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Review

Pacific oyster (*Crassostrea gigas*) aquaculture production in Chile: A review

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ABSTRACT. The aquaculture of Pacific or Japanese oyster (*Crassostrea gigas*) culture in Chile has been developed for almost five decades. Today, it is the most widely cultivated mollusk on the planet, given its introduction in more than 60 countries to produce high-quality protein. The Pacific oyster shows rapid growth in aquaculture production strategies in Chile. Pacific oyster farming is carried out along the entire coast of Chile, being a consolidated productive activity of economic interest in the southern part. By the end of the 1990s, the appearance of norovirus depressed its production, and some small-scale aquaculture producers currently sell their oyster production on the beach. Despite its extensive production, Chile has a significant information gap regarding this resource. This review addresses this gap and examines oyster culture in Chile, emphasizing the introduction stage of the species, production stages, culture methods, diseases, and regulatory, commercial, and social implications. Future challenges for Pacific oyster aquaculture include the production of juveniles in hatcheries to support aquaculture farmers and consolidate this species for the diversification of aquaculture in some coastal areas of Chile under conditions of productive management, simple technologies, and low initial investment. Conditions for the development of small-scale aquaculture systems. Finally, strengthening marketing actions will enable aquaculture farmers to move from a national scenario to the current demand in international markets.

Keywords: *Crassostrea gigas*; *Magallana gigas*; oyster industry; small-scale aquaculture; aquaculture production; economy

INTRODUCTION

The first studies on bivalve mollusks in Chile date back to 1960, mainly on farming the native Chilean oyster, *Ostrea chilensis* (Uriarte 2008). Chile has three macrozones with relatively homogeneous climatological, geological, and ecological attributes suitable for mollusk culture (Jerez & Figueroa 2008). Currently, bivalve mollusk aquaculture in Chile is represented by the Chilean mussel (*Mytilus chilensis*), followed by the Pacific scallop (*Argopecten purpuratus*), native oyster (*Ostrea chilensis*), and Pacific oyster (*Crassostrea gigas*). At least six other potential bivalve mollusk species are at different stages of technological development (Oliva et al. 2017).

Oyster farming in Chile dates back to the 19th century when the Chilean oyster was extracted and commercialized (*O. chilensis*). In 1943, the Pullinque oyster farm was created, and later, the Chilean state created several oyster farms in southern Chile (Morales-Cárdenas 2011). In 1983, after the privatization process, these farming centers were transferred

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to private companies. The native Chilean oyster has a wide geographic distribution spanning Chile and New Zealand (Chanley & Dinamani 1980). It can be found in Chile north of the Chiloé Island, the Guaitecas Islands, and the Aysén region (Solís 1967). A commercial size of 50 mm was reached after three years in suspended culture (Winter et al. 1984). The low growth rate of *O. chilensis* concerning Pacific oysters and other bivalve mollusks in the southern austral region of Chile was the main problem in commercial aquaculture development (Díaz & Sobenes 2022).

In this paper, we use the name *Crassostrea gigas* to refer to the Pacific oyster because of its historical, biological, and commercial significance in scientific literature. Although it is updated as *Magallana gigas* in WoRMS (2024), we consider the concerns raised by Bayne et al. (2017), where 27 researchers suggest that the proposed change in oyster classification may be premature and unnecessary. They recommend a more comprehensive analysis before deciding the implications for research and industry. On the other hand, Backeljau (2018) argues that maintaining the generic name *Crassostrea* is preferable for nomen-clatural stability and is consistent with existing phylogenetic evidence.

The Pacific oyster is a species that presents, on the one hand, high adaptability (i.e. resistance to changes in temperature, salinity, and pH) and, on the other hand, high reproduction and growth rates, which made it suitable for cultivation (Diederich et al. 2004, Troost 2010), since they could reach commercial harvest size in less than 18 months (Helm 2015). The Pacific oyster-growing countries are Canada, China, Korea, USA, Tahiti, Palau Islands, Australia, New Zealand, France, England, South Africa, and Chile (Uriarte 2008, Helm 2015). Both artisanal fishery groups and medium and large seafood companies have developed production in Chile. Geographically, the farmer cultured Pacific oysters in northern Chile between 19 and 21°S (Cultivos Marinos Sarmenia, Pesquera Flamenco, and Cultivos Marinos Tongoy), central zone between 29 and 33°S (Pesquera Ostramar and Hidrocultivos), and in the southern zone between 40 and 44°S (Cultivos Marinos del Pacífico, Pesquera Apiao, and Cultivos Achao). In Chile, various production methods have been used. Longline suspended culture systems in medium-depth waters are used for oyster culture in northern Chile, which is affected by biofouling incrustations that require continuous cleaning (Dawson 1985, Hauer 1988, Hoyl & Uribe 1990). In southern Chile, stretcher systems are employed in the intertidal plains, less affected by these incrustations (Avila et al. 1996).

History of *Crassostrea gigas* introductions

The Pacific oyster requires temperatures above 21°C to induce spawning in its natural environment (Helm 2015). However, in Chile, water temperatures on the north coast fluctuate between 18 and 19°C, except for occasional ENSO -El Niño Southern Oscillation- events (Blanco et al. 2002). Therefore, introducing this nonnative species in Chile required juvenile specimens produced in hatcheries where production conditions are controlled. Given this environmental constraint, the aquaculture industry dedicated to oyster culture had to source spat from hatcheries located in northern Chile, given the higher water temperatures compared to those in southern Chile.

C. gigas specimens were first introduced in 1977 in northern Chile (Caleta Los Pozos, Tongoy). The first import consisted of 40 kg of 1 cm juveniles from Lumi Tribal Enterprises, Seattle (Hoyl & Uribe 1990). Almost simultaneously, in the late 1970s, the Universidad Católica del Norte (UCN), associated with Fundación Chile (FCh), conducted the first culture trials of *C. gigas* on an import of 20,000 spat of 2-5 mm from Moss Landing, California (Hauer 1988). In the 1980s, FCh imported another batch of 120,000 2-5 mm units grown to commercial size. Based on these results, the FCh mariculture center in Tongoy (Cultimar) was founded in 1981 to supply interested national producers.

From the late 1980s to 2015, UCN organized international shellfish and fish farming courses in Chile in collaboration with the Japan International Cooperation Agency (JICA). Over 470 participants from 18 countries attended these courses, learning and mastering Pacific oyster production techniques. These participants, including those from Brazil (Suplicy 2022), have since been crucial in introducing and improving these techniques in their communities or countries, thereby becoming influential figures in aquaculture and Latin American and Caribbean development.

Production

Currently, the worldwide production of *C. gigas* spat in hatcheries is a standard technique that has been simplified and implemented in different countries (Helm & Millican 1977, Vásquez et al. 2007, Rico-Villa et al. 2009, Helm 2015, Reynaga-Franco et al. 2020). The Pacific oyster is cultivated in more than 60 countries due to the standardization of its production protocols and its high outputs in fecundity and growth (Diederich et al. 2004, Guo 2009) facilitated the work of each hatchery to adapt its production protocols according to the characteristics of its facilities, investment, and technological development (Reynaga-Franco et al. 2020).

Japanese technology was adapted to the culture of *C. gigas* in Chile; however, a retrospective look shows that it was necessary to adjust the vessels, types of lines, and anchoring systems, as well as to experiment with different qualities of culture materials (longlines, lanterns, or pearl-nets) (Dawson 1985, Hauer 1988). In addition, there was a lack of information on diseases and the embryonic legislative framework of the time.

In the mid-1980s, producers, authorities, and researchers met for the first time at the UCN for a working group to review Pacific oyster farming issues. This first aquaculture workshop made it possible to determine the technological gaps between Pacific oyster farming and the scallop (*Argopecten purpuratus*). This milestone also promoted the formation of the Chilean Oyster and Scallop Producers Association (APOOCH) in 1988 (Bakit et al. 2024). Among the difficulties recorded for Pacific oyster culture were the appearance of predators (crabs), biofouling in the culture systems, and polychaetes-bore worms. However, the first recorded mortalities did not exceed 7%, which generated reasonable expectations among stakeholders for Pacific oyster farming (Dawson 1985). By the mid-1980s, Cultimar produced 40 to 60 million 3-4 mm spat for domestic sale. Since domestic demand was low, it was exported to the USA and England, subject to production certification (Hauer 1988).

Farming strategies for the Pacific oyster followed the extensive farming techniques of the Chilean oyster, using stretcher systems for intertidal cultivation and suspended systems for subtidal zones in southern Chile (Andrade et al. 2004). The first harvest of *C. gigas*, as reported in official fishery statistics, dates back to 1986 at 244 t. By 1995, harvests had increased to 1,313 t (Fig. 1), mainly from farming centers in southern Chile. In the northern zone, the farming centers opted for the Pacific scallops (Avila et al. 1996).

By 1995, developing continuous oyster farming in Chile was feasible, given the opening of hatcheries that produced Pacific oyster spat. In northern Chile, the hatcheries of UCN and Cultimar were installed, while in the south, Fundación Chinquihue did so (Moller et al. 2001).

According to Uriarte (2008), there was a production boom in Pacific oysters between 1993 and 2005, surpassing the native Chilean oyster production (Fig. 1). In the late 1990s, 22 million oysters were exported (ca. 2,200 t). Thus, in 2001, Chilean oyster farming reached its peak production of 7,089 t, owing to the farming of Pacific oysters in the waters of the Chiloé Archipelago (southern Chile), where the most important companies were Pesquera Apiao and Cultivos Marinos del Pacífico (Félix Howard *comm. per.*).

Production phases and culture systems used

Broodstock and spawning

Since 1982, Pacific oyster aquaculture in Chile has been based on hatchery spat production. Initially, five hatcheries supplied the spat (Avila et al. 1996). Given their high production and maintenance costs, some hatcheries sought strategies to produce *C. gigas* spat commercially, reduced their production to profitable levels, and evaluated financing alternatives (i.e. research projects). Private initiatives such as Cultimar (FCh) opted only for mass production of *C. gigas* spat to supply the domestic market.

Hatcheries require dry and wet room facilities and equipment for larval and spat production (i.e. pumps, filters, UV sterilization, and temperature controllers). These are complemented by ponds of adequate volume, water supply, drainage systems, air supply, fresh water, and electrical power (Uriarte et al. 2001, Helm et al. 2004, Vásquez et al. 2007). Supposing the seawater supply comes from natural conditions, its quality will vary according to weather conditions and the dynamics of the seawater suction zone (i.e. closed, semi-closed, or open areas). These variations require constant monitoring of physicochemical parameters to ensure water quality. In installing an industrial hatchery, it is essential to define suitable sites for installing and constructing land-based culture and seawater collection systems (Merino et al. 2001).

The culture of bivalve mollusks in hatcheries requires the supply of microalgae as high-quality live food (Robert & Trintignac 1997, Helm et al. 2004, Cerviño-Otero et al. 2017). Microalgae production must be protocolized to properly feed oysters at different developmental stages (i.e. broodstock conditioning, larval culture, settlement, metamorphosis, and spat culture). Low microalgae production could generate insufficient feeding, whereas overproduction could increase costs (Reynaga-Franco et al. 2020). The strategy of microalgae production in hatcheries focuses on the culture of some flagellates such as *Isochrysis galbana* (clone T-Iso) and *Diacronema lutheri*, the diatoms *Chaetoceros gracilis*, *C. muelleri*, *Skeletonema costatum* and others such as *Tetraselmis suecica* and *Nannochloropsis oculata*.

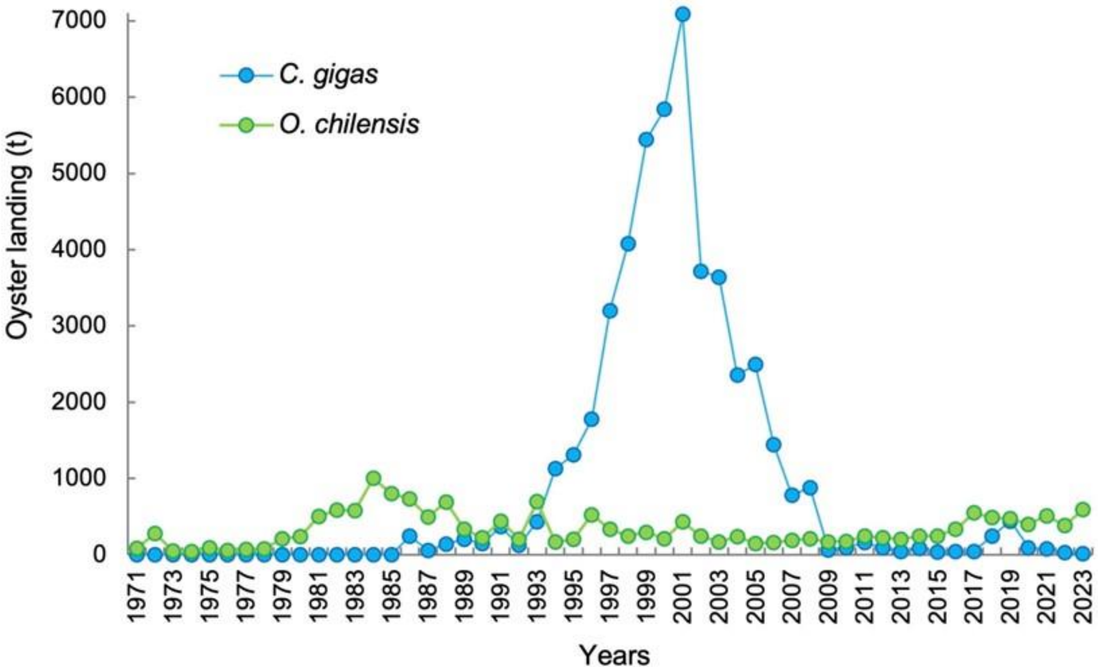

Figure 1. Chilean production of the Pacific oysters (*Crassostrea gigas*) and Chilean oysters (*Ostrea chilensis*) from 1971 to 2023. Elaborated from Anuarios de Sernapesca, Chile.

In Chile, *C. gigas* spawners have been kept in culture systems in a natural environment because the seawater surface temperature does not exceed 15-16°C, so spawning is unlikely to occur, but they are frequently sampled to determine their condition index and reproductive status. The identification and quantity of the individuals used in crosses, together with an adequate follow-up of the offspring, are key elements in improving the genetic variability of spat (Li et al. 2006, Reynaga-Franco et al. 2020). The feeding process (Fig. 2a) is fundamental to obtaining good-quality gametes during broodstock conditioning (Helm et al. 2004).

Gamete collection from Pacific oyster spawns is performed using stripping (Bresse & Malouf 1975, Robert & Gerard 1999, Helm et al. 2004, Cerviño-Otero et al. 2017). This technique performs fine cuts in the gonadal tissue with a scalpel. Then, each gonad is left in 500 mL beakers to separate the female and male gametes (Fig. 2b). Subsequently, the gametes are deposited in a 10 L container and fertilized. One of the disadvantages of this technique is the animal's death, leading to definitive loss of progeny; however, it is a fast method for selecting specimens (male/female) and obtaining gametes. The embryonic development process takes approximately 45-48 h at 24-25°C to obtain D larvae to start rearing (Fig. 2c).

Larval culture

The Pacific oyster's larval development is indirect, so it goes through several stages of planktonic life until metamorphosis, where it settles on a substrate to adhere definitively (Cerviño-Otero et al. 2017). Larval culture generally occurs in discontinuous batch systems (Fig. 2e) (Helm et al. 2004). Ponds with a capacity of ≥500 L are used. The water is changed every 24 h, and sieves from 50 to 150 µm are used for larval retention. For larval culture, 90 µm D-type larvae are placed at a density of 6 larvae mL^{-1}. In batch cultures, the larvae are retained on sieves, selected, and put in new ponds with previously microfiltered water (Fig. 2e). Microalgae-based feed is added to the pond according to the larval stage (i.e. D, veliger, umbonate, and pediveliger larvae). The culture temperature range varied between 24 and 27°C, thus ensuring larval growth and high survival. This Pacific oyster presents a daily growth of approximately 10 µm (Robert & Gerard 1999), reaching the pediveliger larva between 18 and 22 days grown at 28°C and at densities between 1 and 5 larvae mL^{-1}. The pediveliger larva is 330 µm valvar length, showing one spot on each side of the body and one developed foot (Cerviño-Otero et al. 2017). To the UCN hatchery with temperatures close to 25°C, pediveliger competent larvae (Fig. 2d) ± 350 µm are achieved in 28 to 32 days (Carlos Basulto *comm.*

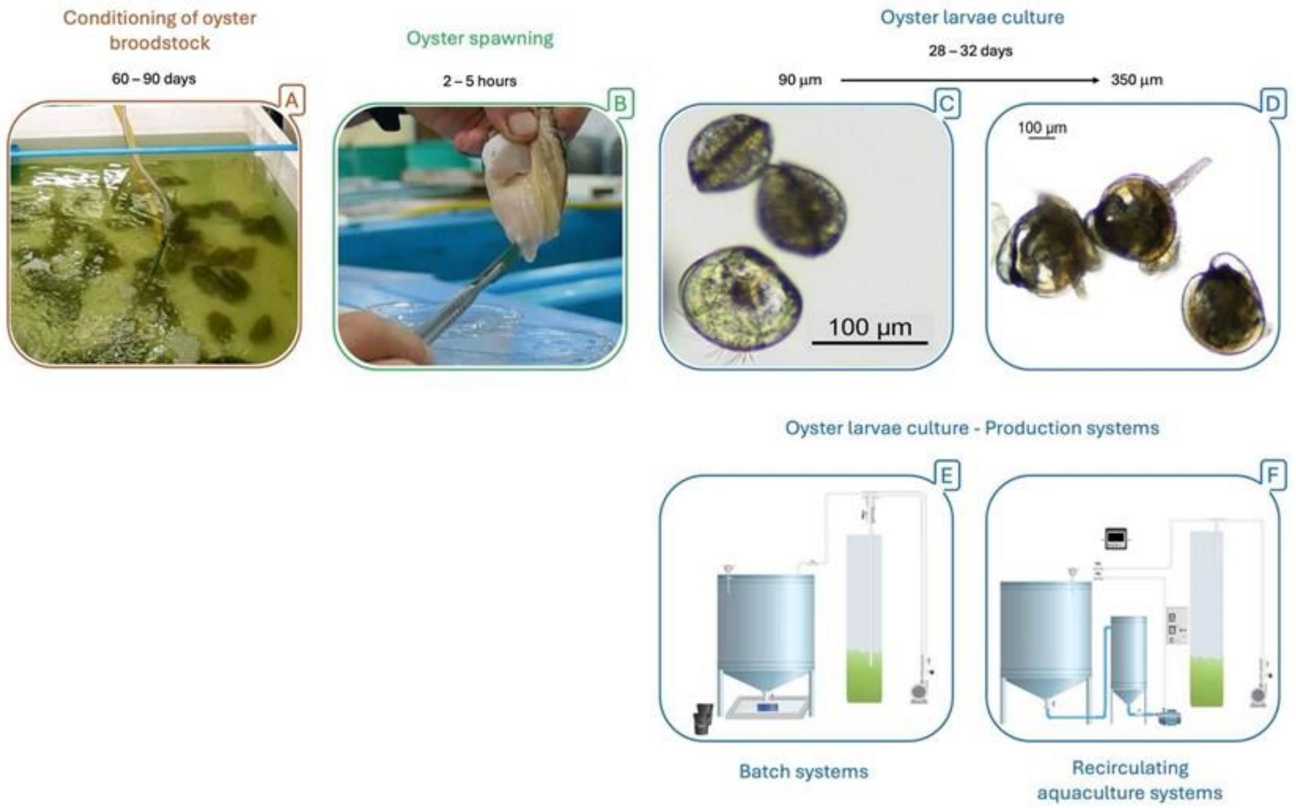

Figure 2. Broodstock, spawning, and larvae culture of Pacific oysters (*Crassostrea gigas*). ©Photos credits by Lira, G. and Abarca, A.

pers.). This methodology requires monitoring of the physical and chemical parameters of seawater. Other larval culture techniques associated with the continuous flow of recirculated seawater or recirculating aquaculture system (RAS) are being used (Fig. 2f), where high larval densities can be achieved, resulting in better survival and shorter culture times in the settlement and growth phases (Rico-Villa et al. 2008, Cerviño-Otero et al. 2017, Ramos et al. 2022).

For larval settlement and metamorphosis, neurotransmitters are used in some hatcheries to accelerate the process (Coon et al. 1990, Beiras & Widdows 1995, Robert & Gerard 1999). In other hatcheries, larval settlement is achieved without the use of chemicals. Instead, trays with sieves at the bottom and ground molluscan shells are utilized (300-400 µm), which provide a substrate for larvae to attach individually (Breese & Malouf 1975, Cerviño-Otero et al. 2017). Other larval settlement techniques have been performed on whole oysters or scallop shells.

Spat culture

Pacific oyster spat is produced in controlled environment systems for settlement and metamorphosis from pediveliger larvae (Fig. 3a). The first system uses recirculation (Fig. 3c), which involves water reuse within the pond, including a booster pump, a biofiltration system, and a heat pump; however, this system promotes efficiency and sustainability in production methods (Badiola et al. 2018). Competent larvae (± 350 µm) are placed on litters with a sieve mesh, and a layer of ground spat shell at a density of 30 larvae cm^{-2}. The settling and metamorphosis process can last from 2 to 5 days. The generated post-larvae are maintained for 30 to 35 days until they reach more than 2 mm (Fig. 3b). The RAS system draws water from the pond. It passes through a sieve containing the larvae fixed in the ground shell, creating a recirculating flow (Ramos et al. 2022). A second controlled environment system is downwelling, where downflow (Fig. 3d) allows

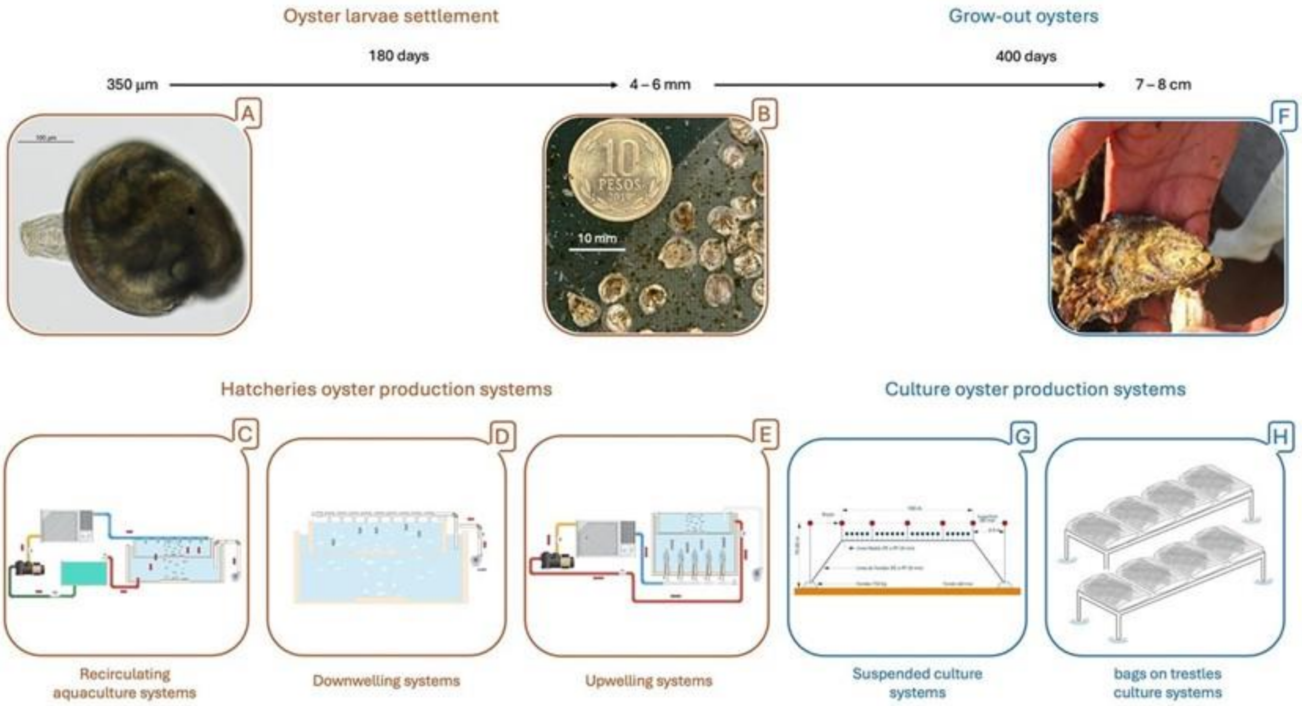

Figure 3. Systems used to settle and grow out Pacific oysters (*Crassostrea gigas*). ©Photos credits by Lira, G. and Abarca, A.

post larvae to attach to the shell substrate and grow to a size close to 3-4 mm. The initial density ranges between 20 and 30 larvae cm^{-2}, and the competent larvae are placed on litters with a sieve mesh and a layer of ground spat shell. The operational parameters for both environmentally controlled systems should be kept at 25°C temperature, 34 salinity, and pH close to 8; Feeding should be maintained at a daily density of 7,000,000 cells mL^{-1}; and operational devices used are 100×50 cm L with a 200 µm sieve mesh, and a 1.0 mm layer of ground spat shell.

Once a size greater than 2-3 mm is reached, the spat generated in RAS or downwelling systems is transferred to systems with upwelling technology (Fig. 3e), where the upward flow can allow a higher concentration of spat per cm$_2$ due to greater availability of nutrients associated with a water circulation system that helps reduce the accumulation of wastes and improve oxygenation in the system. In addition, with this upwelling system, it is possible to increase the spat in smaller spaces in the laboratory by preventing the spat from forming aggregates together (Cerviño-Otero et al. 2017). When the spat are larger than 6 mm (Fig. 3b), they are sent to sea. One commercial hatchery and three laboratories from foundations or universities still produce spat, the first on a lower scale and the second mainly for research purposes (Cárcamo et al. 2023).

Grow-out culture technology

The primary technology used in Chile for the marine culture of *C. gigas* is suspended systems (Fig. 3g), where lanterns or pearl nets stand out from longlines (Robledo & Novoa 2021, Díaz & Sobenes 2022). Longlines of 100-200 m and buoys are used for aquaculture and to avoid sinking. 50,000 to 100,000 individuals per longline are used as pre-determined culture densities (Robledo & Novoa (2021), allowing aquaculture labor in the systems. The suspended systems are used mainly in the northern zone, while in the south, taking advantage of the large extensions of intertidal environments, the oyster bags on trestles systems are used for the marine culture of *C. gigas*. The trestles, 2 m in length and metal or wood materialized, bring support to place the oyster bags (Fig. 3h). Their arrangement in the intertidal zone allows the oysters to be exposed to air and sun at low tide, which contributes to the release of epibiont organisms that affect the production of oysters (Cárcamo et al. 2022). The trays on top of the trestles are 1.5×0.8 m and can tolerate long periods underwater. To protect the spat from predators, they are covered with shade netting. Planting density depends on the size of the spat.

The technology to cultivate the Pacific spat depends on the presentation format of the product. This condition, provided by the destination markets, differentiates a product that presents the meat and shell well to final consumers. In contrast, the presentation of the oyster meat product (IQF) loses relevance. Thus, producing oyster specimens in shells starts with individual spat, with densities of three individuals in netted bags on trestle systems or higher densities in suspended longline systems. For meat production, oyster larvae are settled on shell collars (substrate) in a remote attachment system in hatcheries and are maintained in seawater tanks at 28°C. The substrate and spat attached are then taken to the sea, where 4 to 12 oysters grow per substrate (Ronald Gil, *comm. pers.*). For small coastal communities, the *chinguillos* aquaculture systems emerged as a window of opportunities to improve their livelihoods (Robledo & Novoa 2021). Of these, *chinguillos* have lower investment costs because they are handmade from the remains of fishing nets. Lanterns, on the other hand, have higher investment and maintenance costs than *chinguillos*. In northern Chile, the juveniles placed in culture systems reach commercial size (Fig. 3f) in 14-16 months, while in southern Chile, size is reached in 15-20 months. In both zones, spring and summer promote significantly increased size between 70-80 mm valvar length (Ronald Gil, *comm. pers.*).

Diseases and public health

Cultured oysters are susceptible to various pathogens such as viruses (herpesvirus), bacteria (*Vibrio* sp.), and protozoa. These pathogens can lead to mass mortalities in both natural environments and hatchery production (Renault et al. 2000). In some cases, they can cause gastroenteritis in consumers (Gill et al. 1983). However, no mass mortalities associated with diseases listed by the World Organization for Animal Health (WOAH) have been reported in Chile during commercial oyster culture. Cellular abnormalities in the digestive tracts of *C. gigas* larvae from a southern Chile hatchery were reported in a study by Gonzalez et al. (1999). It was suggested that a marine fungus like *Hyalochlorella* sp. caused these abnormalities (Elston 1980).

In the early 2000s, norovirus, a human enteric virus causing food poisoning (Gill et al. 1983, O'Ryan et al. 1998, Le Guyander et al. 2006, McLeod et al. 2009), was found in Pacific oyster production intended for Asian markets. This reduced production as the Asian markets requested certification guaranteeing Chilean Pacific oysters were norovirus-free. The presence of norovirus in the waters of Chiloé in the early 2000s was linked to the absence of sewage treatment plants and led to the closure of international markets. Production companies in Chile ceased operations due to this, and only a few remain today (Cárcamo et al. 2022). However, according to Campalans & Lohrmann (2009), an analysis of mollusks cultivated in Chile, including general bivalves and *C. gigas* oysters, concluded that they were free of pathogens listed by the WOAH.

The presence of microplastics (MPs) associated with commercially and ecologically essential mollusks has become an urgent concern over the last decade. Due to their chemical properties and long degradation time, these MPs persist long (Zhang et al. 2022). According to Zhu et al. (2021), some MPs, such as rayon and polyester (PES), are in high proportions in China's water, fish, and oyster tissues. Gaspar et al. (2018) confirmed the accumulation of nanoparticles of MPs in the oyster *C. virginica*, mainly in the hepatopancreas tissue. Meanwhile, Sussarellu et al. (2016) assessed the impact of polystyrene microspheres on energy intake, reproduction, and offspring performance in *C. gigas*, emphasizing the ecological consequences for marine ecosystems. It is worth noting that these MPs mainly come from aquaculture and environmental processes, and they can cause severe problems and reduce the quality of aquaculture products and human health (Wu et al. 2023).

Regulations and legal aspects

During the early production of Pacific oysters in Chile, there were no clear or specific environmental regulations for cultivating this resource (Avila et al. 1996). The various decrees enacted by the Ministry of Economy have established a regulatory framework for aquaculture development in Chile (Table 1). Among the regulations issued, the following stand out: the limitation of areas for aquaculture concessions and authorizations (D.S. 550, 1992); the national aquaculture registry (D.S. 499, 1994); the regulation for the internment of first import species (D.S. 730, 1995); and the procedure for the importation of hydrobiological species (D.S. 96, 1996).

Some sanitary regulations of the destination markets were necessary for implementation among Chilean Pacific oyster producers. The first measure was established by the U.S. Food and Drug Administration (FDA) and requires certification of cultivation areas. This measure sought to evaluate microbiological parameters and the presence or absence of toxic microalgae (HABs) (Avila et al. 1996). The second measure was the Bivalve Molluscan Shellfish Health Program (PSMB, by its Spanish acronym), which seeks

Table 1. Chronology of regulations in Chilean Aquaculture standards that affected/promoted Pacific oyster farming. (1) MINECOM; Ministry of Economy, Development and Reconstruction. (2) MINSEGEGOB: Ministry of the General Secretary of the Government. (3) MINSAL: Ministry of Health. (4) MINDEF: Ministry of National Defense.

Ministry - Decree ID - year	Purpose of the standard or regulation	Short URL
MINECOM (1) D.S. 550, 1992	Decree on the regulation of authorizations and the limitation of the size of aquaculture concessions for breeding fish and mollusks	https://bcn.cl/3myor
MINECOM D.S. 499, 1994	The Decree established the National Aquaculture Register as the responsibility of the National Fisheries Service to regulate entries and operations	https://bcn.cl/3lb5e
MINSEGEGOB (2) Law 19300 - 1994	National legislation that promotes the right to live in an environment free from pollution, the protection of the environment, the preservation of nature, and the conservation of the environmental heritage	https://bcn.cl/3i87k
MINECOM D.S. 730, 1995	Regulations for the initial introduction of the species with specific study requirements. Includes knowledge of the life cycle, diseases, isolation units, geographical zones, point of origin and destination	https://bcn.cl/3lvpa
MINECOM D.S. 96, 1996	Decree regulating the procedures for importing hydrobiological species into the country, their foreign origin, and where they need to go	https://bcn.cl/3myr4
MINSAL (3) D.S. 977, 1996	The Bivalve Mollusks Sanitary Program is established under Supreme Decree 977/96 and the Food Sanitary Regulations, which establish the sanitary conditions for the production, importation, processing, storage, distribution, and sale of food, including bivalve mollusks, to protect public health and guarantee food safety.	https://bcn.cl/2mgdw
MINSEGEGOB D.S. 30, 1997	Legislative Decree establishes the Environmental Impact Assessment and Community Participation System rules, following the provisions of Law No. 19,300 on General Environmental Principles	https://bcn.cl/3lb6r
MINECOM D.S. 320, 2001	Regulation that establishes measures to ensure that aquaculture centers maintain the ecological balance and operate following the capacity of the body of water in which the granted area is located	https://bcn.cl/3l62c
MINDEF (4) D.S. 626, 2001	Regulation of certification and other sanitary requirements for the importation of hydrobiological species	https://bcn.cl/3mo02
D.S. 345, 2005	The regulation establishes protection and control measures to prevent the introduction of species that constitute hydrobiological pests, isolate their presence, prevent their propagation, and tend to their eradication.	https://bcn.cl/3gyy3
MINECOM Res. 2536, 2006	Classification of high-risk diseases	https://bcn.cl/3muoo
MINECOM Res.Ex. 3411, 2006	Regulation that establishes the methods of analysis for the elaboration of the preliminary characterization of the site and the environmental information for the aquaculture concessions	https://bcn.cl/3n0md

to comply with the requirements established by the European Union, Singapore, and the USA. This program classifies and monitors bivalve mollusk production areas and other resources susceptible to marine toxins. Both regulatory measures were supervised by Servicio Nacional de Pesca y Acuicultura (SERNAPESCA).

Environmental regulations include the 1997 Environmental Impact Assessment System (SEIA) created with the enactment of the 1994 General Environmental Bases Law. Previously, some decrees applied only to a fraction of the aquaculture activity (i.e. D.S. 175, 1980 and D.S. 427, 1989, Table 1). In 2001, the Environmental Regulation for Aquaculture (RAMA, by its Spanish acronym) established guidelines for the environmentally sustainable development of aquaculture (D.S. 320, 2001, Table 1). Other regulatory measures were the protection, control, and eradication of high-risk diseases for species (D.S. 319, 2001); the regulation of certification and other sanitary requirements for the importation of hydrobiological species (D.S. 626, 2001); the regulation on hydrobiological diseases (D.S. 345, 2005); and the updating of contents and methodologies to prepare the preliminary site characterization, as well as the environmental information of the cultivation centers (R.E. 3411, 2006, Table 1).

Since the mid-2010s, with the creation of the National Institute for Sustainable Development of Artisanal Fisheries and Aquaculture (INDESPA, by its Spanish acronym), a boost towards small-scale aquaculture (SSA) has been promoted in an articulated manner (i.e. public institutions and instruments). SSA in Chile presents a rapid growth justified by its production potential, practices, and high capacity to generate work and welfare, particularly in the most depressed rural sectors (INDESPA 2017). Currently, there are very few hatcheries in Chile that generate oyster spat. A recent Corfo diversification program aimed to recover the cultivation of this oyster through new technologies that enable continuous production, improved survival rates, standardized and cost-effective technologies, and technology transfer to small-scale aquaculture farmers to enhance national and international marketing.

Economic issues

The Pacific oyster was commercialized in Chile in the late 1970s. Introducing this species in Chile responded to both its commercial value in the market and its desirable characteristics for aquaculture (Díaz & Sobenes 2022). According to Villarroel (2021), the expeditious introduction of the Pacific oyster was historically contextualized by a decrease in economic activity, employment, and productivity associated with landings of the Chilean oyster (*O. chilensis*) in the 1960s. Thus, producing Pacific oysters was seen as a strategy to protect local economies by replacing native bivalves with declining populations (Carrasco & Barón 2010). The rapid migration from cultivation of the local species (*O. chilensis*) to the exotic species (*C. gigas*) was because the former grows too slowly compared to the exotic species (Díaz & Sobenes 2022). The reduction of time in the aquaculture production processes resulted in lower costs for the management of the culture system and obtaining economic returns in a shorter period (Molina et al. 2012, Pérez 2014), as well as the reduction of the risk associated with the impact of abrupt climatic events on the culture (Ruiz & Zúñiga-Jara 2018).

One of the obstacles presented by the Pacific oyster industry that impacts economic performance to this day is the impossibility of capitalizing on wild populations that would allow the replenishment of larvae from natural banks (Martínez-García et al. 2022). This situation forced producers to look for *C. gigas* larvae in hatcheries to satisfy their needs, raising production costs and decreasing profit margins. Currently, the supply of *C. gigas* spat for culture comes from the central-northern part of the country (Díaz & Sobenes 2022), which implies a transfer cost for cultures that are not in the surrounding area. Another problem, with repercussions in increased production costs, is encrusting and perforating species, which intensify the work of cleaning the culture systems and can affect the final product's appearance (López et al. 2008).

Exports and national trade

The marketing of the Pacific oyster was initially oriented to the domestic market. Exports began at the end of the 1980s and were consolidated in the 1990s. After the decrease in Pacific oyster exports, the national supply of this product also decreased. Figure 4 shows the Chilean current *C. gigas* production scenario, where only 27 concessions from the more than 400 authorized register production.

The dynamics of domestic marketing of Pacific oysters was conducted in local markets through a reduced value chain. This situation can be explained by low demand from the domestic market (Lopez et al. 2008) due to Chilean consumers' preferences for varied sizes and tastes (Félix Howard *comm. pers.*). Another aspect that defined the domestic market was the low level of associativity among small oyster producers, which limited their productive scale (supply) and hindered them from participating in the national mass market (retail) and accessing the export market. In the domestic market, Pacific oysters reached sales of between US$0.37 and 0.60 per unit in fresh format and US$0.49 for the frozen half-shell format (Cárcamo et al. 2023). To meet the growing needs of the artisanal and SSA fishing sector, another product sold on the domestic market was Pacific oyster larvae and spat, which were sold by size. Prices are c.a. US$590 for one million larvae and c.a. US$39,698 for one million 4 mm spat. The latter amount results from the market value of US$0.00834 per mm spat plus taxes in Chile (Carlos Basulto *comm. pers.*). The considerable price increase between larvae and spat is due to the time that elapses between both stages, where energy, food, and personnel must be financed. The average dollar value for 2023 was US$1.00: CL$839.80 (www.sii.cl).

Exports increased in the 1990s, with the primary markets being Japan, Taiwan, China, and Singapore (Uriarte 2008). Sales peaked in 1999 at approximately US$2.73 million (not adjusted for inflation). In 2004, the most significant volume of Pacific oyster exports, reaching 1,077 m, was recorded (FAO 2023). Exports of various industrial products to the Asian market were made in formats such as Individual Quick Freezing

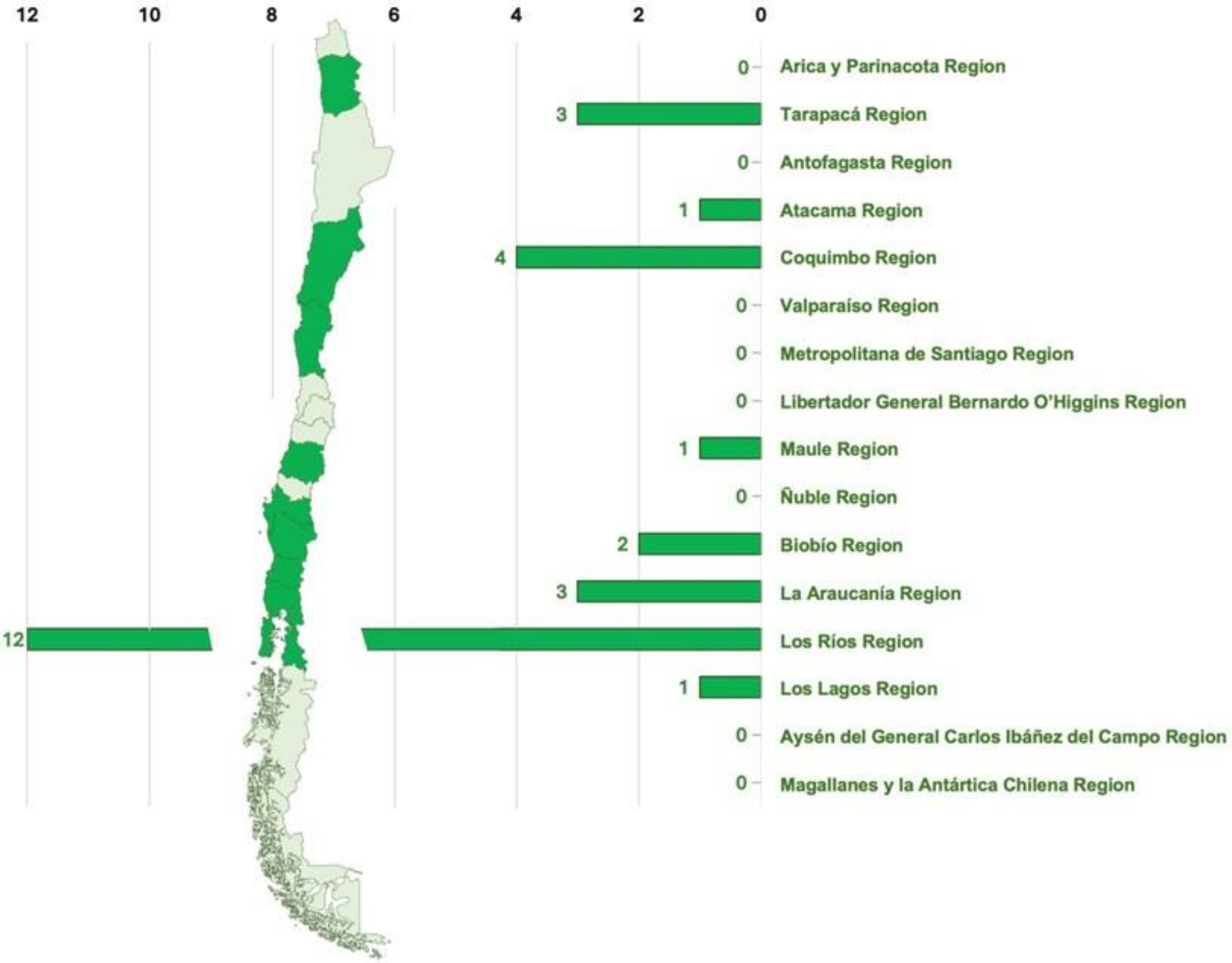

Figure 4. Geographical distribution of active aquaculture production of Pacific oysters (*Crassostrea gigas*) to 2023 (Source: SERNAPESCA 2024).

(IQF), half shell, fresh-refrigerated, whole frozen, and frozen block meat (Ronald Gil, *comm. pers.*). In the 1990s, the main export format was fresh-refrigerated, whereas in the 2000s, frozen meat in blocks of 50 kg^{-1} units predominated (Uriarte 2008). Other significant milestones in the diversification of products and markets were the export of spat from 2014 to the Canadian (Aqua 2014) and Brazilian (Cárcamo et al. 2023) markets, furthermore the export of fresh, chilled oysters and half-shells to Latin American markets (Avila et al. 1996). Prices were c.a. US$6.00 for frozen oyster meat, while the meat in IQF format varied between US$6.00 and 8.00. In 2021, around 1.2 million tons of exports, valued at US$658,990, were recorded. These exports were shipped to various destinations, including Canada, Mexico, and South Africa. Oyster larvae from Chile were also included in the exports. However, it was challenging to quantify prices and quantities accurately due to using the same tariff code for fresh/chilled live oysters and oyster larvae (Prochile 2017). The consumption of Pacific oysters from Chile had different preparations depending on the consumers in the destination markets. They highlighted the preparation of dishes such as sushi in Japan, so it reached high prices and value addition (Technopress 2003); in Mexico, it was consumed naturally, steamed and in haute cuisine, so it is food that was consumed on special occasions and in small quantities due to its high price (Prochile 2011); in South Africa, meanwhile, the oyster found a niche market given the recent expansion of the culinary offer of seafood products (Prochile 2017).

Social implications

By 2001, a period in which landings of 7,089 mt were recorded, Pacific oysters were produced in both northern and southern Chile only by aquaculture companies, and there was no record of landings by artisanal fisheries (SERNAPESCA 2023). Thus, by the mid-2000s, following the sanitary requirements of Asian destination markets, the massive Pacific oyster farms gradually ceased operations and, by 2011, no longer generated production (SERNAPESCA 2023). By 2023, 30-40 small producers were still involved in Pacific oyster aquaculture, which they combined with Chilean oyster farming to supply the domestic market (Cárcamo et al. 2023). Labor supply was reduced, generating workers' migration to other productive activities. The aquaculture industry, not exempt from the migration of workers, saw an increase in the participation of women in the workforce and faced challenges of wage equity and other challenges related to social security, such as education and the availability of safe day care centers for workers' children (Ramírez & Ruerd 2015).

Aquaculture is a productive industrial activity that is developed mainly in natural public spaces, such as marine and inland waters (Silva et al. 2012), so it must be projected so as not to negatively affect other local and regional economic activities, such as tourism and fishing (Carrasco & Barón 2010). Thus, state initiatives have developed an analysis of the potential species that promote aquaculture diversification in Chile. The combination of traditional knowledge of artisanal fishing communities and scientific knowledge sought to use the same technology for the culture of the Pacific scallop (*A. purpuratus*) in the culture of the Pacific oyster (Robledo & Novoa 2021), under which both sectors were motivated to develop public-private actions similar to those that allowed the promotion of the scallop industry (Von Brand et al. 2016, Bakit et al. 2022). The immediate beneficiaries of the economic policy actions aimed at boosting the Pacific oyster industry are the holders of aquaculture concessions granted for farming this species in the national territory (Fig. 5).

SSA in Latin America and the Caribbean (LAC) is presented as an opportunity to achieve the FAO's sustainable development goals (SDGs) through the capture or production of food from sustainable aquaculture to produce high-quality protein at low cost, enhance food security, and create better social development and livelihoods in LAC countries (FAO 2023). Thus, SSA is an opportunity to boost the Pacific oyster industry, including non-industrial production in limited areas associated with simple technologies and low initial investment.

According to a study by Guisado et al. (2017), the productive estimates for the establishment of a Japanese oyster culture of 59 mt (SSA strategy), 6.3 ha of aquaculture concession, and an amount c.a. US$370,000 is required to finance the initial investment and fixed and variable costs. In addition to the SSA strategy, Benthic resource management and exploitation areas (AMERB, by its Spanish acronym) are granted to artisanal fisher's organizations, which can access aquaculture concessions and state support for their immersion in aquaculture. In favor of the incorporation of SSAs and AMERBs in Pacific oyster aquaculture, the high feasibility of transferring simple and low-cost farming technologies to improve the productivity of groups of associated fishers (Robledo & Novoa 2021) and successful transformation from artisanal fishers to SSA, as in the scallop industry (Bakit et al. 2023). Challenges to be overcome include the supply of spat, which today is limited and geographically concentrated at almost 98% in the northern of Chile (Díaz & Sobenes 2022); social and organizational work, which would allow many groups of artisanal fishers to work in association to add their productions and achieve bargaining power with clients (Cárcamo et al. 2023), thus accessing the profits received in the commercialization process (i.e. restaurants, retail, and exports) and circumvent beach sales (Wurmann-Gotfrit 2008).

Future challenges for *C. gigas* culture in Chile

Consolidating *C. gigas* culture in Chile requires addressing productive, economic, and social gaps. Aquaculture initiatives can be undertaken by private companies with state support (Bakit et al. 2024), taking care that government investments do not replace business innovation (Shaddady 2022) and that they persist beyond the period in which state support is sustained (Miranda & Stotz 2021). Initiatives with permanent government funding have also been conducted in other countries (Chávez-Villalba 2014).

At the productive level, it is necessary to advance the standardization of larval and spat production in hatcheries and install the required technical capacities in the personnel of these controlled environment systems. Another production challenge is investigating the effects of pathogens' health effects, harmful algal blooms, and heavy metals on *C. gigas* production.

Technology transfer issues related to sea farming techniques must also be addressed to generate a positive impact on the Pacific oyster industry in Chile.

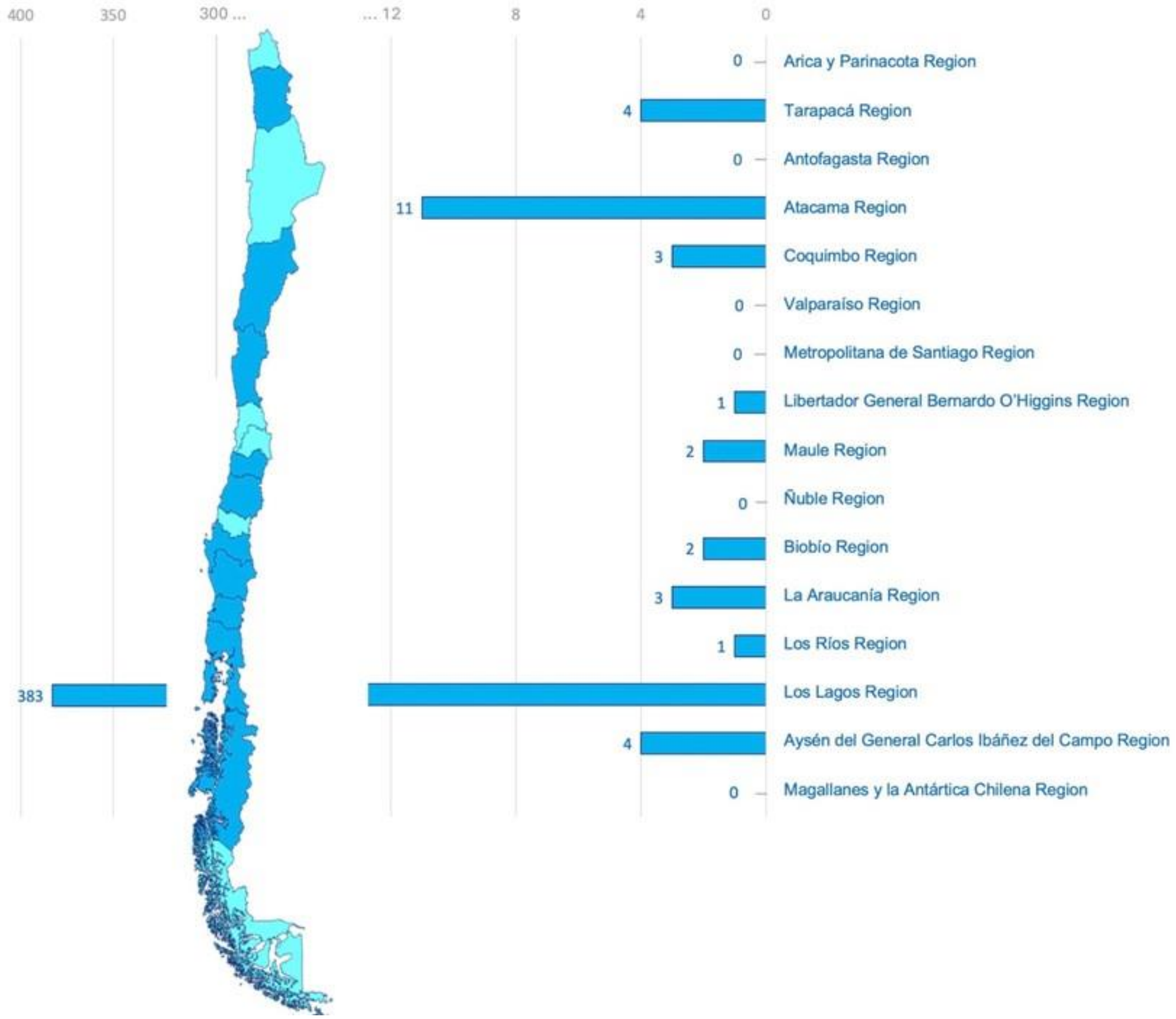

Figure 5. Geographical distribution of aquaculture concessions granted for farming Pacific oysters (*Crassostrea gigas*) to 2023. (Source: SUBPESCA 2023).

Issues of culture systems, system maintenance, and intermediate management of the Pacific oyster (nursery) are a priority along with harvesting. Land and sea farming competencies should consider both industrial entrepreneurs and the existing potential of small-scale fisheries and AMERBs co-management systems (Fig. 5), who are not skilled in *C. gigas* farming but are willing to undertake SSA.

Climate change associated with rising ocean temperatures has generated conditions for naturalizing this nonnative oyster in some coastal sectors of northern Europe (Troost 2010, Des et al. 2022). In southern Chile, there was massive farming of *C. gigas* at an industrial level because this species is highly adapted to different oceanographic conditions (Troost 2010). However, temperatures below 18°C inhibit larval development and settlement (Castaños et al. 2009, Rico-Villa et al. 2009). An increase in predicted seawater temperature may favor conditions of naturalization of *C. gigas* in the inner sea of Chiloé Island, where the SSA of Pacific oysters is still maintained. This situation encourages further research in the southern zones of Chile and Argentina on the effect of the increase in average surface temperature that may be generated in the coming years (Saldías et al. 2021). Potential temperature increases soon imply changes in habitat, generating potential natural spawning of *C. gigas* (Castaños et al. 2009), which may be difficult to predict. Follow-up strategies should be considered, and monitoring should be implemented to mitigate potential ecological and economic effects.

The connection of production issues in *C. gigas* culture with the potential of concessions for Pacific oyster aquaculture and the needs of both the market and small-scale fisheries and AMERBs for the promotion of SSA will enable an integral ecosystem for the promotion of the *C. gigas* industry in Chile.

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Credit author contribution

Alejandro Abarca: conceptualization, research, data curation, writing - original draft, writing - revision and editing; Germán Lira: research; José Bakit: data collection, research, writing - revision and editing.

Conflict of interest

The authors declare no conflict of interest.

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