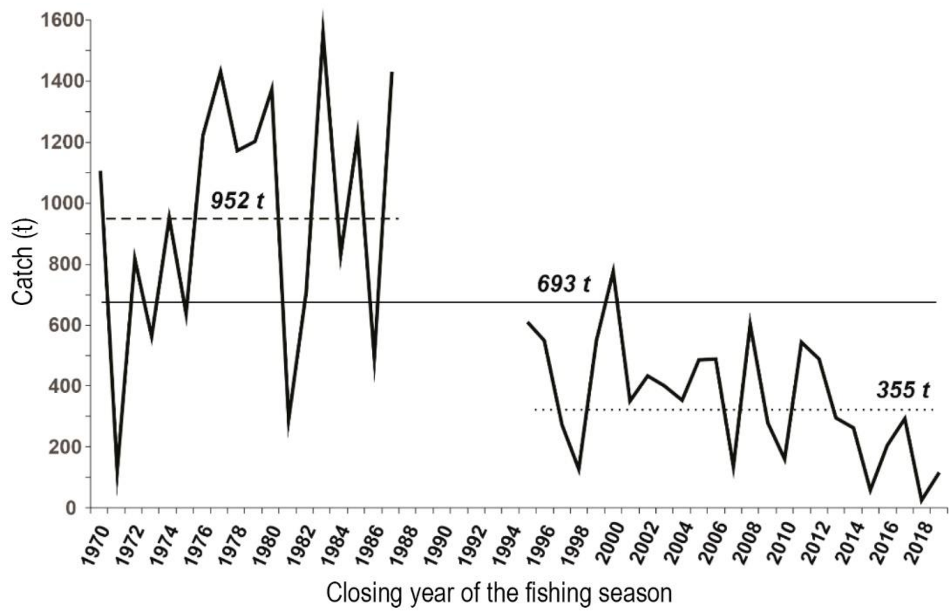

Figure 6. *Penaeus vannamei* catch volumes by fishing season (1969-1970 to 2018-2019). Horizontal lines represent the average catch from fishing seasons of 1969-70 to 1986-87 (- - - -) and 1994-95 to 2018-2019 (········) and the average for the total time series (———).

traditional system that controls horizontal shrimp movements, and the joint surveillance conducted by fishers and the Mexican Navy. Tapos maintain shrimp within the lagoons, allowing for the subsequent integration of lab-reared and wild recruits when their gates are closed. Thus, Tapos resemble an extensive shrimp culture system. In the present study, the wild population appeared dominant within the system. However, this result may also be explained by the genetic information of the laboratory-reared broodstock being similar to that of the wild broodstock. Indeed, the genetic diversity analysis results revealed that little to no significant differences were present between lots. To date, most genetic studies in farmed species have focused on fish, particularly salmonids (e.g. Pacific salmon and steelheads), and indicated that genetic changes within populations that have been subject to interventions reflect a homogenization of allele frequencies, genetic introgression, and changes in population structure (Kitada 2018).

In Mexico, few studies have been performed that evaluate the genetic effects of introducing cultured aquatic individuals into wild populations. Perez-Enriquez et al. (2018a) tracked the possible effects of the release or escape of *P. vannamei* from hatcheries on the genetic profiles of the wild stock. These authors concluded that the number of reared individuals that were released and their survival probability (3-6%) did not compromise the genetic integrity of the wild population. Despite this, the same research group (Perez-Enriquez et al. 2018a,b) suggests avoiding the release of lab-reared postlarvae to reduce the risk of genetic introgression. Cruz et al. (2004) used genomic techniques to manage breeding lines for aquaculture purposes and found a reduction in genetic variability when they compared consecutive generations and the founder stock. However, Valles-Jimenez et al. (2004) analyzed the genetic structure of *P. vannamei* populations from Mexico to Panama to define possible differences at the metapopulation level and concluded that none were significant. For the coasts of Sinaloa (>650 km), the results from Perez-Enriquez et al. (2018a,b) strengthen the idea of a panmictic population, which is consistent with the current results, with no evidence of possible genetic introgression.

In this study, the analysis of released aquaculture recruits suggests that a notable number of recruits (hatchery and wild type) were incorporated into the population. One of the objectives of this project was to protect natural recruitment. However, this claim should be taken cautiously. Although it is likely, this result may not necessarily be attributed to the experimental design, especially considering that no evidence was found of the presence of hatchery shrimp in the samples after their release. When natural recruitment considerably exceeds that of the introduced individuals, introgression or other genetic impacts are minimal (Kitada 2018). This may have occurred in the HCCLS during this study, with recruitment ranging between 900 to 2200 million postlarvae and an estimated survival rate of ~10% (De la Lanza-Espino & García-Calderón 1991).

Given our results, the release of hatchery postlarvae was positive, as adding postlarvae to the wild population resulted in surplus production, which may help avoid a potential future population collapse and alleviate the associated economic and social problems. Thus, we suggest that a comprehensive assessment of stock enhancement, such as the one implemented in this study, should be undertaken to complement any fisheries restocking program to better define the presence of hatchery cohorts added to the wild population, which will allow for improved estimates of the aggregate biomass that contributes to fisheries production.

It should be stressed that continuous surveillance of a fishery is required in proper evaluations to limit the uncertainty of the results. This study was successful in this regard. The results of this study suggest that a window of opportunity exists in which the controlled addition of larvae, preferably from the wild stock, may positively impact the biomass available for the spawning stock and consequently shrimp production. However, the results of this study must be confirmed to ensure that the outputs are derived from recruitment management and not from the direct consequences of environmental conditions or the biological variability of the resource in question.

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