Universidad de Concepción

Facultad de Ciencias Ambientales
Programa de Doctorado en Ciencias Ambientales mención Sistemas Acuáticos Continentales

# Efectos de la acidificación del océano sobre el sistema socio-ecológico de la mitilicultura del sur de Chile: Impactos en el mercado y desafíos para una futura sostenibilidad bajo modelos hipotéticos.

Tesis para optar al grado de

**Doctor en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales**

**Valeska Andrea San Martín Montoya**

CONCEPCIÓN-CHILE
2019

Facultad de Ciencias Ambientales
Programa de Doctorado en Ciencias Ambientales mención Sistemas Acuáticos Continentales

# Efectos de la acidificación del océano sobre el sistema socio-ecológico de la mitilicultura del sur de Chile: Impactos en el mercado y desafíos para una futura sostenibilidad bajo modelos hipotéticos.

Tesis para optar al grado de

**Doctor en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales**

Valeska Andrea San Martín Montoya

Profesor Guía: Doctor Cristian A. Vargas Gálvez

Dpto. de Sistemas Acuáticos, Facultad de Ciencias Ambientales

Universidad de Concepción

CONCEPCIÓN-CHILE

2019

Universidad de Concepción

Facultad de Ciencias Ambientales
Programa de Doctorado en Ciencias Ambientales mención Sistemas Acuáticos Continentales

Comisión Evaluadora de tesis de grado

Dr. Cristian A. Vargas Gálvez

Dpto. de Sistemas Acuáticos, Facultad de Ciencias Ambientales

Universidad de Concepción

Dr. Stefan Gelcich

Departamento de Ecología

Pontificia Universidad Católica de Chile

Dr. Felipe Vásquez

Escuela de Economía y Negocios

Universidad del Desarrollo

Dr. Ricardo Barra

Dpto. de Sistemas Acuáticos, Facultad de Ciencias Ambientales

Universidad de Concepción

Esta tesis fue realizada con financiamiento otorgado por:

Red Doctoral en Ciencias, Tecnología y Ambiente (REDOC.CTA)
Universidad de Concepción

Becas para Estudios de Doctorado en Chile 20151027

Dirección de Postgrado
Universidad de Concepción

Núcleo Milenio, “Centro para el Estudio de forzantes Múltiples sobre sistemas socio ecológicos”, MUSELS

TABLA DE CONTENIDO

INDICE FIGURAS

INDICE TABLAS

RESUMEN

Los efectos del cambio global están modificando las características fundamentales de los océanos, generando variaciones en diferentes parámetros físico-químicos (e.g. temperatura, salinidad, oxígeno, pH, entre otros). Los modelos de gases de efecto invernadero indican que un evidente incremento en los niveles de dióxido de carbono ($CO_2$) atmosférico y en consecuencia en la presión parcial de $CO_2$, esta llevando a un descenso del pH en el agua de mar, proceso conocido como Acidificación del Océano (AO). La AO se presenta como una de las amenazas más importantes para el conjunto de poblaciones marinas y ecosistemas.

La pesca y acuicultura son consideradas actividades de importancia económica y social, además de ser fuentes de proteína, energía y nutrientes esenciales, representando la seguridad alimentaria para una futura población humana en constante crecimiento. En este contexto variados estudios se han centrado en determinar el efecto en respuestas biológicas bajo las nuevas condiciones de cambio global en los océanos, pero la mayoría de estos estudios no han considerado la relación directa que existe entre especies de importancia comercial y el posible impacto en su mercado, pudiendo llegar a tener repercusiones importantes para productores y consumidores. En esta propuesta se pretende establecer un esfuerzo transdisciplinario para reducir estos vacíos en la comprensión de los efectos ambientales en especies de importancia comercial, los cuales podrían llegar a afectar la economía y el bienestar humano.

La presente tesis doctoral tiene como objetivo evaluar el efecto de la exposición a un futuro escenario de AO en el desarrollo temprano y tardío de la especie comercial *Mytilus chilensis*, determinando su sensibilidad y posibles variaciones en atributos físicos (color y dureza de concha) y nutricionales (ácidos grasos Omega3 EPA y DHA, Vitamina B12 y proteínas), los cuales son definidos como índices de mercado con posibles efectos en la oferta y demanda. Junto con lo anterior, este estudio aportará con la exploración y proyección del potencial adaptativo presente en las empresas de mitilicultura para enfrentar las consecuencias del cambio global.

El enfoque metodológico de estas tesis, considera un sistema de manipulación de los niveles de pH/p$CO_2$ en el laboratorio mediante un sistema de mesocosmo, utilizando agua de mar inyectada con $CO_2$ para simular escenarios de $CO_2$ y pH, tanto para niveles actuales y futuros, correspondientes a la localidad de Chiloé (pH 7,9=control y pH 7,6=sistema bajo de pH). Los organismos fueron obtenidos desde un centro de cultivo ubicado en la localidad de Vilupulli, Isla grande de Chiloé (42°49´S y 73°78´O). Se analizaron las respuestas físicas y nutricionales de los mitílidos en un periodo de 30 y 120 días. Conjuntamente se analizaron las preferencias electivas de los consumidores antes diferentes atributos de *M. chilensis* con la finalidad de predecir impactos en el mercado a través de la demanda. A la vez, se trabajó directamente con los principales actores de la actividad mitilicultora del sur de Chile, realizando encuestas y entrevistas con la finalidad de explorar el potencial adaptativo de la mitilicultura para innovar en sistemas de gestión.

Los resultados mostraron efectos negativos en los atributos físicos y nutricionales asociados a la exposición de los mitílidos a condiciones de bajo pH. Observando deterioro visual en las conchas, presentando una erosión y color blanquecino, a la vez disminuyeron significativamente las concentraciones de ácidos grasos, proteínas y vitamina B12 en los organismos expuestos a condiciones de bajo pH. La evaluación de preferencias del consumidor reflejaron que los principales atributos considerados al momento de elegir un producto para efectuar su compra  fueron la apariencia y luego el nivel nutricional, siendo estos justamente los atributos que fueron afectados por la exposición a la AO. En cuanto al análisis de la capacidad que tienen las industrias para anticipar y responder a estos cambios, se evaluaron los factores determinantes en la disposición a invertir en la creación de la capacidad para anticipar los cambios, los cuales mostraron que la industria se adapta de manera heterogénea y que los activos financieros y el capital social impulsan la voluntad de invertir en la capacidad de adaptación.

Los efectos del cambio global en ecosistemas y especies son inevitables, es por ello que es urgente contar con estrategias de adaptación para evitar impactos y disminuir el riesgo del progreso económico y la seguridad alimentaria. Esta investigación contempla la orientación hacia grupos relacionados con la empresa mitilicultora con el fin de entregar  conocimiento para disminuir o anticipar el impacto del cambio global con el desarrollo de estrategias, proporcionando herramientas de apoyo a las partes interesadas y el aprendizaje sobre dinámicas complejas existentes en sistemas socio-ecológicos.

**ABSTRACT**

The effects of global change are modifying the fundamental characteristics of the oceans, generating variations in different physical-chemical parameters (e.g. temperature, salinity, oxygen, pH, among others). Greenhouse gas models indicate that an evident increase in the levels of atmospheric carbon dioxide ($CO_2$) and, consequently, in the partial pressure of $CO_2$, is leading to a decrease in pH in seawater, a process known as Acidification of the Ocean (AO). The AO is presented as one of the most important threats to the group of marine populations and ecosystems.

Fishing and aquaculture are considered activities of economic and social importance, as well as being sources of protein, energy and essential nutrients, representing food security for a future human population in constant growth. In this context, several studies have focused on determining the effect on biological responses under the new conditions of global change in the oceans, but most of these studies have not considered the direct relationship that exists between species of commercial importance and the possible impact on the market, and may even have important repercussions for producers and consumers. This proposal intends to establish a transdisciplinary effort to reduce these gaps in the understanding of environmental effects in species of commercial importance, which could affect the economy and human well-being.

The objective of this thesis is to evaluate the effect of exposure to a future AO scenario in the early and late development of the commercial species *Mytilus chilensis*, determining its sensitivity and possible variations in physical attributes (shell color and hardness) and nutritional (Omega3 fatty acids EPA and DHA, Vitamin B12 and proteins), which are defined as market indexes with possible effects on supply and demand. Along with the above, this study will contribute with the exploration and projection of the adaptive potential present in the mussel farming companies to face the consequences of global change.

The methodological approach of these theses, considers a system of manipulation of the levels of pH/$pCO_2$ in the laboratory through a mesocosm system, using seawater injected with $CO_2$ to simulate $CO_2$ and pH scenarios, both for current and future levels corresponding to the locality of Chiloé (pH 7,9 = control and pH 7,6 = low pH system). The organisms were obtained from a culture center located in Vilupulli, Isla grande de Chiloé (42°49'S and 73°78'W). The physical and nutritional responses of the bivalves were analyzed in a period of 30 and 120 days. Together, the elective preferences of consumers before different attributes of *M. chilensis* were analyzed with the purpose of predicting impacts in the market through demand. At the same time, we worked directly with the main players of the mussel farming in southern Chile, conducting surveys and interviews in order to explore the adaptive potential to innovate in management systems.

The results showed negative effects in the physical and nutritional attributes associated with the exposure of bivalves to low pH conditions. Observing visual deterioration in the shells, presenting an erosion and whitish color, at the same time significantly decreased the concentrations of fatty acids, proteins and vitamin B12 in organisms exposed to low pH conditions. The evaluation of consumer preferences reflected that the main attributes considered when choosing a product to make their purchase were the appearance and then the nutritional level, these being precisely the attributes that were affected by the exposure to the OA. Regarding the analysis of the capacity that the industries have to anticipate and respond to these changes, the determining factors in the willingness to invest in the creation of the capacity to anticipate the changes were evaluated, the caules showed that the industry adapts in a heterogeneous and that financial assets and social capital impel the will to invest in the capacity of adaptation.

The effects of global change on ecosystems and species are inevitable, which is why it is urgent to have adaptation strategies to avoid impacts and reduce the risk of economic progress and food security. This research contemplates the orientation towards groups related to the mussel farming in order to provide knowledge to reduce or anticipate the impact of climate change with the development of strategies, providing support tools to stakeholders and learning about complex dynamics existing in systems socio-ecological.

# INTRODUCCION

Los impactos y efectos del cambio global ocurriran también a escala regional y local, afectando la estructura, dimensión, niveles ecológicos, además de la dinámica de la estructura social y económica del sector pesca y acuicultura (*Uribe*, 2015). Recientes proyecciones de estos efectos en la pesca y acuicultura prevén una disminución en la producción en casi un 85% en los países costeros, con importantes variaciones según su capacidad nacional de adaptación (*FAO*, 2018), lo cual hace destacar la importancia de respuesta al cambio global con el fin de garantizar la maximización de oportunidades, reduciendo los efectos negativos y asegurando la provisión alimentaria hacia la población.

## *1. Importancia de la Acuicultura*

La población humana se encuentra en constante crecimiento, cuyas proyecciones estiman que para fines de este siglo se superaran los 10.000 millones de habitantes, lo que despliega la inquietud de satisfacer objetivos de seguridad alimentaria y nutrición para una población en constante crecimiento (*Golden et al*., 2016). De esta forma, la acuicultura ha emergido como una de las mas importantes vías para apoyar la seguridad alimentaria, debido a que es una fuente de proteínas en regiones económicamente desfavorecidas (*FAO*, 2016).

La acuicultura a nivel mundial es el sector productivo con mayor crecimiento (*FAO*, 2016). Dentro de esta actividad, la producción de mitílidos ocupa el tercer lugar dentro de la categoría de moluscos cultivados a nivel mundial (*Gazeau et al*., 2013), apoyando a la industria acuícola mundial con un valor de más de 3.000 millones de dólares durante el año 2015 (*FAO*, 2015).

En Chile, la acuicultura es una importante actividad económica, destacando en primer lugar la acuicultura del salmón por sus volúmenes de producción (*Valenzuela*, 2005), sin embargo existen otras actividades acuícolas, principalmente la de moluscos tales como ostras, ostión y mitílidos ("choritos") entre los más importantes (*Araneda*, 2009), con una creciente demanda en los mercados internacionales (*Sernapesca,* 2010).

Desde el año 2003 Chile ha incrementado su producción de mitílidos llegando en el año 2016 a alrededor de las 300.000 toneladas, superando la producción de España (http://stats.oecd.org) (Fig. 1). Según el Registro Nacional de Acuicultura 2014, la principal región de Chile dónde se realiza esta actividad es la Región de Los Lagos, encontrando el mayor número de centros inscritos (2.243) y activos (1.531), pertenecientes a concesiones de acuicultura de mitílidos. Dentro del conjunto de cultivo, la especie *Mytilus chilensis* (chorito o mejillón), representa entre el 80 al 96% del volumen total de mitílidos desembarcados, de los cuales el 99,8% proviene de la actividad acuícola concentrada en las aguas del Mar interior de Chiloé, donde se lleva a cabo la captación de larvas que hace posible el sustento de esta actividad (*LeBlanc et al*., 2013).

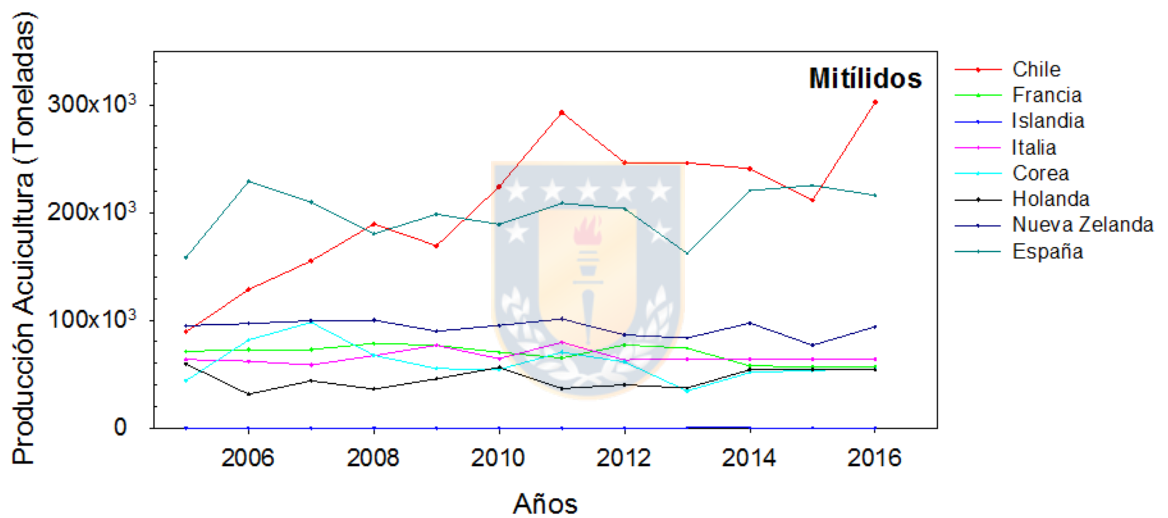


**Fig. 1:** Datos de producción de acuicultura de mitílidos mayores a 50.000 toneladas para los países pertenecientes a la OCDE Stat, obtenidos desde (http://stats.oecd.org). Las series de datos comienzan en el año 2005 hasta el año 2016. Los datos fueron recogidos por la OCDE utilizando metodologías establecidas por el Grupo Coordinador de Trabajo sobre estadísticas de Pesca (CWP) (www.fao.org/fishery/cwp/search/en).

La distribución de esta especie se extiende desde los 37 a los 73ºS, extendiendo su área de distribución hasta Brasil e Islas Malvinas, presentándose en ambientes intermareales sujeto al material rocoso hasta los 10 m de profundidad (*Osorio*, 1979; *Krapivka et al*., 2007), viéndose expuesto a un amplio rango de variabilidad ambiental (*Molinet et al*., 2015).

Presenta además, un patrón de abundancia larval relacionado con el desove de los organismos adultos (*Bayne*, 1976), influenciado por variaciones interanuales en los procesos productivos (*Ekman*, 1996).

### *1.1. Proceso productivo de la mitilicultura*

El proceso productivo de la acuicultura de mitílidos dura entre 14 a 20 meses y se divide en 4 etapas: captación de semillas, crecimiento y engorda, plantas de proceso y finalmente la exportación (*Gonzalez-Poblete et al*., 2018; *Rivera et al*., 2017).

I) *Captación de semilla*: El ciclo reproductivo de *Mytilus chilensis* se inicia con la maduración sexual, produciéndose el desove y posterior fecundación entre septiembre y febrero (*Lozada*, 1968; *Stotz*, 1981; *CORFO*, 2003), obteniendo larvas trocóforas de vida breve, que dan lugar a la larva véliger de vida planctónica (*Bautista*, 1988), periodo que dura alrededor de 40 a 45 días (*Toro et al*., 2006). Durante este período se alcanza una talla mínima de fijación con un rango de longitudes entre 262-341 μm (*Ruiz et al*., 2008). La posterior fijación tiene lugar cuando la larva sufre el proceso de metamorfosis dónde se fija a un sustrato adecuado, pierde el velo y se produce una reestructuración general de todos los órganos y está próxima a convertirse en juvenil (*Gilbert*, 1991) (Fig. 2). El asentamiento de larvas en sustratos naturales y artificiales (colectores), se considera una etapa crítica en el ciclo, afectado por factores de tipo climático e hidrográficos que ocurren a escala regional (*Thouzeau*, 1991). Esta etapa es decisiva y altamente vulnerable a condiciones ambientales, debido a que se presentan mortalidades y en consecuencia regula la edad adulta, el tamaño y la población (*Gosselin & Qian*, 1997).

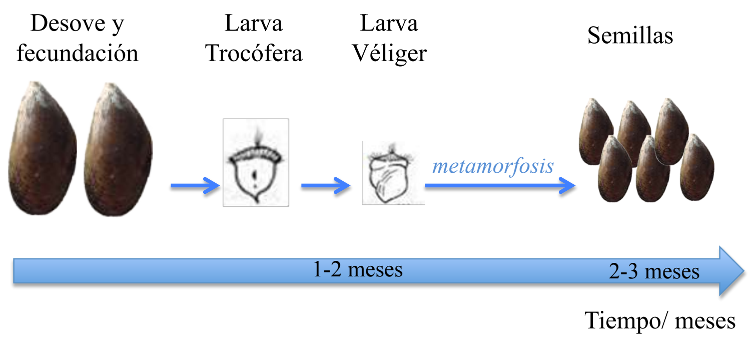


**Fig. 2:** Ciclo reproductivo de *Mytilus chilensis* desde la fecundación hasta aproximadamente los 3 primeros meses de vida.

La obtención de estas semillas se realiza a diferentes profundidades de la columna de agua con alta disponibilidad de larvas en los estuarios de la región de Los Lagos (*Fernández et al*., 2018; *Lara et al*., 2016), principalmente desde cinco áreas: Yaldad, Ilque-Huelmo, Quillaipe-Metri, Seno Reloncaví y Hornopirén-Pichicolo. Estudios disponibles sobre captación de semilla (*López et al.,* 1980; *Winter et al.,* 1984), están relacionados con la localidad de Yaldad, siendo el principal semillero en los años 80 (*Leiva et al.,* 2007). Sin embargo, en los últimos años este semillero ha sufrido disminución en los niveles de captación, pudiendo ser atribuidos a condiciones ambientales en las cuales se encuentran estas semillas, tales como: escenarios locales influenciados por el aporte de aguas provenientes de descargas de ríos (*Lara et al*., 2016), presencia de fármacos liberados al medio ambiente utilizados en la actividad de la salmonicultura (*Rozas y Asencio*, 2007; *Millanao et al*., 2011), aumento de materia orgánica y disminución de oxígeno disuelto (*Soto & Norambuena*, 2004), entre otros.

Estas semillas luego de ser captadas, son trasladadas a los diferentes lugares de la región para seguir el proceso de producción en los centros de cultivo.

II) *Crecimiento y engorda*: Según el Registro Nacional de Acuicultura 2014, existen alrededor de 2.243 centros de cultivos de mitílidos tanto para engorda y semilleros, ubicados en el archipiélago de Chiloé y Calbuco, lo cual se debe principalmente a la calidad de las aguas y las condiciones ambientales favorables para el desarrollo de este recurso. El proceso de engorda se realiza luego de la fijación de las semillas en los colectores que son distribuidos en un sistema de cuelgas, dónde son trasladadas a diferentes áreas a los sistemas de cultivo estando expuestos al ambiente marino. Este periodo puede durar entre 6 a 18 meses, donde se alcanza el tamaño promedio de 5 cm para ser luego cosechado (*Uriarte*, 2008).

III) *Plantas de Proceso:* Luego de la extracción de los organismos, se realiza la limpieza, cocción y envasado de la materia prima recibida de los centros de cultivos, para ser enviada a los mercados finales (*Díaz*, 2010). Si bien desde el origen hay una predominante participación de la industria en conserva, desde el año 2000 comienza a tener preponderancia la producción de congelados. En el año 2010, existian alrededor de 6.000 empleos asociados a esta actividad (*Díaz*, 2010). Actualmente según datos de la Asociación de Mitilicultores de Chile (AmiChile), la industria mitilicultora genera alrededor de 12.000 empleos directos y 5.000 indirectos en la región, posicionando al mitílido chileno como una importante fuente de empleo y progreso para la región.

IV) *Exportación:* corresponde a la comercialización de los mitílidos, la cual varía en diferentes productos incluyendo: fresco, congelado y envasado en conserva. Estos productos congelados se pueden encontrar en formato de cáscara completa, en media cáscara o como carne individual congelada (IQF) (*Monfort*, 2014).

Chile es actualmente el país con la tasa de crecimiento más alta en producción de mitílido (*FAO*, 2016). Desde principios de 1990 hasta 2012, la producción ha aumentado desde 3.000 a 246.462 toneladas, con un año record en 2017 que supera las 300.000 toneladas (*FAO*, 2017; 2018). En cuanto a las exportaciones, según el reporte de IndexMussels, el mitílido chileno alcanzo un total de 80.563 toneladas durante el año 2018, cifra superior en 1,6% a las 79.285 toneladas reportadas en el año 2017. Los principales países de destino del mitílido chileno son: España, Rusia, Estados Unidos, Francia e Italia.

### *1.2. Amenazas presentes en el proceso productivo de la mitilicultura*

La mayor parte del proceso productivo de la mitilicultura (Captación de semillas y engorda) se desarrolla en el mar interior de Chiloé (*Gonzalez-Poblete et al*., 2018; *Figueroa and Dresdner*, 2016), estando sujeta a múltiples fuentes de variabilidad, incluidas las alteraciones ambientales y antropogénicas (e.g. descargas de ríos, variaciones de temperatura, disminución de oxígeno disuelto, presencia de fármacos, aumento de materia orgánica, entre otros) (*Barria et al*., 2012; *Goldburg et al*., 2001). Uno de los cambios antropogénicos más importantes y estudiado ha sido el aumento en las concentraciones de los gases de efecto invernadero, entre ellos el $CO_2$. Este incremento en los niveles de $CO_2$ antropogénico ha tenido consecuencias dramáticas en los océanos, causando cambios generalizados en el pH del agua de mar y la química del carbonato (*Caldeira and Wickett*, 2003; *Orr et al*., 2005), conocido como Acidificación del Océano (AO).

### *1.3. Acidificación de los Océanos*

Alrededor de un tercio de las emisiones antrópicas de $CO_2$ (a partir de combustibles fósiles, cambios en el uso suelo) ha sido almacenada en los océanos desde la revolución industrial (*Sabine et al.,* 2004), como resultado el pH de los océanos ha disminuido por unidad de 0.1 en comparación con los valores pre-industriales (*Orr et al.,* 2005). Se estima que la presión parcial de $pCO_2$ seguirá aumentando con valores proyectados para este fin de siglo que van desde los 500 a 1000 µatm, en función de las emisiones de $CO_2$ (*IPCC*, 2007), con disminución del pH en 0.5-0.7 unidades para el año 2100 (*Caldeira and Wickett*, 2003; *Royal Society*, 2005; *Kurihara et al., 2008,* 2007; *Wood et al.,* 2008), presentando valores de pH en la superficie del océano entre 8.0 a 7.8 (*IPCC*, 2001; *Widdicombe & Needham*, 2007). Ante este escenario de aumento en las concentraciones atmosféricas de $CO_2$, conduce a un incremento en las concentraciones de $CO_2$ en el agua de mar, el que a su vez producirá un incremento en la concentración del carbono inorgánico disuelto (i.e $CO_{2\,(acuoso)}$, $HCO_3^-$, y $CO_3^{2-}$), y disminución en el pH de la superficie del océano (*Kurihara et al.,* 2004; *Widdicombe & Needham*, 2007).

Actualmente, los reportes correspondientes al mes de marzo del año 2019 del observatorio de Mauna Loa en Hawai, E.E.U.U. (NOAA-ESRL), señala una concentración de $CO_2$ atmosférico de 412 ppm, producto de la actividad humana. Estas cifras actualmente están aumentando a una tasa de alrededor de ~0.5% año$^{-1}$ (*Gattuso*, 1998), siendo 100 veces más rápida a los cambios ocurridos hace 650.000 años (*Royal Society*, 2005), esperando un dramático cambio con consecuencias para especies y ecosistemas.

### *1.4. Implicancias biológicas de la Acidificación de los Océanos*

La OA es una de las mayores amenazas para la industria de la acuicultura, especialmente para los moluscos marinos que presentan concha (*Gazeau et al*., 2013). Estas especies son particularmente vulnerables porque dependen de las concentraciones de carbonato para construir sus conchas (*Gazeau et al*., 2013; *Waldbusser et al*., 2015). La OA puede deteriorar significativamente varios rasgos fisiológicos en moluscos marinos como los ostiones (*Cooley & Doney*, 2009; *Schalkhausser et al*., 2014; *Talmage and Gobler*, 2010), gastrópodos (*Bednaršek et al*., 2012; *Wittmann & Portner*, 2013), y mitílidos (*Gazeau et al*., 2013; 2007; *Kroeker et al*., 2010; *Ventura et al*., 2016; *Waldbusser et al*., 2015). Además la OA afecta las tasas de mortalidad (*Gibson et al*., 2011), calcificación y crecimiento, aumentando la vulnerabilidad a enfermedades y parásitos (*Gazeau et al*., 2013; *Mackenzie et al*., 2014; *Thomsen et al*., 2013).

Estudios específicos enfocados en determinar los efectos a la exposición a bajos niveles de pH en el agua de mar en las respuestas biológicas de diferentes especies de bivalvos se muestran en la Tabla Nº1. Los resultados evidencian principalmente efectos negativos sobre las tasas de alimentación, crecimiento y calcificación, lo que permite inferir que la exposición a condiciones de bajo pH en el agua de mar, afectaría de forma negativa a estas especies, principalmente en sus tasas de alimentación con posteriores efectos en el crecimiento y pudiendo llegar a tener efectos negativos en la calidad del individuo.

Tabla Nº 1. Estudios realizados en especies bivalvas, principalmente en *Mytilus chilensis* en la evaluación de diferentes respuestas biológicas afectados por la AO.

| ESPECIE | RESPUESTA | ESTRESOR | EFECTO | AUTORES | PUBLICACION |
|---|---|---|---|---|---|
| *Concholepas concholepas*<br>*Perumytilus purpuratus* | Tasa de ingestión<br>Tasa de aclaramiento | CO2 | − | Vargas et al., 2015 | Estuaries and Coast |
| *Mytilus galloprovincialis* | Tasa de crecimiento<br>Anómalias morfológicas | CO2 | − | Kurihara et al., 2008 | Aquatic Biology |
| *Mytilus edulis* | Tasa de crecimiento<br>Tasa de calcificación | CO2 | − | Gazeau et al., 2010 | Biogeoscience |
| *Mytilus edulis* | Sistema inmune<br>Enfermedades | T<br>CO2 | > − | Mackenzie et al., 2014 | PlosOne |
| *Mytilus chilensis* | Tasa de aclaramiento<br>Tasa de absorción | CO2 | − | Navarro et al., 2013 | Chemosphere |
| *Mytilus chilensis* | Tasa de calcificación<br>Tasa de crecimeinto<br>Tasa sobrevivencia | T<br>CO2 | TC 0 con ↑ T<br>TR −con ↑ CO2<br>0 ↑ CO2 >− | Duarte et al., 2014 | Journal of sea Research |
| *Mytilus chilensis* | Tasa de calcificación neta<br>Tasa de disolución | CO2 | − Huelmo 0 Yaldad<br>0 | Duarte et al., 2015 | Estuaries and Coast |
| *Mytilus chilensis* | Tasa de aclaramiento<br>Tasa de respiración<br>Tasa de crecimiento | T<br>CO2 | TA − con ↑CO2<br>TA +con ↑ T<br>TR − con ↑ CO2<br>TC − con ↑ CO2<br>TC +con ↑ T | Navarro et al., 2016 | ICES journal of Marine Science |
| *Mytilus chilensis* | Inmunidad<br>Fisiología<br>Homeostasis | CO2<br>Infección<br>bacteria | > − | Castillo et al., 2017 | Fish & Shellfish Immunology |
| *Mytilus chilensis* | Tasa de metabolismo<br>Tasa de ingestion<br>Tasa de aclaramiento<br>Expresión genética<br>Tasa de crecimiento<br>Tasa de calcificación | CO2<br>PSU | Trasplante recíproco<br>TM- EG-TI-TA = +<br>PF TC-TC= -<br>sensibles | Osores et al., 2017 | Journal of Experimental Marine Biology and Ecology |

↑aumento del estresor; >combinación estresores; - efecto negativo; +efecto positivo

Si bien existen variados estudios enfocados en determinar el efecto de la AO en respuestas biológicas, la mayoría de estos no consideran la relación que existe con la producción comercial y la calidad del producto que pueden llegar a tener repercusiones importantes para consumidores y el mercado (*Dupont et al*., 2014), debido a que el mitílido chileno es una especie de importancia comercial.

2. *Importancia de los atributos nutricionales y físicos como indicadores de mercado en el cultivo de moluscos bivalvos.*

A pesar de la importancia que tiene el mitílido chileno para las comunidades costeras en términos de generación de trabajo y en la economía nacional, son pocos los esfuerzos realizados para valorizar este molusco como un alimento desde el punto de vista nutricional, ya que es considerado un producto gourmet, sin valorar su aporte nutritivo en la dieta (*Valenzuela et al*., 2011). Esta especie posee atributos nutricionales como proteínas, aminoácidos esenciales, ácidos grasos Omega-3, vitamina B12, fósforo, potasio y Zinc, además presenta bajo aporte en sodio y calorías (*Valenzuela et al*., 2011; *Fuentes et al*., 2009). Existen evidencias que indicarían que su consumo aportaría beneficios en la salud cardiovascular y del sistema nervioso, tanto por su aporte en ácidos grasos Omega-3 (EPA y DHA) (*Swanson et al*., 2012) como por su alto aporte en vitamina B12 de la que sería una excelente fuente (*Valenzuela et al*., 2011). Existen estudios que avalan beneficios atribuidos a la ingesta de ácidos grasos Omega-3 de origen marino (*Mozaffarian and Wu*, 2012), destacando el ácido eicosaepentanoico (EPA) por sus beneficios cardivasculares tales como: efectos hopotrigliceridémicos, hipocolesterolémicos, antitrombóticos, antiinflamatorios, antiarrítmicos, entre otros (*Mozaffarian and Wu*, 2012; *Calder*, 2012). Además, el ácido docosahexaenoico (DHA) contribuye al desarrollo y protección del sistema nervioso (*Richardson et al*., 2012; *Cunnane et al*., 2009), demostrando un beneficio para la salud y nutrición consumiéndolos frecuentemente (*Larsen et al*., 2011).

En cuanto a los atributos físicos que presenta este producto, pueden ser observados por el consumidor en los diferentes formatos existentes (fresco, congelado enteros con concha, congelado con media concha, congelado solo carne y variedades de conservas). En aquellos formatos en los cuales se puede tener un contacto visual con el producto, existen características que nos sirven para tomar la decisión de realizar o rechazar una compra. Basados en estudios previos, existen atributos importantes que definen las preferencias de consumo de mariscos (*Cardoso et al*., 2012; *Sveinsdóttir et al*., 2009; *Penney et al*., 2007). Siendo la apariencia un atributo de calidad clave en la decisión de los consumidores, influyendo en la compra y el precio de mercado (*Grabacki et al*., 2011; *Brenner et al*., 2012). De este modo, finalmente la alta calidad y el valor nutricional de los mariscos son atributos de gran importancia para los consumidores (*Batzios et al*., 2002).

En este contexto, los cambios biológicos observados y descritos en estudios previos con efectos en respuestas biológicas ante escenarios estresantes para la especie, podrían afectar directamente los atributos comerciales asociados con la calidad de estos mitílidos, como el aspecto y la composición nutricional. Hasta la fecha, no existen investigaciones dirigidas a evaluar los efectos de la AO sobre los atributos comerciales de los mitílidos, lo que dificulta las oportunidades para vincular los impactos de la AO sobre las preferencias y el bienestar de los consumidores.

3. *Posibles impactos en el mercado de mitílidos evaluado a través de la percepción social: Preferencias de consumo.*

Existen dos fuerzas que interactúan en el mercado: la oferta y la demanda. Desde el mercado de la mitilicultura definimos la *oferta* como la cantidad de producción de mitílidos ofrecidos bajo determinadas condiciones, donde el precio surge como una de las condiciones para determinar el nivel de oferta. Por otro lado, la *demanda* se define como la cantidad adquirida por los compradores, esta puede estar influenciada por una variedad de factores como: preferencias, hábitos, información del producto, poder de compra (capacidad económica), utilidad o bien estar, precio, existencia de producto complementario o sustituto, entre otros.

Estas preferencias de consumo se pueden estudiar a través de experimentos de elección (*"Choice experiments"*, CE). Este método (CE) surgió en los campos de comercialización y psicología para medir preferencias por diversas características o atributos de los bienes. Estos experimentos de elección se han desarrollado en economía y marketing para determinar preferencias de los consumidores por productos con múltiples características (*Louviere et al.,* 1983). De este modo, este método puede proveer información sobre como los atributos de un bien ayudan a determinar su valor y como este valor es afectado por el cambio en uno o más de sus atributos. Además, nos permite modelar distintos escenarios de bienes, con distintas combinación de atributos y simular los efectos de estos cambios en los atributos sobre las probabilidades de elección (*Vásquez et al.,* 2007). La utilización de este método se ha ampliado a otras áreas como gestión en el medio ambiente y se ha convertido en una herramienta común para valorizar este mismo (*Bennett et al.,* 2001; *Hanley et al.,* 2001). Estos experimentos de elección son considerados como una versión de opción múltiples, de acuerdo a la valoración que se realice del producto (*Shahraki & Dahmardeh*, 2014), cada encuestado tiene dos o más opciones para seleccionar la preferida. Para ello se presenta un número de atributos o características del producto, la cual describe cada opción, estos atributos o características pueden tener diferentes niveles (*Romano et al.,* 2008).

De esta forma, mediante la utilización de experimentos de elección discreta podemos evaluar las respuestas de los consumidores para determinar la relevancia relativa de los diferentes atributos en mitílidos.

4. *Potencial adaptativo de la mitilicultura para reaccionar a la acidificación de los Océanos.*

La mitilicultura en el sur de Chile es una actividad comercial que conecta diversos actores a través del intercambio de recursos pesqueros, existiendo una estrecha relación entre sistemas socio-ecológicos. Durante los últimos años, se ha manifestado una constante preocupación por parte de los principales actores, debido a que las áreas donde se desarrolla esta actividad de la cual dependen, esta expuesta a múltiples riesgos debido a los eventos extremos que se presentan cada vez con mayor frecuencia (*Adger et al*., 2003). Sin embargo, a través de los años las sociedades se han adaptado a las variaciones climáticas y ambientales (*Adger and Vincent*, 2005), reflejando de esta manera la capacidad que tienen las industrias para anticipar, modificar y/o responder a los riesgos asociados con el cambio global, para minimizar y recuperarse de las consecuencias, aprovechando las nuevas oportunidades que surgen del proceso de adaptación (*Adger and Vincent*, 2005, *Grothmann and Patt*, 2005), estimulando la innovación. De esta manera, las actividades que presentan altos niveles de capacidad de adaptación son capaces de enfrentar los cambios (*Handisyde et al*., 2017). Por lo tanto, el cultivo de mitílidos proporciona un entorno único para estudiar la capacidad de adaptación, debido a que es una industria en crecimiento compuesta por pequeños y grandes productores, cuya producción depende del entorno natural (*Kroeker et al*., 2016; *Menge et al*., 2009).

### 5. *Planteamiento de la problemática*

Investigaciones desarrolladas en Chile con respecto a los efectos producidos por la AO en la especie comercial *Mytilus chilensis* han ido aumentando a través del tiempo (Tabla 1). Los primeros estudios estuvieron enfocados en evaluar el efecto del estresor $CO_2$ en las tasas de alimentación (*Navarro et al*., 2013). Posteriores investigaciones han ido incorporando estresores adicionales al $CO_2$, y su efecto en conjunto con otros, tales como: temperatura y/o salinidad, evaluando desde tasas de calcificación, disolución, metabólicas y plasticidad fenotípica entre otras (*Duarte et al*., 2015; *Navarro et al*., 2016; *Osores et al*., 2017). Sin embargo, ninguno de estos estudios contempla los efectos de la AO sobre los atributos de mercado de la especie, que podrían llegar a tener repercusiones en el bienestar de los consumidores.

Las recientes proyecciones de venta de los actuales y potenciales mercados, así como las exigencias nutritivas de este producto, contemplan altos estándares de calidad. De este modo, para mantener las actuales tasas de crecimiento de la industria mitilicultora, se requiere de una rápida búsqueda de alternativas que se centren en solucionar puntos críticos que restan competitividad a la industria de mitílidos en Chile.

Debido a esto, el objetivo de esta tesis doctoral fue estudiar el efecto de la exposición a un futuro escenario de AO sobre los atributos de mercado (físicos y nutricionales) de la especie *Mytilus chilensis*. Además, se evaluó cómo estas variaciones en los atributos de la especie podrían afectar la preferencia de los consumidores, a través de un análisis de los atributos y la disposición marginal a pagar por un producto mediante experimentos de elección. Por otro lado, se analizó el estado de la capacidad adaptativa en el cual se encuentran las industrias de la mitiliculturas del sur de Chile a través de encuestas para determinar si poseen la capacidad de anticiparse, modificar y/o responder a condiciones desfavorables como riesgos asociados a cambios globales (Fig. 3).

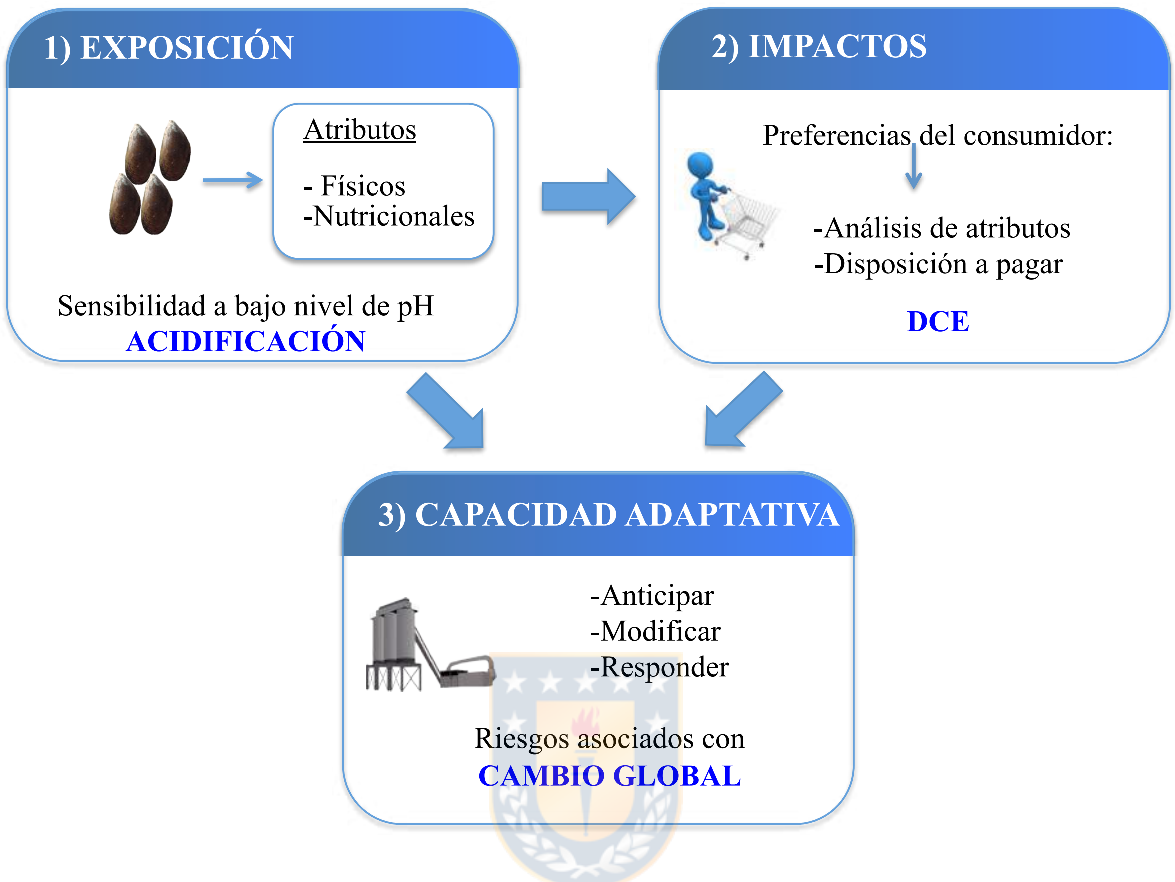


**Fig. 3:** Representación esquemática del planteamiento de la problemática de estudio. Evaluación del efecto de 1) exposición a un escenario de acidificación del océano para determinar variaciones en atributos físicos y nutricionales; 2) Determinar las preferencias de los consumidores ante variaciones en los atributos de mercado en la especie *Mytilus chilensis,* y finalmente *3)* evaluar la capacidad adaptativa presente en las empresas mitilicultoras del sur de Chile.

Basado en los antecedentes antes expuestos y el objetivo general, la presente tesis doctoral esta enfocada a responder las siguientes hipótesis:

HIPOTESIS

$H_1$: La exposición de *Mytilus chilensis* a un futuro escenario de Acidificación del Océano (bajo pH/alto $pCO_2$), impactará negativamente los atributos físicos (color y dureza de concha) y nutricionales (ácidos grasos Omega3 EPA y DHA, Vitamina B12 y proteínas).

$H_2$: La selección de *Mytilus chilensis* por los consumidores estará dada por sus preferencias en atributos físicos (color y dureza de concha), desplazando los atributos nutricionales (ácidos grasos Omega3 EPA y DHA, Vitamina B12 y proteínas).

$H_3$: La capacidad adaptativa de las empresas mitilicultoras frente a un escenario de Acidificación del Océano estará determinada por el tamaño de la empresa y la disponibilidad de capital financiero.

OBJETIVOS

*Objetivo General*

Evaluar el efecto de la exposición a un escenario de acidificación del océano en la especie comercial *Mytilus chilensis* para determinar variaciones en atributos físicos y nutricionales, los cuales pueden afectar la preferencia de consumidores, y la disposición marginal a pagar por el producto, lo que tendrá un efecto en la demanda. A la vez, se analizará el estado de la capacidad adaptativa de las empresas para lograr ser una actividad sostenible mediante el desafío de los futuros cambios ambientales.

*Objetivos específicos*

1. Evaluar cambios en atributos físicos (color y dureza de concha) en individuos juveniles y adultos del mitílido *Mytilus chilensis* expuestos a bajos niveles de pH.
2. Obtener perfiles lipídicos y determinar los niveles de ácidos grasos Omega-3 (EPA y DHA), vitamina B12 y proteínas en individuos juveniles y adultos del mitílido *Mytilus chilensis* expuestos a bajos niveles de pH.
3. Medir y determinar las preferencias de los consumidores en los atributos físicos y nutricionales del mitílido *Mytilus chilensis* mediante la valoración social del producto.
4. Explorar y determinar la capacidad adaptativa presente en el sector mitilicultor del sur de Chile.

## METÓDOS

### 1. *Colección de organismos*

Individuos juveniles y adultos de *Mytilus chilensis* (longitud de concha: 2,5 ± 0,5 cm y 7,4 ± 0,2 cm, respectivamente) fueron recolectados a 5 metros de profundidad durante los meses de julio y octubre del año 2015 en un centro de cultivo privado de mitílidos, ubicado en la localidad de Vilupulli, Chiloé en el sur de Chile (42º35'35''S; 73º47'18''O) (Fig. 4). Las condiciones ambientales promedio para el área oscilaron entre 10,0 a 12,4ºC; 28,2 a 33,5 PSU de salinidad y 7,9 a 8,3 unidades de pH. Luego de la recolección de organismos, estos fueron transportados al laboratorio de Biología Marina en Dichato (Universidad de Concepción). Los organismos se mantuvieron en agua de mar filtrada (0,1 μm) y aireada, con una temperatura de ~ 11ºC, ~ 31 PSU de salinidad y 8,0 ± 0,1 unidades de pH, las cuales representan las variaciones ambientales medias en el área de cultivo de mitílidos durante un ciclo anual. El periodo de aclimatación fue de dos semanas bajo condiciones de mesocosmos, donde los animales fueron alimentados diariamente con una mezcla de dos microalgas (*Isochrysis* sp. y *Pavlova* sp.) correspondiente a un aliemnto comercial FhytoGold-M (Brightwell Aquatics) en una concentración media de 2,5 μg $L^{-1}$ Chl a.

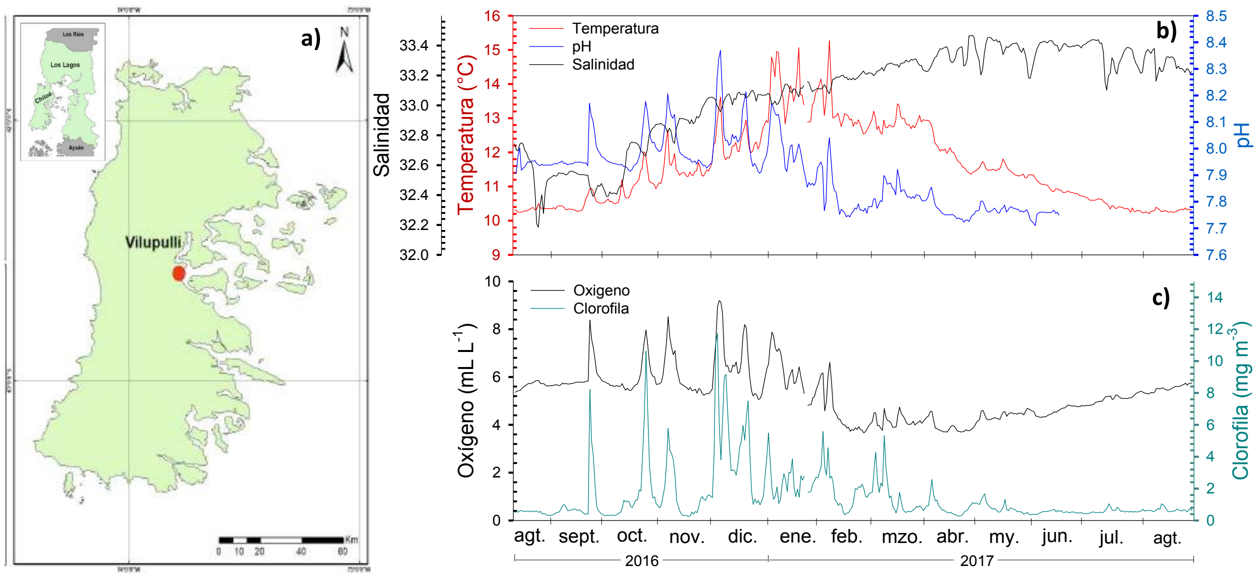


**Fig. 4:** a) Área de Vilupulli, Isla de Chiloé, donde los individuos de *Mytilus chilensis* fueron extraidos de una mitilicultura privada, b y c) Promedios diarios de las principales variables oceanográficas en el área de estudio.

2. *Manipulación de $CO_2$ y condiciones experimentales*

Se utilizaron dos tanques de plástico de 280 L como unidades de acidificación para generar el agua de mar a dos valores nominales de $pCO_2$: 400 µatm (tratamiento control) correspondiente a condiciones actuales simuladas a el nivel promedio existente en el área de cultivo de mitílidos (*Vargas et al.*, 2017) y 1000 µatm (tratamiento con $CO_2$) simulando condiciones de futuro, basadas en el escenario RCP 8.5 que predice tasas de cambio de -0,0018 unidades de pH por año (*Boop et al.*, 2013; *Hartin et al.*, 2016). Para esta investigación se establecieron dos niveles de $pCO_2$ (mezcla de aire/$CO_2$), utilizando una técnica de flujo de masa, suministrando un flujo de aire seco y gas de CO2 ultra puro, a través de un controlador de flujo de masa (MFCs, www.aalborg.com), y se mezclo antes del equilibrio con agua de mar.

3. *Análisis químicos: pH, T, salinidad y alcalinidad*

Durante los experimentos, el pH del agua de mar (escala total, $pH_T$) se controló en cada tanque cada 10 días, midiendo potenciométricamente en celdas de 25 ml a una temperatura de 25 ± 0,1ºC para la estandarización, utilizando un medidor de pH Metrohm 713 (resistencia de entrada >1013 Ohm, 0,1 mV de sensibilidad, y resolución nominal de

0,0001 unidades de pH), utilizando un electrodo de vidrio de doble unión Ag/AgCl (Metrohm modelo 6.0219.100) calibrado con 8,089 Tris buffer a 25ºC, siguiendo el método potenciométrico DOE (*DOE*, 1994). Los valores de pH se reportan en la escala total de iones de hidrógeno.

La temperatura y la salinidad se midieron utilizando un medidor de salinidad portátil Oakton SALT6+ con sonda. La alcalinidad total se midió durante 7 días utilizando el método de titulación de celda abierta (*Dickson et al*., 2007), utilizando el modelo automático de triturador de alcalinidad ASALK2 Apollo SciTech. El sistema AS-ALK2 estuvo equipado con una combinación de electrodo de pH (8302BNUWP Ross Ultra pH/ATC Triode, Termo Scientific, E.E. U.U.) Conectado a un medidor de pH (medidor de pH Orion Star A211, Termo Scientific, E.E.U.U.). Todas las muestras fueron analizadas a 25 ± 0,1ºC con regulación de la temperatura utilizando un baño de agua (Lab Companion CW-05G). La precisión se controló contra un material de referencia certificado (CRM, suministrado por Andrew Dickson, Scripps Institution of Oceanography, San Diego, E.E.U.U.) y la repetibilidad de la AT fue de 2-3 $\mu$mol $Kg^{-1}$. El agua de mar de los experimentos fue reemplazada cada dos días con agua de mar previamente equilibrada.

4. *Estimación de parámetros del sistema de carbonatos*

El pH y la alcalinidad total (AT) fueron utilizados para calcular la presión de CO2 (*p*CO2) y el estado de saturación de aragonita y calcita ($\Omega_{Ar}$; $\Omega_{Cal}$) a través del uso del programa CO2CYS (*Lewis & Wallace*, 1998), con las constantes de solubilidad de Mehrbach (1973) modificadas por Dickson y Millero (1987). Se utilizó la constate de equilibrio de KHSO4 determinada por Dickson (1990).

5. *Desarrollo experimental*

Después del periodo de aclimatación, 60 individuos fueron limpiados y separados en 10 grupos de 6 individuos en acuarios de 9L de capacidad, cada tratamiento fue replicado 5 veces con un total de 30 individuos juveniles para el tratamiento control (11ºC y 400 ppm $CO_2$) y 30 individuos para tratamiento alto en $CO_2$ (11ºC y 1000 ppm $CO_2$). El mismo procedimiento fue realizado para organismos adultos, obteniendo 30 individuos adultos para el tratamiento control y 30 individuos adultos para tratamiento alto en $CO_2$.

El tiempo de exposición para los diferentes tratamientos fue de 120 días para juveniles y 30 días para adultos.

6. *Análisis de atributos comerciales: Atributos físicos*

Luego del periodo de exposición, se realizaron evaluaciones en las propiedades mecánicas de la concha de los organismos.

*6.1 Resistencia a la flexión:* fue medida con una máquina de prueba Universal Zwick Roell Z050 con celda de carga de 55 N. La velocidad de prueba fue de 5 mm $s^{-1}$; similar a los utilizados en estudios de resistencia en otras especies de gasterópodos (*Kent*, 1981; *Bushbaum et al*., 2007; *Coleman et al*., 2014). El tamaño de las muestras de prueba fueron de 5 mm de ancho y 20 mm de espacio de soporte, extraídas desde las áreas más planas de las conchas. Cada muestra se sometió a carga de flexión hasta la factura de la concha. La carga máxima se registró para calcular la resistencia a la flexión utilizando:

$$\sigma_{MAX} = \frac{3FL}{2bd^2}$$

Donde: *L* es el intervalo de soporte, *b* es el ancho y *d* el espesor (Resistencia a la Flexión ASTM C1161 de las Cerámicas Avanzadas a Temperatura Ambiente).

*6.2 Dureza:* Se utilizaron 20 muestras de juveniles y 20 de adultos. Para la determinación se utilizó la valva izquierda de cada mitílido y se embutieron en un emplasto de alta resistencia (Dental Plaster, Boral$^{TM}$) para dar soporte plano a la muestra y no tener interferencias en los resultados. Para la medición se utilizó un medidor de microdureza Vickers LM 300 AT con una carga de 100g con un tiempo de carga de 30s, realizando 7 puntos de medición en cada concha.

*6.3 Cambios en el color de valvas:* El extenso periodo de exposición para individuos juveniles permitió asegurar la detección de cambios significativos en el color de la concha. Esto variación del color fue analizada mediante fotografías semanales tomadas a cada individuo de cada tratamiento. Todas las imágenes fueron procesadas usando el Software ImageJ (V.145s; NIH, Bethesda, MD, USA).

7. *Análisis de atributos comerciales: Atributos nutricionales*

A diferencia de los organismos juveniles, el tiempo de exposición para adultos fue menor debido a que se encontraban en una etapa previa al desove (50 mm longitud de concha, *Lagos et al*., 2012). Se conoce que luego de este tamaño, los adultos cambian su gasto energético destinado principalmente a la etapa de reproducción (*Freites et al*., 2002). Por lo tanto, eran propensos al desove, lo que podría haber resultado en potenciales cambios en la composición nutricional, afectando nuestro análisis comparativo con los individuos juveniles. Las muestras de tejido de los mitílidos fueron obtenidas mediante extracción de las gónadas y músculo abductor. El análisis de ácidos grasos se realizó en el Instituto de Farmacología de la Universidad Austral de Chile. La concentración de ácidos grasos se analizó después de la extracción y metilación (*Kattner & Fricke*, 1986) con un cromatógrafo de gases Perkin Elmer Sigma 300 equipado con un vaporizador inyector programable de temperatura, una columna capilar OmegaWax 53 fusionada y un detector de ionización de llama. Las cantidades relativas se expresaron como porcentaje del total de ácidos grasos en cada muestra. La determinación de Vitamina B12 se realizo mediante la técnica de HPLC.

8. *Valoración social de los atributos comerciales*

Las preferencias sociales fueron modelas usando un modelo de utilidad aleatorio (*McFadden*, 1984; *Train*, 2009). Considerando que no existen datos de mercado para un escenario futuro, confiamos en el enfoque de experimentos de elección (*Hensher et al*., 2005), el cual brinda a los consumidores la oportunidad de declarar sus preferencias eligiendo entre varias alternativas que fueron diferenciadas por la combinación de niveles de atributos afectados por la AO. Estas encuestas, que incluyen experimentos de elección, han sido utilizadas ampliamente para estudiar las preferencias de los consumidores en una gran gama de atributos (*Tirachini et al*., 2017; *Carlsson & Martinson,* 2001), siendo importantes componentes en estudios de preferencia alimentaria y ambiental durante las ultimas décadas (*Brécard et al*., 2012; *Chau et al*., 2010; *Alfnes et al*., 2006).

Las entrevistas fueron realizadas personalmente entre octubre y diciembre del año 2016 en Santiago y Concepción. El proceso de muestreo aleatorio se baso en el programa de

Encuestas de Hogares Socioeconómico Nacional (CASEN), seleccionando hogares al azar con una muestra final de 1,278 individuos, cada uno de los cuales recibió 6 escenarios de elección con 3 alternativas, lo que resulto con una muestra total de 7,668 observaciones útiles, incluyendo la combinación de atributos, con o sin efecto de la AO y los precios. Para la entrevista se utilizó información a través de figuras y ayudas visuales. Se estimó el bienestar del individuo y la disposición a pagar por cada atributo del mitílido en función del bienestar de cada individuo.

9. *Capacidad adaptativa del sector mitilicultor chileno*

La capacidad de adaptación es una característica que refleja la capacidad que tienen las industrias para anticipar y responder a cambios, y de esta forma poder minimizar, enfrentar y recuperarse de las consecuencias aprovechando las nuevas oportunidades que surgen del cambio. Para esta determinación se realizó una encuesta presencial a 90 empresas de acuicultura de mitílidos en la localidad de Chiloé (42º40'36"S; 73º59'36"W) durante noviembre del 2014 y febrero del año 2015. Los entrevistados fueron seleccionados de acuerdo a la producción total por temporada. Estableciendo 3 categorías: 1) Pequeños: con una producción total de 400 t/temporada; 2) Medianos: con una producción de 400 y 1350 t/temporada y 3) Grandes: con una producción total de más de 1350 t/temporada.

La encuesta estuvo compuesta por 4 secciones: percepción, respuestas a perturbaciones pasadas, comportamiento contingente y la relación entre las diferentes dimensiones y la disposición a pagar.

Se caracterizó la forma en la que la industria se ha adaptado y recuperado de factores de estrés específicos en la capacidad productiva. Además se evaluó los factores determinantes de la disposición de las industrias a invertir en la creación de capacidad para anticipar los cambios a través de los activos de las compañías para aprovechar en momentos de necesidad (capital), flexibilidad para cambiar estrategias, percepción de las empresas sobre la organización social de las industrias para actuar colectivamente (capital social), su confianza en la ciencia y su respuesta a escenarios hipotéticos en la capacidad productiva.

REFERENCIAS


Adger, W. N. & K. Vincent. 2005. Uncertainty in adaptive capacity. *Comptes Rendus Geoscience.* 337, 399-410. doi:10.1016/j.crte.2004.11.004

Adger, W. N., S. Huq, K. Brown, D. Conway & and M. Hulme. 2003. Adaptation to climate change in the developing world. *Progress in Development Studies*. 3(3), 179–195. doi:10.1191/1464993403ps060oa

Alfnes, F., A. G. Guttormsen, G. Steine & K. Kolstad. 2006. Consumers' willingness to pay for the color of salmon: a choice experiment with real economic incentives. *American Agricultural Economics Association*. 88, 1050-1061.

Araneda, D. 2009. El consumo de productos pesqueros y de acuicultura en Chile. Ministerio de Economía, Fomento y Reconstrucción. Informe Técnico N 43.

Barria, A., P. Gebauer & C. Molinet. 2012. Variabilidad espacial y temporal del suministro larval de mitílidos en el Seno Reloncaví, sur de Chile. *Revista de Biología Marina y Oceanografía*. 47(3), 461-473. doi:10.4067/S0718-19572012000300009

Bautista, C. P. 1988. Moluscos: Tecnología de cultivo. Ed. Mundi Prensa. 25. 37pp.

Batzios, C. h., P. Angelidis, D. K. Moutopoulos, C. H. Anastasiadou & V. Chrisopolitou. 2002. Investigation of consumer preferences towards the farmed fish market in greece. In: proceedings of the 1st International Congress on Aquaculture, Fisheries Technology and Environmental Management, June 2002, Athens.

Bayne, B. L. 1976. Marine mussels: their ecology and physiology. *International Biological Programme*. Cambridge University Press, 269.

Bednaršek, N., G. A. Tarling, D. C. E. Bakker, S. Fielding, E. M. Jones, H. J. Venables, P. Ward, A. Kuzirian, B. Lézé, R. A. Feely & E. J. Murphy. 2012. Extensive dissolution of live pteropods in the Southern Ocean. *Nature Geoscience*. 5, 881. doi:10.1038/NGEO1635

Bennett, J. & R. Blamey. 2001. The choice modeling approach to nonmarket valuation. Cheltenham UK and Northampton, MA, USA: Edward Elgar.

Boop, L., L. Resplandy, J. C. Orr, S. C. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra & M. Vichi. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences*. 10, 6225-6245 (2013). doi.org/10.5194/bg-10-6225-2013

Brécard, D., S. Lucas, N. Pichot, & F. Salladarré. 2012. Consumer preferences for eco, health and fair trade labels. An application to seafood product in France. Journal Agricultural & Food Industrial Organization. 10(1)-30-62. doi:10.1515/1542-0485.1360

Brenner, M., C. Buchholz, O. Heemken, B. H. Buck & A. Koehler. 2012. Health and growth performance of the blue mussel (*Mytilus edulis* L.) from two hanging cultivation sites in the German Bight: a nearshore-offshore comparison. *Aquaculture International*. 20, 751-778. doi:10.1007/s10499-012-9501-0

Buschbaum, C., G. Buschbaum, I. Schrey & D. W. Thieltges. 2007. Shell-boring plychaetes affect gastropod shell strength and crab predation. *Marine Ecology Progress Series.* 329, 123-130.

Caldeira, K. & M. E. Wickett. 2003. Oceanography: anthropogenic carbon and ocean pH. *Nature*. 425, 365. doi:10.1038/425365[a]

Calder, P. C. 2012. Omega-3 polyunsaturated fatty acids and inflammatory processes: nutrition or farmacology? British Journal of Clinical Pharmacology. 75(3), 645-662. Doi: 10.1111/j.1365-2125.2012.04374.x.

Cardoso, C., H. Lourenço, S. Costa, S. Gonçalves, & M. L. Nunes. 2012. Survey into the seafoodconsumption preferences and pattern in the portuguese population. Gender and regional variability. *Appetite.* 64, 20–31. doi:10.1016/j.appet.2012.12.022

Carlsson, F. & P. Martinsson. 2001. Do hypothetical and actual marginal willingness to pay differ in choice experiments?. *Journal of Environmental Economics and Management*. 41(2), 179-192. doi.org/10.1006/jeem.2000.1138

Chau, C. K., M. S. & K. Y. Chung. A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. *Building and Environmental.* 45, 2553-2561. doi:10.1016/j.buildenv.2010.05.017

Coleman D.W., M. Byrne & A. R. Davis. 2014. Molluscs on acid: gastropod shell repair and strength in acidifying oceans. *Marine Ecology Progress Series.* 509, 203-211. doi:10.3354/meps10887

Cooley, S. R., & S. C. 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*. 4, 024007. doi:10.1088/1748-9326/4/2/024007

Corporación de Fomento de la Producción (CORFO). 2003. Bases para un programa de diversificación de la acuicultura regional. Informe final, 68 pp.

Cunnane S. C., M. Plourde, E. Pifferi, M. Bégin, C. Féart & P. Barberger-Gateau. 2009. Fish, docosahexaenoic acid and alzheimer´s disease. Progress in Lipid Research. 48(5), 239-256.doi:10.1016/j.plipres.2009.04.001

Díaz, E. 2010. Mitílidos en la región de Los Lagos: Condiciones de trabajo en la industria del chorito, Departamento de Estudios de la Dirección del trabajo, Santiago, Chile, pp. 182.

Dickson, A. G., C. L. Sabine & J. R. Christian (Eds.) Guide to best practices for ocean $CO_2$ measurements. In PICES Special Publication 3, 191 (2007).

Dickson, A.G. 1990. Estándar potential of the reaction: $AgCl_{(s)}+1.2H_{2(g)}=Ag_{(s)}+HCl_{(aq)}$, and the estandar acidity constant of the ion $HSO^{-4}$ in synthetic sea wáter from 273.15 to 318.15 ºK. *The Journal of Chimical Thermodynamic.* 22, 113-127.

Dickson, A. G. & F. J. A. Millero. 1987. Comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. *Deep Sea Research*. 34, 1733–1743.

DOE (1994) Handbook of methods for the analysis of the various parameters of the carbón dioxide system in seawater; version 2. In: Dickson, A. G. & C. Goyet (Eds.), ORNL/CDIAC, 74.

Duarte, C., J. M. Navarro, K. Acuña, R. Torres, P. H. Manríquez, M. A. Lardies, C. A. Vargas, N. A. Lagos, & V. Aguilera. 2015. Intraspecific variability in the response of the edible mussel *Mytilus chilensis* (Hupe) to ocean acidification. Estuaries and coasts. 38: 590-598. doi:10.1007/s12237-014-9845-y

Dupont, S., E. Hall, P. Calosi & B. Lundve. 2014. First evidence of altered sensory quality in a shellfish exposedto dcresed pH relevant to ocean acidification. Journal of Shellfish Research. 3(3), 857–861. doi.org/10.2983/035.033.0320

Ekman, J. E. 1996. Closing the larval loop: linking larval ecology to the population dynamics of marine invertebrates. *Journal Experimental Marine Biological Ecological*. 200, 207-237.

FAO. 2018. Food and Agriculture Organization of The United Nations. Globefish. Analysis and information on world fish trade. In http://www.fao.org/in action/globefish/market-reports/resource-detail/en/c/1136590/

FAO, IFAD, UNICEF, WFP & WHO. 2017. The state of food security and nutrition in the world 2017. Building resilience for peace and food security. Rome, FAO.

FAO (2016). Food and Agriculture Organization of The United Nations. The state of world fisheries and aquaculture. Contributing to food security and nutrition for all. Rome. 200 pp.

FAO, 2016. El estado mundial de la pesca y la acuicultura. Food and Agriculture Organization of the United Nations.

Food Agriculture Organization: *Yearbook fisheries and aquaculture statistics* (2015).

Fernández, F. J., R. D. Ponce, F. Vásquez-Lavin, Y. Figueroa, S. Gelcich & J. Dresdner. 2018. Exploring typologies of artisanal mussel seed producers in southern Chile. *Ocean and Coastal Management* 158, 24-31. doi:10.1016/j.ocecoaman.2018.03.013

Figueroa, Y. & J. Dresdner. 2016. Are mussel seed producers responsive to economic incentives? Empirical evidence from the Benthic Resource Management areas in Chile. *Aquaculture Ecnomics and Management.* 20(3), 283-311. doi:10.1080/13657305.2016.1180647

Fuentes, A., I. Fernández-Segovia, I. Escriche & J. A. Serra. 2009. Comparison of physico-chemical parameters and composition of mussels (Mytilus galloprovincialis Lmk) from different Spanish origins. Food Chemistry 112, 295-302. doi:10.1016/j.foodchem.2008.05.064

Freites, L., M. J. Fernández-Reiriz & U. Labarta. 2002. Fatty acid profiles of *Mytilus galloprovincialis* (Lmk) mussel of subtidal and rocky shore origin. *Comparative Biochemistry and Physiology*. Part B 132, 453-461.

Gattuso, J. P., M. Frankignoulle, I. Bourge, S. Romaine & R. W. Buddemeier. 1998. Effects of calcium carbonate saturation of seawater in coral calcification. *Global Planet Change*. 18: 37-46.

Gazeau, F., Parker L. M., Comeau S., Gattuso J.-R., Pörtner H.-O. & P.M. Ross. 2013. Impacts of ocean acidification on marine shelled molluscs. *Marine Biology.* 160, 2207-2245. doi:10.1007/s00227-013-2219-3

Gazeau, F., C. Quiblier, J. M. Jansen, J.-P. Gattuso, J. J. Middelburg & C. H. R. Heip. 2007. Impact of elevated $CO_2$ on shellfish calcification. Geophysical Research Letters. 34, 1-5. doi:10.1029/2006GL028554, 2007 Impact

Gibson, R., R. J. A. Atkinson, J. D. M. Gordon, I. P. Smith & D. J. Hughes (eds) Taylor & Francis. 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential for persistence in a changing ocean. *Oceanography and Marine Biology*. An Annual Review. 49, 1–42.

Gilbert, B. (1991) En: Omega. Ed. Acuicultura. Vol I. La mitilicultura tradicional. 238-291.

Golden, C. D., E. H. Allison, W. W. L. Cheung, M. M. Dey, B. S. Halpern, D. J. McCauley, M. Smith, Vaitla B., Zeller D. & S. S. Myers. 2016. *Nature*. 534, 317–320.

Goldburg, R., M. S. Elliott, R. Naylor, Commission, P.O., et al., 2001. Marine aquaculture in the United States: environmental impacts and policy options. Pew Oceans Commission. Arlington, Virginia.

Gonzalez-Poblete, E., F. C. F. Hurtado, S. C. Rojo & C. R. Norambuena. 2018. Blue mussel aquaculture in Chile: Small or large scale industry? *Aquaculture*. 493, 113-122. doi: org. 10.1016/j.aquaculture.2018.04.026

Gosselin, L. A. & P. Y. Qian. 1997. Juvenile mortality in benthic marine invertebrates. *Marine Ecology Progress Series*. 146:265-282.

Grabacki, S. T. Onboard quality systems. In Environmental effects on seafood availability, safety, and quality. (eds. Daczkowska-Kozon, E. G. & Sun, Pan B.) pp 401. Chemical and functional properties of food components series. (Boca Raton: CRC Press, 2011).

Grothmann, T. & A. Patt. 2005. Adapatative capacity and human cognition: The process of individual adapatation to cliamte change. *Global Environmental Change.* 15, 199-213. doi: 10.1016/j.gloenvcha.2005.01.002

Handisyde, N., T. C. Telfer & L. G. Ross. 2017. Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. *Fish and Fisheries*. 18. 466-488. doi.org/10.1111/faf.12186

Hanley, N, S. Mourato & R. E. Wright. 2001. Choice modeling approaches: A superior alternative for environmental valuation. *Journal of Economic Surveys*. 15: 435-462. doi.org/10.1111/1467-6419.00145

Hartin, C. A., B. Bond-Lamberty, P. Patel & A. Mundra. 2016. Ocean acidification over the next three centuries using a simple global climate carbon-cycle model: projections and sensitivities. *Biogeosciences*. 13, 4329-4342. Doi:10.5194/bg-13-4329-2016

Hensher, D. A., J. M. Rose & W. H. Greene. 2005. Applied choice analysis: a primer. (Cambridge Univ. Press, Cambridge, 2005). doi:10.1017/CBO9781316136232

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment, Report of the Intergovernmental Panel on Climate Change. In: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller, (Eds.), Cambridge University, Cambridge, UK, p. 996.

IPCC (2001a) Climate Change 2001: Impacts, Adaptation & Vulnerability, Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Vol. Cambridge University Press, Cambridge.

Kattner, G. & H. S. G. Fricke. 1986. Simple gas–liquid chromatographic method for the simultaneous determination of fatty acids and alcohols in wax esters of marine organisms. *Journal Chromatography*. 361, 263–268.

Kent, R.M.L. 1981. The effect of *Polydora ciliate* on the shell strength of *Mytilus edulis*. *Journal du Conseil International Explor Mer* 39, 252-255.

Kurihara, H., T. Asai, S. Kato & A. Ishimatsu. 2008. Effects of elevated $pCO_2$ on early development in the mussel *Mytilus galloprovincialis*. *Aquatic biology*. 4, 225-233.

Kurihara, H, S. Kato & A. Ishimatsu. 2007. Effects of increased seawater $pCO_2$ on early development of the oyster *Crassostrea gigas*. *Aquatic Biology*. 1:91-98.

Kurihara, H. & Y. Shirayama. 2004. Effects of increased atmospheric $CO_2$ on sea urchin early development. *Marine Ecology Progress Series*. 274, 161-169.

Krapivka, S., J. E. Toro, A. C. Alcapan, M. Astorga, P. Presa, M. Pérez & R. Guiñez. 2007. Shell-shape variation along the latitudinal range of the Chilean blue mussel *Mytilus chilensis* (Hupe 1854). Aquaculture Research 38 (16), 1770–1777. Doi:10.1111/j.1365-2109.2007.01839.x

Kroeker, K. J., E. Sanford, J. M. Rose, C. A. Blanchette, F. Chan, F. P. Chavez, B. Gaylord, B. Helmuth, T. M. Hill, G. E. Hofmann, M. A. McManus, B. A. Menge, K. J. Nielsen, P. T. Raimondi, A. D. Russell & L. Washburn. 2016. Interacting environmental mosaics drive geographic variation in mussel performance and predation vulnerability. *Ecology Letters*. 19, 771-779. doi: 10.1111/ele.12613

Kroeker, K.J., R. L. Kordas, R. N. Crim & G. G. Singh. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecology Letters*. 13, 1419–1434. doi: 10.1111/j.1461-0248.2010.01518.x

Lagos, L., I. Uriarte & G. Yany. 2012. Evaluación del potencial reproductivo del chorito (*Mytilus chilensis*) en dos poblacioanes naturales sometidas a diferentes temperaturas de acondicionamiento. Latin American Journal of Aquatic Research. 40(2), 389-397.doi:10.3856/vol40-issue2-fulltext-13

Lara, C., G. S. Saldías, F. J. Tapia, J. L. Iriarte & B. R. Broitman. 2016. Interannual variability in temporal patterns of Chlorophyll-a and their potential influence on the supply of mussel larvae to inner waters in northern Patagonia (41-44ºS). *Journal of Marine Systems*. 155, 11-18. doi.org/10.1016/j.jmarsys.2015.10.010

Larsen, R., K.-E. Eilertsen & E. O. Elvevoll. 2011. Health benefits of marine foods and ingredients. *Biotechnology Advances.* 29, 508-518. doi:10.1016/j.biotechadv.2011.05.017

LeBlanc, A, T. Landry & G. Miron. 2003. Fouling organisms of the blue mussel *Mytilus edulis*: their effect on nutrient uptake and release. Journal Shellfish Research. 22(3), 633-638.

Leiva, G, C. Santibañez, J. Bartheld, C. Molinet & J. Navarro. 2007. Definición de criterios biológicos, ambientales, sanitarios y operativos para la instalación de colectores de moluscos bivalvos en la X Región. Informe final proyecto FIP 2005-18: 197 pp.

Lewis, E. & D. Wallace. 1998. Program developed for $CO_2$ system calculations. Carbon dioxide information analysis center. Oak Ridge, Tennessee, U.S.A.

López, M., T. Von Plessing, G. Navarrete, G. Lara, E. Ruiz, G. Villarroel & M. Donoso (1980) Presencia de larvas de mitílidos en el plancton y organismos adherentes en colectores de Yaldad Chiloé - X Región. Informe final convenio Intendencia X Región - Universidad de Concepción, Concepción, 54 pp.

Louviere, J. J. & G. Woodworth. 1983. Design and analysis of simulated consumer choice or allocation experiments: an approach based on aggregate data. *Journal of Marketing Research*. 20: 350-367.

Lozada, E. 1968. Contribución al estudio de la cholga *Aulacomya ater*, en Putemún (Mollusca, Bivalva, Mytilidae). Biol. Pesq. 3, 3-39.

McFadden, D. L. 1984. Econometric analysis of qualitative response models. In *Handbook of econometrics*. 2, 1395-1457.

Mackenzie, C.L., S. A. Lynch, S. C. Culloty & S. K. Malham. 2014. Future oceanic warming and acidification alter immune response and disease status in a commercial shellfish species, *Mytilus edulis* L. PLoS One 9, e99712. Doi:10.1371/journal.pone.0099712

Mehrbach, C., C. H. Culberson, J. E. Hawley & R. N. Pytkowicw. 1973. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnology Oceanography*. 18, 897–907.

Menge, B. A., F. Chan, K. J. Nielsen, E. Di Lorenzo & J. Lubchenco. 2009. Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment. *Ecological monographs*. 79(3), 379-395.

Millanao, A., M. Barrientos, C. Gómez, A. Tomova, A. Buschmann, H. Dölz & F. Cabello. 2011. "Uso inadecuado y excesivo de antibióticos: Salud pública y salmonicultura en Chile". *Revista Médica de Chile*. 139, pp. 107-118.

Molinet Flores, C. A., M. A. Díaz Gomez, C. B. Arriagada Muñoz, L. E. Cares Pérez, S. L. Marín Arribas, M. P. Astorga Opazo & E. J. Niklitschek Huaquin. 2015. Spatial distribution pattern of Mytilus chilensis beds in the Reloncaví fjord: hypothesis on associated processes. *Revista chilena de historia natural* 88, 1-12. doi.org/10.1186/S40693-015-0041-7

Monfort, M.-C. 2014. Globefish consultant. The European market for mussels. *Globefish Research Programme*. Vol. 115, Rome, FAO 2014. 65 pp.

Mozzaffarian, D. & J. H. Y. 2011. Omega-3 fatty acids and cardiovacular disease: effects on risk factors, molecular pathways, and clinical events. *Journal of the American College Cardiology.* 58(20), 2047-2067. doi:10.1016/j.jacc.2011.06.063

Navarro, J.M., C. Duarte, P. H. Manríquez, M. A. Lardies, R. Torres, K. Acuña, C. A. Vargas & N. A. Lagos. 2016. Ocean warming and elevated carbon dioxide: multiple stressor impact on juvenile mussels from southern Chile. *ICES Journal of Marine Science*. 73(3): 764-771. doi.org/10.1093/icesjms/fsv249

Navarro, J.M., R. Torres, K. Acuña, C. Duarte, P. H. Manriquez, M. A. Lardies, N. A. Lagos, C. A. Vargas & V. Aguilera. 2013. Impact of medium-term exposure to elevated $pCO_2$ levels on the physiological energetics of the mussel *Mytilus chilensis*. *Chemosphere*. 90(3), 1242-1248. doi:10.1016/j.chemosphere.2012.09.063

Orr, J.C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos. *et al*., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*. 437(7059), 681-686.doi: 10.1038/nature04095

Osores, S. J. A., N. A. Lagos, V. San Martin, P. H. Manriquez, C. A. Vargas, R. Torres, J. M. Navarro, M. J. Poupin, G. S. Saldias & M. A. Lardies. 2017. Plasticity and inter-population variability in physiological and life-history traits of the mussel *Mytilus chilensis*: A reciprocal transplant experiment. Journal of Experimental Marine Biology and Ecology. 490, 1-12. doi.org/10.1016/j.jembe.2017.02.005

Osorio, C. 1979. Moluscos marinos de importancia económica en Chile. *Biologia Pesquera*. Chile, (11): 3-47.

Penney, R.W., M. J. Hart & N. D. Templema. 2007. Shell strength and appearance in cultured blue mussels *Mytilus edulis*, *M. trossulus*, and *M. Edulis* X *M. trossulus* hybrids. *North American Journal of Aquaculture*. 69, 281–295.doi: 10.1577/A06-044.1

Richardson, A. J., J. R. Burton, R. P. Sewell, T. F. Spreckelsen & P. Montgomery. 2012. Docosahexaenoic acid for reading, cognition and behavior in children aged 7-9 years: A randomized, controlled trial (The DOLAB Study). *Plos One*. 7: e43909, 1-14. doi:10.1371/journal.pone.0043909

Riviera, A., J. Unibazo, P. León, F. Vásquez-Lavín, R. Ponce, L. Mansur & S. Gelcich. 2017. Stakeholder perceptons of enhancement opportunities in the Chilean small and medium scale mussel aquaculture industry. Aquaculture. 479, 423-431. doi.org/10.1016/j.aquaculture.2017.06.015

Romano, D., D. de Groot, S. Grafakas, L. Hein, G. Nocella & V. Tassone. 2008. Internet-based valuation and group valuation methodologies. SENSOR Report Series. Available at http://www.sensor-ip.eu, ZALF, Germany.

Royal Society. 2005. Ocean Acidification due to increasing atmospheric carbon dioxide. Policy document 12/05. London: The Royal Society.

Rozas, M. & G. Asencio. 2007. "Evaluación de la situación epidemiológica de la caligiasis en Chile; hacia una estrategia de control efectiva", SalmoCiencia 2, pp. 43-59.

Ruiz, M., E. Tarifeño, A. Llanos-Rivera, C. Padget & B. Campos. 2008. Efecto de la temperatura en el desarrollo embrionario y larval del mejillón, *Mytilus galloprovincialis* (Lamarck, 1819). *Revista de Biolpogía Marina y Oceanografía*. 43(1): 51-61.

Sabine, C. L., et al. 2004. Current status and past trend of the Global carbon cycle, in The Global Carbon Cycle: Integrating Humans, Climate and the Natural World. SCOPE 62, Edited by C. B. Field & M. R. Raupack, Island Press, Washington. D.C.

Servicio Nacional de Pesca y Acuicultura. 2014. Anuarios estadisticos, Valparaiso, Chile.

Servicio Nacional de Pesca y Acuicultura. 2010. Anuarios estadisticos, Valparaiso, Chile.

Schalkhausser, B., C. Bock, H.-O. Pörtner, H.-O., G. Lannig. 2014. Escape performance of temperate king scallop, Pecten maximus under ocean warming and acidification. *Marine Biology*. 161, 2819–282. doi:10.1007/s00227-014-2548-x

Shahraki, J. & M. Dahmardeh. 2014. Economic Valuation of Environmental Resources in Hamoon International Wetland, Using the Choice Experiment Method. *International Journal of Agriculture and Forestry, 4*(5), 394-401.

Soto, D. & F. Norambuena. 2004. "Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: a large-scale mensurative experiment", *Journal of Applied Ichthyology*. 20, pp. 493–501.

Stotz, W. 1981. Aspectos ecológicos de *Mytilus edulis* chilensis (Hupé, 1854) en el estuario del Río Lingue (Valdivia, Chile). *Revista de Biología Marina*. Valparaíso, 17(3): 335- 377.

Sveinsdóttir, K., E. Martinsdóttir, D. Greem-Petersen, G. Hyldig, R. Schelvis & C. Delahunty. 2009. Sensory characteristics of different cod products related to consumer preferences and attitudes. *Food Quality and Preference*. 20,120-132 . doi:10.1016/j.foodqual.2008.09.002

Swanson, D., R. Block & S. A. Mousa. 2012. Omega-3 fatty acids EPA and DHA: health benefits throughout life. *Advances in Nutrition.* 3, 1-7. doi:10.3945/an.111.000893

Talmage, S.C. & J. G. Gobler. 2010. Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. *Proceedings of the National Academy of the Science*. 107(40), 17246–17251. doi:10.1073/pnas.0913804107

Thomsen, J., I. Casties, C. Pansch, A. Körtzinger & F. Melzner. 2013. Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. *Global Change Biology*. 19, 1017–1027. doi:10.1111/gcb.12109

Thouzeau, G. 1991. Déterminisme du pré-recrutement de *Pecten maximus* (L.), en baie de Saint-Brieuc: processus régulateurs de l'abondance, de la survie et de la croissance des post-larves et juvéniles. *Aquatic Living Resources*. 4(2), 77-99. doi:10.1051/alr:1991008

Tirachini, A., R. Hurtubia, T. Dekker & R. A. Daziano. 2017. Estimation of crowding discomfort in public transport: results from Santiago de Chile. *Transportation Research*. Part A- Police and Practice. 103, 311-326. doi:10.1016/j.tra.2017.06.008

Toro, J. E., G. C. Castro, J. A. Ojeda & A. M. Vergara. 2006. Allozymic variation and differentiation in Chilean blue mussel, *Mytilus chilensis*, along in natural distribution. *Genetics and Molecular Biology*. 29(1), 174-179. doi:10.1590/S1415-47572006000100031

Train, K. E. 2009. Discrete choice methods with simulation (Cambridge univ. press, Cambridge, 2009).

Uriarte, I. 2008. Estado actual del cultivo de moluscos bivalvos en Chile. En A. Lovatelli, A. Farías & I. Uriarte (eds). Estado actual del cultivo y manejo de moluscos bivalvos y su proyección futura: de agosto de 2007, Puerto Montt, Chile. FAO Actas de Pesca y Acuicultura. No. 12. Roma, FAO. pp. 61–75.

Uribe, E. 2015. Estudios del cambio climático en América Latina. El cambio climático y sus efectos en la biodiversidad en América Latina. Comisión Económica para América Latina y el Caribe (CEPAL). Naciones Unidas, 86 pp.

Valenzuela, A., C. G. Yáñez & C. Golusda. 2011. The scallop from the Chilean north (*Argopecten purpuratus*), a food with a high nutritional value. *Revista Chilena de Nutrición*. 38, 148-155. doi:10.4067/S0717-75182011000200005.

Valenzuela, A. 2005. Salmon: a Health banquet. *Revista Chilena de Nutrición*. 32, 8-17. Doi.org/10.4067/S0717-75182005000100001.

Vargas, C. A., N. A. Lagos, M. A. Lardies, C. Duarte, P. H. Manríquez, V. M. Aguilera, B. Broitman, S. Widdicombe & S. Dupont. 2017. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. Nature Ecology & Evolution. 1, 84-90. doi:10.1038/s41559-017-0084.

Vásquez, F., A. Cerda & S. Orrego. 2007. *Valoración económica del ambiente: fundamentos económicos, econométricos y aplicaciones*: Thomson Learning, Buenos Aires.

Ventura, A., S. Schulz & S. Dupont. 2016. Maintained larval growth in mussel larvae exposed to acidified under-saturated seawater. Nature Scientific Reports. 6, 23728. doi:10.1038/srep23728

Waldbusser, G.G., B. Hales, C. J. Langdon, B. A. Haley, P. Schrader, E. L. Brunner, M. W. Gray, C. A. Miller & I. Gimenez. 2015. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nature Climate Change*. 5, 273. doi: 10.1038/NCLIMATE2479

Winter, J., J. E. Toro, J. Navarro, G. S. Valenzuela & O. Chaparro. 1984. Recent development, status and prospects of molluscan aquaculture on the Pacific coast of South America. *Aquaculture*, 39(1-4), 95-134. doi:10.1016/0044-8486(84)90261-8

Widdicombe, S. & H. R. Needham. 2007. Impacts of $CO_2$ induced seawater acidification on the burrowing activity of Nereis virens and sediment nutrient flux. *Marine Ecology Progress Series*. 341, 111-122.

Wittmann, A. C. & H.-O. Pörtner. 2013. Sensitivities of extant animal taxa to ocean acidification. *Nature Climate Change*. 3, 995. doi:10.1038/NCLIMATE1982

Wood, H. L., J. I. Spicer & S. Widdicombe. 2008. Ocean acidification may increased calcification rates, but at a cost. *Proceedings of the Royal Society B: Biological Sciences*. 275(1644), 1767-1773. doi:10.1098/rspb.2008.0343

CAPITULO I:

**Effect of low pH/high $pCO_2$ ocean acidification conditions on biomineralization of the mussel shells *Mytilus chilensis.***

Valeska A. San Martin[1,2*],Carlos Medina[3], Laura Ramajo[2,4], Alejandro B. Rodriguez-Navarro[5], Christian Grenier[5], Rocío Román[5] and Cristian A. Vargas[1,2]

[1] *Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepcion, Concepcion, Chile.*

[2] *Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile.*

[3] *Department of Mechanical Engineering, Faculty of Engineering Universidad de Concepción, Concepción, Chile.*

[4] *Centro de Estudios avanzados en Zonas Aridas (CEAZA), Avenida Ossandon 877, Coquimbo, Chile.*

[5] *Department of Mineralogy and Petrology, Faculty of Science, Universidad de Granada, Granada, Spain.*

[*] *Corresponding author: V.A. San Martin (valezkasanmartin@gmail.com)*

En preparación

Effect of low pH/high $pCO_2$ ocean acidification conditions on biomineralization of the mussel shells *Mytilus chilensis*.

Valeska A. San Martin[1,2*], Carlos Medina[3], Laura Ramajo[2,4], Alejandro B. Rodriguez-Navarro[5], Christian Grenier[5], Rocío Román[5] and Cristian A. Vargas[1,2]

[1]*Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepcion, Concepcion, Chile.* [2]*Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile.*

[3]*Department of Mechanical Engineering, Faculty of Engineering Universidad de Concepción, Concepción, Chile.*

[4]*Centro de Estudios avanzados en Zonas Aridas (CEAZA), Avenida Ossandon 877, Coquimbo, Chile.*

[5]*Department of Mineralogy and Petrology, Faculty of Science, Universidad de Granada, Granada, Spain.*

*Corresponding author: valezkasanmartin@gmail.com

Abstract

Increasing atmospheric carbon dioxide levels are causing ocean acidification compromising the ability of some marine organisms to build and maintain support structures from calcium carbonate. *Mytilus chilensis* is one of the most important cultivated resources in southern Chile. However, this activity is constantly facing unfavourable environmental and anthropogenic conditions such as low concentration of food (e.g. phytoplankton), pollution and climatic stressors that have an impact on its development and production.

We designed an experiment with exposure to an AO condition and we measured the mechanical properties (biomineralization) in the mussel shells *Mytilus chilensis* in order to determine the effects of a high level of CO2 on the mussel's mineralization adults and juveniles.

Our showed that shell of the *Mytilus chilensis* were significantly weaker than those held at ambient pH even after 30 days exposure in adults and 120 days exposure in juveniles. Suggesting that the structural integrity of the shells is compromised in exposures to treatments of AO causing reduction in the resistance of the shells, resulting in weak shells.

The OA can cause a formation of weak and thin shells, less resistant to break in the mussel M. chilensis, which could be problematic under a scenario of environmental change and the physical impact with other nearby organisms, when they are in the crop line.

## Introduction

Aquaculture worldwide is the fastest growing productive sector (FAO, 2016). Within this activity, the production of mussels occupies the third place in the category of molluscs cultivated worldwide (Gazeau et al., 2013), supporting the world aquaculture industry with a value of more than 3 thousand billion dollars during the year 2015 (FAO, 2015). However, this activity is subject to multiple sources of variability, including environmental and anthropogenic alterations (Barria et al., 2012, Goldburg et al., 2001). One of the most important anthropogenic changes studied has been the increase in greenhouse gas concentrations, including $CO_2$. This increase in anthropogenic $CO_2$ levels has had dramatic consequences in the ocean, through the absorption of atmospheric $CO_2$ with a significant reduction in pH and carbonate ion concentration ([CO3-2] (Sabine et al., 2004; Caldeira and Wickett, 2003; Orr et al., 2005), known as Acidification Ocean (AO), whith effects negative in marine species vulnerable to OA, mainly calcifying organisms such as mussels (Gazeau et al., 2013). OA can significantly impair various physiological features in marine molluscs such as oysters (Cooley & Doney, 2009; Schalkhausser et al., 2014; Talmage and Gobler, 2010), gastropods (Bednaršek et al., 2012; Wittmann and Portner, 2013), and mussels (Gazeau et al., 2013; 2007; Kroeker et al., 2010; Ventura et al., 2016; Waldbusser et al., 2015). In addition, OA affects mortality rates (Gibson et al., 2011), calcification and growth, increasing vulnerability to diseases and parasites (Gazeau et al., 2013, Mackenzie et al., 2014, Thomsen et al., 2013). Furthermore, recent studies have demonstrated that OA may impact the quality of mussels in nutritional characteristics (San Martin et al., 2018) and the linking whit the preferences in the consumers (Ponce et al., 2019). These calcifying organisms are particularly vulnerable because they depend on carbonate concentrations to build their shells (Gazeau et al., 2013; Waldbusser et al., 2015).

In Chile, the principal specie of mollusc in aquaculture is mussel Mytilus chilensis, where of the production for human consumption implies some form of intervention in the natural rearing process such as seed uptake for to continue then stage of grown and the methods of cultivation in lines to ensure the stock of organisms (Fernández et al., 2018).

When the organisms reach commercial size (~ 5 cm), they are removed from the fattening lines submerged in the sea where they were fixed, the mussel is detached, cleaned and selected by size to be bagged for transport to the process plants for later commercialization (Días, 2010). In this stage of handling (harvest), losses associated with low caliber specimens are generated that are not commercialized and in addition an important fraction of specimens that suffer the breakage of their shells due to the collision between specimens on the harvesting platforms.

Furthermore, considering that shell in mollusc has mechanical properties with unique structural organization and composition (Kamat et al., 2000). This structure can be damage by the increase of the concentration of $CO_2$ in the ocean, increasing the rates of dissolution and weakening of the shells (Beniash et al., 2010). Which could result, greater losses in the primary processing due to the rupture of the shell and the sacrifice of the mussels considered visually unattractive from a market perspective (San Martín et al., 2019). In this way, the Ocean Acidification in addition to having biological implications could have potential economic consequences for the industries that depend on them (Ponce et al., 2019). Given a condition of OA, we believe that the shells of organisms can make me more fragile and increase the break causing more losses associated with the industry.

To evaluate this condition, we conducted a study focused on determining the impact of low pH/high $pCO_2$ ocean acidification conditions on physical (i.e. shell hardness) relevant market attribute for consumers in one of the main mussel farming industry worldwide.

**Material and Methods**

*Organism collection:* Juvenile and adults individuals of *Mytilus chilensis* (Shell length: 2.5 ± 0.5 cm and 7.4 ± 0.2 cm, respectively) were collected at a mean depth of 5 m from a mussel farming facility located in Vilupulli, Chiloé, southern Chile (42°49´S; 73°78´W). Samples were collected during July and October 2015, when environmental conditions in the area averaged between 10.0 and 12.4 ºC; 32.0 and 32.9 PSU of salinity, and 7.9 and 8.3 pH units). Once collected, organisms were immediately transported to the Marine Biology Laboratory at Dichato (Universidad de Concepción). Individuals were kept in filtered (0.1 mm) and aerated seawater at a temperature of ~ 11°C, ~31 psu salinity, and 8.0 ± 0.1 pH units, which indeed represented the mean ambient conditions in the mussel farming area. We considered an acclimatization period of two weeks in these mesocosm conditions and animals were fed daily with the commercial food phytogold-s (*Isochrysis sp.* and *Pavlova sp.*), at a mean concentration of 2.5 μ $L^{-1}$ Chl *a*.

*$CO_2$ manipulation and experimental conditions:* Two plastic 280L tanks were used as acidification units to generate seawater to two nominal levels of $pCO_2$: 400 (control treatment) simulated present day conditions and 1000 ($CO_2$ treatment) were selected taking into account the rate of change projected by the years 2070-2110 (i.e. based on rate of

change in pH predicted by the most extreme scenario [RCP8.5 scenario] of atmospheric $CO_2$ (Meinshausen *et al.*, 2011). Air/$CO_2$ mixtures were produced using a bulk flow technique, where know flow of dry air and ultra-pure $CO_2$ gas were supplied, via mass flow controller (MFC), and mixed before equilibration with seawater. To obtain the $CO_2$ concentration 400 ppm, pure atmospheric air was bubbled into control tank and $CO_2$ flow was set manually to 4.25 mL min $^{-1}$, to produce $CO_2$ treatment of 1000 ppm. During the experiments seawater pH (total scale, $pH_T$) were monitored in each tank every 7 day in 25 mL cell thermostatted at 25 ± 0.1 ºC for standardization, with meter Metrohm® using a glass combined double junction Ag/AgCl electrode following DOE potentiometric method (DOE, 1994).

*Experimental setup:* after the acclimation period, sixty individuals were cleaned and separated in ten groups of 6 individuals in aquariums with 9 L of capacity, each treatment was replicated five times with total 30 individuals for control (11°C and 400 ppm $CO_2$) and 30 individuals for high treatment (11°C and 1000 ppm $CO_2$).

Total alkalinity was measured 7 day using the open-cell titration method (Dickson *et al.*, 2007), by using an automatic Alkalinity Tritator Model AS-ALK2 Apollo SciTech. The AS-ALK2 system is equipped with a combination pH electrode (8302BNUWP *Ross Ultra* pH/ATC *Triode*, Thermo Scientific, USA) connected to a pH meter (Orion star A211 pH meter, Thermo Scientific, USA). All samples were analysed at 25 ºC (± 0.1 ºC) with temperature regulation using a water-bath (Lab companion CW-05G). The accuracy was controlled against a certified reference material (CRM, supplied by Andrew Dickson, Scripps Institution of Oceanography, San Diego, USA) and the $A_T$ repeatability averaged 2-3 μmol $kg^{-1}$.

The pH, total alkalinity (AT), phosphate (Strickland and Parson, 1968) and dissolved silicate (Strickland and Parson, 1968) were used to calculate the rest of the carbonate system parameters and the saturation stage of omega, aragonite and calcite using $CO_2$SYS software (Lewis and Wallace, 1998) set with Mehrbach solubility constants (Mehrbach *et al.*, 1973) refitted by Dickson and Millero (1987) (Table 1). Seawater in each experiment was replaced every two days with seawater that had been previously balanced.

*Shell preparation*: After exposing the mussels to high $p$CO$_2$ conditions for 120 days for the juveniles and 30 days for the adults, the soft material (meat) was removed and the shells were collected, for cleaning and washing with distilled water to remove the material present organic that adheres to the shell.

To study the effect on mechanical properties were performance two tests:

*1. Flexural strength and Hardness.* For flexural strength test, we tested 2 groups of adult *Mytilus chilensis* (10 individuals each): (1) Control Treatment and (2) $CO_2$ Treatment. The tests were performed on a universal testing machine Zwick Roell Z050 with a 500 N load cell. The testing speed was 5 mm $s^{-1}$; similar to used in studies of resistance in other gastropod species (Kent, 1981; Buschbaum *et al.* 2007; Coleman *et al.*, 2014). The size of tests samples were 5 mm width and 20 mm support span, were extract of flatter area on the shell. Each sample was subjected to flexion load until the shell fracture. The maximum load ($F$) was recorded and calculated the flexural strength using:

$$\sigma_{MAX} = \frac{3FL}{2bd^2}$$

where $L$ is the support span, $b$ is width and $d$ is the thickness (ASTM C1161 Flexural Strength of Advanced Ceramics at Ambient Temperature).

*2. For shell hardness,* twenty juvenile and twenty adults were used. The left shell valve of each mussel was set in a high strength plaster (Dental Plaster, Boral $^{TM}$) to give a flat support to the sample. The hardness was measured using a LM 300 AT Vickers microhardness tester with a load of 100 g and a loading time of 30 s. Seven measurement points were made in each valve.

*Relationship Calcite / Nacre M.chilensis*

Two groups of *Mytilus chilensis* specimens were analyzed to establish the Calcite / Nacre relationship: "Adults" and "Juveniles".

For the group of "Adults" a total of 29 rectangular sections (40x12 mm) of the shell from different experimental groups were analyzed: "Adults control" (n = 11), "Adults natural" (n = 8) and "Acidified adults" (n = 10). Some sections correspond to the area near the umbo (section A) and others to the area near the edge of apical growth (section B).

For the group of "Juveniles" a total of 14 rectangular sections (25x6 mm) were used, corresponding to the experimental groups "control juvenile" (n = 7) and "$CO_2$ juvenile" (n = 7).

For each samples, the medial part of the sections were analyzed. Photos were taken with an optical binocular loupe (Nikon SMZ1000) with a magnification of 0.8x. Along the cross section of each piece, 3 measurements were made in adults and 6 in juveniles to establish the thickness of the nacre layer and the total thickness (calcita + nacre layer). The measurements of the thickness of each layer were carried out with the program ImageJ (advanced version FIJI). Finally, the data of the measurements were processed with the Microsoft Excel program.

## Results

### Shell strength

We measured the force required to crack the shell of *M. chilensis*. This experiment found a significant decline in shell strength as treatment pH decreased. We observed 32% reduction of shell strength in adults exposed to pH low versus control treatment (Figure 1). The maximum force that shell in the pH 7.6 treatment could withstand was significantly lower than that for shell in the control pH (7.9-8.0). Shell from the control pH had a mean (±S.E) maximum load of 182.03 ± 56.97 N, while those from the treatment pH level 7.6, had maximum load of 124.34 ± 42.09 N, with differences significant when compared between treatments by Mann Whitney test ($p < 0.05$).

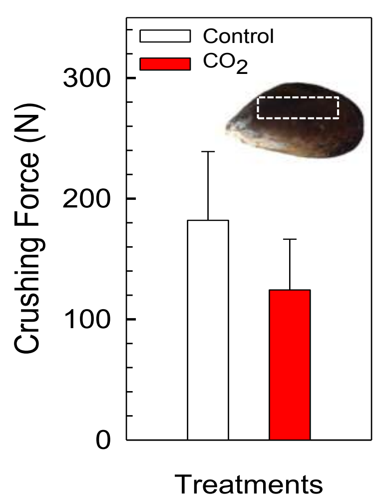

Figure 1: Mean (±S.D.) maximum force required to crush [N] required to caused fracture, after 30 d exposed in pH low and in control pH conditions, the rectangle indicates the section used to realized the flexural strength (seven measurement in each shell).

**Microhardness**

The hardness of the shell was evaluated in two sections. Section A= corresponding to the first larval formation and from shell growth continues with time. Section B= half to last growth of the shell. Our results show that juvenile and adults exposed to low pH treatment presented lower hardness in their shells compared to controls (Figure 2). The results obtained of comparison between the two sections of the shell, evidenced the most hardness in section A, where juvenile shell from pH control had hardness a mean (±S.E) maximum load of 70.7 ± 9.1 versus 47.7 ± 3.6 of treatment pH level 7.6 (Figure 2 a), and adults with maximum load of 63.0 ± 14.8 versus 30.1 ± 7.3 respectively (Figure 2 b). Hardness presented decreased highly significantly in those mussel shell under 400 and 1000 matm $pCO_2$ ($p<0.0001$).

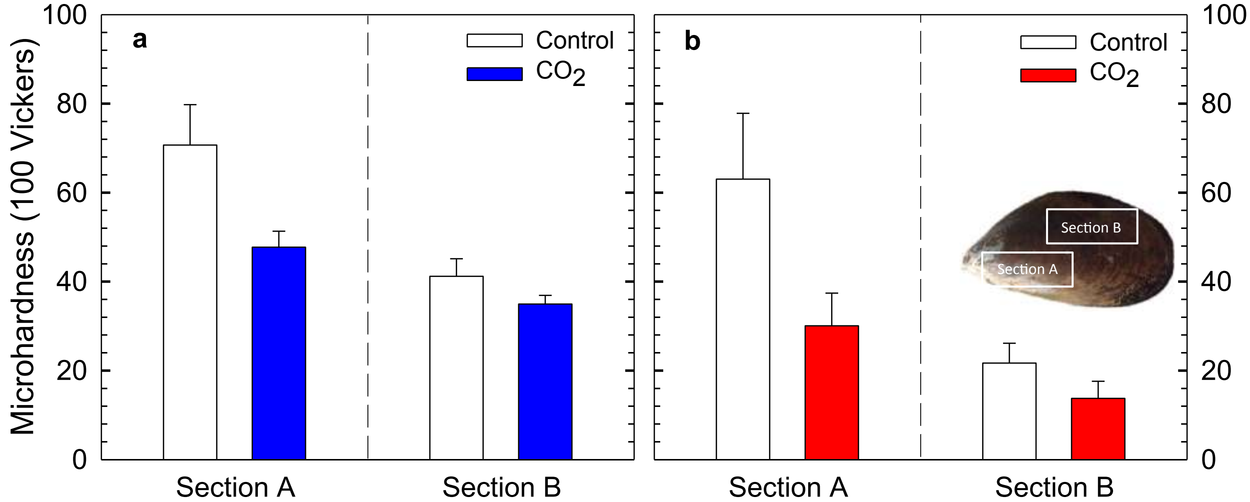


Figure 2: Shell hardness at the end experiment in two section of the valve. Bars blue color represents $CO_2$ treatment for juvenile mussel and red color represent $CO_2$ treatment in adult mussel.

**Relationship Calcite / Nacre *M. chilensis***

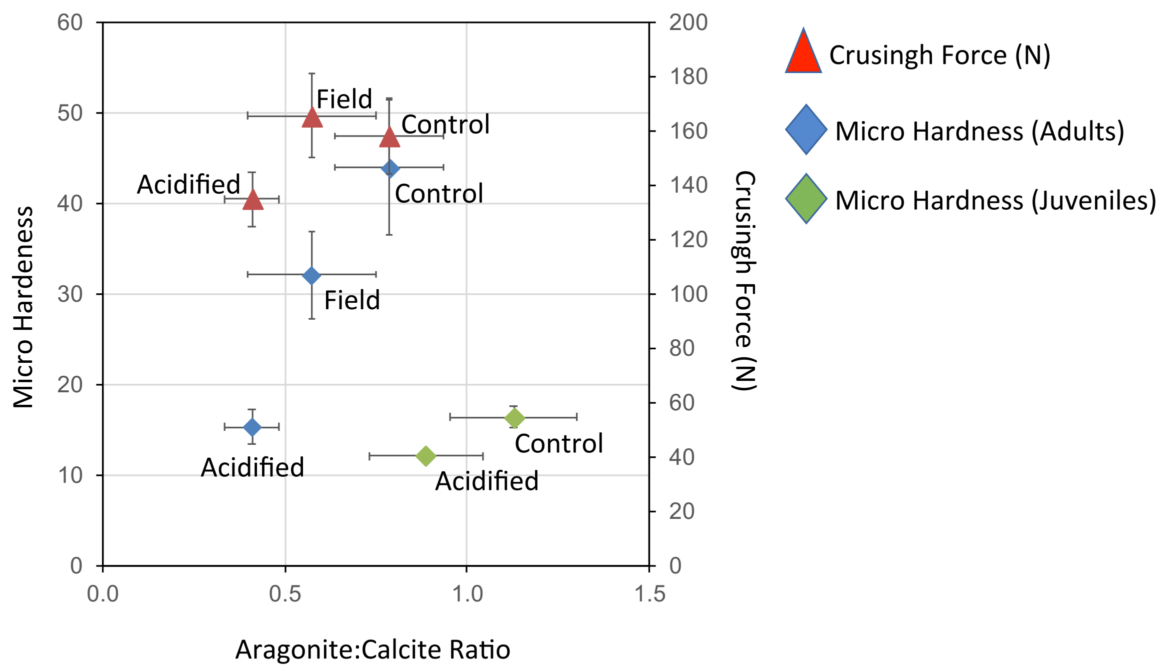

Figure 3: Relationship between micro hardness, crushing force and aragonita: calcite ratio in shells of mussel juveniles and adults exposed to control and pH low ($CO_2$ treatment) conditions.

All the organisms that were exposed $CO_2$ treatment conditions presented the lowest values for aragonite: calcite ratio. A similar response is observed in the micro hardness (adults) and crushing force, because both measures were performed in the group corresponding to adults.

**Discussion**

Although many marine invertebrates depend on their shells for protection, and although these could be weakened by the AO, evaluations of the effects of acidified seawater on shell resistance are limited (Beniash et al., 2010; Welladsen et al., 2010).

Our results are similar to has been report by Welladsen et al., (2010), where *Pinctada fucata* bivalve shells exposed to AO conditions 28 days were significantly weaker than those maintained at an ambient pH. Similarly, studies with shorter exposure times (8 days) in mussels of *Mytilus galloprovincialis*, presented a reduction in calcification with a result of weak and thin shells (Gaylord et al., 2011). Similar observation was realized in bivalves exposed to $CO_2$ acidified seawater at pH 7.4 (McClintock et al., 2009).

In addition, several studies show the dissolution of calcareous structures and loss of shell structural integrity when exposed to acidified seawater conditions such as:  Michaelidis et al. (2005), in the mussel *Mytilus galloprovincialis*; Buschbaum et al. (2007), in *Littorina littorea*; Gazeau et al. (2007), in *Mytilus edulis* and *Crassostrea gigas*; Ries et al. (2009), in 18 calcifying species; McClintock et al. (2009), in Antarctic molluscs such as *Laternula elliptica*, *Yoldia eightsi* and *Nacella concinna* and even Watson et al. (2009), in oyster shells *Saccostrea glomerata* in the larval stage.

In the same way, similar results of microhardness were found by Fitzer et al. (2014) where the hardness of *Mytilus edulis* shells decreased as they were grown in seawater with higher levels of $pCO_2$. Also, *Mytilus californianus* cultured at $CO_2$ levels were presented shells weaker and thinner (Gaylord et al., 2011). Shell grown under increasing $pCO_2$ would become more fragile; which may result in shells more likely to shatter under impact and thus being more vulnerable to breakage through friction. This could have ecological implications for bivalves and potential economic impacts for industries. However, different results were presented in *M. mercenaria* and *C. virginica*, was the shell fracture toughness or microhardness in level 800 $min^{-1}$ $pCO_2$ was not affected (Ivanina et al., 2013).

That is why, in evaluating this response, we have shown that the AO degrades the mechanical integrity of the Chilean mussel shells considerably, making them weaker and thinner compared to those exposed to control conditions. Suggesting that the structural integrity of the shells is compromised in exposures to treatments of AO causing reduction in the resistance of the shells, resulting in weak shells.

## Conclusion

This potential effect to OA can cause a formation of weak and thin shells, less resistant to break in the mussel M. chilensis, which could be problematic under a scenario of environmental change and the physical impact with other nearby organisms, when they are in the crop line. The study highlights the impact of ocean acidification on shell properties damage, these results provide important insights into to exposed near future scenarios of environmental change.

Future research is needed in this area to evaluate the critical effects of the various $CO_2$ exposure scenarios, in addition to studies that include more than one generation in the species, to determine possible phenotypic plasticity. In addition, further work using mechanistic approaches that reveal functional, ecologically relevant costs of OA are necessary to improve understanding of this major anthropogenic alteration to the world's oceans.

## Acknowledgments

The work was supported by 21151027 CONICYT. Additional support from the Millennium Nucleus "*Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS)*" funded by funded by MINECON NC120086, Red Doctoral REDOC. CTA MINEDUC project UCO1202 at Universidad de Concepción. The authors grateful to D. Rojas, Department of Materials Engineering in Universidad de Concepción and K. Garrido PhD student for their valuable assistance during this investigation.

## References


1. Asche F. & Zhang, D. Testing structural changes in the U.S. whitefish import market: An inverse demand system approach. Agricultural and Resource Economics Review **42**, 453-470 (2013).
2. Barclay K., Mcllgorm A., Mazur N., Voyer M., Schnierer S. and Payne, A.M. Social and Economic Evaluation of NSW Coastal Aquaculture, Fischeries Research and Development Corporation (FRDC 2015/302) and University of Technology Sydney, Sydney (2016).
3. Bednaršek N., Tarling G.A., Bakker D.C.E., Fielding S., Jones E.M., Venables H.J., Ward P., Kuzirian A., Lézé B., Feely R.A. & Murphy, E.J. Extensive dissolution of live pteropods in the southern Ocean. Nature Geoscience. 5, 881885 (2012).
4. Beniash E., Ivanina A., Lieb N. S., Kurochkin I. and Sokolova I. M. (2010) Elevated level of carbon dioxide affects metabolism and shell formation in oysters *Crassostrea virginica*. Marine Eclogy Progress Series. 419: 95-108.
5. Buschbaum C., Buschbaum G., Schrey I. & Thieltges, D.W. Shell-boring plychaetes affect gastropod shell strength and crab predation. Marine Ecology Progress Series 329, 123-130 (2007).
6. Caldeira K. & Wickett, M.E. Anthropogenic carbon and ocean pH. Nature. 425, 365 (2003).
7. Cardoso C., Lourenço H., Costa S., Gonçalves S. & Nunes, M. L. Survey into the seafood consumption preferences and pattern in the portuguese population. Gender and regional variability. Appetite. **64**:20–31 (2013).

**8.** Coleman D.W., Byrne M. & Davis A.R. Molluscs on acid: gastropod shell rapair and strength in acidifying oceans. Marine Ecology Progress Series. **509**, 203-211 (2014).

**9.** Cooley S.R., Rheuban J.E., Hart D.R., Luu V., Glover D.M., Hare J.A., & Doney, S.C. An Integrated Assessment Model for Helping the united states Sea Acallop (*Placopecten magellanicus*) Fischery Plan Ahead for Ocean Acidification and Warming. PlosOne. **10**(5), (2015).

**10.** Dickson A.G., Sabine C.L. & Christian, J.R. Guide to Best Practices for Ocean $CO_2$Measurements. Pices Special Publication 3 IOCCP Report 8 (2007).

**11.** Dickson A.G. & Millero, F.J. A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. Dee Sea Research Part A: Oceanographic Research Paper 34, 1733-1743 (1987).

**12.** Doney S.C., Ruckelshaus M., Duffy J.E., Barry J.P., Chan F., English C.A., Galindo H.M., Grebmeier J.M., Hollowed A.B., Knowlton N.N., Sydeman W.J. & Talley, D. Climate Change Impacts on Marine Ecosystems. Annu. Rev. Mar. Sci.11-37 (2012).

**13.** Doney, S. C., Fabry V. J., Feely R. A. and Kleypas J. A. (2009) Ocean acidification: the other $CO_2$ problem. Annu Rev Mar Sci 1: 169-192.

**14.** Duarte C., Navarro J.M., Acuña K., Torres R., Manríquez P.H., Lardies M. Vargas C.A., Lagos N.A. & Aguilera, V. Combined effects of temperature and ocean acidification on the juvenile individuals of the mussel *Mytilus chilensis*. Journal of Sea Research. **85**, 308-314 (2014).

**15.** Ekstrom J.A., Suatoni L., Cooley S.R., Pendleton L.H., Waldbusser G.G., Cinner J.E., Ritter J., Langdon C., Van Hooidonk R., Gledhill D., Wellman K., Beck M.W., Brander L.M., Rittschof D., Doherty C., Edwuard P.E.T. & Portela, R. Vulnerability and adaptation of US shellfisheries to ocean acidification. Nature Climate Change. **5**, 207-214 (2015).

**16.** Food Agriculture Organization. Estado mundial de la pesca y la acuicultura 2016. Roma 224 pp. (2016).

**17.** Food Agriculture Organization. The state of the world fisheries and aquaculture 2014. Rome: Food and Agriculture Organization (2014).

**18.** FAO. The State of World Fisheries and Aquaculture 2014. Opportunities and challenges. Rome: Food and Agriculture Organization of the United Nation, 223 (2014).

**19.** FAO Yearbook: Fishery and aquaculture statistics, 2009 (Statistics and Information Services of the Fishery and aquaculture Department, 2011).

**20.** Ferreira M., Lago J., Vieites J.M. & Cabado A.G. World production on bivalve mollusks and socioeconomic facts related to the impact of marine biotoxins. Seafood and Freshwater Toxins. Pharmacology, Physiology and Detection. 291-311 (2014).

**21.** Fitzer S.C., Zhu W., Tanner K.E., Phoenix V.R., Kamenos N.A. & Cusack M. Ocean acidification alters the material properties of *Mytilus edulis* shells. J. R. Soc. Interface 12, 20141227 (2014).

**22.** Gaylor B., Hill T.M., Sanford E., Lenz E.A., Jacobs L.A., Sato K.N., Russell A.D. & Hettinger A. Functional impact of ocean acidification in a ecologically critical foundation species. The Journal of Experimental Biology 214, 2586-2594 (2011).

**23.** Gattuso J.P., Magnan A., Billé R., Cheung W.W.L., Howes E.L., Joos F., Allemand D., Bopp L., Cooley S., Eakin M., Hoegh-Guldberg O., Kelly R.P., Pörtner H.-O., Rogers A.D., Baxter J.M., Laffoley D., Osborn D., Rankovic A., Rochette J., Sumaila U.R., Treyer S. and Turley, C. Contrasting futures for ocean and society from different anthropogenic $CO_2$ emissions scenarios. Science **349**: aac4722 (2015).

**24.** Gazeau F, Parker L. M., Comeau S., Gattuso J. P., O'Connor W. A., Martin S., Pörtner H. O. & Ross, P. M. Impacts of ocean acidification on marine shelled molluscs. Marine Biology. 160(**8**), 2207-45 (2013).

**25.** Gazeau F., Alliouane S., Bock C., Bramanti L., López correa M., Gantile M., Hirse T., Pörtner H.O. & Ziveri, P. Impact of ocean acidification and warming on the Mediterranean mussel (*Mytilus galloprocincialis*). Front. Mar. Sci. **1**, (2014). Gazeau F., Quiblier C., Jansen J., Gattuso J. P., Middleburg J. & Heip, C. Impact of elevated $CO_2$ on shellfish calcification. Geophys Res Lett. **34**, L07603 (2007).

**26.** Golden C., Allison E.H., Cheung W.W.L., Dey M.M., Halpern B.S., McCauley D.J., Smith M., Vaitla B., Zeller D. & Myers, S.S. Fall in fish catch threatens human health. Nature. **534**, 317-320 (2016).

**27.** Grienke U., Silke J. & Tasdemir D. Bioactive compounds from marine mussels and their effects on human. Food Chemistry **142**, 48-60 (2014).

**28.** Halpern B.S., Walbridge S., Selkoe K.A., Kappel C.V., Micheli F., D´Agrosa C., Bruno J.F., Casey K.S., Ebert C., Fox H.E., Fujita R., Heinemann D., Lenihan H.S., Madin E.M.P., Perry M.T., Selig E.R., Spalding M., Steneck R. & Watson, R. A global map of human impact on marine ecosystems. Science. **319**, 948-952 (2008).

**29.** Haylor G. & Bland, S. Integrating aquaculture into rural development in coastal and inland areas. In Subasinghe R.P., Bueno P., Phillips M.J., Hough C., McGladdery S.E. & Arthur J.R., eds. Aquaculture in the Third Millennium. Technical Proceeding of the conference on Aquaculture in the Third Millennium, Bangkok, Thailand, 20-25 February 2000. pp.73.81. NACA, Bangkok and FAO, Rome. (2001).

**30.** Ivanina A.V., Dickinson G.H., Matoo O.B., Bagwe R., Dickinson A., Beniash E. & Sokolova I.M. Interactive effects of elevated temperature and $CO_2$ levels on energy metabolism and biomineralization of marine bivalves *Crassostrea virginica* and *Mercenaria mercenaria*. Comparative Biochemistry and Physiology Part A 166, 101-111 (2013).

**31.** Kamat S., Su X., Ballarini R. and Heuer A. H. (2000) structural basis for the fracture toughness of the shell of the conch *Strombus gigas*. Nature 405: 1036-1040.

**32.** Kattner G. & Fricke H.S.G. Simple gas-liquid chromatographic method for the simultaneous determination of fatty acids and alcohols in wax esters of marine organisms. J. Chromatogr. 361, 263-268 (1986).

**33.** Kent R.M.L. The effect of *Polydora ciliate* on the shell strength of *Mytilus edulis*. J. Cons Int Explor Mer 39, 252-255 (1981).

**34.** Kroeker K., Kordas R. L., Crim R., Hendriks I., Ramajo L., Singh G., Duarte C. & Gattuso, J. P. Impacts of ocean acidification on marine organisms: quantifying sensitivies and interation with warming. Global Change Biology **19**, 1884-1896 (2013).

**35.** Kroeker K.J., Kordas R.L., Crim R.N. & Singh, G.G. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology Letters. *13*, 1419-1434 (2010).

**36.** Larsen R., Eilertsen K., & Elvevoll, E. Health benefits of marine foods and ingredients. Biotechnol. Adv. **29**, 508-518 (2011).

**37.** Lewis E. & Wallace, D. Program developed for $CO_2$ System calculation. Carbon Dioxide Information Analysis Center, Oak Ridge, Tennessee, USA (1998).

**38.** Mabardy R.A., Waldbusser G.G., Conway F. & Olsen C.S. Perception and response of the U.S. west coast shellfish industry to ocean acidification: The voice of the Canaries in the coal mine. Journal of shellfish Research. 34 (2), 565-572 (2015).

**39.** Mackenzie C.L., Lynch S.A., Culloty S.C. & Malham, S.K. Future Oceanic Warming and Acidification alter Immune Response and Disease status in a commercial Shellfish species, Mytilus edulis L. PlosOne. **9** (2014).

**40.** Magnan A.K., Colombier M., Billé R., Joos F., Hoegh-Guldberg O., Pörtner H.O., Waisman H., Spencer T. & Gattuso, J.P. Implications of the Paris Agreement for the ocean. Nature Climate Change. 6, 732-735 (2016).

**41.** McClinctock J.M., Angus R.A., McDonald M.R., Amsler C.D., Catledge S.A. & Vohra Y.K. Rapid dissolution of shells of weakly calcified Antarctic benthic macroorganisms indicates high vulnerability to ocean acidification. Antarctic Science 21 (5), 449-456 (2009).

**42.** Mehrbach C., Culberson C.H., Hawley J.E., & Pytkowicz, R.N. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. Limnology and Oceanography **18**, 897-907 (1973).

**43.** Meinshausen M., Smith S.J., Calvin K., Daniel J.S., Kainuma M.L.T., Lamarque J.F., Matsumoto K., Montzka S.A., Raper S., Riahi K., Thomson A., Velders G.J.M. & Van Vuuren, D.P.P. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change **109**: 213–241 (2011).

**44.** Michaelidis B., Ouzounis C., Paleras A. & PÖrtener, H. O. Effects of long term moderate hypercapnia on acid base balance and growth rate in marine mussels *Mytilus galloprovincialis*. Mar. Ecol. Prog. Ser. **293**, 109-118 (2005).

**45.** Monford M:C: The European market for mussels. Globalfish Research Programme.

FAO. 115 (2014).

46. Morrison W. & Smith, L. Preparation of fatty acid methyl esther and dimethylacetals from lipids with fluoride- methanol. J. Lipid Res 25, 600-608 (1964).

47. Narita D., Rehdanz K. & Tol, R. S. J. Economic costs of ocean acidification: a look into the impacts on global shellfish production. Climate Change. **113**, 1049-1063 (2012).

48. Navarro J. M., Torres R., Acuña K., Duarte C., Manriquez P. H., Lardies M. Lagos N. A., Vargas C. & Aguilera, V. Impact of médium-term exposure to elevated $pCO_2$ levels on the physiological energetics of the mussel *Mytilus chilensis*. Chemosphere. **90**, 1242-1248 (2013).

49. Olsen S.O. Understanding the relationship between age and seafood consumption: the mediating role of attitude, health involvement and convenience. Food Quality and Preference. **14**:199–209 (2013).

50. Pörtner, H.O., Langenbuch M., Reipschlager A. (2004). Biological impact of levated ocean CO2 concentrations: Lessons from animal physiology and earth history. J. Oceanogr 60: 705-718.

51. Richardson A. & Ploczanska, E.S. Under-Resourced, Under Threat. Science. 320, 1294-1295 (2008).

52. Sabine, C.L., Feely R.A., Gruber N., Key R.M., Lee K., Bullister J.L. and Rios A.F. (2004). The oceanic sink for anthropogenic CO2. Science 305: 367-371.

53. Samir K.C. & Lutz, W. The human core of the shared socioeconoimic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change. **42**, 181-192 (2017).

**54.** Schalkhausser B., Bock C., Pörtner H.O. & Lanning, G. Escape performance of temperature King scallops, *Pecten maximus* under ocean warming and acidification. Marine Biology. 161(12), 2819-2829 (2014).

**55.** Stramma L., Johnson G.C., Sprintall J. and Mohrholz, V. Expanding Oxygen-Minimun zones in the Tropical Oceans. Science **320**: 655-658 (2008).

**56.** Strickland J.D.H. & Parsons, T.R. Determination of reactive phosphorus. A practical handbook of seawater analysis. Fischeries Research Board of Canada, Bulletin **167**, 49-56 (1968).

**57.** Sveinsdóttir K., Martinsdóttir E., Green-Petersen D., Hylding G., Schelvis R. & Delahunty, C. Sensory characteristics of different cod products related to consumer preferences and attitudes. Food Quality and Preference. **20**, 120-132 (2009).

**58.** Syvitski J.P.M., Vörösmarty C.J., Kettner A.J. & Green, P. Impact of human on the flux of terrestrial sediment to the global coastal ocean. Science. **308**, 376-381 (2005).

**59.** Talmage S.C. & Gobler, C.J. The effects of elevated carbon dioxide concentrations on the metamorphosis, size and survival of larval hard clams (*Mercenaria mercenaria*), bay scallops (*Argopecten irridians*), and Eastern oysters (*Crassotrea virginica*). Limnol. Oceanogr. 54(**6**), 2072-2080 (2009).

**60.** Thomsen J., Casties I., Pansch C., Körtzinger A. & Melzner, F. Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. Global change Biology (2012).

**61.** UN. World Population Prospects: The 2010 Revision. Department of Economic and Social Affairs. Population Division. New York (2010).

**62.** Vargas C.A., Lagos N.A., Lardies M.A., Duarte C., Manríquez P.H., Aguilera V.M., Broitman B., Widdicombe steve & Dupont, S. Species-specific responses to ocean acidification should account for local adaptation and adaptative plasticity. Nature Ecology & Evolution. 1, (2017).

**63.** Vargas C.A., Aguilera V.M., San Martin V., Manríquez P.H., Navarro J.M., Duarte C., Torres R., Lardies M.A. and Lagos N.A. (2015). $CO_2$-Driven Ocean Acidification Disrupts the Filter Feeding Behavior in Chilean Gastropod and Bivalve species from Different Geographic Localities. Estuaries and Coasts 38: 1163-1177.

**64.** Ventura A., Schulz S. & Dupont, S. Maintained larval growth in mussel larvae exposed to acidified under-saturated seawater. Scientific Report Nature. 6 (2016).

**65.** Welladsen H.M., Southgate P.C. & Heimann K. The effect of exposure to near-future levels of ocean acidification on shell characteristics of *Pinctada fucata* (Bivalvia: Pteriidae). Molluscan Research 30(3), 125-130 (2010).

**66.** Waldbusser G.G., Hales B., Langdon C.J., Haley B.A., Schrader P., Brunner E.L., Gray M.W., Miller C.A. & Gimenez, I. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. Nature Climate Change. **5**, 273-280 (2015).

**67.** Waldbusser G.G. & Salisbury J.E. Ocean Acidification in the Coastal Zone from an Organism´s Perspective: Multiple System Parameters, Frequency Domains, and Habitats. Annu. Rev. Mar. Sci. 6, 221-247 (2014).

**68.** Wittmann A.C. & Pörtner, H.O. Sensitivities of extant animal taxa ocean acidification. Nature Climate Change. **3**, 995-1001 (2013).

**Table 1**. Average (±SD) conditions of carbonate system parameters during experiment conducted with *Mytilus chilensis*. Total alkalinity (TA in μmol $Kg^{-1}$), partial pressure of $CO_2$ (levels of $pCO_2$ in seawater in μatm), carbonate ions concentration ($CO^{2-}_3$ in μmol $Kg^{-1}$), saturation state of the seawater with respect to aragonite minerals ($\Omega_{arag}$).

| $CO_2$ System parameters | Experimental treatments (nominal levels of $CO_2$ ppm) | |
|---|---|---|
| | 400 (current) | 1000 (year 2070-2110) |
| pH in situ (pH units) | 7.99± 0.06 | 7.65± 0.05 |
| Salinity (psu) | 29.40± 0.65 | 29.26± 0.61 |
| Temperature in situ (°C) | 11.70± 0.67 | 12.08± 0.45 |
| TA (μmol $Kg^{-1}$) | 2000.77± 172.46 | 2068.50± 182.90 |
| $pCO_2$ in situ (μatm) | 414.06± 97.53 | 1005.15± 183.99 |
| [$CO_3^{2-}$] in situ (μmol $Kg^{-1}$) | 97.54± 5.39 | 49.09± 3.70 |
| $\Omega_{calc}$ | 2.40± 0.13 | 1.21± 0.09 |
| $\Omega_{arag}$ | 1.51± 0.08 | 0.76± 0.06 |

CAPITULO II:

**Linking social preferences and ocean acidification impacts in mussel aquaculture**

Valeska A. San Martin[1,2], Stefan Gelcich[2,3], Felipe Vasquez[2,4], Roberto Ponce[2,4], Ignacio Hernández[2,4], Nelson A. Lagos[2,5], Silvana N.R. Birchenough[6], and Cristian A. Vargas[1,2,7*]

[1] *Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepcion, Concepcion, Chile.*

[2] *Centre for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile.*

[3] *Centre of Applied Ecology and Sustainability, Department of Ecology. Universidad Católica de Chile, Santiago, Chile.*

[4] *School of Economics and Business, Universidad del Desarrollo, Concepcion, Chile.*

[5] *Centro de Investigación e Innovación para el Cambio Climático (CiiCC), Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile.*

[6] *Marine Climate Change Centre (MC3), Cefas, Lowestoft Laboratory, Suffolk, United Kingdom.*

[7] *Millennium Institute of Oceanography (IMO), Universidad de Concepcion, Concepcion, Chile.*

[*] *Corresponding author: C.A. Vargas (crvargas@udec.cl)*

*Nature Scientific Reports (2019) 9:4719*

Received 13 July 2018

Accepted 20 Febrery 2019

DOI:10.1038/s41598-019-41104-5

SCIENTIFIC REPORTS

OPEN

# Linking social preferences and ocean acidification impacts in mussel aquaculture

Received: 13 July 2018
Accepted: 20 February 2019
Published online: 18 March 2019

Valeska A. San Martin[1,2], Stefan Gelcich[2,3], Felipe Vásquez Lavín[2,3,4], Roberto D. Ponce Oliva[2,3,4], José I. Hernández[2,4], Nelson A. Lagos[2,5], Silvana N. R. Birchenough[6] & Cristian A. Vargas[1,2,7]

**Ocean Acidification (OA) has become one of the most studied global stressors in marine science during the last fifteen years. Despite the variety of studies on the biological effects of OA with marine commercial species, estimations of these impacts over consumers' preferences have not been studied in detail, compromising our ability to undertake an assessment of market and economic impacts resulting from OA at local scales. Here, we use a novel and interdisciplinary approach to fill this gap. We experimentally test the impact of OA on commercially relevant physical and nutritional attributes of mussels, and then we use economic discrete choice models to assess the marginal effects of these impacts over consumers' preferences and wellbeing. Results showed that attributes, which were significantly affected by OA, are also those preferred by consumers. Consumers are willing to pay on average 52% less for mussels with evidences of OA and are willing to increase the price they pay to avoid negative changes in attributes due to OA. The interdisciplinary approach developed here, complements research conducted on OA by effectively informing how OA economic impacts can be analyzed under the lens of marginal changes in market price and consumer' welfare. Thereby, linking global phenomena to consumers' wellbeing, and shifting the focus of OA impacts to assess the effects of local vulnerabilities in a wider context of people and businesses.**

Linking the effects of global environmental drivers over human wellbeing associated to food security is a key area of research across multiple disciplines[1]. Shellfish aquaculture one of the largest food production sectors globally (USD$ 19 billion[2]) could experience significant economic losses and social disruptions due to changing ocean conditions, namely OA[3,4]. Mussel production ranks third, within the category of shelled mollusks cultivated globally[5], supporting a global aquaculture industry worth more than US$3.0 billion in 2015[6]. Studies addressing the effects of OA over mussels have focused either on biological[5] or economic dimensions[4,7] with the objective of estimating overall population sustainability[5], revenue[4] or vulnerability[7] of the industry[8]. While these studies have been important to highlight the potential impacts of OA over gross production and revenues, they do not link biological impacts with social preferences and ultimately human wellbeing. The ability to link biological and nutritional impacts of OA to consumers' preferences is key, as it will allows to connect global phenomena with local scale impacts, thereby providing place-based information which allows to estimate OA impacts over businesses and people's wellbeing[9].

Studies have reported effects of OA on mussel biological attributes such as survival, shell dissolution, calcification rates[4,10,11], shell growth rates, ingestion, respiration[12–14], and increased vulnerability to diseases and parasites[5,15,16]. These biological changes could directly affect commercial attributes associated to mussel quality, such as taste, appearance, and nutritional composition[17–19]. Studies have also assessed potential economic impacts of OA on shellfish production[3,8,20,21], However, to date, research aimed at assessing the effects of OA over

[1]Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepcion, Concepcion, Chile. [2]Centre for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile. [3]Centre of Applied Ecology and Sustainability, Department of Ecology, Pontificia Universidad Católica de Chile, Santiago, Chile. [4]School of Economics and Business, Universidad del Desarrollo, Concepcion, Chile. [5]Centro de Investigación e Innovación para el Cambio Climático (CiiCC), Facultad de Ciencias, Universidad Santo Tomás, Santiago, Chile. [6]Marine Climate Change Centre (MC3), Cefas, Lowestoft Laboratory, Suffolk, United Kingdom. [7]Millennium Institute of Oceanography (IMO), Universidad de Concepcion, Concepcion, Chile. Correspondence and requests for materials should be addressed to C.A.V. (email: crvargas@udec.cl)

commercial attributes of mussels has not been addressed in detail, hindering opportunities to link impacts of OA over consumers' preferences and wellbeing (Table S1). In order to fill this gap, we adopted an interdisciplinary approach. We first experimentally assessed the impacts of OA over different physical (i.e. shell color) and nutritional (i.e. vitamin B12, protein content, and fatty acid composition) attributes of mussels under controlled laboratory conditions. Secondly, we adopted an economic valuation approach (i.e. discrete choice experiments) to assess consumers' preferences of these attributes, undertaken with in-person surveys. This approach helped to: (i) characterize consumers' preferences, (ii) link the preferences to the biological impacts of OA, and (iii) estimate the effects of OA, as a global driver, over consumers' wellbeing when purchasing mussels at local scales. We ground-truth our approach using the Chilean mussel aquaculture industry, which is one of the lead industries in mussel production worldwide[22,23].

## Results and Discussion

A set of physical and nutritional attributes of mussels, which have been described as relevant in terms of commercial value[24] and human wellbeing[25] were experimentally tested to assess the effects of OA. Those attributes were classified into 1) appearance, which includes the physical attribute experimentally tested (shell color), and others identified as relevant for consumers and potentially affected by OA (shell size and meat color), and 2) nutritional characteristics, which include vitamin B12, protein content, and fatty acid composition (SFA, MUFA and PUFA) (Table 1, column 1, column 2, and column 3). Our results evidenced that physical attributes were significantly impaired under OA conditions. Figure 1 shows that as seawater pH declines from 7.9 to 7.6 (according to the RCP 8.5 scenario for 2100)[26] on the total scale (i.e. $CO_2$ increases from 400 to 1,000 ppm), the outer surfaces of shells deteriorated and its color was clearly lost in adults (≈50%) and juveniles (≈10%) (Table 1, column 4; Table S2). The deterioration in the outer layer (periostracum) of the mussel shell exposed to high $pCO_2$ is similar to that found other studies[27–29]. For instance, whelk and oyster shells presented greater whitening as the pH becomes lower, resulting in a visually unattractive product from a marketing perspective[30]. Furthermore, our study is consistent with results observed by Osores *et al.*[31], which links the trade-offs between shell carbonates precipitation and periostracum thickness of *M. chilensis* when exposed to low $\Omega_{aragonite}$ corrosive estuarine waters. It is well known that outermost layer of the periostracum provides most of mussel shell coloration[32], thus these external changes may be attributed to acidification-induced reduction in shell thickness due to increased abrasion[33] and/or alteration in the concentration of organic compounds[34] of the shell periostracum.

When evaluating consumers' choices for mussels with different combinations of physical attributes, shell appearance was the most preferred attribute (Table 1, column 5). Our results indicated that more than 70% of the respondents preferred mussel shells that did not show evidence of OA impacts (i.e. not decolored). The relative importance of attributes in consumers' wellbeing (i.e. shell color), can be expressed in term of the Marginal Willingness to Pay (MWTP). The MWTP for changes in shell color was US$3.78, meaning that consumers are willing to pay up to US$ 3.78 to avoid a negative change, due to OA, on shell color per 250 g of mussels (Table 1, column 6; Table S3). On the other hand, 55% of the respondents also preferred large shell size and yellow meat color, attributes not tested experimentally in this study, but which have shown to be susceptible to OA (Table 1, column 5). Shell appearance as a quality attribute has been identified as key in consumers' decisions, influencing purchase[35] and market price[36]. In this study, we have shown how OA is coupled to consumers' wellbeing, for a set of appearance attributes (shell size, meat color, and shell color), jeopardizing local and national scale mussel market price. Our results showed that the maximum Willingness to Pay (WTP) decreases 57.2% from a baseline of a non-acidified product (USD$ 10.04), to a product with acidified appearance (USD$ 5.75) (Table 1, column 7). Thus, the variation of these attributes considered under future climate change scenarios could have serious implications to the mussel farming industry with impacts on the economy and human welfare.

In our study the second most preferred attribute for consumers were the nutritional characteristics sush as Polyunsaturated Fatty Acids (PUFA), vitamin B12 and protein, which are preferred by 61% of respondents (Table 1, column 5). Research has shown that the consumption of mussels has been recommended for presenting important nutritional attributes[18,37], which have been linked with positive effects on human health[38–41] (Table 1, column 3). As expected, results showed that the mussel's tissue was characterized by a high proportion of unsaturated fatty acids. The highest fatty acid proportion corresponds to monounsaturated (MUFA) and polyunsaturated fatty acids (PUFA) (Fig. 2a,b). Our results evidenced a significant impact of OA on the fatty acid composition. The PUFA content was significantly reduced under high $pCO_2$ conditions for juvenile mussels (one-way ANOVA, $F(1.12) = 4.83$; $p = 0.048$) (Fig. 2a). Adults showed the same decreasing pattern in PUFA, although the comparisons did not show statistical significance (Fig. 2b). The PUFA content in this species is mostly contributed by Omega-3, with a major proportion of eicosapentaenoic acid (C20:5n-3, EPA) than docosahexaenocic acid (C22:6n-3, DHA) for both juvenile and adult mussels (Fig. 2a,b, respectively). The decrease in PUFA is mainly associated to stearidonic acid (C18:4n-3), α-linolenic acid (C18:3n-3), and docosapentaenoic acid (C22:5n-3) (Table S4). Importantly, analyses evidenced a lower protein content and Vitamin B12 in mussels exposed to high $pCO_2$ for both juveniles and adults (Fig. 2c,d). The decrease in mussel nutritional quality upon high $pCO_2$ conditions has been a major feature observed for other species. For instance, Valles-Regino *et al.*[42] observed significant changes in fatty acid composition in whelks (i.e. reduction in Omega 3 PUFAs), and a reduction in the protein content of mussels[43], oysters[44], and whelks[45] has been also observed upon high $pCO_2$ conditions. Therefore, these changes can be attributed to a decrease in the ability to maintain lipid homeostasis[44,46], a reduction in the abundance of proteins associated to the desaturation and elongation of fatty acids[47,48] interfering in its synthesis[49]. Therefore, our results evidenced that stressful low pH/high $pCO_2$ conditions might trigger significant changes in the physiology, metabolism and/or fatty acid storage of mussels.

Our survey results, which presented consumers with the nutritional importance of mussels compared to other food items and to the reductions in nutritional value associated to OA, showed that the MWTP for nutritional characteristics is US$ 1.39, meaning that consumers were willing to pay up to US$ 1.39 to avoid a negative change

| Category | Attributes Measured | Impact on market and/or wellbeing | OA experimental results. | Attributes' social valuation (%)* | Attributes' WTP** | WTP for 250 g of mussels quality loss*** | Previous study | Previous study approach |
|---|---|---|---|---|---|---|---|---|
| Appearance | SHELL SIZE | impact on marketability, consumer election and buyer rejections | not tested | shell size: valued by 53,42% of respondents. | Shell size US$ 0.25 | From Baseline product to shell size loss product: US$10.04 ->US$9.81 | Adams *et al.*, 2011[76] Batzios *et al.*, 2004[77] Penney *et al.*, 2007[30] | Growers perception (Slightly Economic) Consumer attitude (Social) Variability on appearance (Biological) |
| | MEAT COLOR | impact on marketability, consumer election and buyer rejections | not tested | meat color: valued by 57,90% of respondents. | Color of the meat US$ 1.22 | From shell size loss product to color meat loss product: US$ 9.81 -> US$8.73 | | |
| | SHELL COLOR | impact on marketability, consumer election and buyer rejections | negative | not decolotated shell color: valued by 73,43% of respondents. | Color of the shell US$ 3.78 | From color meat loss product to color shell loss product US$ 8.73 -> US$5.75 | | |
| Nutritional Characteristics | OMEGA-3 | impact on marketability, consumer election and buyer rejections/ Vascular benefits, lower triglyderides, cardiac filling and myocardial efficiency, inflammation, thrombosis, and arrhythmia | negative | nutritional characteristics: valued by 61.65% of respondents. | nutritional characteristics US$ 1.39 | From color shell loss product to nutritional characteristics loss product: US$ 5.75 -> US$4.79 | Mozaffarian *et al.*, 2011[41] Grienke *et al.*, 2014[25] | Benefits on human health (Biological) Effect on human health (Biological) |
| | EPA & DHA | impact on marketability, consumer election and buyer rejections/ reduced risk of cardiovascular events, diabetes mellitus, inhibiting growth of tumor cells, antiinflammatory activity, essential for fetal development | neutral | | | | Kaur *et al.*, 2011[40] Swanson *et al.*, 2012[39] | Benefits on human health (Biological) Benefits on human health (Biological) |
| | VIT B12 | impact on marketability, consumer election and buyer rejections/ Essential for metabolism of fats and carbohydrates and the synthesis of proteins | negative | | | | Huskisson *et al.*, 2007[78] Lund, 2013[79] | Importance in metabolism (Biological) Benefits in human health (Biological) |
| | PROTEIN | impact on marketability, consumer election and buyer rejection/ proteins are highly digestible and have a high biological value | negative | | | | Tacon and Metian, 2013[80] | Human nutrition (Biological) |

**Table 1.** Summary of evaluations conducted under relevant physical and nutritional attributes of the commercial and human welfare in mussels affected by ocean acidification. *Distribution of heterogeneity of preferences for mussel's attributes, under normally distributed random coefficients. For instance, consumers showed preferences for OA-free shells (73.43%), the remaining 26,57% of respondents does not show preferences for this attribute. **Marginal Willingness to Pay (MWTP) for an improvement in the selected attribute. ***The maximum Willingness to Pay (WTP) for 250 gr of mussel.

on nutritional quality per 250 g of mussels (Table 1, column 6). Maximum WTP decreases 16.6% from USD$ 5.75 for a product with acidified appearance to USD$ 4.79 for a product with also has reduced nutritional value (PUFA and vitamin B12 characteristics). Overall, the impacts of OA over mussels commercial attributes reduces consumers maximum WTP in 52% from USD$ 10.04 (baseline product- not acidified) to USD$ 4.79 (fully acidified product) (Table 1, column 7). This change is computed as follows: the maximum WTP will change from a not acidified product, to a product with change in the shell size in USD$ 0.23 (USD$ 10.04–USD$ 9.81). Then, the maximum WTP will change in USD$ 1.08 (USD$ 9.81–USD$ 8.73), from changing from a product affected by OA only in their shell size, to product in which also change the meat color. In general, the maximum WTP will change in USD$ 5.25 (USD$ 10.04–USD$ 4.79) for changing a not acidified product (baseline) to a fully acidified product (with changes in all the attributes).

Consumer responses revealed significant MWTP values for avoiding a decrease in quality of the attributes critically affected by the levels of OA predicted for the year 2100 [RCP8.5 scenario][26,50]. These results did reflect

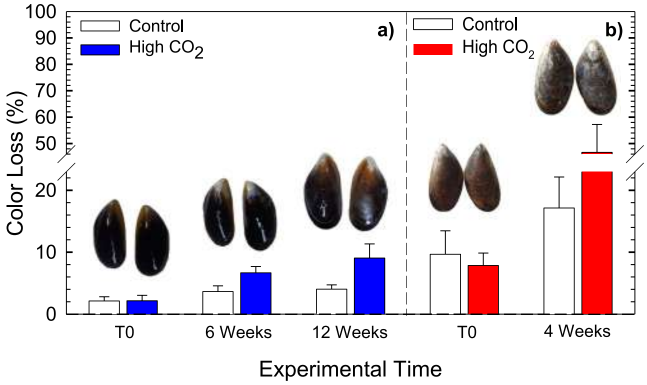


**Figure 1.** Summary of experimental results from changes observed over the physical attribute of mussels exposed to high $pCO_2$ conditions. Mean ± standard deviation of color loss (%) in (**a**) juvenile mussels after 120 d (n = 30) and (**b**) adults mussels after 30 d (n = 10) exposed to high $pCO_2$ and control $pCO_2$ conditions. Significant statistical differences were found between mussels subjected to both treatments in juvenile (ANOVA, a priori comparison between treatments along time: $F(2, 87) = 6.96$; $p = 0.002$) and adults mussels ($F(1, 18) = 91.88$; $p < 0.001$).

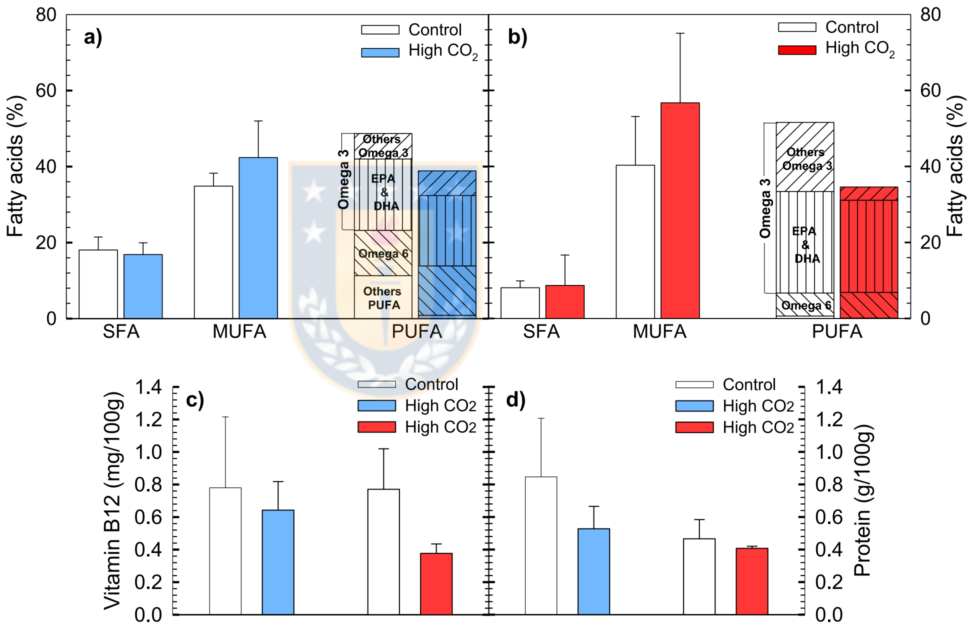


**Figure 2.** Summary of changes in nutritional attributes of mussels exposed to high $pCO_2$ conditions. Mean (±S.D.), (**a**,**b**) fatty acid composition, and (**c**) vitamin B12 content in juvenile and adult and (**d**) Protein content, in both juvenile and adult mussels. Juvenile and adult individuals were exposed during 120 and 30 d to both treatments, respectively.

the behavior of current consumer's faced with future changes in mussel attributes and as such, did not consider the possibility of consumers lowering quality expectations in time. This possible shift in baselines cannot be assessed empirically as no market data exist for such a distant future[51]. However, data did show consumer attitudes were consistent in stating that appearance and nutritional levels of mussels were the most important attributes influencing purchasing behavior. Under this scenario, results suggest that OA will have real economic consequences at the individual level, which can have important consequences, not only by harming human well-being but also by increasing the vulnerability of producers being more affected by OA.

Linking global phenomena such as OA to tangible local industries and people's wellbeing is a prerequisite for quantifying and planning effective place-based adaptation strategies[8]. Existing assessments and projections of the effects of OA over shellfish aquaculture production systems have in general estimated economic impacts through extrapolating direct losses in production associated to the effect of OA over calcification, growth rate, and larvae survival[20,21]. While this information is important for raising awareness of the potential risks, advocating direct measures to reduce global drivers of OA and safeguarding the shellfish industry, one of the biggest drawbacks is the lack of provision of information to support local industries to plan and adapt to potential market changes associated to this global driver. Through integrating the combined effects of biological responses related to commercial attributes, and the expected impacts over consumers' marginal willingness to pay for those attributes, this study has contributed to furthering our current understanding of the effects of OA over the mussel industry. The interdisciplinary approach developed in this study, complements previous research conducted on OA by effectively informing how OA economic impacts can be analyzed under the lens of marginal changes in market prices, thereby linking global phenomena to consumers' wellbeing, shifting the focus to local vulnerabilities for both people and businesses.

## Methods

**Organism collection.** Juvenile and adults of *Mytilus chilensis* (Shell length: $2.5 \pm 0.5$ cm and $7.4 \pm 0.2$ cm, respectively) were collected at 5 m depth during July and October 2015 from a mussel farming facility located in Vilupulli, Chiloé, southern Chile (42°35′35″S; 73°47′18″W). Environmental conditions in the area averaged between 10.0 to 12.4 °C; 28.2 to 33.5 PSU of salinity, and 7.9 to 8.3 pH units. Once the organisms were collected, these were immediately transported to the Marine Biology Laboratory at Dichato (Universidad de Concepción). Individuals were kept in filtered (0.1 μm) and aerated seawater at a temperature of ~11 °C, ~31 psu salinity, and $8.0 \pm 0.1$ pH units, which indeed represented the mean ambient conditions in the mussel farming area during an annual cycle. An acclimatization period of two weeks under mesocosm conditions, animals were fed daily with the commercial food phytogold-s (*Isochrysis sp*. and *Pavlova sp*.), at a mean concentration of 2.5 μg $L^{-1}$ Chl *a*.

**$CO_2$ manipulation and experimental conditions.** Two plastic 280 L tanks were used as acidification units to generate seawater to two nominal levels of $pCO_2$: 400 μatm (control treatment) simulated present day conditions corresponding to the average level in mussel farming area[13] and 1000 μatm ($CO_2$ treatment) simulated the future conditions based on RCP8.5 scenario which predicts pH change rates of −0.0018 pH units by year[26,50]. The study was set up at two different level of $pCO_2$, Air/$CO_2$ mixtures, using a bulk flow technique, where know flow of dry air and ultra-pure $CO_2$ gas were supplied, via mass flow controller (MFC), and mixed before equilibration with seawater. During the experiments seawater pH (total scale, $pH_T$) was monitored in each tank every 10 day, measuring potentiometrically in 25 mL cell thermostatted at $25 \pm 0.1$ °C for standardization, using a Metrohm 713 pH meter (input resistance >1013 Ohm, 0.1 mV sensitivity, and nominal resolution 0.001 pH units) using a glass combined double junction Ag/AgCl electrode (Methrom model 6.0219.100) calibrate with 8.089 Tris buffer 25ªC. following DOE potentiometric method[52]. pH values are reported on the total hydrogen ion scale. Temperature and salinity were measured using an Oakton SALT6+ handheld salinity meter with probe. Total alkalinity was measured 7 days using the open-cell titration method[53], by using an automatic Alkalinity Tritator Model AS-ALK2 Apollo SciTech. The AS-ALK2 system is equipped with a combination pH electrode (8302BNUWP *Ross Ultra* pH/ATC *Triode*, Thermo Scientific, USA) connected to a pH meter (Orion star A211 pH meter, Thermo Scientific, USA). All samples were analyzed at 25 °C (±0.1 °C) with temperature regulation using a water-bath (Lab companion CW-05G). The accuracy was controlled against a certified reference material (CRM, supplied by Andrew Dickson, Scripps Institution of Oceanography, San Diego, USA) and the $A_T$ repeatability averaged 2–3 μmol $kg^{-1}$.

The pH, total alkalinity (AT), phosphate and dissolved silicate[54] used to calculate the rest of the carbonate system parameters and the saturation stage of omega, aragonite and calcite using $CO_2$SYS software[55] set with Mehrbach solubility constants[56] refitted by Dickson and Millero (1987)[57], presented in Supplementary Information Table 5. Seawater in each experiment was replaced every two days with seawater that had been previously balanced.

**Experimental setup.** After the acclimation period, sixty individuals were cleaned and separated in ten groups of 6 individuals in aquariums with 9 L of capacity, each treatment was replicated five times with total 30 individuals for control (11 °C and 400 ppm $CO_2$) and 30 individuals for high $pCO_2$ treatment (11 °C and 1000 ppm $CO_2$).

Color change determinations were measured with weekly photographs of each specimen in each treatment. All images were processed using ImageJ software (v.1.45 s; NIH, Bethesda, MD, USA). The exposure time to the different treatments was 120 days for juvenile and 30 days for adult. The long period of exposure for juvenile allowed us to make sure to detect significant changes in shell color. However, for adult individuals the exposure time was shorter, since adult mussels considered in our study were at pre-spawning stage (50 mm shell length, Lagos *et al*.[58]). It is well known that after that size, adult mussels change their energy expenditure destined mainly to the reproduction phase[59]. Therefore, they were prone to spawning, which could result in potential changes in their nutritional composition, affecting our comparative analysis with juvenile individuals. The samples of mussel tissue were obtained by means of the extraction of the gonads and the adductor muscle, for individual juvenile ($n = 7$) and adults ($n = 2$). Fatty acid analysis was performed in the Institute of Pharmacology at the Universidad Austral de Chile in Valdivia, Chile. The fatty acid concentration was analyzed after extraction and methylation[60] with a gas chromatograph Perkin Elmer sigma 300 equipped with a programmable temperature vaporizer-injector, a fused Omegawax 53 capillary column, and a flame ionization detector and vitamin B12 by HPLC technique. Relative quantities were expressed as percent of total fatty acids in each sample.

**Data analysis.** The proportional data of physical (color loss) and nutritional attributes (fatty acids composition and PUFA) was arcsine transformed for posterior analysis. Due the repeated measures of loss of color of the mussels' tissues, we used ANOVA model nesting individual mussels (random effect) along time and $pCO_2$ treatment (fixes effects). The effects of exposure to high $pCO_2$ in nutritional attributes (fatty acids composition, PUFA, protein and vitamin B12 content) were analyzed using a one-way ANOVA followed by a Tukey post hoc test.

**Social valuation of commercial attributes.** Social preferences were modeled using a Random Utility Model[61,62]. As mentioned above, we carried out a simulated experiment of impacts with a projection towards the years 2070–2100, corresponding to the rate of change in the pH predicted by the most extreme scenario [RCP8.5 scenario] of atmospheric $CO_2$[26,50]. Considering that no market data exist for such distant future, and following[51,63], we rely on the choice experiment approach[64], providing the opportunity to consumers to declare their preferences choosing between several alternatives that were differentiated by the combination of levels of attributes, mainly known to be affected by OA, mainly appearance and nutrition. Surveys, which include choice experiments, have been widely used to study consumer preferences for bundles of attributes in the literature[65–67] and have gained important traction in food preference and environmental literature during the past decades[68–73]. (Table S6).

We developed a choice experiment survey which complied with ethical approval of both project Musels and Universidad del Desarrollo. As such, all interviewees were presented with an informed consent form, which had to be approved. The in-person interviews were conducted from October to December 2016 in two Chilean cities: Santiago (Chile's capital) and Concepción (the second-largest city). We also conducted four focus groups (two each in Concepción and Santiago) to explore people's reactions to specific aspects of the experiment and to identify wording problems or misleading sections in the survey. Then, we conducted 125 pilot surveys to field-test the design of the instrument (one pilot with 25 observations and two pilots with 50 observations each). We rely on a random sampling process based on the National Socioeconomic Household Survey (CASEN), using a probabilistic polietapic sampling design, in which we randomly select neighborhoods and blocks. Next, we systematically select the households to be interviewed. Here, we select one household in each block, starting in the northern corner. If there is no answer from that house, we skip the next four houses and try the fifth. The sampling process yielded a useful sample of 1,278 individuals, each of whom were presented with six decisions, with three alternatives for each choice. This yielded a final sample of 7,668 useful observations.

A choice example used in the survey is presented in Supplementary Information Table 7. Following a D-optimality experimental design[74] consumer interviewed face six choice scenarios with three alternatives each. For the choice experiment a consumer was presented with three alternatives included the combination of different levels of appearance with and without OA (e.g. small size, large size; pale meat, yellow meat; decolorated shell, not decolorated shell color), nutritional characteristics (low nutritional composition, high nutritional composition), and prices. Using visual aids, we informed interviewees about the differences in nutritional characteristic by referring to components of the PUFA complex, vitamin B12 and proteins as key nutritional characteristics of mussels. We presented information through figures and visual aids, which compared these characteristics with other food items which had similar nutritional attributes and that are perceived as healthy by the Chilean population (i.e salmon, and mackerel).

The model was estimated using random parameters allowing capturing unobserved heterogeneity (Table S3). Other attributes were also evaluated but we focus on those related to OA in this discussion.

The welfare attain by individual r for choosing alternative i, in RUM approach is given by Equation(1).

$$V_{ir} = \alpha_{ir} X_i + \epsilon_i \quad (1)$$

where X is a vector of attributes of the alternatives, $\epsilon_i$ is an stochastic component that allow us to estimate a probability model and $\alpha_{ir} = \alpha + \beta S + \sigma\eta_r$ is a set of parameters to be estimated that depend on observed individual characteristics S (age, sex, education, etc.) and unobserved characteristics $\eta_r$ that are stochastically distributes in the population, $\eta_r$ is random component (different for each coefficient). The full model is given by Equation(2).

$$V_{ir} = (\alpha + \beta S + \sigma\eta_r)X_i + \epsilon_i = \alpha X_i + \beta S X_i + \sigma\eta_r X_i + \epsilon_i \quad (2)$$

If $\epsilon_i$ has an Extreme value distribution type I, then the RUM is estimated using a random parameter logit model in which the probability of choosing alternative i is given by Equation(3).

$$P_i = \int \frac{e^{V_i}}{\sum_j^J e^{V_j}} f(\alpha_r) \partial\alpha_r \quad (3)$$

where J is the total number of alternatives included in the choice sets. The sociodemographic variables capture the observed heterogeneity among individuals, and the random parameter $\eta_r$ captures the unobserved heterogeneity. Both sources of heterogeneity are crucial to understand people's preferences for mussels. Using the fitted model, it is possible to estimate willingness to pay for each attribute and level of the attribute. The method allows us to estimate the relevance of each attribute of the alternative, in this case attribute differentiated mussel products, in the welfare function for each individual. With those results it is possible to estimate the marginal willingness to pay for each attribute and eventually aggregate this value to the extension of the mussel market[75].

**Ethics statement.** Through the consent of the Ethics, Bioethics and Biosafety Committee of the Vice-Rector for Research and Development of the University of Conception, President: Dr. Andrea Rodríguez Tastets. Checked compliance with the ethical, bioethical and biosecurity norms and procedures established nationally and internationally for research in the field of environmental sciences, considering the study of hydro biological species and that includes manipulation of biological and chemical material and waste. Written informed consent was obtained from the respective institution in Concepcion, Chile, previously approved the ethic protocol from all subjects for this study.

**Permission statement.** Once the ethics protocol of the Universidad de Concepción was approved in this study, the correct permits for the collection of commercial molluscs were obtained, which were donated by a mussel farming facility located in Vilupulli, Chiloé, southern Chile.

## Data Availability

Any data used in this paper can be obtained by contacting the corresponding author.

## References


1. Liu, J. *et al*. Systems integration for global sustainability. *Science.* **347**, 963–972 (2015).
2. Food agriculture organization. *Estado mundial de la pesca y la acuicultura*. Roma 224 pp. (2016).
3. Ekstrom, J. A. *et al*. Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nat. Clim. Change.* **5**, 207–214 (2015).
4. Narita, D., Rehdanz, K. & Tol, R. S. J. Economic costs of ocean acidification: a look into the impacts on global shellfish production. *Clim. Chang.* **113**, 1049–1063 (2012).
5. Gazeau, F. *et al*. Impacts of ocean acidification on marine shelled molluscs. *Mar. Biol.* **160**, 2207–45 (2013).
6. Food agriculture organization: Yearbook fisheries and aquaculture statistics (2015).
7. Cooley, S. R., Lucely, N., Kite-Powell, H. & Doney, S. Nutrition and income form molluscs today imply vulnerability to ocean acidification tomorrow. *Fish. Fish.* **13**, 182–215 (2012).
8. Mabardy, R. A., Waldbusser, G. G., Conway, F. & Olsen, C. S. Perception and response of the U.S. west coast shellfish industry to ocean acidification: the voice of the Canaries in the coal mine. *J. Shellfish Res.* **34**, 565–572 (2015).
9. Brander, L. M., Narita, D., Rehdanz, K. & Tol, R. S. J. The economic impacts of ocean acidification. In *Handbook on the economics of ecosystem services and biodiversity*, (eds Nunes, P. A. L. D., Kumar, P., & Dedeurwaerdere, T. 78–92 (Cheltenham: Edward Elgar, 2014).
10. Cooley, S. R. & Doney, S. C. Anticipating ocean acidification's economic consequences for commercial fisheries. *Environ. Res. Lett.* **4**, 024007 (2009).
11. Kroeker, K. *et al*. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biol.* **19**, 1884–1896 (2013).
12. Waldbusser, G. G. *et al*. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. *Nat. Clim. Change.* **5**, 273–280 (2015).
13. Vargas, C. A. *et al*. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nat. Ecol. Evol.* **1**, 84–90 (2017).
14. Kroeker, K. J., Kordas, R. L., Crim, R. N. & Singh, G. G. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. *Ecol. Lett.* **13**, 1419–1434 (2010).
15. Thomsen, J., Casties, I., Pansch, C., Körtzinger, A. & Melzner, F. Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. *Global change Biol.* **19**, 1017–1027 (2012).
16. Mackenzie, C. L., Lynch, S. A., Culloty, S. C. & Malham, S. K. Future oceanic warming and acidification alter immune response and disease status in a commercial shellfish species. *Mytilus edulis L. PlosOne* **9**(6), e99712 (2014).
17. Olsen, S. O. Understanding the relationship between age and seafood consumption: the mediating role of attitude, health involvement and convenience. *Food. Qual. Prefer.* **14**, 199–209 (2003).
18. Cardoso, C., Lourenço, H., Costa, S., Gonçalves, S. & Nunes, M. L. Survey into the seafood consumption preferences and pattern in the portuguese population. Gender and regional variability. *Appetite* **64**, 20–31 (2013).
19. Sveinsdóttir, K. *et al*. Sensory characteristics of different cod products related to consumer preferences and attitudes. *Food Qual. Prefer.* **20**, 120–132 (2009).
20. Narita, D. & Rehdanz, K. Economic impact of ocean acidification on shellfish production in. *Europe. J. Environ. Plann. Man.* **60**, 500–518 (2017).
21. Falbenberg, L. J. & Tubb, A. Economic effects of ocean acidification: publication patterns and directions for future research. *Ambio*. 1–11 (2017).
22. Food agriculture organization. *The state of world fisheries and aquaculture. Opportunities and challenges*. Rome: Food and agriculture organization of the United Nation, 223 (2014).
23. Ferreira, M., Lago, J., Vieites, J. M. & Cabado, A. G. World production on bivalve mollusks and socioeconomic facts related to the impact of marine biotoxins. Seafood and freshwater toxins. Pharmacology, physiol. Detection 291–311 (2014).
24. Azpeitia, K., Ferrer, L., Revilla, M., Pagaldai, J. & Mendiola, D. Growth, biochemical profile, and fatty acid composition of mussel (*Mytilus galloprovincialis* L.) cultured in the open ocean of the bay of Biscay (northern Spain). *Aquaculture.* **454**, 95–108 (2016).
25. Grienke, U., Silke, J. & Tasdemir, D. Bioactive compounds from marine mussels and their effects on human health. *Food chem.* **142**, 48–60 (2014).
26. Bopp, L. *et al*. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**, 6225–6245 (2013).
27. Duquette, A. *et al*. Effects of ocean acidification on the shells of four mediterranean gastropod species near a $CO_2$ seep. *Marine Poll. Bull.* **124**, 917–928 (2017).
28. Sezer, N., Kılıç, Ö., Metian, M. & Belivermiş, M. Effects of ocean acidification on $^{109}$Cd, $^{57}$Co, and $^{134}$Cs bioconcentration by the european oyster (*Ostrea edulis*): biokinetics and tissue-to-subcellular partitioning. *J. Environ. Radioact.* **192**, 376–384 (2018).
29. Le Moullac, G. *et al*. Impact of $pCO_2$ on the energy, reproduction and growth of the shell of the pearl oyster *Pinctada margaritifera*. *Estuar. Coast. Shelf. Sci.* **182**, 274–282 (2016).
30. Penney, R. W., Hart, M. J. & Templema, N. D. Shell strength and appearance in cultured blue mussels *Mytilus edulis*, *M. trossulus*, and *M. Edulis* X *M. trossulus* hybrids. *N. Am. J. Aquac.* **69**, 281–295 (2007).
31. Osores, S. J. A. *et al*. Plasticity and inter-population variability in physiological and life-history traits of the mussel *Mytilus chilensis*: a reciprocal transplant experiment. *J. Exp. Mar. Biol. Ecol.* **490**, 1–12 (2017).
32. Bayne, B. L. Marine mussels: their ecology and physiology. *International Biological Programme*. Cambridge University Press, 269 (1976).
33. Rodolfo-Metalpa, R. *et al*. Coral and mollusk resistance to ocean acidification adversely affected by warming. *Nat. Clim. Change.* **1**, 308–312 (2011).
34. Ramajo, L. *et al*. Plasticity and trade-offs in physiological traits of intertidal mussels subjected to freshwater-induced environmental variation. *Mar. Ecol. Prog. Ser.* **553**, 93–109 (2016).
35. Grabacki, S. T. Onboard quality systems. *In Environmental effects on seafood availability, safety, and quality*. (eds Daczkowska-Kozon, E. G. & Sun, P. B.) pp 401. Chemical and functional properties of food components series. (Boca Raton: CRC Press, 2011).
36. Brenner, M., Buchholz, C., Heemken, O., Buck, B. H. & Koehler, A. Health and growth performance of the blue mussel (*Mytilus edulis* L.) from two hanging cultivation sites in the German Bight: a nearshore-offshore comparison. *Aquaculture Int.* **20**, 751–778 (2012).
37. Orban, E. *et al*. Seasonal changes in meat content, condition index and chemical composition of mussels (*Mytilus galloprovincialis*) cultured in two different Italian sites. *Food Chem.* **77**, 57–65 (2002).

38. Larsen, R., Eilertsen, K.-E. & Elvevoll, E. O. Health benefits of marine foods and ingredients. *Biotechnol Adv.* **29**, 508–518 (2011).
39. Swanson, D., Block, R. & Mousa, S. A. Omega-3 fatty acids EPA and DHA: health benefits throughout life. *Adv. Nutr.* **3**, 1–7 (2012).
40. Kaur, G., Cameron-Smith, D., Garg, M. & Sinclair, A. J. Docosapentaenoic acid (22:5n-3): a review of its biological effects. *Progr. Lip. Res.* **50**, 28–34 (2011).
41. Mozzaffarian, D. & Wu, J. H. Y. Omega-3 fatty acids and cardiovacular disease: effects on risk factors, molecular pathways, and clinical events. *J. Am. Coll. Cardiol.* **58**(20), 2047–2067 (2011).
42. Valles-Regino, R. *et al*. Ocean warming and $CO_2$-induced acidification impact the lipid content of a marine predatory gastropod. *Mar. Drugs.* **13**, 6019–6037 (2015).
43. Colombo, J. *et al*. Composición química proximal y perfil de ácidos grasos del mejillón *Mytilus edulis* provenientes de cultivos y bancos naturales en el Golfo San Jorge, Argentina. *Rev. Biol. Mar. Oceanogr.* **51**, 293–299 (2016).
44. Timmins-Schiffman, E. *et al*. Shotgun proteomics reveals physiological response to ocean acidification in *Crassostrea gigas*. *BMC Genomics* **15**, 951–968 (2014).
45. Tate, R. D., Benkendorff, K., Ab Lah, R. & Kelaher, B. P. Ocean acidification and warming impacts the nutritional properties of the predatory whelk *Dicathais orbita*. *J. Exp. Mar. Biol. Ecol.* **493**, 7–13 (2017).
46. Matson, P. G., Yu, P. C., Sewell, M. A. & Hofmann, G. E. Development under elevated $pCO_2$ conditions does not affect lipid utilization and protein content in early life-history stage of the purple sea urchin *Strongylocentrotus purpuratus*. *Biol. Bull.* **223**, 312–327 (2012).
47. Holloway, P. W. & Wakil, S. J. Requirement for reduced diphosphoryidine nucleotide-cytochrome b5 reductase in stearyl coenzyme a desaturation. *J. Biol. Chem.* **245**, 1862–1865 (1970).
48. Rossoll, D. *et al*. Ocean acidification-induced food quality deterioration constrains trophic transfer. *PlosOne.* **7**(4), e34737 (2012).
49. Masson, L. & Mella, M. A. Materia grasa de consumo habitual y potencial en Chile: composición de ácidos grasos. Universidad de Chile, Santiago, Chile. 31pp (1985).
50. Hartin, C. A., Bond-Lamberty, B., Patel, P. & Mundra, A. Ocean acidification over the next three centuries using a simple global climate carbon-cycle model: projections and sensitivities. *Biogeosciences.* **13**, 4329–4342 (2016).
51. Rodrigues, L. C., van den Bergh, J. C. J. M. & Ghermandi, A. Socio-economic impacts of ocean acidification in the Mediterranean Sea. *Mar Policy.* **38**, 447–456 (2013).
52. DOE Handbook of methods for the analysis of the various parameters of the carbon dioxide system in seawater; version 2. In: Dickson, A. G. & Goyet, C. (Eds), ORNL/CDIAC, 74 (1994)
53. Dickson, A. G., Sabine, C. L. & Christian, J. R. (Eds) Guide to best practices for ocean $CO_2$ measurements. In *PICES Special Publication* 3, 191 (2007).
54. Strickland, J. D. H. & Parsons, T. R. A practical handbook of seawater analysis. *Fish. Res. Board Can., Bull.* **167**, 311 (1968).
55. Lewis, E. & Wallace, D. *Program developed for $CO_2$ system calculations*. Carbon dioxide information analysis center. (Oak Ridge, Tennessee, USA, 1998).
56. Mehrbach, C., Culberson, C. H., Hawley, J. E. & Pytkowicw, R. N. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limn. Oceanogr.* **18**, 897–907 (1973).
57. Dickson, A. G. & Millero, F. J. A. Comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. *Deep. Sea. Res.* **34**, 1733–1743 (1987).
58. Lagos, L., Uriarte, I. & Yany, G. Evaluación del potencial reproductivo del chorito (*Mytilus chilensis*) en dos poblacioanes naturales sometidas a diferentes temperaturas de acondicionamiento. *Lat. Am. J. Aquat. Res.* **40**, 389–397 (2012).
59. Freites, L., Fernández-Reiriz, M. J. & Labarta, U. Fatty acid profiles of *Mytilus galloprovincialis* (Lmk) mussel of subtidal and rocky shore origin. *Com. Biochem. Physiol. Part B* **132**, 453–461 (2002).
60. Kattner, G. & Fricke, H. S. G. Simple gas–liquid chromatographic method for the simultaneous determination of fatty acids and alcohols in wax esters of marine organisms. *J. Chromatogr.* **361**, 263–268 (1986).
61. McFadden, D. L. Econometric analysis of qualitative response models. *In Handbook of econometrics* 2, (1395–1457 (1984).
62. Train, K. E. *Discrete choice methods with simulation* (Cambridge univ. press, Cambridge, 2009).
63. Layton, D. F. Random coefficient models for stated preference surveys. *J. Env. Econ & Management* **40**, 21–36 (2000).
64. Hensher, D. A., Rose, J. M. & Greene, W. H. *Applied choice analysis: a primer*. (Cambridge Univ. Press, Cambridge, 2005).
65. Li, Z. & Hensher, D. A. Crowding and public transport: a review of willingness to pay evidence and its relevance in project appraisal. *Transport Policy* **18**, 880–887 (2011).
66. Tirachini, A., Hurtubia, R., Dekker, T. & Daziano, R. A. Estimation of crowding discomfort in public transport: results from Santiago de Chile. *Transportation Res. Part A* **103**, 311–326 (2017).
67. Carlsson, F. & Martinsson, P. Do hypothetical and actual marginal willingness to pay differ in choice experiments? *J. Env. Econ. & Management* **41**, 179–192 (2001).
68. Chau, C. K., Tse, M. S. & Chung, K. Y. A choice experiment to estimate the effect of green experience on preferences and willingness-to-pay for green building attributes. *Build. Environ.* **45**, 2553–2561 (2010).
69. Alfnes, F., Guttormsen, A. G., Steine, G. & Kolstad, K. Consumers' willingness to pay for the color of salmon: a choice experiment with real economic incentives. *Am. J. Agr. Econ.* **88**, 1050–1061 (2006).
70. Wessels, C. R., Johnston, R. J. & Donath, H. Assessing consumer preferences for eco-labeled seafood: the influence of species, certifier, and household attributes. *Am. J. Agr. Econ.* **81**, 1084–89 (1999).
71. Brécard, D., Lucas, S., Pichot, N. & Salladarré, F. Consumer preferences for eco, health and fair trade labels. An application to seafood product in France. *J. Agric. & Food Ind. Organ.* **10**, 1–30 (2012).
72. Xu, P., Zeng, Y., Fong, Q., Lone, T. & Liu, Y. Chinese consumers' willingness to pay for green- and eco-labeled seafood. *Food control* **28**, 74–82 (2012).
73. Gracia, A., Loureiro, M. L. & Nayga, R. M. Consumers' valuation of nutritional information: a choice experiment study. *Food Qual. Prefer.* **20**, 463–471 (2009).
74. Zwerina, K., Huber, J. & Kuhfeld, W. F. A. *General method for constructing efficient choice designs*. (Durham, NC: Fuqua School of Business, Duke University, 1996).
75. Hensher, D. A. Hypothetical bias, choice experiments and willingness to pay. *In transportation research part B: methodological* **44**, 735–752 (2010).
76. Adams, C. M. Biofouling in marine molluscan shellfish aquaculture: a survey assessing the business and economic implications of mitigation. *J World Aquac. Soc.* **42**, 242–252 (2011).
77. Batzios, C., Angelidis, P., Moutopoulos, D. K., Anastasiadou, C. H. & Chrisopolitou, V. Consumer attitude toward shellfish in the greek market: a pilot study. *Mediterr. Mar. Sci.* **4**, 155–174 (2004).
78. Huskisson, E., Maggini, S. & Ruf, M. The role of vitamins and minerals in energy metabolism and well-being. *J. Inter. Med. Res.* **35**, 277–289 (2007).
79. Lund, E. K. Health benefits of seafood; is it just the fatty acids? *Food Chem.* **140**, 413–420 (2013).
80. Tacon, A. G. J. & Metian, M. Fish matters: importance of aquatic foods in human nutrition and global food supply. *Rev. Fish. Science* **21**, 22–38 (2013).

## Acknowledgements

The present work was supported by the Millennium Nucleus "*Center for the Study of Multiple-drivers on Marine Socio-Ecological Systems* (MUSELS)" funded by MINECON NC120086 and the *Millennium Institute of Oceanography (IMO)*, IC 120019. SG thanks Conicyt Basal 0002. NAL thanks PIA CONICYT ACT172037. During the analysis and preparation of the manuscript, VASM was fully supported by a scholarship from CONICYT N° 21151027.

## Author Contributions

All authors provided input into data availability and preliminary discussions. V.A.S.M., S.G. and C.A.V. led the design and the drafting of the text, with main contributions in the same order from R.P., F.V., I.H., N.A.L. and S.N.R.B. V.A.S.M., C.A.V. and S.G. carried out data analysis, figures, and main structure of the study.

## Additional Information

**Supplementary information** accompanies this paper at https://doi.org/10.1038/s41598-019-41104-5.

**Competing Interests:** The authors declare no competing interests.

**Publisher's note:** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

CAPITULO III:

**Ocean Acidification, Consumers' Preferences, and Market Adaptation Strategies in the Mussel Aquaculture Industry**

Roberto D. Ponce Oliva[a,b,e], Felipe Vasquez-Lavín[a,b,c,e], Valeska A. San Martin[b,d,*], José Ignacio Hernández[a,b], Cristian A. Vargas[b,d], Pablo S. Gonzalez[f,g,h], Stefan Gelcich[b,c,e]

[a] *School of Business and Economics, Universidad del Desarrollo, Concepción, Chile.*

[b] *Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile.*

[c] *Millennium Nucleus Center for the Socioeconomic Impact of Environmental Policies (CESIEP), Santiago, Chile.*

[d] *Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepción, Concepción, Chile.*

[e] *Center of Applied Ecology and Sustainability (CAPES), Department of Ecology, Pontificia Universidad Católica de Chile, Santiago, Chile.*

[f] *Master Program in Natural Resources and Environmental Economics, Universidad de Concepción, Concepción, Chile.*

[g] *Research Nucleus on Environmental and Natural Resource Economics (NENRE), Universidad de Concepción, Concepción, Chile.*

[h] *Regional Center for Environmental Studies (RCES), Universidad Católica de la Santísima Concepción, Concepción, Chile.*

[*] *Corresponding author at: Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepcion, Concepcion, Chile.*

*E-mail address: valsanmartin@udec.cl (V.A. San Martin).*

*Ecological Economics 158 (2019) 42-50*

Received 5 May 2018

Accepted 13 December 2018

DOI:10.1016/j.ecolecon.2018.12.011

Ecological Economics 158 (2019) 42–50

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

# Ocean Acidification, Consumers' Preferences, and Market Adaptation Strategies in the Mussel Aquaculture Industry

Roberto D. Ponce Oliva[a,b,e], Felipe Vasquez-Lavín[a,b,c,e], Valeska A. San Martin[b,d,*], José Ignacio Hernández[a,b], Cristian A. Vargas[b,d], Pablo S. Gonzalez[f,g,h], Stefan Gelcich[b,c,e]

[a] School of Business and Economics, Universidad del Desarrollo, Concepción, Chile
[b] Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile
[c] Millennium Nucleus Center for the Socioeconomic Impact of Environmental Policies (CESIEP), Santiago, Chile
[d] Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepción, Concepción, Chile
[e] Center of Applied Ecology and Sustainability (CAPES), Department of Ecology, Pontificia Universidad Católica de Chile, Santiago, Chile
[f] Master Program in Natural Resources and Environmental Economics, Universidad de Concepción, Concepción, Chile
[g] Research Nucleus on Environmental and Natural Resource Economics (NENRE), Universidad de Concepción, Concepción, Chile
[h] Regional Center for Environmental Studies (RCES), Universidad Católica de la Santísima Concepción, Concepción, Chile

ARTICLE INFO

*Keywords:*
Ocean acidification
Economic impacts
Aquaculture
Choice experiment
Industry adaptation strategies
Consumers' welfare

ABSTRACT

Ocean acidification (OA) is one of the largest emerging and significant environmental threats for the aquaculture industry, jeopardizing its role as an alternative for supporting food security. Moreover, market conditions, characterized by price volatility and low value-added products, could exacerbate the industry's vulnerability to OA. We use a literature review on the biological consequences of OA over marine commercial species attributes to inform the empirical assessment of consumers' preferences for those attributes affected by OA, and consumers' responses to a set of market adaptation strategies suggested by the industry. We found that OA will have a negative impact on consumers' welfare due to the effects on commercial attributes of mussels aquaculture products. However, the main concerns for the industry are the market conditions. Thus, the industry's current adaptation strategies are focused on increasing their market share by offering new product assortments (with more value-added), regardless of the effect of OA on consumers' welfare. Despite this fact, the industry's strategies could eventually contribute to cope with OA since some specific segments of the market are willing to pay for new product assortments. This new market composition highlights the role of public institutions' reputation in issues related to food safety.

## 1. Introduction

Current trends in emissions of carbon dioxide ($CO_2$) and human population growth are jeopardizing the possibility of achieving food security and nutrition targets for the human population (Golden et al., 2016). As a result, aquaculture has emerged as one the most important ways in which to support food security, mostly because it is an affordable source of protein in economically deprived regions (FAO, 2016). Unfortunately, increasing levels of anthropogenic $CO_2$ have dramatic consequences for oceans, causing widespread changes in seawater pH and carbonate chemistry (Caldeira and Wickett, 2003; Orr et al., 2005), known as ocean acidification (OA). OA threatens the potential of aquaculture to support food security (Gattuso et al., 1999) and the ways in which the industry can adapt to and/or mitigate the relative effects of this global stressor (Clements and Chopin, 2017).

OA is a significant threat to the aquaculture industry, especially for marine shelled mollusks (Gazeau et al., 2013). These species are particularly vulnerable because they depend on carbonate concentrations to build their shells (Gazeau et al., 2013; Waldbusser et al., 2015). OA can significantly impair various physiological traits in marine mollusks such as scallops (Cooley and Doney, 2009; Schalkhausser et al., 2014; Talmage and Gobler, 2010), gastropods (Bednaršek et al., 2012; Wittmann and Pörtner, 2013), and mussels (Gazeau et al., 2013; Gazeau et al., 2007; Kroeker et al., 2010; Ventura et al., 2016; Waldbusser et al., 2015). OA also affects these species' mortality rates (i.e. larvae (Gibson et al., 2011)), calcification, and growth rates, as well as increasing their vulnerability to diseases and parasites (Gazeau et al., 2013; Mackenzie et al., 2014; Thomsen et al., 2013).

Research exploring the effects of OA on commercial attributes associated with mollusk quality, such as taste, appearance, and

* Corresponding author at: Center for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile.
*E-mail address:* valsanmartin@udec.cl (V.A. San Martin).

https://doi.org/10.1016/j.ecolecon.2018.12.011
Received 5 May 2018; Received in revised form 6 October 2018; Accepted 13 December 2018
Available online 26 December 2018

nutritional composition, is still in its infancy (Olsen, 2003; Sveinsdóttir et al., 2009). As a result, the potential links between the impact of OA and consumers' preferences and well-being have not been studied sufficiently, with just a handful of papers analyzing the economic dimension of OA. Of these, Finnoff (2010) analyzes the impact of OA on the provision of ecosystem services, highlighting that welfare effects should be measured in terms of changes in consumer and producer surplus, rather than changes in gross revenue. Narita and Rehdanz (2017) evaluate the economic impact of OA on the production of mollusks in Europe. Using a partial-equilibrium model, they show that countries such as France, Italy, and Spain (the largest producers in Europe) are among those most affected by OA. Moore (2015) estimates the welfare effects of OA for four species of mollusks by estimating an inverse demand function and calculating the consumer surplus associated with a reduction in supply. Falkenberg and Tubb (2017) provide a review of studies on the economic impacts of OA, identifying the current state of knowledge, key gaps in its understanding, and promising methods and approaches for future research. Their results show that more (and better) inter-disciplinary work is needed to increase our understanding of the links between OA and human welfare.

In order to understand the impacts of OA on human welfare and to inform adaptation strategies for the aquaculture industry, it is crucial that we connect the effects of OA on market attributes and assess the roles of these attributes in human well-being. Unfortunately, evaluations of commercial attributes and adaptation strategies in the shellfish industry under OA scenarios have not received the attention they deserve (Mabardy et al., 2015). Here, we conduct a detailed analysis of the evidence identified in the literature related to the physiological, organoleptic, and nutritional consequences of OA in marine commercial species, focusing on mussels, in order to assess consumers' preferences for attributes affected by OA. We use discrete-choice experiments (DCEs) to evaluate consumers' responses to a set of market adaptation strategies aimed at reducing shellfish producers' vulnerability to OA, international prices variations, and other stressors. In doing so, we explicitly link the ecological and socioeconomic dimensions of climate change in the aquaculture socioecological system.

This study contributes to the literature on the economic impacts of OA by (i) linking the effects of OA to consumers' preferences using stated-preference methods, and (ii) assessing the effectiveness of the market adaptation strategies identified by the industry. Unlike a cost–benefit analysis, which focuses on average net benefit, we examine market segmentation based on consumers' preferences as an adaptation strategy to cope with OA. Our study is novel in two ways: i) we examine OA effects on multiple product attributes; and ii) we offer suggestions to the industry on adaptation strategies by product form.

## 2. Materials and Methods

Mussel aquaculture production includes four stages: i) collection of larvae from the natural environment and fixing and settling larvae in long-line systems ("substrates"); ii) growing individuals in a marine environment until they reach the size necessary for harvesting; iii) industrialization in processing plants; and iv) marketing to national and international markets (Rivera et al., 2017). The greatest exposure of mussel production to OA occurs during the first two stages, but its consequences are found throughout the supply chain.

To gain insight into the industry's adaptation opportunities and challenges under OA scenarios, we follow a two-stage approach. In the first stage, using a literature review, we identify the impacts of OA on mussels' market attributes (i.e., shell appearance, shell size, and nutritional composition). In the second stage, we conduct participatory activities with industry representatives to assess their awareness of OA and to examine current and expected market adaptation strategies aimed at increasing value and adaptive capacity. The literature review and participatory activities are used to design a DCE that investigates consumers' responses to changes in mussels' market attributes and to the adaptation strategies suggested by the industry, enabling us to identify the attributes consumers find most valuable. As such, we evaluate whether the proposed industry strategies will be accepted by the market (or by certain segments within the market).

### 2.1. Literature Review of the Impact of OA on Market Attributes

We conduct a systematic literature review of the impact of OA on mollusks' market attributes, such as shell size, meat color, shell appearance, texture, taste, and nutritional composition (lipid and protein content, Vitamin B12, and fatty acid). These attributes are selected based on previous surveys on seafood consumption preferences (e.g., Cardoso et al., 2013; Sveinsdóttir et al., 2009). Here, we search the databases of Scopus, Science Direct, Web of Knowledge/Science, and Google Scholar. In our literature analysis, we consider only original research papers and review papers, but exclude conference proceedings and other non-peer-reviewed publications. However, we include unpublished information from ongoing experiments by the authors of the present study on evaluating the impact of OA on mussel color.

### 2.2. Industry Awareness

Participatory activities (interviews and seminars) are used to understand both the industry's awareness of OA and the current and expected market situation (prices, production levels, main markets). We conducted 20 semi-structured interviews with key industry representatives between June and August 2014. These interviews examined the cost structure, production, main threats, future expectations about activities, and market adaptation strategies, among other topics. Using this information, and collaborating closely with the Chinquihue Foundation (private non-profit organization that promotes artisanal fisheries and small-scale aquaculture sectors) and the Chilean mussel industry association (AmiChile), we designed and administered surveys to 87 of 148 firms in the industry between November 2014 and January 2015.[1] This survey analyzes participation in various stages of the value chain (seed producer, feeder, processing, and commercialization), main industry threats (production, environment, market), and market characteristics (main markets served, product assortment offered[2]). With regard to industry threats, the survey included 10 potential threats to the industry, grouped into the following categories: environmental (lack of knowledge about the environment, water pollution, red tide, environmental standards); production (seed shortages, labor shortages), market (dependency on international prices, input-market concentration, fixed-capital replacement, and environmental certification).

We included specific questions related to environmental issues, asking the interviewees whether they were familiar with OA, global warming, anoxia, phytoplankton decrease, eutrophication, water pollution by antibiotics, and water pollution by other compounds. In each case, we also inquired about the potential threat to the industry and the level of relevance they assign to each issue.

Finally, we held two seminars (May 2015 and July 2016) in which we discussed the results of the industry survey and designed the DCE consumer survey. In these seminars, we discussed the market adaptation strategies, including information related to potential changes in product presentation (product assortments). The seminars were targeted at industry representatives responsible for the marketing/management and production/processes in their respective organizations.

[1] The remaining 61 firms did not participate owing to various constraints (time, geographical, and budget).

[2] Product assortment refers to the number of different product presentations available for commercializing the product.

**Table 1**
Attributes and levels used in the choice sets and references to studies which justify their inclusion.

| Category | Attributes | Levels | Group | Number of studies | Total studies |
|---|---|---|---|---|---|
| Physiological | Shell size | Small (5 cm) | Mussel | 23 | 52 |
| | | Large (7 cm) | Oyster | 13 | |
| | | | Clam | 4 | |
| | | | Snail | 2 | |
| | | | Scallop | 2 | |
| | Meat color | Yellow | Oyster | 4 | |
| | | White | Fish | 1 | |
| | | | Snail | 2 | |
| | Shell appearance | Acidified (decolorated) | Mussel | 2 | |
| | | Not acidified (shinny) | Oyster | 3 | |
| Organoleptic | Texture | Soft | Snail | 1 | 4 |
| | | Hard | Fish | 1 | |
| | Taste-sea scent | Intense | Shrimp | 1 | |
| | | Moderate | Oyster | 1 | |
| Nutritional composition | Nutritional composition | High | Mussel | 6 | 9 |
| | | Low | Oyster | 2 | |
| | | | Seafood | 1 | |
| Product | Product depth/assortment | Fresh with shell | Mussel | 2 | 2 |
| | | Fresh only meat | | | |
| | | Frozen with shell | | | |
| | | Frozen only meat | | | |
| | | Canned in oil or water | | | |
| | | Canned in hot sauce | | | |
| | | Canned in green sauce | | | |
| | | Bagged with shell, in butter and garlic dressing | | | |
| | | Bagged with shell, in white wine dressing | | | |
| | | Bagged with shell, in tomatoes dressing | | | |
| Price | Price (250 g) | Six prices per product assortment ranging from [US$1.3–US$5] | Mussel | 1 | 1 |

### 2.3. Consumer Preferences

DCEs are widely used in the fields of marketing and environmental economics (Louviere et al., 2000) to assess the relative relevance of different attributes for consumers. The method is grounded in both the theory of value (Lancaster, 1966) and random utility theory (McFadden, 1974).

The utility level obtained by individual $n$ selecting alternative $j$ from among $j = 1, \ldots, J$ alternatives in choice situation $t$, for $t = 1, \ldots, T$, is given by:

$$U_{njt} = V_{njt} + \varepsilon_{njt}, \tag{1}$$

where $V_{njt}$ is the observed component of the utility of individual $n$ when choosing alternative j in choice situation $t$, and $\varepsilon_{njt}$ is an unobserved random component. The model assumes that people choose the alternative that provides the highest utility (McFadden, 1974; Train, 2009).

Assuming a linear specification for $V_{njt}$ and an identical and independent Gumbel-distributed stochastic component, the probability that individual $n$ makes a sequence of independent $T$ choices, conditioned on coefficients $\alpha_i$ and $\beta_n$, is given by:

$$L_{ni}(\alpha_i, \beta_n) = \prod_{t=1}^{T} \left[ \frac{e^{\alpha_i + \beta_n' x_{nit}}}{\sum_j e^{\alpha_i + \beta_n' x_{njt}}} \right], \tag{2}$$

where $x_{njt}$ represents the attribute levels; $\alpha_i$ is an alternative specific constant (ASC), independent of the attribute levels we use to model the utility of the "opt-out" option; and $\beta_n$ is a random parameter vector associated with the attribute levels, with distribution function f ($\beta \mid \mathbf{b}, \mathbf{W}$), in which **b** corresponds to the vector of means and **W** indicates the covariance matrix. We use a random parameter specification (mixed logit model) because the standard conditional logit model does not allow the random error to be correlated between alternatives and observations and suffers from the independence of irrelevant alternative (IIA) property (Train, 2009). Because we cannot obtain an analytical expression for the unconditional probability, we develop a simulation method that allows us to assess the integral of the probability. Values for $\beta$ are generated from the distribution f ($\beta \mid \mathbf{b}, \mathbf{W}$), called $\beta^r$, which in turn allows us to calculate a value according to the probability $L_{ni}(\alpha_i, \beta^r)$ given in Eq. (2). The simulated unconditioned probability of choosing alternative $i$, $\check{P}_{ni}$, is obtained as the average of R simulations:

$$\check{P}_{ni} = \frac{1}{R} \sum_{r=1}^{R} L_{ni}(\alpha_i, \beta^r). \tag{3}$$

The simulated maximum-likelihood estimator corresponds to the values of $\alpha_i$, **b**, and **W** that maximize the likelihood function constructed with the simulated probabilities $\check{P}_{ni}$ (Train, 2009).

#### 2.3.1. Experiment Design

We developed a face-to-face survey that we conducted from October to December 2016 in two Chilean cities: Santiago (Chile's capital) and Concepción (the second-largest city). As mentioned above, the design of the final survey was the result of close collaboration with the industry, and the final DCE was presented in two seminars with industry representatives. After the seminars, we conducted four focus groups (two each in Concepción and Santiago) to explore people's reactions to specific aspects of the experiment and to identify wording problems or misleading sections in the survey. Then, we conducted 125 pilot surveys to field-test the design of the instrument (with 25, 50, and 50 observations, respectively).

We rely on a socioeconomic sampling process based on the National Socioeconomic Household Survey (CASEN), using a probabilistic polietapic sampling design, in which we randomly select neighborhoods and blocks. Next, we systematically select the households to be interviewed. Here, we select one household in each block, starting in the northern corner. If there is no answer from that house, we skip the next four houses and try the fifth. The sampling process yielded a useful sample of 1278 individuals, each of whom were presented with six decisions, with three alternatives for each choice. This yielded a final sample of 7668 useful observations.

The final questionnaire consists of four parts. The first part provides information about mussels' characteristics, the second explains the relationship between mussel production and OA as an environmental stressor. Here, we also evaluated respondents' trust in public institutions on issues related to food safety. In the third section, we explain the choice exercise, the attributes of the alternatives, and the levels for each attribute. We provide an example of a choice to the interviewees to ensure their understanding of the cognitive task. After this explanation, we applied the final choice question. The final part focuses on socioeconomic characteristics (age, educational level, income, and household size).

The interviewees were presented with six choice sets, each with three alternatives: two mussel profiles and one opt-out alternative. Through the interviews, seminars, focus groups, and pilots, we identified eight main attributes (see Table 1). We classified the attributes into five categories: physiological, organoleptic, nutritional, product assortments, and price. Physiological attributes include shell size, meat color, and shell appearance; organoleptic attributes include texture and taste; and the categories of nutritional composition, product, and price contain one element only.

Physiological, organoleptic, and nutritional attributes are included in the DCE because all are affected by OA. The relationships between these categories and OA were identified from previous studies on the effects on shell appearance, shell size, meat color, texture, and nutritional composition. The last column of Table 1 shows the total number of studies reviewed, supporting the presence of each attribute category.[3]

The product attributes were defined after close discussion with the industry on both current product assortments (fresh and frozen formats) and new product assortments they wished to offer in future (bagged and dressed formats) in order to enhance their market performance. Finally, we also include six values for price. The ranges of prices vary according to the product assortment. These ranges were identified through focus groups, and were tested and adjusted after pilot surveys.

After the focus groups and pilot surveys, we decided to reduce the levels of most of the attributes (physiological, organoleptic, and nutritional) from three to two, given the complexity of the original choice exercise. We decided to retain the complexity in the product assortment attribute (10 levels) because the assortments represent both the current and the future options identified by the industry as the main market adaptation strategies available. To make prices comparable between different presentations of the product, we adjust the prices to represent the same weight (250 g of meat).

When appropriate, we used pictures to help interviewees understand the outcomes of each alternative (e.g., physiological attributes (shell size, meat color, and shell appearance), with and without impacts of OA). Based on secondary information, we informed interviewees about the nutritional characteristics (omega 3, omega 6 and Vitamin B12) of mussels by comparing them with other food with similar nutritional characteristics perceived as healthy by the Chilean population (olive oil, avocados, salmon, and mackerel). We also used pictures to illustrate the different product assortments, where we informed respondents (before the choice question) that 250 g of meat is approximately equivalent to 45 mussel units. An example of a choice set is shown in Fig. 1.

We include a constant opt-out alternative, representing a non-purchase choice. This is a standard design in choice experiments (Hanley et al., 2001; Meyerhoff and Liebe, 2009; Veldwijk et al., 2014). This opt-out alternative may be associated with elements of utility derived from characteristics that differ from those already included in the options (Bahamonde-Birke et al., 2017; Hanley et al., 2001; Hess et al., 2014; Kontoleon and Yabe, 2003; von Haefen et al., 2005; Zijlstra et al., 2015). This design offers several advantages. For example, it provides a more realistic choice scenario, the possibility of estimating an unconditional demand model rather than a conditional model, and correct estimates of welfare measures (Bateman et al., 2002; Batsell and Louviere, 1991; Kontoleon and Yabe, 2003; Louviere et al., 2000; Ortuzar and Willumsen, 2011; Zijlstra et al., 2015).

The choice sets are defined following state-of-the-art practices in the choice-modeling literature (Goos et al., 2010; Louviere et al., 2000; Scarpa et al., 2005; Street and Burgess, 2007; Street et al., 2005). Because the number of treatment combinations (full factorial) may be too costly in terms of data collection, we defined a subset of this design using an efficiency criterion. In the pilot surveys, we used an orthogonal design (Louviere et al., 2000; Street and Burgess, 2007) of 36 choice situations, divided into six blocks, each with six choice questions. For the final survey, we constructed a D-efficient design (Street and Burgess, 2007) using prior coefficients retrieved from the pilot regressions,[4] assuming a mixed logit model (Kuhfeld, 2005; Vermeulen et al., 2008) and using the Ngene software package (Quan et al., 2011). The final design consisted of 60 choice sets, each with two alternatives and an opt-out option, divided into 10 blocks of six choice questions. The final sample was fairly balanced, with about 10% of the sample in each block. The final distribution is shown in Appendix A.

To estimate the welfare measures, we adapted the classical welfare log sum expression to our profiles, following Bockstael and McConnell (2007). The baseline utility has only the opt-out alternative. However, in the choice situation, respondents face a new profile that includes the non-purchase option. Therefore, the willingness to pay (WTP) for a new mussel profile is given by:

$$WTP = -\frac{1}{\gamma}\cdot\ln\left[\frac{e^{v_0}}{e^{v_0}+e^{v_1}}\right].$$

Here, $v_0$ is the utility level at the opt-out alternative, and $v_1$ is a predefined profile. A marginal WTP (MWTP) for an increase in quality of one attribute only is calculated as:

$$MWTP = \frac{1}{\gamma}\cdot[v_1^M - v_0^M],$$

where ${v_0}^M$ is the utility level of the baseline profile, represented by the lowest levels of the physiological, organoleptic, and nutritional composition categories. These are the levels we expect to find in a mussel affected by OA (labeled as “with OA”). This profile is completed by including the reference level for the product assortment (fresh with shell) and the lowest price. Then, ${v_1}^M$ is the utility achieved by incrementing one level of one attribute only.

Finally, for the OA scenario, we rely on the RCP 8.5 scenario, which predicts around 1000 μatm of $pCO_2$ for 2100 in the open ocean (i.e. high seas). Although the timing assumed in this scenario is far in the future, living organisms in coastal zones could already be facing ocean acidification values in that range, owing to the natural variability in upwelling and river flows which are part of Chile's complex coastal system (Vargas et al., 2017). In fact, in situ studies show that in some places along the coast, the levels of $pCO_2$ reach 1800 μatm. This implies a pH level of between 7.4 and 7.6, which are the values predicted for 100 years from now (Vargas et al., 2017).

## 3. Results

### *3.1. Literature Review on the Impact of OA on Market Attributes*

We identified 49 papers on the impact of OA on the market attributes of the main commercial marine species. Of these, only 24 papers (49% of the total) focused on mussels. Note that these studies, despite examining species of commercial importance, focus only on the effects on physiological responses, such as growth rate, size, and shell appearance. Similarly, only two studies examine the variation in organoleptic characteristics under OA scenarios (shrimp and oysters,

[3] We provide detailed information about these studies in the Supplementary material.

[4] We estimate a conditional logit (CL) model from the pilot responses.

| | Option 1 | Option 2 | Not Buying |
|---|---|---|---|
| Shell Size | Small (5 cm.) | Large (7 cm.) | |
| Texture | Hard | Soft | |
| Taste – sea scent | Intense | Moderate | |
| Nutritional composition | High | Low | |
| Product depth/assortment |  |  | |
| Shell appearance |  |  | |
| Meat Color |  |  | |
| Price (250 gr) | $1.700 | $1.000 | $0 |
| **Your choice** | | | |

**Fig. 1.** Choice-set example.

respectively). However, these studies do not link their findings to consumers' preferences or how these preferences might vary if products with different attributes are made available.

Our analysis shows that OA can significantly impair attributes such as shell size, shell appearance, nutritional composition, and organoleptic characteristics (see Supporting Information, Table S1). The studies identified typically consider the response of *Mytilus* species to low pH/high $pCO_2$ conditions. Furthermore, our unpublished information shows that OA can impair shell color in both juvenile and adult mussels (*Mytilus chilensis*), with a 48% reduction in shell color in adult organisms and a 9% reduction in juvenile individuals (data not shown).

### 3.2. Industry Awareness

Only 10.1% of the firms participate in all stages of the value chain (seed supply, feeding, processing, and commercialization). Considering the overall sample, the largest share (58%) participates in feeding, followed by seed supply (27%), and commercialization (8%). Firms perceive that the greatest threats relate to red tide events (95%), followed by seed shortages (92%), and a dependency on international prices (86%).[5] A lack of environmental knowledge is recognized as a threat by 68% of respondents.

With regard to the specific environmental issues included in the survey, 94% of respondents indicated that they were familiar with water pollution from antibiotics, 91% with the phytoplankton decrease, and 89% were familiar with global warming. At the same time, 89% of respondents viewed the phytoplankton variability as a threat to the industry, as did 21% for the direct effects of OA. Fig. 2 shows the results for all of the environmental categories, including the familiarity and perceived threat level in each case.

All firms that participate in all stages of the value chain produce individual quick-freezing (IQF) meat, 75% produce whole-shell IQF, 63% produce half-shell fresh meat, 50% produce canned meat, and 13% produce other formats. All formats are characterized as low value-added. Firms sell almost all of their products to international markets (Spain, France, Italy, USA, and China), with a small share devoted to the domestic market (3%–5%), which increases their vulnerability to international price variations. Given the dependence on the international market with low value-added products, the respondents stated that they would like to increase the share of the domestic market by offering new product assortments.

### 3.3. Consumer Preferences

Table 2 presents the estimates of the mixed logit model. Here, we include all attributes from Table 1 and the sociodemographic variables interacting with the opt-out option. We report only the significant results for the demographic variables (trust in institutions and household size).

The table presents the mean and standard deviation for each attribute (columns 3 and 5, respectively). For the physiological attributes, the means of meat color and shell appearance are statistically significant. The mean of nutritional composition is also significant, indicating that consumers prefer mussels with yellow meat, without evident color changes in the shell (not acidified) and with a high nutritional level. The aforementioned attributes also have statistically significant standard deviations. Despite the other attributes (shell size, texture, and taste) of mussels not being statistically significant, all have a statistically significant standard deviation, suggesting strong heterogeneity across consumers' preferences. In other words, for some consumers, these attributes reduce welfare, while for others, they have positive effects from an economic perspective.

With regard to product assortments, the means of fresh-only meat, frozen with shells, canned (oil or water), and canned (green sauce) are not statistically significant. However, the means of frozen-only meat, canned (hot sauce), bagged with shell (butter and garlic), bagged (white wine), and bagged (tomato) are statistically significant. Notably, all of these product assortments have a negative sign, indicating that they reduce consumers' welfare (compared with choosing the "fresh with shell" option). However, in most cases, there is heterogeneity across consumers' preferences, meaning that some consumers do prefer these formats. Note that the standard deviations are not statistically significant for bagged (white wine) and frozen-only meat, indicating

[5] These categories are not mutually exclusive; that is, respondents could select more than one option.

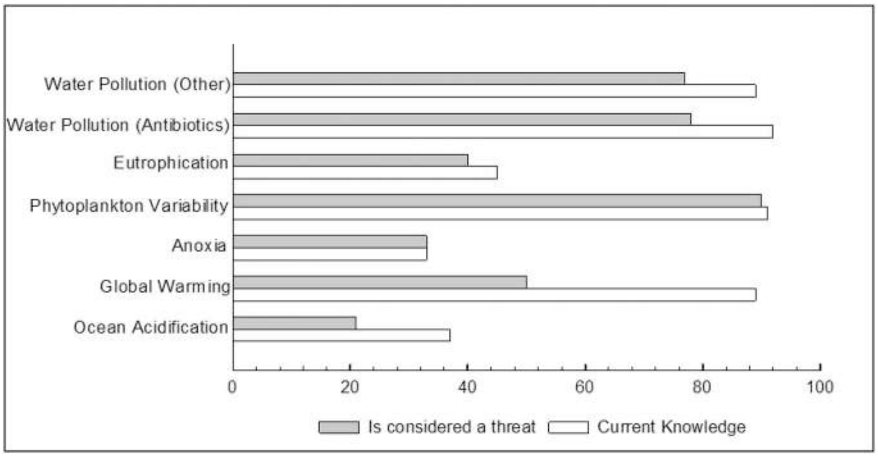


**Fig. 2.** Environmental knowledge and level of threat perceived by mussel firms.

**Table 2**
DCE results/social valuation of the attributes and marketing format. Distribution of heterogeneity of preferences for mussel attributes and product assortment under normally distributed random coefficients.

| Category | | Mean | Std. err | SD | std. err | % negative | % positive |
|---|---|---|---|---|---|---|---|
| Random coefficients | | | | | | | |
| Physiological | Shell size (large) | 0.057 | (0.05) | 0.659*** | (0.087) | 46.58% | 53.42% |
| | Meat color (yellow) | 0.269*** | (0.061) | 1.349*** | (0.082) | 42.10% | 57.90% |
| | Shell appearance (not acidified) | 0.828*** | (0.065) | 1.322*** | (0.076) | 26.57% | 73.43% |
| Organoleptic | Texture (soft) | 0.044 | (0.049) | −0.596*** | (0.085) | 47.03% | 52.97% |
| | Taste - sea scent (moderate) | 0.058 | (0.051) | 0.742*** | (0.08) | 46.90% | 53.10% |
| | Nutritional composition (high) | 0.306*** | (0.055) | 1.033*** | (0.073) | 38.35% | 61.65% |
| Product assortment | Format: fresh - only meat | −0.045 | (0.117) | −0.793*** | (0.26) | 52.25% | 47.75% |
| | Format: frozen - with shells | −0.079 | (0.127) | −0.998*** | (0.237) | 53.17% | 46.83% |
| | Format: frozen - only meat | −0.409* | (0.128) | 1.276 | (0.214) | – | – |
| | Format: canned - oil or water | 0.155 | (0.12) | 1.342*** | (0.258) | 45.40% | 54.60% |
| | Format: canned - hot sauce | −0.420** | (0.13) | −1.607*** | (0.206) | 60.31% | 39.69% |
| | Format: canned - green sauce | −0.170 | (0.137) | 1.613*** | (0.23) | 54.19% | 45.81% |
| | Format: bagged with shell - butter and garlic | −0.628*** | (0.125) | 0.926** | (0.284) | 75.11% | 24.89% |
| | Format: bagged - white wine | −0.619*** | (0.124) | 0.474 | (0.348) | – | – |
| | Format: bagged - tomato | −0.881*** | (0.124) | 0.780*** | (0.224) | 87.05% | 12.95% |
| Fixed coefficients | | | | | | | |
| | Price | −0.362*** | (0.052) | | | | |
| | Opt-out | −1.346** | (0.129) | | | | |
| Opt-out and interactions | Opt-out ∗ trust | −0.309** | (0.107) | | | | |
| | Opt-out ∗ household size | −0.103** | (0.03) | | | | |

Standard errors in parentheses.
*** $p < 0.001$.
** $p < 0.01$.
* $p < 0.05$.

that these attributes are negative for consumers.[6]

Columns 7 and 8 of Table 2 present the percentages of the sample that have positive or negative signs for the "individual parameter" of the attribute (i.e., these values represent the probability that the coefficient is greater than or less than zero, respectively). For the physiological, organoleptic, and nutritional composition attributes, we find that the means are positive and that the heterogeneity among consumers is significant and, broadly speaking, evenly distributed between the negative and positive parts of the distribution. For those cases with significant means (meat color, shell appearance, and nutritional composition), the distribution leans toward the positive side of the distribution, with shell appearance and nutritional composition having the highest proportion of consumers in this area.

For bagged with shell (butter and garlic) and bagged (tomato), the percentage of negative signs is larger than 75%, suggesting that the majority of consumers do not value these presentations. For each of the five remaining assortments, the share of positive values is greater than or equal to 40%, suggesting that the industry can reach at most 40% of the market using this differentiation strategy. Thus, the results suggest that a market differentiation strategy (offering different product assortments) is appropriate for different market segments.

With regard to socio-economic characteristics, consumers can increase their welfare by selecting any of the available alternatives (the opt-out constant is negative and statistically significant). In other words, there is a preference for the purchasing option. The interaction of opt-out and trust, which is also negative and statistically significant, shows that greater trust in institutions related to food safety is associated with a larger probability of buying the product (i.e., consumers are less likely to choose the opt-out alternative). Furthermore, the larger the size of a family, the lower is the probability of choosing the opt-out alternative. Lastly, as expected, the price coefficient is negative and statistically significant.

Table 3 presents the assessment of OA on consumers' welfare. The first column presents three products assortments: the baseline case

[6] Note that they do not have an interval in columns 7 and 8 in Table 2.

**Table 3**
Consumers' WTP. Results for each profile, with and without OA effects.

| | With OA | Without OA |
|---|---|---|
| Frozen - only meat | 2.88<br>(1.01; 4.75) | 7.15<br>(5.28; 9.01) |
| Canned - standard | 3.41<br>(1.78; 5.04) | 8.02<br>(5.9; 10.13) |
| Fresh - with shells | 3.05<br>(1.3; 4.81) | 7.44<br>(5.47; 9.41) |

Confidence intervals in parentheses.

**Table 4**
MWTP for attributes (USD).

| Attribute | MWTP | MWTP (positive only) |
|---|---|---|
| Shell size (from small to large shells) | 0.259<br>(−0.198; 0.717) | 2.512<br>(0.102; 6.936) |
| Meat color (from pale to yellow) | 1.23<br>(0.612; 1.848) | 5.402<br>(0.223; 14.69) |
| Shell appearance (without acidification) | 3.784<br>(2.623; 4.945) | 6.517<br>(0.329; 16.429) |
| Texture (softer) | 0.203<br>(−0.242; 0.648) | 2.235<br>(0.092; 6.225) |
| Taste - sea scent (lighter taste) | 0.264<br>(−0.196; 0.723) | 2.804<br>(0.113; 7.772) |
| Nutritional composition (from low to high composition) | 1.4<br>(0.778; 2.021) | 4.322<br>(0.197; 11.587) |
| Product assortment (baseline: fresh with shells) | | |
| Fresh - only meat | −0.205<br>(−1.244; 0.834) | 2.825<br>(0.116; 8.065) |
| Frozen - with shells | −0.364<br>(−1.519; 0.792) | 3.512<br>(0.135; 9.985) |
| Frozen - only meat | −1.888<br>(−3.143; −0.634) | – |
| Canned - oil or water | 0.709<br>(−0.37; 1.789) | 5.18<br>(0.221; 14.268) |
| Canned - hot sauce | −1.921<br>(−3.283; −0.559) | 5.2<br>(0.194; 15.165) |
| Canned - green sauce | −0.776<br>(−2.061; 0.51) | 5.573<br>(0.217; 15.877) |
| Bagged with shell - butter and garlic | −2.871<br>(−4.201; −1.541) | 2.525<br>(0.087; 7.765) |
| Bagged with shell - white wine | −2.83<br>(−4.291; −1.369) | – |
| Bagged with shell - tomato | −4.027<br>(−5.598; −2.456) | 1.773<br>(0.058; 5.665) |

95% confidence interval indicated in parentheses.

(fresh, with shells; frozen-only meat; and canned (standard)), which are the current options offered by the industry. Columns 2 and 3 present the total WTP for a profile with and without OA. Profiles “with OA” are small in size and have discolored shells, white meat, and a hard texture (the lowest levels of each attribute, except price and assortment).

For the currently marketed products, the WTP decreases between 41% and 43%, depending on the profile analyzed. The largest impact is observed for the canned (standard) offering.

An analysis of the MWTP is presented in Table 4. The second column shows the MWTP for the whole population, which is a standard indicator used in cost–benefit analyses. Nevertheless, from a marketing perspective, we are more interested in the MWTP for the proportion of the population who are willing to buy the product (i.e., those on the positive side of the distribution). This is because the differentiation strategies identified by the producers can target different segments of the market in order to decrease their vulnerability.

For the physiological, organoleptic, and nutritional attributes, the MWTP values are all positive. The highest MWTP is shown for an improvement in shell appearance (from small shells to large shells; USD 3.7). In contrast, the lowest MWTP is related to an improvement in meat softness (from a hard to a soft texture; USD 0.2). The MWTP values for the product attributes need to be compared with those of the baseline product assortment (fresh, with shell). For example, consumers' MWTP will increase by USD 0.71 when changing from “fresh, with shell” to “canned (oil or water).” As expected, the MWTP will decrease when changing from the “fresh, with shell” format to any of the other product assortments.

If we restrict our analysis to the positive side of the distribution, focusing on those consumers who are willing to buy the different assortments, the attribute “bagged with shell (butter and garlic)” is valued similarly by consumers to the attributes taste, texture, and shell size (approximately USD 2.5). For the remaining product attributes, the MWTP of the canned formats are similar (approximately USD 5). This is a promising result, because it tells us that producers can compensate for the loss due to OA by offering these product assortments to at least one segment of the market.

## 4. Discussion

The literature review showed that OA has a direct impact on mussels' physiological characteristics and nutritional content. Previous studies have suggested that shell appearance is decisive in terms of informing consumption decisions (Alfnes et al., 2006; Azpeitia et al., 2016; Batzios et al., 2003; Brenner et al., 2012; Grabacki, 2011). Furthermore, as shown by Colombo et al. (2016), a decrease in nutritional quality indicates a higher content of proteins and lipids in specimens that have not been exposed to environmental stress (i.e., temperature, habitat, and air exposure). Our results show a strong link between these biological/physiological consequences of OA and human welfare. Similarly to Batzios et al. (2003) and Batzios et al. (2002), we find that the nutritional content of shellfish is an important and significant attribute for consumers. In addition, we find that consumers consider both the appearance and the color of the meat.

Market price is highly dependent on both the quality of the meat and mussels' appearance (Brenner et al., 2012). Thus, any variation in these attributes due to OA will have implications for the mussel industry and, thus, will affect the local economy and consumers' welfare. The industry has identified market segmentation as a strategy to cope with the low value-added products, price volatility, and producers' dependency on international markets by creating new product assortments. However, our results show that these strategies will only help for specific segments of consumers. Unlike Batzios et al. (2003), who found that shellfish packaging is not a relevant criterion in consumers' purchasing decisions, our results show that, on average, consumers place a low value on these new and innovative assortments (i.e., different bagging and dressing options). The heterogeneity analysis of the WTP for different attributes identified segments of the population that could be targeted using these strategies. Despite the proposed product assortments having a negative sign, thus reducing consumers' welfare, a significant segment of the population (40%) is willing to pay for them. Discrete-choice models can help to identify these market segments in order to increase producers' revenue. Our results complement those of other studies, showing that OA affects mussel production and, thus, prices (Moore, 2015). However, we go beyond the price (quantity) effect by considering other mussels attributes affected by OA that consumers find relevant. In other words, OA not only affects prices (by affecting quantities), but also affects other relevant attributes of the products, thus exacerbating the impact of OA.

Based on our results, it is possible to inform future scenarios for the industry by considering the interplay between market adaptation strategies, such as that between offering new product assortments and the traditional mussel attributes preferred by consumers. Implementing these adaptation options will require that the industry educate consumers about the characteristics (i.e., nutritional quality) of the new product assortments in order to inform the buying process. As our results show, greater trust in institutions leads to a higher probability of buying the products. Therefore, there is space to build a fruitful private–public partnership with regard to food safety. This is a highly relevant result, because public policies rely heavily on providing information to consumers (McDowell, 2006).

Our results can be extended in three ways. First, it would be worth including foreign consumers and conducting a similar analysis for the main markets of Chilean mussels (Spain, China, France, and the United States). This new information would enrich our results with regard to the most valuable attributes. Another possible extension of the study would be to empirically test the organoleptic characteristics under different OA scenarios in order to compare consumers' perceptions to the laboratory results. Finally, our results could be complemented with information about the industry's adaptive capacity, which would enable an assessment of whether the aquaculture industry can face the burden of climate change.

## 5. Conclusion

In this study, we explicitly link the expected impact of OA on physiological, organoleptic, and nutritional characteristics of commercial mussel species with consumers' preferences. Our results suggest that OA will affect biological and physiological characteristics that are highly valued by consumers and, thus, will affect their welfare. The attribute analysis suggests that the product assortment that mussel producers would like to offer does not meet consumers' expectations, on average. However, a heterogeneity analysis shows that different product assortments would meet the expectations of a significant share of the market. This point reveals the effectiveness of the adaptation strategies developed by the industry.

OA is not identified as a main threat by the industry, where producers are more concerned about their vulnerability to international market price volatility and would like to increase their domestic market share by introducing new product assortments (with higher value-added). However, these strategies could also contribute to coping with OA because reductions in physiological, organoleptic, and nutritional attributes can be compensated for, at least for some segments of the market, by introducing new product assortments.

The greatest challenge the aquaculture industry is going to face when confronted by OA is, arguably, preserving the attributes of appearance and nutritional composition. This is because the industry has less adaptive capacity in the first stages of the value chain, when organisms are more exposed to environmental oceanographic conditions. Thus far, industry efforts have focused on adaptation strategies such as using hatcheries, nurseries, artificial seawater, alternative food supplements, long-line systems with photosynthetic species, among others, which are costly and imply changes to production processes. Our results reveal the complexities and opportunities of using adaptation strategies in subsequent value-chain stages, such as labeling, product assortments, and market differentiation. Identifying the roles of these adaptation measures is critical to informing future strategic investments of the industry along the supply chain.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2018.12.011.

## Acknowledgments

Authors acknowledge support from Millenium Nucleus Center for the Study of Multiple Drivers on Marine Socio- Ecological Systems (MUSELS) funded by MINECON NC120086. VSM thanks scholarship from CONICYT Nº 21151027, and SG thanks to Conicyt Basal 0002-2014 (CAPES).

## Appendix A. Distribution of Blocks in the Sample

Table 1
Distribution of blocks in the sample.

| Blok | Individuals | Decision occasions | Percent | Cum. |
|---|---|---|---|---|
| 1 | 129 | 774 | 10.09 | 10.09 |
| 2 | 125 | 750 | 9.78 | 19.87 |
| 3 | 132 | 792 | 10.33 | 30.20 |
| 4 | 129 | 774 | 10.09 | 40.30 |
| 5 | 128 | 768 | 10.02 | 50.31 |
| 6 | 130 | 780 | 10.17 | 60.49 |
| 7 | 126 | 756 | 9.86 | 70.34 |
| 8 | 127 | 762 | 9.94 | 80.28 |
| 9 | 124 | 744 | 9.70 | 89.98 |

## References

Alfnes, F., Guttormsen, A.G., Steine, G., Kolstad, K., 2006. Consumers' willingness to pay for the color of salmon: a choice experiment with real economic incentives. Am. J. Agric. Econ. 88, 1050–1061.
Azpeitia, K., Ferrer, L., Revilla, M., Pagaldai, J., Mendiola, D., 2016. Growth, biochemical profile, and fatty acid composition of mussel (*Mytilus galloprovincialis* Lmk.) cultured in the open ocean of the Bay of Biscay (northern Spain). Aquaculture 454, 95–108.
Bahamonde-Birke, F.J., Navarro, I., de Dios Ortúzar, J., 2017. If you choose not to decide, you still have made a choice. J. Choice Model. 22, 13–23.
Bateman, I.J., Carson, R.T., Day, B., Hanemann, M., Hanley, N., Hett, T., Jones-Lee, M., Loomes, G., Mourato, S., Pearce, D., 2002. Economic Valuation With Stated Preference Techniques: A Manual.
Batsell, R.R., Louviere, J.J., 1991. Experimental analysis of choice. Mark. Lett. 2, 199–214.
Batzios, C., Angelidis, P., Moutopoulos, D., Anastasiadou, C., Chrisopolitou, V., 2002. Investigation of consumer preferences towards the farmed fish market in Greece. In: Proceedings of the 1st International Congress on Aquaculture, Fisheries Technology and Environmental Management.
Batzios, C., Angelidis, P., Moutopoulos, D., Anastasiadou, C., Chrisopolitou, V., 2003. Consumer attitude towards shellfish in the Greek market: a pilot study. Mediterr. Mar. Sci. 4, 155–174.
Bednaršek, N., Tarling, G., Bakker, D., Fielding, S., Jones, E., Venables, H., Ward, P., Kuzirian, A., Lézé, B., Feely, R., 2012. Extensive dissolution of live pteropods in the Southern Ocean. Nat. Geosci. 5, 881.
Bockstael, N.E., McConnell, K.E., 2007. Environmental and Resource Valuation With Revealed Preferences: A Theoretical Guide to Empirical Models. Springer Science & Business Media.
Brenner, M., Buchholz, C., Heemken, O., Buck, B.H., Köhler, A., 2012. Health and growth performance of the blue mussel (*Mytilus edulis* L.) from two hanging cultivation sites in the German Bight: a nearshore—offshore comparison. Aquac. Int. 20, 751–778.
Caldeira, K., Wickett, M.E., 2003. Oceanography: anthropogenic carbon and ocean pH. Nature 425, 365.
Cardoso, C., Lourenço, H., Costa, S., Gonçalves, S., Nunes, M.L., 2013. Survey into the seafood consumption preferences and patterns in the Portuguese population. Gender and regional variability. Appetite 64, 20–31 (%@ 0195-6663).
Clements, J.C., Chopin, T., 2017. Ocean acidification and marine aquaculture in North America: potential impacts and mitigation strategies. Rev. Aquac. 9, 326–341. https://doi.org/10.1111/raq.12140.

Colombo, J., Varisco, M., Isola, T., Crovetto, C., Rost, E., Risso, S., 2016. Composición química proximal y perfil de ácidos grasos del mejillón *Mytilus edulis* provenientes de cultivos y bancos naturales en el Golfo San Jorge, Argentina. Rev. Biol. Mar. Oceanogr. 51, 293–299.
Cooley, S.R., Doney, S.C., 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. Environ. Res. Lett. 4, 024007.
Falkenberg, L.J., Tubb, A., 2017. Economic effects of ocean acidification: publication patterns and directions for future research. Ambio 46, 543–553.
FAO, 2016. El estado mundial de la pesca y la acuicultura. Food and Agriculture Organization of the United Nations.
Finnoff, D., 2010. Modeling economic impacts of climate change and ocean acidification to fisheries. Working Paper, US Environmental Protection Agency, National Center for Environmental Economics, pp. 11
Gattuso, J.-P., Allemand, D., Frankignoulle, M., 1999. Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: a review on interactions and control by carbonate chemistry. Am. Zool. 39, 160–183.
Gazeau, F., Quiblier, C., Jansen, J.M., Gattuso, J.P., Middelburg, J.J., Heip, C.H., 2007. Impact of elevated $CO_2$ on shellfish calcification. Geophys. Res. Lett. 34.
Gazeau, F., Parker, L.M., Comeau, S., Gattuso, J.-P., O'Connor, W.A., Martin, S., Pörtner, H.-O., Ross, P.M., 2013. Impacts of ocean acidification on marine shelled molluscs. Mar. Biol. 160, 2207–2245.
Gibson, R., Atkinson, R., Gordon, J., Smith, I., Hughes, D., 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential for persistence in a changing ocean. Oceanogr. Mar. Biol. Annu. Rev. 49, 1–42.
Golden, C., Allison, E.H., Cheung, W.W., Dey, M.M., Halpern, B.S., McCauley, D.J., Smith, M., Vaitla, B., Zeller, D., Myers, S.S., 2016. Fall in fish catch threatens human health. Nature 534, 317–320.
Goos, P., Vermeulen, B., Vandebroek, M., 2010. D-optimal conjoint choice designs with no-choice options for a nested logit model. J. Stat. Plan. Infer. 140, 851–861.
Grabacki, S.T., 2011. Environmental effects on seafood availability, safety, and quality. In: Daczkowska-Kozon, E.G., Sun-Pan, B. (Eds.), Chemical and Functional Properties of Food Components Series. CRC Press.
von Haefen, R.H., Massey, D.M., Adamowicz, W.L., 2005. Serial nonparticipation in repeated discrete choice models. Am. J. Agric. Econ. 87, 1061–1076.
Hanley, N., Mourato, S., Wright, R.E., 2001. Choice modelling approaches: a superior alternative for environmental valuatioin? J. Econ. Surv. 15, 435–462.
Hess, S., Beck, M.J., Chorus, C.G., 2014. Contrasts between utility maximisation and regret minimisation in the presence of opt out alternatives. Transp. Res. A Policy Pract. 66, 1–12.
Kontoleon, A., Yabe, M., 2003. Assessing the impacts of alternative 'opt-out' formats in choice experiment studies: consumer preferences for genetically modified content and production information in food. J. Agric. Policy Resour. 5, 1–43.
Kroeker, K.J., Kordas, R.L., Crim, R.N., Singh, G.G., 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecol. Lett. 13, 1419–1434.
Kuhfeld, W.F., 2005. Marketing research methods in SAS. In: Experimental Design, Choice, Conjoint, and Graphical Techniques. SAS-Institute TS-722, Cary, NC.
Lancaster, K.J., 1966. A new approach to consumer theory. J. Polit. Econ. 74, 132–157.
Louviere, J.J., Hensher, D.A., Swait, J.D., 2000. Stated Choice Methods: Analysis and Applications. Cambridge University Press.
Mabardy, R.A., Waldbusser, G.G., Conway, F., Olsen, C.S., 2015. Perception and response of the US west coast shellfish industry to ocean acidification: the voice of the canaries in the coal mine. J. Shellfish Res. 34, 565–572.
Mackenzie, C.L., Lynch, S.A., Culloty, S.C., Malham, S.K., 2014. Future oceanic warming and acidification alter immune response and disease status in a commercial shellfish species, *Mytilus edulis* L. PLoS One 9, e99712.
McDowell, I., 2006. Measuring Health: A Guide to Rating Scales and Questionnaires. Oxford University Press, USA.
McFadden, D., 1974. Conditional logit analysis of qualitative choice behavior. Front. Econ. 105–142.
Meyerhoff, J., Liebe, U., 2009. Status quo effect in choice experiments: empirical evidence on attitudes and choice task complexity. Land Econ. 85, 515–528.
Moore, C., 2015. Welfare estimates of avoided ocean acidification in the US mollusk market. J. Agric. Resour. Econ. 40.
Narita, D., Rehdanz, K., 2017. Economic impact of ocean acidification on shellfish production in Europe. J. Environ. Plan. Manag. 60, 500–518.
Olsen, S.O., 2003. Understanding the relationship between age and seafood consumption: the mediating role of attitude, health involvement and convenience. Food Qual. Prefer. 14, 199–209.
Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437, 681.
Ortuzar, J., Willumsen, L.G., 2011. Modelling Transport. John Wiley & Sons.
Quan, W., Rose, J.M., Collins, A.T., Bliemer, M., 2011. A Comparison of Algorithms for Generating Efficient Choice Experiments.
Rivera, A., Unibazo, J., Leon, P., Vásquez-Lavín, F., Ponce, R., Mansur, L., Gelcich, S., 2017. Stakeholder perceptions of enhancement opportunities in the Chilean small and medium scale mussel aquaculture industry. Aquaculture 479, 423–431 (%@ 0044-8486).
Scarpa, R., Ferrini, S., Willis, K., 2005. Performance of error component models for status-quo effects in choice experiments. In: Applications of Simulation Methods in Environmental and Resource Economics. Springer, pp. 247–273.
Schalkhausser, B., Bock, C., Pörtner, H.-O., Lannig, G., 2014. Escape performance of temperate king scallop, *Pecten maximus* under ocean warming and acidification. Mar. Biol. 161, 2819–2829.
Street, D.J., Burgess, L., 2007. The Construction of Optimal Stated Choice Experiments: Theory and Methods. John Wiley & Sons.
Street, D.J., Burgess, L., Louviere, J.J., 2005. Quick and easy choice sets: constructing optimal and nearly optimal stated choice experiments. Int. J. Res. Mark. 22, 459–470.
Sveinsdóttir, K., Martinsdóttir, E., Green-Petersen, D., Hyldig, G., Schelvis, R., Delahunty, C., 2009. Sensory characteristics of different cod products related to consumer preferences and attitudes. Food Qual. Prefer. 20, 120–132.
Talmage, S.C., Gobler, C.J., 2010. Effects of past, present, and future ocean carbon dioxide concentrations on the growth and survival of larval shellfish. Proc. Natl. Acad. Sci. 107, 17246–17251.
Thomsen, J., Casties, I., Pansch, C., Körtzinger, A., Melzner, F., 2013. Food availability outweighs ocean acidification effects in juvenile *Mytilus edulis*: laboratory and field experiments. Glob. Chang. Biol. 19, 1017–1027.
Train, K.E., 2009. Discrete Choice Methods with Simulation. Cambridge University Press.
Vargas, C.A., Lagos, N.A., Lardies, M.A., Duarte, C., Manríquez, P.H., Aguilera, V.M., Broitman, B., Widdicombe, S., Dupont, S., 2017. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. Nat. Ecol. Evol. 1 (0084 %@ 2397-0334X).
Veldwijk, J., Lambooij, M.S., de Bekker-Grob, E.W., Smit, H.A., De Wit, G.A., 2014. The effect of including an opt-out option in discrete choice experiments. PLoS One 9, e111805.
Ventura, A., Schulz, S., Dupont, S., 2016. Maintained larval growth in mussel larvae exposed to acidified under-saturated seawater. Sci. Rep. 6, 23728.
Vermeulen, B., Goos, P., Vandebroek, M., 2008. Models and optimal designs for conjoint choice experiments including a no-choice option. Int. J. Res. Mark. 25, 94–103.
Waldbusser, G.G., Hales, B., Langdon, C.J., Haley, B.A., Schrader, P., Brunner, E.L., Gray, M.W., Miller, C.A., Gimenez, I., 2015. Saturation-state sensitivity of marine bivalve larvae to ocean acidification. Nat. Clim. Chang. 5, 273.
Wittmann, A.C., Pörtner, H.-O., 2013. Sensitivities of extant animal taxa to ocean acidification. Nat. Clim. Chang. 3, 995.
Zijlstra, T., Goos, P., Vanoutrive, T., Verhetsel, A., 2015. A 'no choice' option in discrete choice experiments: a case study of the mobility budget. In: Proceedings of the BIVEC-GIBET Transport Research Day 2015, May 28–29, 2015, pp. 261–270 Eindhoven/Rasouli, S.[edit.].

CAPITULO IV:

## Exploring the adaptive capacity of the mussel mariculture industry in Chile

Valeska A. San Martin[1,2*], Felipe Vasquez Lavín[2,3,4,5], Roberto D. Ponce Oliva [2,3,5]; Ximena Paz[6]; Antonella Rivera [3,7], Leticia Sarramalera[2,3], Stefan Gelcich[2,3,4]

[1]*Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepcion, Concepcion, Chile.*

[2] *Centre for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile.*

[3] *Centre of Applied Ecology and Sustainability, Department of Ecology. Universidad Católica de Chile, Santiago, Chile.*

[4] *Millennium Nucleus Center for the Socioeconomic Impact of Environmental Policies (CESIEP).*

[5] *School of Economics and Business, Universidad del Desarrollo, Concepcion, Chile.*

[6] *Department of Economic and Finance, School of Business Sciences, Bío-Bío University, Concepción, Chile.*

[7] *The Coral Reef Alliance, 1330 Broadway, Suite 1602, Oakland, California 94612.*

[*]*Corresponding author: V.A. San Martin (valezkasanmartin@gmail.com)*

*Paper enviado a: Regional Environmental Change*

# Regional Environmental Change

## Exploring the adaptive capacity of the mussel mariculture industry in Chile

--Manuscript Draft--

| | |
|---|---|
| **Manuscript Number:** | |
| **Full Title:** | Exploring the adaptive capacity of the mussel mariculture industry in Chile |
| **Article Type:** | Original Research Article |
| **Keywords:** | Adaptive capacity; mariculture; climate change; contingent behaviour; vulnerability |
| **Corresponding Author:** | Valeska Andrea San Martin, phD<br>Universidad de Concepcion<br>Concepcion, concepcion CHILE |
| **Corresponding Author Secondary Information:** | |
| **Corresponding Author's Institution:** | Universidad de Concepcion |
| **Corresponding Author's Secondary Institution:** | |
| **First Author:** | Valeska Andrea San Martin, PhD |
| **First Author Secondary Information:** | |
| **Order of Authors:** | Valeska Andrea San Martin, PhD |
| | Felipe Vásquez Lavín, PhD |
| | Roberto Daniel Ponce Oliva, phD |
| | Ximena Paz |
| | Antonella Rivera, PhD |
| | Leticia Sarramalera |
| | Stefan Gelcich, PhD |
| **Order of Authors Secondary Information:** | |
| **Funding Information:** | Center for the Study of Multiple-drivers on Marine Socio-Ecological Systems (MUSELS) funded by MINECON NC120086 (MINECON NC120086) — Not applicable |
| | Conicyt Basal (CAPES) (0002-2014) — Mr Felipe Vásquez Lavín<br>Mr Roberto Daniel Ponce Oliva<br>Mr Stefan Gelcich |
| | CONICYT (21151027) — Mrs Valeska Andrea San Martin |

**Abstract:**

Societies have adapted to climate and environmental variability throughout history. However, projected climate change poses multiple risks to aquaculture because of the increased frequency of extreme events that lie outside the realm of present day experience. Adaptive capacity is a latent characteristic that reflects the ability of aquaculture industries to anticipate and respond to these changes, and to minimize, cope with, and recover from the consequences of and take advantage of new opportunities arising from change. Drawing on a survey to 90 mussel aquaculture companies in Chiloe-Chile, we have characterized the way the industry has adapted and recovered from specific stressors in productive capacity, namely; reduced growth rates and reduced larval settlement. We additionally assess determinants of the mussel industry's willingness to invest in building capacity to anticipate changes through analysing mussel aquaculture companies' assets to draw upon in times of need (capital; access to credit), the flexibility to change strategies, the companies' perception of the industry's social organization to act collectively (social capital), and their response to hypothetical scenarios regarding shocks in productive capacity.

| | |
|---|---|
| | Results show heterogeneity in production decisions when facing environmental stressors. Results also show that the industry adapts in heterogeneous ways and that financial assets and social capital drive willingness to invest in adaptive capacity. Understanding past adaptation strategies and the willingness of the industry to invest in anticipating stressors allows us to begin exploring and generating hypotheses of the consequences of new stressors, such as ocean acidification, on the mussel aquaculture industry. Importantly, as Chile and other countries are developing adaptation plans to face the multiple stressors of climate change, information about stakeholders' existing adaptation strategies and their determinants is becoming a critical bottleneck to inform these processes and assure they are in line with stakeholder needs and interest. While we use the Chilean mussel industry as a working example in this talk, the approach presented can inform other countries/regions wishing to explore the adaptive capacity of their aquaculture sectors. |
| **Additional Information:** | |
| **Question** | **Response** |
| Has your submission been invited to a special issue currently in preparation for this journal? | No |
| If yes, please ensure that your submission occurs according to the approved plans of the respective guest editors. If this is the case, please give the title of the Special Issue and the name of the editors you have been in contact with here. | |
| **Author Comments:** | Through the consent of the Ethics, Bioethics and Biosafety Committee of the Vice-Rector for Research and Development of the University of Conception, President: Dr. Andrea Rodríguez Tastets. Checked compliance with the ethical, bioethical and biosecurity norms and procedures established nationally and internationally for research in the field of environmental sciences, Written informed consent was obtained from the respective institution in Concepcion, Chile, previously approved the ethic protocol from all subjects for this study. In adition, the choice experiment survey which complied with ethical approval of both project Musels and Universidad del Desarrollo. |

# Exploring the adaptive capacity of the mussel mariculture industry in Chile

Valeska A. San Martin[1,2*], Felipe Vasquez Lavín[2,3,4,5], Roberto D. Ponce Oliva [2,3,5]; Ximena Paz[6]; Antonella Rivera[3,7], Leticia Sarramalera[2,3], Stefan Gelcich[2,3,4]

[1]Department of Aquatic Systems, Faculty of Environmental Sciences, Universidad de Concepcion, Concepcion, Chile; [2]Centre for the Study of Multiple-Drivers on Marine Socio-Ecological Systems (MUSELS), Universidad de Concepción, Concepción, Chile; [3]Center of Applied Ecology and Sustainability, Department of Ecology. Pontificia Universidad Católica de Chile, Santiago, Chile; [4] Millennium Nucleus Center for the Socioeconomic Impact of Environmental Policies (CESIEP); [5]School of Economics and Business, Universidad del Desarrollo, Concepcion, Chile; [6]Department of Economic and Finance, School of Business Sciences, Bío-Bío University, Concepción, Chile; [7]The Coral Reef Alliance, 1330 Broadway, Suite 1602, Oakland, California 94612.

*Corresponding Author: valezkasanmartin@gmail.com

## Abstract

Societies have adapted to climate and environmental variability throughout history. However, projected climate change poses multiple risks to aquaculture because of the increased frequency of extreme events that lie outside the realm of present day experience. Adaptive capacity is a latent characteristic that reflects the ability of aquaculture industries to anticipate and respond to these changes, and to minimize, cope with, and recover from the consequences of and take advantage of new opportunities arising from change. Drawing on a survey to 90 mussel aquaculture companies in Chiloe-Chile, we have characterized the way the industry has adapted and recovered from specific stressors in productive capacity, namely; reduced growth rates and reduced larval settlement. We additionally assess determinants of the mussel industry's willingness to invest in building capacity to anticipate changes through analysing mussel aquaculture companies' assets to draw upon in times of need (capital; access to credit), the flexibility to change strategies, the companies' perception of the industry's social organization to act collectively (social capital), and their response to hypothetical scenarios regarding shocks in productive capacity. Results show heterogeneity in production decisions when facing environmental stressors. Results also show that the industry adapts in heterogeneous ways and that financial assets and social capital drive willingness to invest in adaptive capacity. Understanding past adaptation strategies and the willingness of the industry to invest in anticipating stressors allows us to begin exploring and generating hypotheses of the consequences of new stressors, such as ocean acidification, on the mussel aquaculture industry. Importantly, as Chile and other countries are developing adaptation plans to face the multiple stressors of climate change, information about stakeholders' existing adaptation strategies and their determinants is

becoming a critical bottleneck to inform these processes and assure they are in line with stakeholder needs and interest. While we use the Chilean mussel industry as a working example in this talk, the approach presented can inform other countries/regions wishing to explore the adaptive capacity of their aquaculture sectors.

**Keywords** Adaptive capacity, mariculture, climate change, contingent behaviour, vulnerability

## Introduction

Aquaculture is the fastest growing food production system in the world (Asche 2013; FAO 2014). In 2014, the aquaculture production was 73.8 (million tons), represented by mariculture – aquaculture in the ocean's coasts and estuaries (FAO 2016). Based on current per capita consumption targets and population growth trends, mariculture has been proposed as the best means of satisfying the world's growing demand for aquatic food products (Duarte et al. 2009). Mariculture could contribute substantially to the income, livelihoods, nutrition and therefore, to the indirect food security of many millions of people (Allison et al. 2011; Bené et al. 2015). Mariculture is elemental for economic growth, and a diversification strategy in the face of environmental change is needed (Allison et al. 2007). The rapid expansion of mariculture is taking place mostly in developing or underdeveloped countries, areas that are highly exposed to human-induced climate change and depend for a major part of their livelihood on resources whose distribution and productivity are known to be influenced and dependent on local environmental climatic and oceanographic conditions (Handisyde et al. 2017; Allison et al. 2009; Allison et al. 2005).

Mariculture benefits are potentially reduced through the increases in uncertainty that climate change brings (Barange et al. 2014). Vulnerability to climate change is often conceptualized as being made up of three dimensions: exposure to change (e.g. increases in ocean acidification); sensitivity to change (e.g. how much mariculture would be affected by ocean acidification); and the capacity to anticipate, respond to, and recover from change (referred to as adaptive capacity) (Adger 2006; Allison et al. 2009; Ekstrom et al. 2015). Studies indicate that dimensions of exposure and sensitivity can determinate the impact generated by a change, while the capacity for adaptation influences the final impact on mariculture and society (Cinner et al. 2015). In addition, adaptive capacity relates to the capacity to recover from the losses derived from climate impacts and exploits the new opportunities that arise in the adaptation process (Allison et al. 2007).

Societies have adapted to climate and environmental variability throughout history (Adger and Vincent 2005). However, future climate change projections for mariculture pose multiple risks due to extreme events presented with increasing frequency (Adger et al. 2003). Adaptive capacity reflects the capacity of the mariculture industries to anticipate, modify and/or respond to the risks associated with climate change and to minimize, confront, and recover from the consequences, exploiting new opportunities arising from the adaptation process (Adger and Vincent 2005; Grothmann and Patt 2005). In this way, those activities with high levels of adaptation capacity are able to deal with the changes (Handisyde et al. 2017). After the Fourth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (AR4 IPCC) report (2007), which proposed to determine the adaptation by means of full estimates of the costs and benefits, scientific literature has established a different conceptual framework to deal with adaptive capacity (Hughes et al. 2012; Cinner et al. 2015; Cinner et al. 2018). Many of these frameworks consider breaking the concept down into dimensions, such as assets, the role of flexibility, learning, and social organization (Cinner et al. 2018; Hughes et al. 2012; MacClanahan and Cinner 2012). While establishing key dimensions has been helpful to assess potential strengths and weaknesses in adaptive capacity (Hughes et al. 2012; Cinner et al. 2018), considerable gaps still remain in: 1) our basic understanding of how mariculture has devised local-scale adaptive strategies and how they can vary according to different scales of operation (large mariculture enterprises, small enterprises) and 2) understanding the determinants of the industry's willingness to invest in building capacity (i.e., knowledge) to anticipate for change.

Mussel mariculture provides a unique setting for studying adaptive capacity, it is a growing industry which is composed of small rural producers and large-scale farms, in which production depends on natural supply of larvae and natural food availability (Kroeker et al. 2016; Menge et al. 2009). However, it is under the risk of being affected by multiple climatic stressors, such as variations in salinity, temperature, reduced pH (Ocean Acidification), and dissolved oxygen and nutrient (Range et al. 2014; IPCC 2007a) could affect life cycles of shellfish with adverse effects on their productivity, viability, nutritional quality, or market value, which may have relevant societal implications (Ponce et al. 2019; San Martin et al. 2019; Cooley et al. 2011).

Drawing on the previous adaptation experiences of the mussel industry in Chile, we characterize the way in which the industry has responded and recovered from the stressors in productive capacity due to reduced growth rates and reduced larval settlement. We additionally determine industry drivers of investing in building capacity to anticipate change. We assess willingness to invest in building capacity to anticipate changes through analyzing mussel aquaculture company assets to draw upon in times of need (capital, access to credit), the flexibility to change strategies, the companies' perception of the industry's social organization to act collectively (social capital) and their trust in science. While we use the Chilean mussel mariculture sector as a working example, the analysis can inform other countries/regions wishing to explore the adaptive capacity of their mariculture sectors.

## Material and Methods

### Case Study

Chile is currently the country with the highest growth rate in mussel mariculture (FAO 2016). From the early 1990s to 2012 production has increased from 3,000 to 257,800 tons, with a record year in 2017 exceeding 300,000 tons (FAO 2017; FAO 2018). In addition, the mussel mariculture industry has suffered two important crises, one in 2009-2010, which related to the lack of microalgal food (Lara et al. 2016; FAO 2017) and another between 2011 and 2013, a larval supply crisis, which caused a reduction in mussel harvest of 18% between 2011 and 2014 (SSPA 2014; Figueroa and Dresdner 2016). Studies have also shown the potential detrimental impacts of multiple stressors over mussel aquaculture under different acidification scenarios (Gazeau et al. 2010; Bibby et al. 2008; Parker et al. 2013).

### Research setting: Mussel Mariculture in Chile

In Chile, mussel mariculture began in 1943 in Quellón, in the Chiloé Island (Navarro and Guttierrez 1990). In 1967, semi-intensive suspension systems began to be used (López et al. 2008). At the beginning of the 1980s, due to the growing demand, the private sector developed the commercial cultivation of mussels (Díaz 2010). Although the extraction of *Mytilus chilensis* dates from 1930-1940s, the development of commercial scale cultivation began in the 1990s (Plaza et al. 2005), with the arrival of Spanish capital that invested in processing plants and the opening of international markets for mussels that led to an exponential growth phase. In less than 20 years (2000-2017), production has increased from less than 26,000 to more than 300,000 tons (Sernapesca 2014; FAO 2018). Chilean mussel are mainly exported to Spain, the United States of America, Russian Federation, France, and Italy (FAO 2017).

Mussel production is divided into four stages: seed collection, feed and grow, processing and marketing or export (Gonzalez-Poblete et al. 2018; Rivera et al. 2017). The mussel production cycle lasts between 14 and 20 months, beginning in the spring with the natural collection of larvae in the estuaries of the Los Lagos Region. One hundred percent of the *seed uptake* process is obtained from the natural environment by artisanal fishers, who act as aquaculture entrepreneurs (Fernández et al. 2018; Saavedra Gallo and Macías Vázquez 2016). Competent planktonic larvae are collected with suspended artificial substrates through ropes that hang from the buoys by placing them at different depths of the water column deployed in areas of high larval availability (Lara et al. 2016; Avendaño et al. 2011). Then, these ropes are transferred to different areas to the culturing systems for *fattening* and growing around 12-18 months. The *processing stage* corresponds to the cleaning, cooking, and packaging of the raw material received from the centers of crops, to be sent to the final markets (Díaz 2010), and mussels *marketing stage* is carried out in several ways, including fresh, frozen, ice-packed, vacuum-packed or cooked and processed. Exported products come in a frozen form, either shell-on, in half a shell, or as individually quick frozen (IQF) meat (Monfort 2014).

Most of the mussel mariculture in Chile is developed on the inner sea of Chiloé (Gonzalez-Poblete et al. 2018; Figueroa and Dresdner 2016; Fernández et al. 2018). This activity is subject to multiple sources of variability, including environmental and anthropogenic disturbances (Barria et al. 2012; Goldburg et al. 2001). In addition, previous studies have indicated that chlorophyll-a concentration and sea surface temperature can alter larval supply and growth rate (Lara et al. 2016; Figueroa and Dresdner 2016). Although hatchery technology is available, it is seldom used due to the low cost/benefit ratio.

Each stage of production is carried out by specialized actors. In this research, we focused exclusively on actors involved in the growth production phase. These actors depend both on the supply of larvae, as they have to buy it from suppliers, and on the environmental conditions, which determine growth rates. In addition, actors involved in the growth production phase are the most heterogeneous in the production chain and can range from small producers to large ones (Fernández et al. 2018).

## Field Methods

Data collection was conducted in the island of Chiloé (42º 40’ 36” S; 73º 59’ 36” W) (Fig. 1) over the period from November 2014 to February 2015 through face-to-face interviews with mussel farmers, with a total of 87 questionnaires answered.

The interviewees were selected according to the total production per season. Three categories of producers were established: small, with a total production of less than 400 t/season, medium, with a total production between 400 t/season and 1,350 t/season, and large, with a total production of more than 1,350 t/season.

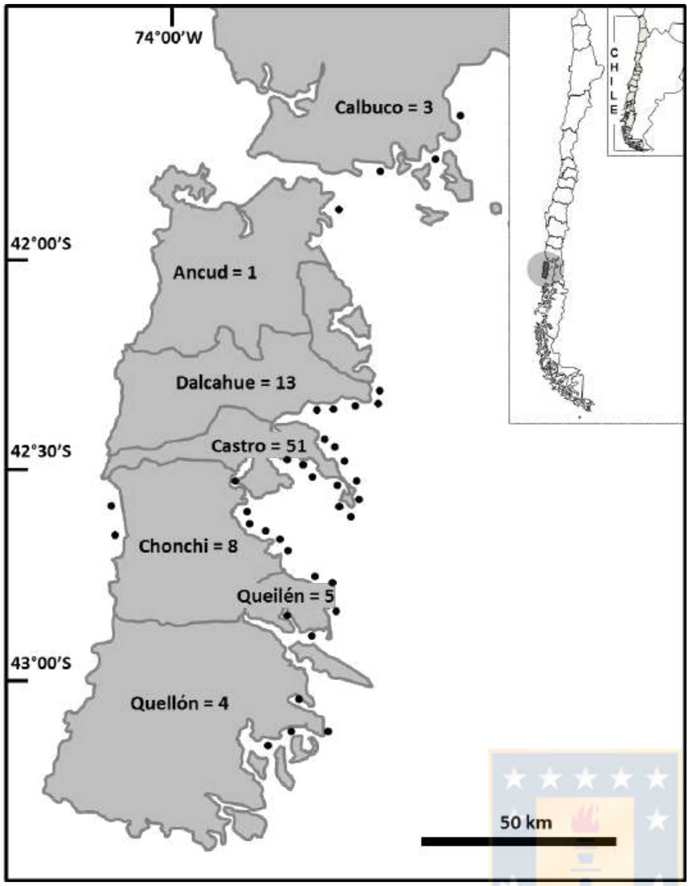


**Fig. 1** Map of the X Region of Los Lagos study area. Different areas (n=7) where surveys and questionnaires were carried out among producers: small n=25, medium n=43 and large n=17. Two interviewees did not give information about the total production per season and were not considered in the data set (final sample size: n=85)

## Survey

We used participatory activities to understand the industry perceptions and main threats. Based on information from semi-structured interviews with key industry representatives, we designed and administered 87 surveys (out of 148 nationwide firms) between November 2014 and January 2015. The survey was tested through one pilot study (10 observations). The final version of the survey included four sections.

I. *Perception*. This section provides information on the main impact of different environmental and social factors. For this evaluation, a list of potential threats was used, asking the producer: How important are these threats to you? A scale of 1 to 10 score was used, where 1 is not important and 10 is very important.

II. *Past responses to perturbations*. Here, we asked about the past responses to two specific disturbances in the following way: (1) Do you considers that the food crisis (under nutritional supplement by phytoplankton) that affected fattening in 2009/2010 harmed your business? and (2) Did the crisis of reduction of seeds presented in the year 2012, damage your business?. Both were closed questions with two options: yes or no. Furthermore, we also asked: (3) What were the main effects on your business? and (4) What were the measures taken after these crises? Both corresponded to an open questions.

III. *Contingent behaviour*. Here, it was asked what the person would do in the future if she/he were faced with two different hypothetical scenarios. The scenarios are used for several reasons, including helping us to explore to ability of people to anticipate change and to develop strategies to respond (Cinner et al. 2011). The mussel producers were asked what they would do in response to (1) 50% declines in their normal production and (2) 50% decrease in the international market price. For the answers, a list of options was made, with the follow-up of one of them probing for details about the time willing to remain in that situation, and also in the list there was an option of “other”.

IV. *Relations between different dimensions and Willingness to pay*. This section defines adaptive capacity through five dimension related to: **Assets**=financial, technological, and service resources that people have access to (Cinner et al. 2018); **Social Capital**=reflects the organization to allow (or inhibit) cooperation and the exchange of knowledge for the collective good (Moser et al. 2010); **Agency**=capacity that peoples have to freely choose how to respond to events that affect their lives (Bandura 2000); and **Flexibility**=this dimension reflects opportunities for switching between adaptation strategies and captures the diversity of potential adaptation options available as well as the capacity to shift into different occupational sectors. These dimensions determined the willingness to invest in the anticipating of change (**Learning**), essential capacity of knowledge construction, and learning to generate and process disturbance information, evaluating possible answers (Badjeck et al. 2010). Finally, through contingent valuation (CV), we evaluated whether or not the industries willing to pay (WTP) for a hypothetical program that could provide an early warning signal to the industry, which would aid in anticipating changes in marine environment.

CV uses questionnaires to elicit economic agents’ WTP for a good or service, creating a hypothetical market in which people can declare their preferences for the good. There have been thousands of CV applications in diverse areas of economics; the main results have been summarized in numerous publications on theoretical and empirical issues (Bateman et al. 2001; Carson et al. 2003; Hoyos and Mariel 2010).

*Econometric specification.* As each industry representative was asked about the maximum amount of money that she/he would be willing to pay (WTP), we used a univariate Tobit model, which takes into account the presence of censoring at zero (Amemiya 1984). The equation estimated is:

$$y_i^* = \beta' x_i + u_i \qquad (1)$$

$$y_i = y_i^* \; if \; y_i^* \geq 0$$

$$y_{it} = 0 \; if \; y_i^* < 0$$

where i=1,2…,N denotes individuals; therefore $y_{1t}^*$ is the latent variable, $x_{1t}$ is a vector of explanatory variables, and $u_{1t}$ is an error term with mean zero and variance $\sigma^2$. We use a maximum likelihood estimator of the function:

$$l(\beta, \sigma) = \prod_{j=1}^{N} \left( \frac{1}{\sigma} \emptyset \left( \frac{y_i - \beta' x_i}{\sigma} \right) \right)^{d_i} \left( 1 - \Phi \left( - \frac{\beta' x_i}{\sigma} \right) \right)^{1-d_i}$$

$d_i$ takes the value 1 if $y_i^* \geq 0$ and 0 otherwise.

## Results

### I. *Perception*

The threats with the highest level of importance for producers are associated with environmental stressors (Fig. 2) related to the main crises experienced in aquaculture: plankton supply and larvae supply (over 85%), followed by red tides and pollution (80-85%). On the other hand, the social threats are categorized on a second plane, with values lower than 80% among  respondents and the lowest with less than 5% for environmental certification.

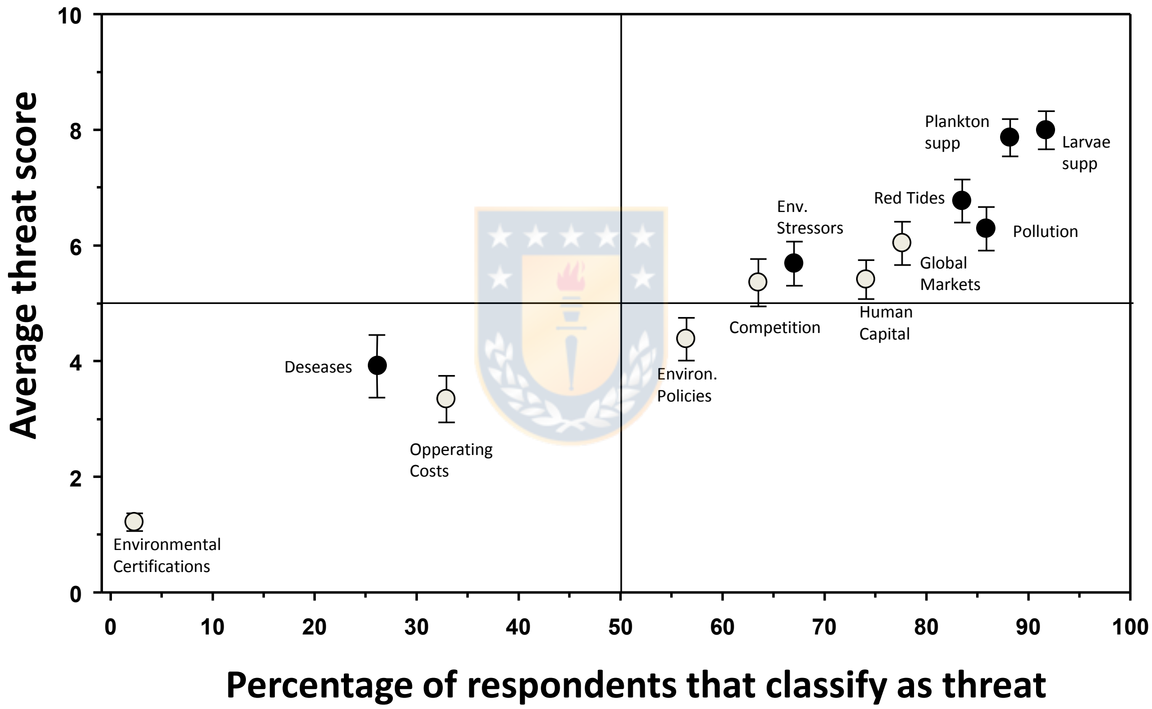


**Fig. 2** Mussel producers' perceived level of importance on different threats. Dark circles show environmental threats and grey circles social threats

II. *Past responses to perturbations*

When consulting the different groups of producers regarding their experiences in the year 2009 (under nutritional supplement by phytoplankton), most of them reported that they were effects (Fig. 3a). Small producers were the most affected (91,67%) (Fig. 3a). Considering only the small producers, 65% of them delayed the harvesting date, while 35% decreased their production (Fig. 3b). For the medium and large groups of producers, the main response to the crisis was decreasing their production instead of delaying the harvesting date.

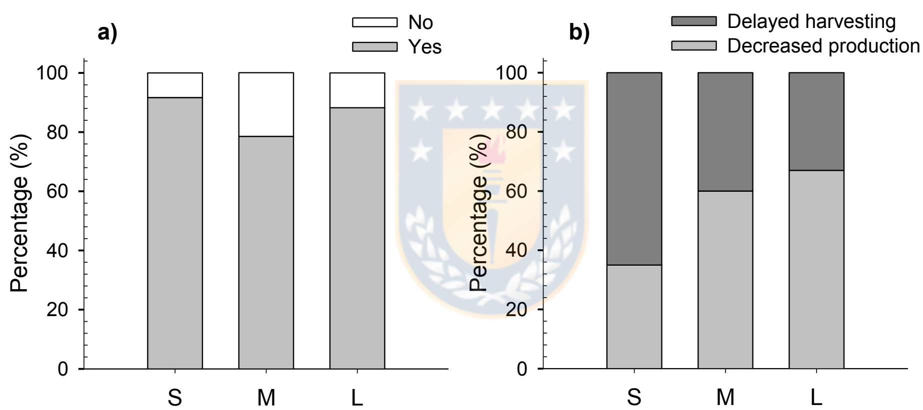


**Fig. 3** a) Percentage of respondents that were affected by the phytoplankton crisis in 2009. b) Effects of the crisis of 2009 in different groups of producers: S= small, M= medium, and L= large

Producers during the crisis of 2009 responded and managed the uncertainty of stress differently. The majority of mussel producers (more than 50%) indicated that they did not take measures to deal with the negative effects of the crisis. The highest percentage of responses (47%) indicates that the main action was to sell the available products and save to invest the following year (Table 1), while a lower percentage (15%) decided to leave the activity until the next season.

Table 1 Main responses of mussel producers when confronted with the lack of plankton and consequent mussel growth crisis in 2009 (past responses to perturbation)

| *Response* | *% Respondents* |
|---|---|
| **Stopped participating:** Sold as soon as crises was felt and retired for 1 season | 15.29 |
| **Decreased harvest:** Continue in the industry by selling what was available. Save money to re-invest following year (Risk Adverse). | 47.05 |
| **Delay harvest:** Continue in the industry by waiting until mussels grow, in order to sell at larger sizes, assuming costs associated with delay (Risk-acceptant). | 37.64 |

### III. *Contingent behaviour*

The contingent behaviour of producers against hypothetical scenarios of possible decrease in the international market price (50% decrease) showed that the main response is to intensify production (over 40%), then continue with the activity for a certain number of seasons (mainly 2-3 season). Leaving or changing the activity occurred to a lesser extent (close to 20%) (Fig. 4a). For the scenario of a 50% decrease in production, the producers clearly responded to continue with the activity (over 60% of the answers, mainly in the second season), while close to 30% retired or performed another activity, and a amall percentage (less than 10%) intensified its activity (Fig. 4b).

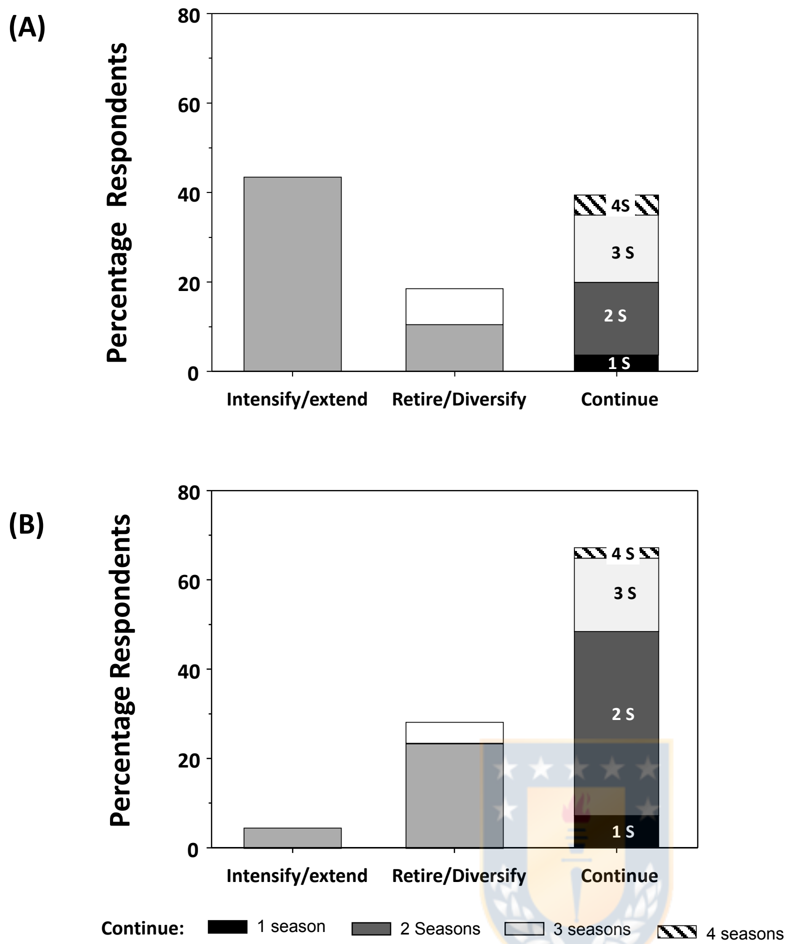


**Fig. 4** Mussel producer's response to contingent behaviour exercise for (a) 50% decreases in price and (b) 50% drop in yield

IV. *Relations between different dimensions and Willingness to invest in adaptive capacity*:

We examined a total of five indicators representing adaptive capacity that is derived largely from the broader economic and policy landscape (Table 2). Our results show that producers (regardless of their size) adapt in a heterogeneous way, where financial assets stimulate the willingness to invest in the capacity of adaptation. As Table 2 shown, the variables with statistical significance, explaining the WTP are related to assets and agency.

The size of the producer is one of the relevant characteristics that make the difference at the time choosing to invest in adaptation measures. The larger the producer, larger the probability of paying for the research program. This is because larger producers are expected to have more resources to invest, and because their opportunity cost of an external shock is also larger. Regarding agency, responses to a price decrease is significant, meaning that those producers that decided to stay in business after a price shock have larger WTP for the research program. This suggests that producers are willing to invest more in measures instead of waiting for the harvest till the market price recovers. Historical response to crises also explains the WTP. In this case, those producers that decreased their production in 2009 are WTP more, indicating that those who have already faced the cost of a crisis are WTP more to avoid it. Finally, the mean WTP for the research program is around USD $1,000 (CLP $674,000), while the median is slightly smaller (USD 920).

Table 2 Regression on factors, which determine willingness to invest in anticipating change (capacity to learn)

| Variable | Description | Coefficient | Std. Error | T | P |
|---|---|---|---|---|---|
| **Assets: Small Producer** | Binomial: 1=small size producer (<400t/season) and 0=other sizes | -50.87397 | 12.53741 | -4.06 | 0.000 |
| **Assets: Medium size Producer** | Binomial: 1=medium size producer 400-1350t/season) and 0=other sizes | -27.3549 | 11.0499 | -2.48 | 0.016 |
| **Social Capital: Invest in collective action for standardization in industry** | Binomial: agreeing to act collectively to standardize quality protocols: 1= grade >5 and 0= grade <5 | -1.286959 | 1.372837 | -0.94 | 0.352 |
| **Agency: Contingent response to production decrease** | Binomial: Staying in the business after a production decrease (1). | -14.71723 | 10.58502 | -1.39 | 0.169 |
| **Agency: Contingent response to price decrease** | Binomial: Staying in the business after a price decrease (1) | 19.40761 | 10.01869 | 1.94 | 0.057 |
| **Flexibility: Invest in quality standards as market diversification** | Binomial: Agreeing that investing in quality standards is positive (1). | -9.570078 | 9.322577 | -1.03 | 0.308 |
| **Flexibility: current off-sector diversification opportunities** | Binomial: Having an alternative occupation (1). | 11.41318 | 9.06827 | 1.26 | 0.212 |
| **Agency: Historical Response to crises** | Binomial: response to phytoplankton crisis in 2009, 1=decreased production and 0=delayed harvesting | -23.90706 | 8.923296 | -2.68 | 0.009 |
| **Constant** | | 58.03282 | 15.54569 | 3.73 | 0.000 |

## Discussion and conclusion

Adaptations have stimulated and favor innovation, allowing societies to overcome challenges (Cinner et al. 2018). This ability to adapt reflects the ability of a society to anticipate and face change (Adger and Vicent 2005). Previous research emphasizes that the capacity of adaptation is determined by the availability of capital (Hinkel 2011), but new studies have suggested that it is not enough to have resources, but also the willingness and ability to convert resources into an effective adaptation action (Coulthard 2012). In addition, Cinner et al. (2018) propose to build the capacity of adaptation through the analysis of different domains. Here, we build this work in two key ways: we have linked *hypothetical scenarios* allowing us to project the future impact of climate change with *past experiences* in the mussel farming (producers) to create a program that improves the capacity of industry to anticipate future changes and developing response strategies.

Our results indicate that the producers perceive environmental stress as the main threat to the industry, due to events that occurred in the past, such as the decrease of food (phytoplankton) and mussel seeds. A similar effect was reported by Adams et al. (2011), indicating that producers feel more vulnerable to possible environmental stress events. The negative experiences that have impacted the industry have forced producer to take measures to respond a priori to a negative event (Barton et al. 2005) to achieve activity over time.

The contingent behaviour of producers against hypothetical scenarios has been proven to be environmentally optimistic, continuing in the industry (~70%), suggesting that it is a potential response to learn and develop knowledge in the face of change and uncertainty (Carpenter and Gunderson 2001). By contrast, they prove to be pessimistic from the economic point of view. They even stop participating (~20%) and sell when they feel the crisis.

When working with the different dimensions of exposure and sensitivity, we must consider evaluating where the dimensions will have the greatest benefits. In this way, when evaluating **assets**, it is determined if the company has the possibility of opting for financial and technological access that helps them in their operations and can be drawn upon in times of need (Cinner et al. 2018; Fenichel et al. 2016). for example, a situation of financial loss, destruction of infrastructure, repair of boats, etc. Our study shows that those large producers are more willing to invest in anticipating change. This could be because they have more assets that could be used to help anticipate an event with negative effects on their production because they have more to lose and invest.

The **agency** indicator presented under the price decrease scenario proved to be significant, indicating that the producers who remain in the business have a higher WTP for the research program.

Finally, learning to adapt to the events generated by climate change requires an investment in research that will help evaluate potential risks and patterns of climate change and reduce losses in aquaculture through monitoring systems (Brooks et al. 2005). It has been demonstrated that access and availability to science have helped shellfish farmer to identify and avoid some of the consequences of ocean acidification, a major negative event in production in the Pacific Northwest (Ekstrom et al. 2015). Science is fundamental to promote the development of climate change research, generating knowledge from the climate modelling for different scenarios of climate change, evaluation of possible environmental and socio-economic effects, and determining the potential effects on the vulnerability of socio-ecological systems, possible adaptation options, mitigation measures and new technologies (PANCC 2017). However, the need to develop an adaptive capacity to help anticipate and face these increasingly reiterative environmental changes will continue to grow, so developing this adaptive capacity under the evaluation of multiple domains will be fundamental to an effective adaptation to a global change affecting multiple scales and places.

Due to the constant climate hazards and their multiple associated risks, the profitability of Chilean mussel producers can be affected in different ways, either directly, by altering the availability of larvae and plankton for growth, or indirectly, by altering costs of the inputs of a mariculture operation. The red tide event occurred during the year 2016 in the south of Chile was not considered, since our study was carried out during the period from November 2014 to February 2015. Despite the negative events experienced by Chilean aquaculture in recent years, producers are adapting to the multiple consequences with which they have been faced. This will continue to depend on the price paid for mussels as well as human behaviour and the opportunity costs of mariculture.

When societies understand the impacts and possible responses, they position research as a support for learning, thus they are willing to invest in tools that can anticipate or mitigate possible impacts. Our study has shown that the historical response of those producers who were affected by the crisis in 2009 and decreased their production, have a high WTP to try to avoid a similar crisis.

However, learning can only allow adaptation when other domains of adaptive capacity, such as agency, flexibility, and social organization are sufficiently developed. Therefore, companies that depend on resources should anticipate and prepare for climate-related challenges, and institutions should support the sustainability of the industries and social systems that depend on them (Marshall 2010).

From these results arises the need to have innovative finance that supports anticipated responses to environmental change where this activity is developed, being exposed to multiple risks due to extreme events that occur with increasing frequency (Adger et al. 2003). Suggesting the implementation of adaptation policies and allocating economic resources to vulnerable sectors due to the vulnerability of these systems should stop being an academic exercise and move to a political need.

National Adaptation Programs of Action (NAPAs) are being funded by the World Bank/ United Nations Environment Program Global Environment Facility to address the urgent adaptation needs in Chile. Coastal and fishery sector management plans are only partly considered due to lack of appropriate knowledge on the sector. Our results can directly inform the types of adaptation made to the mussels farmer sector in the south of Chile in response to climate change. In this context, in order to strengthen the adaptive capacity of the fisheries and aquaculture sector to face the challenges and opportunities of climate change, Chile in its National Adaptation Programs of Action (PANCC 2017), addresses the development of research to improve knowledge on the impacts of climate change on the conditions and ecosystem services upon which fisheries and aquaculture are based.

**Compliance with Ethical Standards**

Through the consent of the Ethics, Bioethics and Biosafety Committee of the Vice-Rector for Research and Development of the University of Conception, President: Dr. Andrea Rodríguez Tastets. Checked compliance with the ethical, bioethical and biosecurity norms and procedures established nationally and internationally for research in the field of environmental sciences, Written informed consent was obtained from the respective institution in Concepcion, Chile, previously approved the ethic protocol from all subjects for this study. In adition, the choice experiment survey which complied with ethical approval of both project Musels and Universidad del Desarrollo.

**Funding information**

The research leading to these results has received funding from the Millennium Nucleus "Center for the Study of Multiple-drivers on Marine Socio-Ecological Systems (MUSELS)" funded by MINECON NC120086. FVL, RDP and SG thanks to Conicyt Basal 0002-2014 (CAPES).

During the analysis and preparation of the manuscript, VASM was fully supported by a scholarship from CONICYT N° 21151027.

**Conflict of Interest**

The authors declare that they have no conflict of interest

**Data Availability**

Any data used in this paper can be obtained by contacting the corresponding author.

## References

Adams CM, Shumway SE, Whitlatch RB, Getchis T (2011) Biofouling in marine molluscan shellfish aquaculture: a survey assessing the business and economic implications of mitigation. J World Aquac Soc 42: 242–252. doi.org/10.1111/j.1749-7345.2011.00460.x

Adger WN (2006) Vulnerability. Glob Environ Change 16: 268–281. doi.org/10.1016/j.gloenvcha.2006.02.006

Adger WN, Vincent K (2005) Uncertainty in adaptive capacity. Incertitudes dans la capacité d`adaptation. Comptes Rendus Geoscience 337: 399-410. doi.org/10.1016/j.crte.2004.11.004

Adger WN, Huq S, Brown K, Conway D, Hulme M (2003) Adaptation to climate change in the developing world. Prog Dev Stud 3: (3) 179–195. doi.org/10.1191/1464993403ps060oa

Aldrich DP (2012) Building Resilience: Social Capital in Post-Disaster Recovery. University of Chicago Press, Cambridge.

Allison EH, (2011) Aquaculture, fisheries, poverty and food security. The WorldFish Center, 60pp. (WorldFish Center Working Paper,2011-65) Penang, Malaysia.

Allison EH, Perry AL, Badjeck M-C, Adger WN, Brown K, Conway D, Halls AS, Pilling GM, Reynolds JD, Andrew NL, Dulvy NK (2009). Vulnerability of national economies to potential impacts of climate change on fisheries. Fish Fish 10: 173-196. doi:10.1111/j.1467-2979.2008.00310.x

Allison EH, Andrew NL, Oliver J (2007) Enhancing the resilience of inland fisheries and aquaculture systems to climate change. An Open Access Journal published by ICRISAT 4: (1).

Allison EH, Adger WN, Badjeck MC, Brown K, Conway D, Dulvy NK, Halls A, Perry A, Reynolds JD (2005). Effects of climate change on the sustainability of capture and enhancement fisheries important to the poor: analysis of the vulnerability and adaptability of fisherfolk living in poverty. Project No. R4778J. Final Technical Report, Fisheries Management Science Programme, MRAG/DFID, London. 164 pp. www.fmsp.org.

Avendaño M, Cantillánez M, Le Pennec M, Varela C, Garcias C (2011) Temporal distribution of larvae of *Mytilus chilensis* (hupe, 1854)(mollusca: Mytilidae), in the interior sea of Chiloé southern Chile. Lat Am J Aquat Res 39: (3) 416–426. doi: 10.3856/vol39-issue3-fulltext-3

Bandura A (2000) Exercise of human agency through collective efficacy. Current Directions Psychological Science 9: (3) 75-78.

Barange M, Merino G, Blanchard JL, Scholtens J, Harle J, Allison EH, Allen JI, Holt J, Jennings S (2014) Impacts of climate change on marine ecosystem production in societies dependent on fisheries. Nat Clim Change 4: 211-216. doi: 10.1038/NCLIMATE2119 Impacts

Barria A, Gebauer P, Molinet C (2012) Variabilidad espacial y temporal del suministro larval de mitílidos en el Seno de Reloncaví, sur de Chile. Rev Biol Mar Oceanogr 47: (3) 461-473. doi.org/10.4067/S0718-19572012000300009

Bateman IJ, Willis KG, Arrow KJ (2001, March 2008) Valuing environmental preferences: theory and practice of the contingent valuation method in the US, EU, and developing countries;Oxford University Press, New York, 1999, 645 pp., ISBN 0-19-828853-0 (hardcover)

Béné C, Barange M, Subasinghe R, Pinstrup-Andersen P, Merino G, Hemre G-I, Willians M (2015) Feeding 9 billion by 20150- puting fish back on the menu. Food Security 7: (2) 261-274. doi: 10.1007/s12571-015-0427-z

Bibby R, Widdicombe S, Parry H, Spicer J, Pipe R (2008) Effect of ocean acidification on the immune responses of the blue mussel *Mytilus edulis*. Aquat Biol 2: 67-74. doi:org/10.3354/ab00037

Bockstael NE, McConnell KE (2007) Environmental and resource valuation with revealed preferences: a theoretical guide to empirical models. Springer Science & Business Media.

Brooks N, Adger WN, Kelly PM (2005) The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. Glob Environ Change 15: (2) 151-163. doi:org/10.1016/j.gloenvcha.2004.12.006

Brown K, Westaway E (2011) Agency, capacity, and resilience to environmental change: lessons from human development, well-being, and disasters. Annu Rev of Environ Resour 36: 321-342. doi:org/10.1146/anurev-environ-052610-092905

Carson RT, Mitchell RC, Hanemann M, Kopp RJ, Presser S, Ruud, PA (2003) Contingent valuation and lost passive use: damages from the Exxon Valdez oil spill. Environ Resour Economics 25: (3) 257-286. doi.org/10.1023/A:1024486702104

Carpenter SR, Gunderson LH (2001) Coping with collapse: ecological and social dynamics in ecosystem management. Like flight simulators that train would-be aviators, simple models can be used to evoke people's adaptive, forward-thinking behavior, aimed in this instance at sustainability of human–natural systems. Biosci 51: (6) 451–457. doi.org/10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2

Cinner JE, Adger WN, Allison EH, Barnes ML, Brown K, Cohen PJ, Gelcich S, Hicks CC, Hughes TP, Lau J, Marshall NA, Morrison TH (2018) Building adaptive capacity to climate change in tropical coastal communities. Nat Clim Change 8:117-123. doi.org/10.1038/s41558-017-0065-x

Cinner JE, Huchery C, Hicks CC, Daw TM, Marshall N, Wamukota A, Allison EH (2015) Changes in adaptive capacity of Kenyan fishing communities. Nat Clim Change 5: 872-876. doi: 10.0.4.14/nclimate2690

Cooley SR, Lucey N, Kite-Powell H, Doney SC (2011) Nutrition and income from molluscs today imply vulnerability to ocean acidification tomorrow. Fish Fish 13: 182–215. doi.org/10.1111/j.1467-2979.2011.00424.x

Coulthard S. (2012) Can we be both resilient and well, and what choices do people have? Incorporating agency into the resilience debate from a fisheries perspective. Ecol Soc 17: (1): 4. doi.org/10.5751/ES-04483-170104

Daw T, Adger WN, Brown K, Badjeck M-C (2009) Climate change and capture fisheries: potential impacts, adaptation and mitigation. In Cochrane K, De Young C, Soto D, Bahri T (eds) Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper. No. 530. Rome, FAO. pp.107-150.

Díaz E (2010) Mitílidos en la región de Los Lagos: condiciones de trabajo en la industria del chorito. Departamento de Estudios de la Dirección del trabajo, Santiago, Chile, pp. 182.

Duarte CM, Holmer M, Olsen Y, Soto D, Marbà N, Guiu J, Black K, Karakassis I (2009) Will the oceans help feed humanity? BioSci 59: (11) 967-976. doi:1 0.1525/bio.2009.59.11.8

Ekstrom JA, Suatoni L, Cooley SR, Pendleton LH, Waldbusser GG, Cinner JE, Ritter J, Langdon C, van Hooidonk R, Gledhill D, Wellman K, Beck MW, Brander L.M., Rittschof D, Doherty C, Edwuards PET, Portela R (2015) Vulnerability and adaptation of US shellfisheries to ocean acidification. Nat Clim Change 5: 207-214. doi: 10.1038/NCLIMATE2508

FAO (2018) Food and agriculture organization of the United Nations. Globefish. Analysis and information on world fish trade. In http://www.fao.org/in action/globefish/market-reports/resource-detail/en/c/1136590/

FAO (2017) Food and agriculture organization of the United Nations. Planning for aquaculture diversification: the importance of climate change and other drivers. Technical workshop. (eds. Harvey B., Soto D., Carolsfeld J. and Bartley D. M.) Rome, Italy.

FAO (2016) Food and agriculture organization of the United Nations. The state of world fisheries and aquaculture. Contributing to food security and nutrition for all. Rome. 200 pp.

FAO (2014) Food and agriculture organization of the United Nations. The state of world fisheries and aquaculture 2014. Rome: FAO.

Fenichel EP, Levin SA, McCay B, St. Martin K, Abbott JK Pinsky ML (2016) Wealth reallocation and sustainability under climate change Nat Clim Change 6: 237-244. doi:10.1038/NCLIMATE2871

Fernández FJ, Ponce RD, Vásquez-Lavin F, Figueroa Y, Gelcich S, Dresdner J (2018) Exploring typologies of artisanal mussel seed producers in southern Chile. Ocean Coast Manage 158: 24-31. doi: org/10.1016/j.ocecoaman.2018.03.013

Figueroa Y, Dresdner J (2016) Are mussel seed producers responsive to economic incentives? Empirical evidence from the benthic resource management areas in Chile. Aquacult Econ Manage 20: (3) 283-311. doi:10.1080/13657305.2016.1180647

Gazeau F, Gattuso J-P, Dawber C, Pronker AE, Peene F, Peene J, Heip CHR, Middelburg JJ (2010) Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. Biogeosciences 7: 2051-2060. doi:10.5194/bg-7-2051-2010

Goldburg R, Elliott MS, Naylor R, Commission, P.O., et al., 2001. Marine aquaculture in the United States: environmental impacts and policy options. Pew Oceans Commission Arlington, Virginia.

Gonzalez-Poblete E, Hurtado F CF, Rojo S C, Norambuena CR (2018) Blue mussel aquaculture in Chile: Small or large scale industry? Aquac 493: 113-122. doi: org. 10.1016/j.aquaculture.2018.04.026

Grothmann T, Patt A (2005) Adaptive capacity and human cognition: the process of individual adaptation to climate change. Glob Environ Change 15: 199-213. doi: 10.1016/j.gloenvcha.2005.01.002

Handisyde N, Telfer TC, Ross LG (2017) Vulnerability of aquaculture-related livelihoods to changing climate at the global scale. Fish Fish 18: 466-488. doi: 10.1111/faf.12186

Hensher DA, Rose JM, Greene WH (2005) Applied choice analysis: A Primer. Cambridge university Press, New York , 742 pp.

Hinkel J (2011) "Indicators of vulnerability and adaptive capacity": towards a clarification of the science–policy interface. Glob Environ Change 21: 198–208. doi: 10.1016/j.gloenvcha.2010.08.002

Hoyos D, Mariel P (2010) Contingent valuation: past, present and future. Prague economic papers. 4: 329-343.

Hughes S, Yau A, Max L, Petrovic N, Davenport F, Marshall M, McClanahan TR, Allison EH, Cinner JE (2012) A Framework to asses national level vulnerability from the perspective of food security: the case coral reef fisheries. Environ Sci Policy 23: 95-108. doi:org/10.1016/j.envsci.2012.07.012

Intergovernmental Panel on Climate Change (IPCC) (2007a) Summary for policymakers. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the IPCC. Cambridge University Press, Cambridge, pp 7–22.

Kroeker K, Sanford E, Rose JM, Blanchette CA, Chan F, Chavez FP, Gaylord B, Helmuth B, Hill TM, Hofmann GE, McManus MA, Menge BA, Nielsen KJ, Raimondi PT, Russell D, Washburn L (2016) Interacting environmental mosaics drive geographic variation in mussel performance and predation vulnerability. Ecol Lett 19: 771-779. doi:10.1111/ele.12613

Lara C, Saldías GS, Tapia FJ, Iriarte JL, Broitman BR (2016) Interannual variability in temporal patterns of chlorophyll-a and their potential influence on the supply of mussel larvae to inner waters in northern Patagonia (41-44ºS). J Mar Syst 155: 11-18. doi:org/10.1016/j.jmarsys.2015.10.010

López DA, López BA, González ML (2008) Shellfish culture in Chile. Int J Environ Pollut 33: (4) 401-431.

MaClanahan TR, Cinner JE (2012) Adapting to a Changing Environment: Confronting the consequences of climate change. Oxford University Press, New York, 192 pp.

McLaughlin P, Dietz T (2007) Structure, agency and environment: toward and integrated perspective on vulnerability. Glob Environ Change 18: 99-111. doi:10.1016/j.gloenvcha.2007.05.003

Menge BA, Chan F, Nielsen KJ, Di Lorenzo E, Lubchenco J (2009) Climatic variation alters supply-side ecology: impact of climate patterns on phytoplankton and mussel recruitment. Ecol Monograph 79: (3) 379-395.

Monfort M-C (2014) Globefish consultant. The European market for mussels. Globefish Research Programme. Vol. 115, Rome, FAO 2014. 65 pp.

Moser C, Stein A (2011) Implementing urban participatory climate change adaptation appraisals: a methodological guideline. Environ Urban 23:(2) 463-485. doi.org/10.1177/0956247811418739

Navarro JM, Gutierrez A (1990) Sinopsis sobre el estado actual del cultivo de mitílidos en Chile. In: Cultivo de moluscos en America Latina (ed. by A. Hernandez), pp. 189-210. Editorial Guadalupe, Bogota, Colombia.

Parker LM, Ross PM, O´Connor WA, Pörter HO, Scanes E, Wright JM (2013) Predicting the responses of Molluscs to the impact of ocean acidification. Biology 2: 651-692. doi.org/10.3390/biology2020651

Plan de Acción Nacional de Cambio Climático (PANCC) 2017-2011. Ministerio del Medio Ambiente.

Plaza H, Ortazar Y, Gonzalez M, Aros J (2005) Estado de situación y perspectivas de la industria del chorito. Informe Fish. Partn. Ltda. Retrieved from http://docslide.com.br/ documents/200507151158550estado-de-situacion-y-perspectivas-de-la-industria-del chorito.html

Ponce Oliva RD, Vasquez-Lavín F, San Martin VA, Hernández JI, Vargas CA, Gonzalez PS, Gelcich S (2019) Ocean acidification, consumers' preferences, and market adaptation strategies in the mussel aquaculture industry. Ecol Econ 158: 42-50. Doi:org/10.1016/j.ecolecon.2018.12.011

Range P, Chícharo MA, Ben-Hamadou R, Piló D, Fernandez-Reiriz MJ, Labarta U, Marin MG, Bressan M, Matozzo V, Chinellato A, Munari M, El Menif NT, Dellai M, Chícharo L (2014) Impacts of CO2-induced seawater acidification on coastal Mediterranean bivalves and interactions with other climatic stressors. Reg Environ Change 14: (1) 19,19-30. Doi: 10.1007/s10113-013-0478-7

Riviera A, Unibazo J, León P, Vásquez-Lavín F, Ponce R, Mansur L, Gelcich S (2017) Stakeholder perceptions of enhancement opportunities in the Chilean small and medium scale mussel aquaculture industry. Aquac 479: 423-431. doi.org/10.1016/j.aquaculture.2017.06.015

Saavedra Gallo G, Macías Vázquez A (2016) Collective action and symbolic capital in the artisanal fisheries: an analysis of the local food systems of Reloncaví Estuary (Los Lagos), Chile. Cul Hist Dig J 5: (1). doi: http://dx.doi.org/10.3989/chdj.2016.005

San Martin VA, Gelcich S, Vásquez Lavín F, Ponce Oliva RD, Hernández JI, Lagos NA, Birchenough SRN, Vargas CA (2019) Linking social preferences and ocean acidification impact in mussel aquaculture. Nature Sci Rep 9:4719. Doi:10.1038/s41598-019-41104-5

Shaw A, Sheppard S, Burch S, Flanders D, Wiek A, Carmichael J, Robinson J, Cohen S (2009) Making local futures tangible-synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. Glob Environ Change 19: 447-463. doi:10.1016/j.gloenvcha.2009.04.002

Sernapesca (2014) Anuario Estadístico de Pesca. Ministerio de Economía Fomento y Reconstrucción. República de Chile. Retrieved from http://www.sernapesca.cl/index.php?option=com_content&task=view&id=2010&Itemid=889

Subsecretaria de Pesca y Acuicultura (SSPA) (2014) Balance de gestión del sector Acuicultor Nacioanl para periodo 2010-2013. Subsecretaria de Pesca y Acuicultura.

Toro JE, Alcapán AC, Vergara AM, Ojeda JA (2004) Heritability estimates of larval and spat shell height in the Chilean blue mussel (*Mytilus chilensis* Hupe 1854) produced under controlled laboratory conditions. Aquac Res 35: 56-61. doi.org/10.1111/j.1365-2109.2004.00985.x

DISCUSION

Durante los últimos 30 años, la acuicultura a nivel mundial ha tenido un importante crecimiento contribuyendo a la seguridad alimentaria bajo una sociedad en constante crecimiento (*FAO,* 2018). Entender cómo la producción y la calidad de los productos marinos pueden ser influenciados por los cambios ambientales en una proyección de escenario de AO es crítico para poder determinar posibles consecuencias económicas para la industria y de esta forma evitar un futuro colapso en esta relevante actividad socio-económica. Si bien dada su importancia comercial y social para nuestro país, existen estudios enfocados en determinar los efectos de la AO en la especie *Mytilus chilensis*, es escasa la información que existe considerando el análisis integrado desde un punto de vista socio-económico. Por lo que esta tesis, enfrentó un desafío al escalar el estudio de la AO sobre los impactos en atributos comerciales de la especie *M. chilensis*, y los impactos socioeconómicos mediante un análisis transdisciplinario.

A lo largo de la costa de Chile se presenta una alta heterogeneidad en las condiciones oceanográficas, otorgando a las especies marinas hábitats variables como zonas de surgencia, zonas cercanas a desembocaduras de ríos, fiordos y glaciares en los cuales los niveles de pH y $pCO_2$ tienen mayor fluctuación que los ecosistemas de océano abierto (*Vargas et al*., 2017). Sin embargo estos organismos marinos estarán expuestos a tasas de cambio de $pCO_2$ en el agua de mar que van más allá de los peores escenarios previstos para los océanos (*Caldeira and Wickett*, 2003). Estos efectos pueden ser parcialmente predecibles a través de experimentos de mesocosmos, los cuales proporcionan evidencia convincente de los efectos de la AO (*Hale et al*., 2011; *Jokiel et al*., 2008). Basados en estos supuestos, los experimentos realizados en esta tesis doctoral, entregan información crucial para la industria de la mitilicultura, evidenciando efectos negativos en los principales atributos de mercado (atributos físicos y nutricionales) del mitílido *M. chilensis* (Fig. 16).

En cuanto a los atributos físicos, si bien muchos invertebrados marinos dependen de sus conchas como medio de protección, y aunque éstas podrían debilitarse bajo escenarios de AO, los estudios enfocados a evaluar el efecto de condiciones de bajo pH/alto $pCO_2$ sobre la resistencia de las conchas de mitílidos son bastante escasos (*Beniash et al*., 2010;

*Welladsen et al*., 2010). Es por ello que al evaluar esta respuesta biológica (**PAPER I**), hemos demostrado en esta tesis que la AO puede degradar significativamente la integridad mecánica de las conchas de *M. chilensis*, haciéndolas más débiles y delgadas en comparación con las expuestas a condiciones control. En este sentido, nuestros resultados son relativamente similares a los reportados por *Welladsen et al*. (2010), donde conchas del bivalvo *Pinctada fucata* expuestas a 28 días a condiciones de AO, fueron significativamente más débiles que aquellas mantenidas a un pH ambiental. Otros estudios, incluso con tiempos de exposición menores (8 días) en el mitílido *Mytilus galloprovincialis*, evidenciaron una reducción significativa en la calcificación con un resultado de conchas débiles y delgadas (*Gaylord et al*., 2011). Además, varios estudios han demostrado la disolución y pérdida de integridad estructural en conchas de moluscos al ser expuestas a condiciones de agua de mar acidificada tales como: *Michaelidis et al*. (2005), en el mitílido *Mytilus galloprovincialis*; *Buschbaum et al*. (2007), en el caracol *Littorina littorea*; *Gazeau et al*. (2007), en el mitílido *Mytilus edulis* y la ostra *Crassostrea gigas*; *Ries et al*. (2009), en 18 especies calcificadoras; *McClintock et al*. (2009), en moluscos antárticos como *Laternula elliptica*, *Yoldia eightsi* y *Nacella concinna* e incluso *Watson et al*. (2009), en conchas de ostras *Saccostrea glomerata* en estado larvario. Todos estos estudios sugieren que la integridad estructural de las conchas se ve comprometida en exposiciones a tratamientos de AO causando reducción en la resistencia de las conchas, resultando conchas débiles. Sin embargo, en esta tesis doctoral se trabajo con un periodo de exposición prolongado (30 a 120 días) a niveles de bajo pH/alto $pCO_2$ para ejemplares juveniles y adultos respectivamente, demostrando una disminución significativa en la resistencia de las conchas de *M. chilensis*. Además la microdureza medida en dos secciones de la concha, evidenció niveles de dureza significativamente más bajos en la zona cercana al borde de crecimiento en comparación con la zona del umbo. Esto debido a que es la zona de crecimiento de la especie en la cual se esta formando la concha, siendo la zona más afectada por las nuevas condiciones ambientales de exposición.

Otro de los atributos físicos observados fue la apariencia, medida en este estudio como pérdida de color en las valvas (**PAPER II**). La concha de estos organismos esta compuesta por 3 capas: la interna nacarada, la capa prismática en la zona media y la externa llamada periostraco (*Narasimhulu and Rao*, 2000). Esta última capa una vez formada no sigue su mantenimiento, por lo que con el paso del tiempo puede llegar a estar ausente en algunos lugares de la concha (*Guenther & De Nys*, 2006). Estudios han sugerido que el periostraco puede ayudar a proteger a las conchas de la disolución causada por el contacto con agua acidificada (*Ries et al*., 2009). Sin embargo, no hay evidencia concluyente. En contraste, existen estudios que demuestran que la exposición a condiciones de AO puede aumentar la erosión del periostraco (*Bushbaum et al*., 2007; *Welladsen et al*., 2010).

Al analizar la variación de color en las conchas (**PAPER II**), demostramos una erosión causando una pérdida de color de ~50% en adultos y ~10% en organismos juveniles. Nuestros resultados son consistentes con los reportados por *Duquette et al*. (2017), donde 4 especies de gastrópodos presentaron evidencia visible de la disolución de la capa externa de la concha. Del mismo modo, *Hall-Spencer et al*. (2008), evidenciaron un severo deterioro en las conchas de 3 especies de moluscos expuestos a condiciones de bajo pH (pH=7,4). En otro estudio realizado por *Green et al*. (2004), reportaron evidencias de disolución masiva en las conchas de juveniles de bivalvos de la especie *Mercenaria mercenaria*, tan solo con 24 horas de exposición a condiciones de AO (pH=7,2-7,0). Del mismo modo, *Sezer et al*. (2018), demostraron un blanqueamiento gradual en las conchas de ostras durante 40 días de exposición a condiciones de AO (pH= 7,8-7,5). Incluso, estudios en los cuales se evalúan respuestas *in situ* de trasplantes recíprocos entre ambientes locales contrastantes (e.g. zona de estuario y zona costera) (*Osores et al*., 2017), evidenciaron cambios en la superficie de la concha de *M. chilensis* en organismos que estuvieron expuestos a aguas estuarinas corrosivas con bajo contenido de Omega aragonita.

En contraste a nuestros hallazgos, *Rodofo-Metalpa et al*. (2011), observó diferencias al exponer a *Mytilus galloprovincialis* a condiciones de pH= 7,2. Esta exposición que duró 3 meses en las conchas de organismos muertos presentaron una notoria disolución, en cambio los organismos que fueron expuestos vivos con sus conchas durante 5 meses, mantenían su periostraco, salvo pequeñas erosiones causadas por la frotación entre individuos. Presentando áreas dañadas, sugiriendo una reducción en la capacidad para reparar el periostraco a un pH bajo. La mayoría de estas evidencias de deterioro en las conchas fueron realizadas en estudios con condiciones de exposición a un pH bajo (7,5 a 7,0), condiciones de proyecciones superior a los 160 años (*Bopp et al.*, 2013), difícilmente observables en un futuro cercano, aún considerando las variables condiciones que se presentan en la zona costera. En cambio, éste estudio doctoral demostró que al trabajar con proyecciones más realistas y cercanas a condiciones esperables en ambientes altamente variables, podrían evidenciar un efecto significativo en la apariencia del mitílido *M. chilensis* en un futuro cercano.

Por lo tanto, esta disminución de periostraco presentada en *M. chilensis* deja expuestas las conchas a la disolución, haciéndolas mas delgadas y frágiles, lo que podría llegar a ser favorable para una gran variedad de depredadores tales como: gastrópodos, cangrejos, estrellas de mar, decápodos, mamíferos marinos, y organismos incrustantes (*Reimer & Tedengren*, 1996; *Reimer & Harms-Ringdahl*, 2001; *Beadman et al*., 2003; *Soto et al*., 2004; *Soto*, 1996; *Kirk et al*., 2007). En éste contexto, además de tener estas implicancias biológicas, podría tener consecuencias económicas potenciales para las industrias que dependen de ellos (*San Martin et al*., 2019). Pudiendo resultar, mayores pérdidas en el procesamiento primario debido a la rotura de la concha y al sacrificio de los mitílidos considerados visualmente poco atractivos desde una perspectiva de mercado.

Los mitílidos son especies con una alta calidad nutricional (*Cardoso et al*., 2012; *Orban et al*., 2002), por lo que su consumo es recomendado para la salud humana (*Mozzaffarian & Wu*, 2011; *Larsen et al*., 2011). Lamentablemente los atributos nutricionales de *M. chilensis* evaluados en esta tesis (**PAPER II**), evidenciaron un efecto negativo ante la exposición a condiciones de AO. Mis resultados evidencian una disminución significativa en la composición de ácidos grasos polisaturados (PUFA), diferencia aportada principalmente por los ácidos grasos EPA y DHA, que son algunos de los ácidos grasos presentes en el Omega-3. Además los resultados revelan un menor contenido de proteínas y vitamina B12 en los individuos expuestos a un alto nivel de $pCO_2$. Estos cambios pueden ser atribuidos a una disminución en la capacidad para mantener la homeostasis lipídica (*Matson et al*., 2012), reducción en la abundancia de proteínas asociadas a la desaturación y el alargamiento de los ácidos grasos (*Rossoll et al*., 2012) que interfieren en su síntesis.

Los resultados de esta tesis son contrarios a los reportados por *Valles-regino et al*., (2015), los cuales expusieron a una condición de combinación entre temperatura y $CO_2$ a el molusco *D. orbita*, registrando una disminución en el contenido de PUFA sólo cuando en esta combinación se aumentaba la temperatura del agua (~2ºC), mientras que los ácidos grasos saturados y monosaturados se redujeron al aumentar la condición de AO. Esta especie, al contrario de *M. chilensis* tiene mayor proporción de ácidos grasos saturados y monosaturados, además el tiempo de exposición fue de 35 días en comparación con los 120 días de exposición realizados en esta tesis doctoral. Por otro lado, *Timmins-Schiffman et al*. (2014), expusieron a un elevado $pCO_2$ la ostra *Crassostrea gigas*, y no encontró efecto en la composición de ácidos grasos, pero evidenció diferencias fisiológicas en las conchas.

En el estudio de *Anacleto et al*. (2014), demostraron que la temperatura elevada disminuye significativamente la proporción relativa de algunos ácidos grasos, pero no de proteínas. En cambio, resultados reportados por *Tate et al*. (2017), demostraron que las condiciones futuras de AO y calentamiento del océano reducirán la calidad del molusco *Dicathais orbita*, principalmente en el contenido proteíco, resultados parcialmente semejantes a los reportados en esta tesis, debido a que se presentaron diferencias en el contenido proteico pero solo con exposición a niveles de bajo pH/alto $pCO_2$. Estos resultados son relevantes, considerando que durante el estrés de AO los bivalvos cambian del metabolismo de los carbohidratos y lípidos a un mayor uso de recursos proteicos (*Clark et al*., 2013; *Michaelidis et al*., 2005), y que la acumulación de proteínas en el tejido corporal de los moluscos proporciona energía para el crecimiento y la gametogénesis (*Moussa et al*., 2014; *Racotta et al*., 1998; *Rodriguez-Astudillo et al*., 2005), bajo futuras condiciones de AO podría llevar a una reducción de la fecundidad.

Teniendo en cuenta lo relevante de estos resultados para los consumidores y empresas mitilicultoras, se hizo indispensable hacer el vínculo entre el impacto de la AO, las preferencias y bien estar de los consumidores, ya que no han sido estudiado suficientemente, existiendo solo unos pocos artículos que analizan la dimensión económica de la OA (*Finnof et al*., 2010; *Narita and Rehdanz*, 2017; *Moore*, 2015; *Falkenberg and Tubb*, 2017). Demostrando que se necesita más y mejor trabajo interdisciplinario para aumentar la comprensión de los vínculos entre la AO y el bienestar humano.

De esta forma, los resultados de la encuesta realizada ayudaron a caracterizar las preferencias de los consumidores, vincularlas con los impactos de la AO y estimar los efectos de la AO sobre el bienestar de los consumidores al comprar mitílidos a escalas locales. Con los resultados de este trabajo (**PAPER II**), se demuestra que la preferencia de los consumidores esta dada principalmente por los atributos físicos y nutricionales. Siendo la apariencia el aspecto mas preferido, donde el 70% de los encuestados elijen mitílidos que no tengan impactos en la apariencia de sus conchas producto de la AO. Esta preferencia ha sido también demostrada por *Penney et al*. (2007), donde la percepción visual del consumidor hacia la apariencia de la concha es un factor importante en la comercialización de mitílidos, debido a que las impresiones de los consumidores sobre la apariencia de un producto están influenciadas por la variabilidad en forma, color y presencia o no de epifauna o flora.

A través de estos resultados, se demuestra que la apariencia definida como un atributo de calidad ha sido identificada como clave en las decisiones de los consumidores (*Adams, et al* 2011), influyendo en las compras (*Grabacki et al*., 2011) y en el precio de mercado (*Brener et al*., 2012). Determinando, que los consumidores están dispuestos a pagar hasta ~$2.500 pesos chilenos por 250 gr de mitílidos para evitar un efecto negativo producto de la AO. Además, este estudio evidenció que el 55% de los encuestados, prefirió atributos como tamaño grande y color de carne amarillo, los cuales no fueron probados experimentalmente en este estudio, pero se han demostrado ser susceptibles a la AO (*Kurihara et al*., 2008; *Gazeau et al*., 2010; *Duarte et al*., 2014; *Navarro et al*., 2016; *Osores et al*., 2017).

Por otro lado, los consumidores posicionan a los atributos nutricionales como el segundo aspecto importante al momento de realizar una elección de compra, dispuestos a pagar hasta ~$900 pesos chilenos por 250 gr de mitílidos para evitar un cambio negativo en la calidad nutricional. Con estos resultados hemos evidenciado que la actitud de los consumidores afirman que la apariencia y los niveles nutricionales de los mitílidos son los atributos más importantes que influyen en el comportamiento de compra. Por lo tanto, cualquier variación en estos atributos debido a la AO tendrá implicaciones para la industria afectando la economía local y el bienestar de los consumidores.

Debido a esto, es crucial saber el conocimiento que tienen las empresas con respecto a este estrés ambiental. De acuerdo a los resultados reportados en el **PAPER III**, las empresas perciben que las mayores amenazas se relacionan con los eventos de marea roja (95%), seguidos por la escasez de semilla (92%) y una dependencia de los precios internacionales (86%). Además la falta de conocimiento ambiental se reconoce como una amenaza en un (68%) y por otro lado, el 21% de los encuestados vieron la AO como una amenaza directa para la industria. Estos resultados sugieren que las empresas mitilicultoras están más familiarizadas con los eventos presentados con mayor frecuencia o durante el último tiempo, los cuales han tenido un impacto económico negativo afectando su producción. Respuesta similar fue presentada por productores de moluscos en 7 regiones geográficas de Estados Unidos (*Adams et al*., 2011), evidenciando como uno de los principales problemas aquellos que se presentaban de forma periódica y constante generando un impacto en los costos de operación y comercialización del producto. Similar respuesta fue presentada en la investigación de *Fitridge et al*. (2012), reconociendo diferentes tipos de impactos en especies de moluscos con importancia comercial.

Las empresas mitilicultoras chilenas que participan en la cadena de valor, producen carne de congelación rápida (IQF), el 75% produce IQF con concha entera, el 63% con media concha y el 50% solo enlatados y el 13% en otros formatos. Pero todos estos formatos se conocen como de bajo valor agregado, por lo que los encuestados declararon que les gustaría aumentar la participación en el mercado mediante la creación y ofrecimiento de nuevos formatos de productos como una estrategia para hacer frente a los productos de bajo valor agregado. Esta intención de procesos de innovación en la industria de la mitilicultura con el fin de establecer rutas externas adicionales para la comercialización de sus productos ha sido realizada también por una cadena de actores (*Chesbrough*, 2003; *Simard & West*, 2006). Sin embargo, son escasas las empresas que participan en la innovación con el fin de satisfacer las necesidades heterogéneas de los consumidores (*Sarkar & Costa*, 2008; *Knudsen*, 2007), observando últimamente un interés por alimentos singulares, sabores únicos (*Costa et al*., 2007) y alimentos fáciles de cocinar (*Batzios et al*., 2003).

Cuando analizamos las preferencias de los consumidores a los posibles nuevos formatos de productos, los formatos de “mitílidos con concha a la mantequilla y ajo” y “envasados al tomate", no son presentaciones valoradas por la mayoría de los consumidores. En cambio para las presentaciones de: "carne enlatada al aceite o agua", "carne enlatada con salsa picante", "enlatado salsa verde" y "embolsado al vino blanco" obtuvieron una participación positiva, lo que sugiere que la industria puede alcanzar como máximo el 40% del mercado. Sin embargo, los resultados muestran que estas estrategias solo ayudaran a segmentos específicos de consumidores. Como resultado, estos formatos reducen el bien estar de los consumidores en comparación con la elección de la opción de formato "fresco con concha". Donde, los consumidores están dispuestos a pagar hasta $480 pesos chilenos, al cambiar desde el formato "fresco con concha" a "enlatado en aceite o agua". En cambio, la disposición a pagar disminuye al cambiar del formato "fresco con concha" a cualquiera de los restantes formatos. Ahora, si consideramos solo los consumidores que están dispuestos a comprar otras presentaciones, el formato "mitílido a la mantequilla y ajo" es valorado de forma similar a los atributos de sabor, textura y tamaño de concha. Resultado prometedor, para los productores, ya que pueden compensar los efectos de la AO en los mitílidos al ofrecer estos formatos de productos al menos a un segmento del mercado.

En consecuencia, se necesita mayor información sobre los requisitos y deseos básicos del consumidor (*Batzios et al.,* 2002; *Batzios et al*., 2003) para que las empresas puedan implementar estrategias para el desarrollo de productos con el fin de satisfacer las necesidades del consumidor. Por lo cual, los resultados evidenciados en esta tesis doctoral ayudan a identificar las demandas de los consumidores respecto a la presentación y formato de *M. chilensis* en la industria de la acuicultura. Estos resultados complementan previos estudios, demostrando que la AO afecta la producción de mitílidos y por lo tanto los precios (*Moore et al*., 2015). Sin embrago, este estudio va más allá del efecto del precio, considerando otros atributos afectados por la AO que los consumidores consideran importantes, lo que exacerba el impacto de la AO.

En base a los resultados observados, se puede determinar que esta implementación de nuevas opciones de productos, requerirá que la empresa implemente una asociación público-privada con respecto a la seguridad alimentaria, donde tendrá que instruir a los consumidores sobre las características de los nuevos formatos de productos para ayudar en el proceso de compra (i.e. calidad nutricional), ya que se ha demostrado que los consumidores examinan y confían en la información del etiquetado de productos para realizar una elección de lo que están adquiriendo (*Batzios et al*., 2003).

Finalmente, estos resultados fueron complementados con la vinculación de escenarios hipotéticos (**PAPER IV**), que nos ayudan a proyectar el futuro impacto del cambio global, con experiencias pasadas en la industria (productores) de cultivo de mitílido para crear una base de referencia sobre la capacidad de la industria, anticipar cambios y desarrollar estrategias de respuesta mediante adaptaciones.

Estas adaptaciones han estimulado y favorecido la innovación, permitiendo a la sociedad superar desafíos (*Cinner et al*., 2018), reflejando la capacidad para anticipar y enfrentar el cambio (*Adger and Vicent*, 2005). De esta manera, las experiencias pasadas ayudan a desarrollar estrategias y permite proyectar una respuesta a un impacto futuro de la AO al plantear escenarios hipotéticos (*Shaw et al*., 2009).

Los resultados de las encuestas realizadas a productores (**PAPER IV**), indican que perciben el estrés ambiental como la principal amenaza para la industria, posiblemente debido a eventos que ocurrieron en el pasado cercano, tales como: la disminución de los alimentos (fitoplancton) y las semillas de *M. chilensis*. Un efecto similar fue informado por *Adams et al*. (2011), evidenciando que los productores se sienten más vulnerables a posibles eventos de estrés ambiental si han sido afectados previamente. Estas experiencias negativas que han impactado a la industria, han obligado al productor a tomar medidas permitiéndoles responder *a priori* a un evento negativo (*Barton et al*., 2012), para lograr una actividad sostenible en el tiempo. Cuando evalué el comportamiento contingente de los productores frente a escenarios hipotéticos, se demuestra una posición ambientalmente optimista, continuando en la industria (~ 70%), lo que sugiere que es una respuesta potencial para aprender y desarrollar conocimiento frente al cambio y la incertidumbre (*Carpenter and Gunderson*, 2001). Sin embargo, desde un punto de vista económico, se muestran pesimistas hasta el punto en que dejan de participar (~ 20%) y venden cuando sienten la crisis.

Esta tesis doctoral evidencia que los grandes productores están más dispuestos a invertir para anticipar el cambio, esto podría ser porque tienen más activos para invertir y más para perder durante una crisis (Fig.16). El indicador de agencia presentado en el escenario de disminución de precios demostró ser significativo, lo que indica que los productores que permanecen en el negocio tienen una disposición a pagar más alta para el programa de investigación. Esto indica que aquellos que ya enfrentaron el costo de una crisis han aumentado la conciencia y están dispuestos a invertir para evitarla.

Finalmente, aprender a adaptarse a los eventos generados por el cambio global requiere una inversión en investigación que ayude a evaluar los riesgos potenciales, los patrones de cambio climático, a reducir las pérdidas en la acuicultura a través de sistemas de monitoreo, entre otros (*Brooks et al*., 2005). Se ha demostrado que el acceso y la disponibilidad de la ciencia han ayudado a los criadores de moluscos a identificar y evitar algunas de las consecuencias de la AO, un evento negativo importante en la producción en el noroeste del Pacífico (*Ekstrom et al*., 2015).

Se evidencia que la ciencia es fundamental para promover el desarrollo de la investigación sobre el cambio global, evaluando los posibles efectos ambientales y socioeconómicos, y determinando los posibles efectos sobre la vulnerabilidad de los sistemas socioecológicos, a través de opciones de adaptación, medidas de mitigación y nuevas tecnologías (*PANCC*, 2017). Por lo tanto, existe la necesidad de desarrollar una capacidad de adaptación para ayudar a anticipar y enfrentar estos cambios ambientales que cada vez son más reiterativos y que seguirán en aumento, por lo que el desarrollo de esta capacidad de adaptación bajo la evaluación de múltiples dominios será fundamental para una adaptación efectiva a un cambio global con efecto en múltiples escalas y lugares.

Por esta razón , el aprendizaje solo puede permitir la adaptación cuando otros dominios de capacidad de adaptación como la agencia, la flexibilidad y la organización social están suficientemente desarrollados. En este sentido, las empresas que dependen de recursos, deben anticiparse y prepararse para los desafíos relacionados con el clima, y las instituciones deben apoyar la sostenibilidad de las industrias y los sistemas sociales que dependen de ellos (*Marshall*, 2010).

De estos resultados surge la necesidad de contar con opciones financieras innovadoras que respalden las respuestas anticipadas al cambio ambiental en las áreas donde se desarrolla esta actividad de la que dependen, estando expuestos a múltiples riesgos debido a eventos extremos que ocurren con mayor frecuencia (*Adger et al*., 2003). Sugerir la implementación de políticas de adaptación y asignar recursos económicos a sectores vulnerables, ya que la vulnerabilidad de estos sistemas debería dejar de ser un ejercicio académico y pasar a una necesidad política en nuestro país.

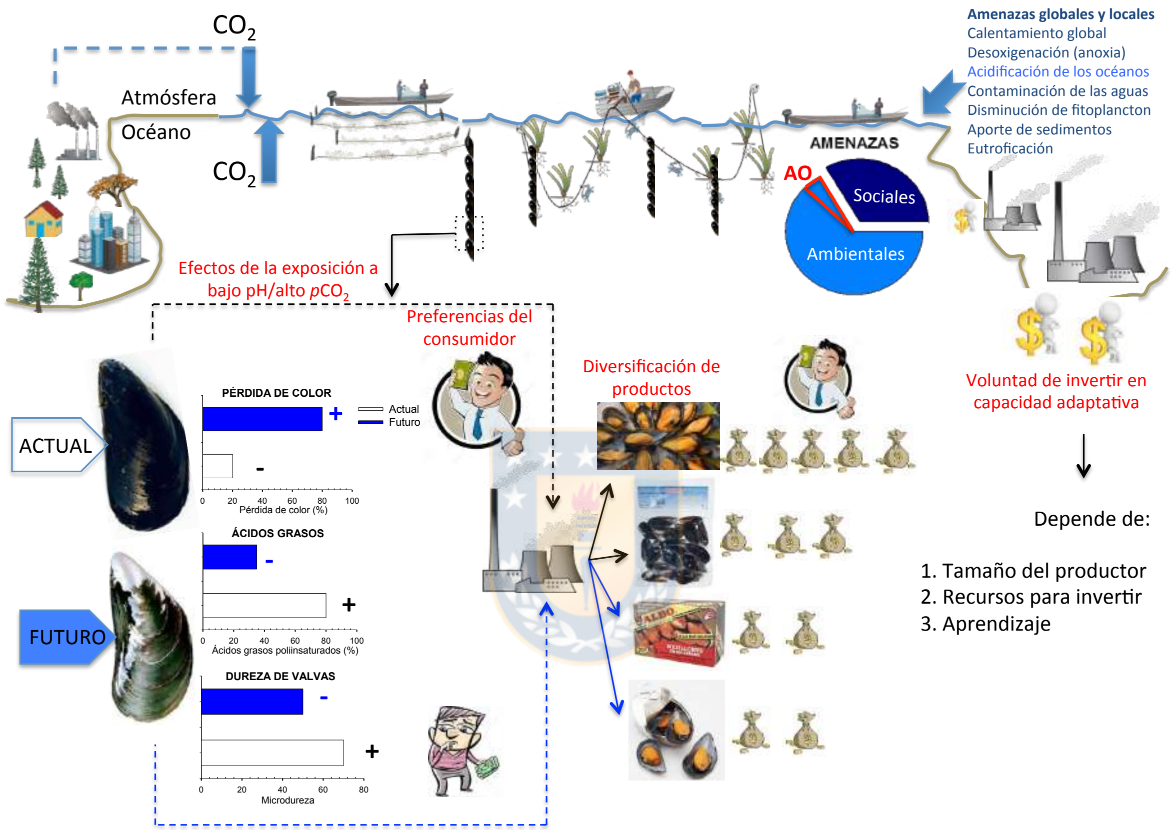


Figura 16: Esquema integrativo de lso resultados obtenidos en los cuatro capítulos de esta tesis Doctoral.

## CONCLUSION

En relación a los resultados obtenidos en este trabajo, podemos determinar que la primera hipótesis ***"La exposición de Mytilus chilensis a bajos niveles de pH y altos niveles de pCO₂, impactará negativamente los atributos físicos y nutricionales"*** es aceptada, ya que los resultados evidenciaron una disminución en la calidad (física y nutricional). Demostrando que las condiciones estresantes de pH bajo/alto $pCO_2$ podrían desencadenar cambios significativos en la fisiología, el metabolismo y/o el almacenamiento de ácidos grasos de los mitílidos.

La segunda hipótesis formulada ***"La selección de Mytilus chilensis por los consumidores estará dada por sus preferencias en atributos físicos, desplazando los atributos nutricionales"***, es aceptada con las siguientes conclusiones:

La apariencia es el aspecto mas preferido, donde el 70% de los encuestados elijen mitílidos que no tengan impactos en la apariencia de sus conchas producto de la AO. Determinando, que los consumidores están dispuestos a pagar hasta ~$2.500 pesos chilenos por 250 gr de mitílidos para evitar un efecto negativo producto de la AO.

Por otro lado, los consumidores posicionan a los atributos nutricionales como el segundo aspecto importante al momento de realizar una elección de compra, dispuestos a pagar hasta ~$900 pesos chilenos por 250 gr de mitílidos para evitar un cambio negativo en la calidad nutricional.

La tercera hipótesis de este trabajo ***"La capacidad adaptativa de las empresas mitilicultoras estará determinada por el tamaño de la empresa y la disponibilidad de capital financiero"*** es aceptada, debido a que los productores de mayor tamaño están más dispuestos a invertir para anticipar el cambio, esto podría ser porque tienen más activos para invertir y más para perder durante una crisis.

RECOMENDACIONES

Los resultados de esta tesis permiten concluir que la AO afectará la calidad física y nutricional del mitílido *M. chilensis*, principales atributos considerados en el momento de realizar una compra por el consumidor (*San Martín et al*., 2019). Sin embargo la AO es uno más de los múltiples factores que afectan la sostenibilidad de la industria de los mitílidos.

Si bien nuestros hallazgos indican una disminución en la calidad (física y nutricional), se requiere realizar exposiciones a un largo plazo y estudios multigeneracionales para evaluar el potencial de aclimatación y adaptación de las capacidades metabólicas y biosintéticas de la especie para las futuras condiciones de AO para lograr una producción de productos marinos saludables y sostenible en el tiempo. Por lo tanto, el mayor desafío de la industria de la acuicultura frente a la AO, será preservar los atributos de apariencia y composición nutricional. Sugiriendo a través de nuestros resultados que la acuicultura de mitílidos puede ser sostenible en el tiempo a través de la mitigación, ya sea modificando la química del agua de mar, la evolución y adaptación de las especies, utilizando una selección artificial de larvas que sean más resistentes a la AO, que ayuden a preparar a la acuicultura para los cambios que se avecinan.

Hasta el momento, los esfuerzos de la industria se han centrado en estrategias de adaptación como el uso de criaderos, viveros, agua de mar artificial, complementos alimenticios alternativos (*Branch et al*., 2013), sistemas de cultivos mixtos que incluyen especies fotosintéticas (e.g. algas marinas; “pelillo” o *Gracilaria chilensis*) (*Chopin*, 2013), entre otros. Los cuales son costosos e implican cambios en los procesos de producción, llegando a ser soluciones inviables (*Logan*, 2010). Nuestros resultados revelan las complejidades y oportunidades del uso de estrategias de adaptación en etapas posteriores de la cadena de valor, como el etiquetado, el surtido de productos y la diferenciación del mercado. La identificación de los roles de estas medidas de adaptación es fundamental para informar las futuras inversiones estratégicas de la industria a lo largo de la cadena de suministro.

Los resultados de esta tesis doctoral se pueden extender de dos maneras. Primero, valdría la pena incluir a los consumidores extranjeros y realizar un análisis similar para los principales mercados de mitílidos chilenos (España, China, Francia y Estados Unidos). Esta nueva información enriquecería nuestros resultados con respecto a los atributos más valiosos. Otra posible extensión del estudio sería probar empíricamente las características organolépticas bajo diferentes escenarios de OA para comparar las percepciones de los consumidores con los resultados de laboratorio.

REFERENCIAS

Adams, C. M., S. E. Shumway, R. B. Whitlatch & T. Getchis. 2011. Biofouling in marine molluscan shellfish aquaculture: a survey assessing the business and economic implications of mitigation. *Journal of the World Aquaculture Society*. 42, 242–252. doi.org/10.1111/j.1749-7345.2011.00460.x

Adger, W. N., K. Vincent. 2005. Uncertainty in adaptive capacity. *Comptes Rendus Geoscience*. 337, 399-410. doi.org/10.1016/j.crte.2004.11.004

Adger, W. N., S. Huq, K. Brown, D. Conway & M. Hulme. 2003. Adaptation to climate change in the developing world. *Progress in Development Studies*. 3(3), 179–195. doi.org/10.1191/1464993403ps060oa

Anacleto, P., A. L. Maulvault, N. M. Bandarra, T. Repolho, M. L. Nunes,R. Rosa & A. Marques. 2014. Effect of warming on protein, glycogen and fatty acid content of native and invasive clams. Food Research International. 64, 439–445. doi:10.1016/j.foodres.2014.07.023

Barton, A., B. Hales, G. G. Waldbusser, C. Langdon & R. A. Feely. 2012. The Pacific oyster, *Crassostrea gigas*, shows negative correlation to naturally elevated carbon dioxide levels: implications for near-term ocean acidification effects. *Limnology and Oceanography*. 57(3), 698–710. doi:10.4319/lo.2012.57.3.0698

Batzios, C., P. Angelidis, D. K. Moutopoulos, C. H. Anastasiadou & V. Chrisopolitou. 2003. Consumer attitude towards shellfish in the Greek market: a pilot study. Mediterranean Marine Science. 4(2), 155–174. doi: 10.12681/mms.236

Beadman, H., R. Caldow, M. Kaiser & R. Willows. 2003. How to toughen up your mussels: using mussel shell morphological plasticity to reduce predation losses. *Marine Biology*. 142(3),487–494. doi:10.1007/ s00227-002-0977-4

Beniash, E., Ivanina, A., Lieb, N. S, Kurochkin, I. and Sokolova, I. M. (2010). Elevated level of carbon dioxide affects metabolism and shell formation in oysters *Crassostrea virginica*. *Marine Ecology Progress Series*. 419, 95-108. doi: 10.3354/meps08841

Bopp, L., L. Resplandy, J. C. Orr, C. S. Doney, J. P. Dunne, M. Gehlen, P. Halloran, C. Heinze, T. Ilyina, R. Séférian, J. Tjiputra & M. Vichi. 2013. Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* 10, 6225–6245. doi:10.5194/bg-10-6225-2013

Buschbaum, C., G. Buschbaum, I. Schrey & D. W. Thieltges. 2007. Shell-boring plychaetes affect gastropod shell strength and crab predation. *Marine Ecology Progress Series.* 329, 123-130. doi: 10.3354/meps329123

Branch, T. A., B. M. DeJoseph, L. J. Ray & C. A. Wagner. 2013. Impact of ocean acidification on marine seafood. *Trends in Ecology & Evolution*. 28(3), 178-186. doi.org/10.1016/j.tree.2012.10.001

Brenner, M., C. Buchholz, O. Heemken, B. H. Buck & A. Koehler. 2012. Health and growth performance of the blue mussel (*Mytilus edulis* L.) from two hanging cultivation sites in the

German Bight: a nearshore-offshore comparison. *Aquaculture International*. 20, 751-778. doi:10.1007/s10499-012-9501-0

Brooks, N, W. N. Adger & P. M. Kelly. 2005. The determinants of vulnerability and adaptive capacity at the national level and the implications for adaptation. *Global Environmental Change.* 15(2), 151-163. doi:org/10.1016/j.gloenvcha.2004.12.006

Caldeira, K. & M. E. Wickett. 2003. Oceanography: anthropogenic carbon and ocean pH. *Nature*. 425, 365. doi:10.1038/425365[a]

Cardoso, C., H. Lourenço, S. Costa, S. Gonçalves, & M. L. Nunes. 2012. Survey into the seafoodconsumption preferences and pattern in the portuguese population. Gender and regional variability. *Appetite.* 64, 20–31. doi:10.1016/j.appet.2012.12.022

Carpenter, S. R. & L. H. Gunderson. 2001. Coping with collapse: ecological and social dynamics in ecosystem management. Like flight simulators that train would-be aviators, simple models can be used to evoke people's adaptive, forward-thinking behavior, aimed in this instance at sustainability of human–natural systems. *Bioscience.* 51(6), 451–457. doi.org/10.1641/0006-3568(2001)051[0451:CWCEAS]2.0.CO;2

Chesbrough, H. W. 2003. The era of open innovation. *MIT Sloan Management Review*. 44, 35-41.

Chopin, T., 2013. Integrated Multi-Trophic Aquaculture – Ancient, adaptable concept focuses on

ecological integration. *Global Aquaculture Advocate*, 16(2), 16-19.

Cinner, J. E., W. N. Adger, E. H. Allison, M. L. Barnes, K. Brown, P. J. Cohen, S. Gelcich, C. C. Hicks, T. P. Hughes, J. Lau, N. A. Marshall & T. H. Morrison. 2018. Building adaptive capacity to climate change in tropical coastal communities. *Nature Climate Change*. 8, 117-123. doi.org/10.1038/s41558-017-0065-x

Clark, M. S., M. A. S. Thorne, A. Amaral, F. Vieira, F. M. Batista, J. Reis, D. M. Power. 2013. Identification of molecular and physiological responses to chronic environmental challenge in an invasive species: the Pacific oyster, *Crassostrea gigas*. *Ecology and Evolution*. 3(10), 3283–3297. doi:10.1002/ece3.719. 52.

Costa, A. I. A., D. Schoolmeester, M. Dekker & W. M. F. Jongen. 2007. To cook or not to cook: a means-end study of the motivations behind meal choice. *Food Quality and Preference*. 18, 77-88.

Duarte, C., J. M. Navarro, K. Acuña, R. Torres, P. H. Manríquez, M. A. Lardies, C. A. Vargas, N. A. Lagos & V. Aguilera. 2014. Combined Effect of temperature and ocean acidification on the juvenile individuals of the mussel *Mytilus chilensis*. *Journal of Sea Research*. 85,308-314. doi.org/10.1016/j.seares.2013.06.002

Duquette, A., J. B. McClintock, C. D. Amsler, A. Pérez-Huerta, M. Milazzo & J. M. Hall-Spencer. 2017. Effects of ocean acidification on the shells of four mediterranean gastropod species near a $CO_2$ seep. *Marine Pollution Bulletin.* 124, 917-928 (2017). doi:10.1016/j.marpolbul.2017.08.007

Ekstrom, J. A., L. Suatoni, S. R. Cooley, L. H. Pendleton, G. G. Waldbusser, J. E. Cinner, J. Ritter, C. Langdon, R. Van Hooidonk, D. Gledhill, K. Wellman, M. W. Beck, L. M. Brander, D. Rittschof, C. Doherty, P. E. T. Edwards & R. Prtela. 2015. Vulnerability and adaptation of US shellfisheries to ocean acidification. *Nature Climate Change*. 5, 207–214. doi:10.1038/NCLIMATE2508

Falkenberg, L. J. & A. Tubb. 2017. Economic effects of ocean acidification: publication patterns and directions for future research. *Ambio*. 46, 543–553. doi:10.1007/s13280-017-0895-9

Finnoff, D. 2010. Modeling economic impacts of climate change and ocean acidification to fisheries. Working Paper, US Environmental Protection Agency, National Center for Environmental Economics, pp. 11

Fitridge, I., T. Dempster, J. Guenther & R. De Nys. 2012. The impact and control of biofouling in marine aquaculture: a review. *Biofouling*. 28(79), 649-669. doi.org/10.1080/08927014.2012.700478

Gazeau, F., C. Quiblier, J. M. Jansen, J.-P. Gattuso, J. J. Middelburg & C. H. R. Heip. 2007. Impact of elevated $CO_2$ on shellfish calcification. *Geophysical Research Letters*. 34, 1-5. doi:10.1029/2006GL028554, 2007

Gazeau, F., J. P. Gattuso, C. Dawber, A. E. Pronker, F. Peene, J. Peene, C. H. R. Heip & J. J. Middelburg. 2010. Effect of ocean acidification on the early life stages of the blue mussel *Mytilus edulis*. *Biogeosciences.* 7, 2051–2060. doi:10.5194/bg-7-2051-2010

Gaylord, B., T. M. Hill, E. Sanford, E. A. Lenz, L. A. Jacobs, K. N. Sato, A. D. Russell & A. Hettinger. 2011. Functional impacts of ocean acidification in an ecologically critical foundation species. *The Journal of Experimental Biology*. 214, 2586–2594. doi:10.1242/jeb.055939

Grabacki, S. T. 2011. Onboard quality systems. In Environmental effects on seafood availability, safety, and quality. (eds Daczkowska-Kozon, E. G. & P. B. Sun) pp 401. *Chemical and functional properties of food components series*. (Boca Raton: CRC Press, 2011)

Green, M.A., M. E. Jones, C. L. Boudreau, R. L. Moore & B. A. Westman. 2004. Dissolution mortality of juvenile bivalves in coastal marine deposits. *Limnology and Oceanography*. 49, 727–734.

Guenther, J. & R. De Nys. 2006. Differential community development of fouling species on the pearl oysters *Pinctada fucata*, *Pteria penguin* and *Pteria chinensis* (Bivalvia, Pteriidae). *Biofouling*. 22, 163–171. doi.org/10.1080/08927010600691929

Hale, R., P. Calosi, L. McNeill, N. Mieszkowska & S. Widdicombe. 2011. Predicted levels of future ocean acidification and temperature rise could alter community structure and biodiversity in marine benthic communities. *Oikos*. 120, 661–674. doi.org/10.1111/j.1600-0706.2010.19469.x

Hall-Spencer, J. M., R. Rodolfo-Metalpa, S. Martin, E. Ransome, M. Fine, S. M. Turner, S. J. Rowley, D. Tedesco & M.-C. Buia. 2008. Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. *Nature*. 454, 96–99. doi.org/10. 1038/nature07051.

Jokiel, P. L., K. S. Rodgers, I. B. Kuffner, A. J. Andersson & E. F. Mackenzie. 2008. Ocean acidification and calcifying reef organisms: a mesocosm investigation. *Coral Reefs*. 27(3), 473–483. doi.org/10.1007/s00338-008-0380-9

Kirk, M, D. Esler & W. S. Boyd. 2007. Morphology and density of mussels on natural and aquaculture structure habitats: implications for sea duck predators. *Marine Ecology Progress Series*. 346, 179–187. doi: 10.3354/meps07046.

Knudsen, M. P. 2007. The relative importance of interfirm relation- ships and knowledge transfer for new product development success. *Journal of Product Innovation Management*. 24, 117-138.

Kurihara, H., T. Asai, S. Kato & A. Ishimatsu. 2008. Effects of elevated $pCO_2$ on early development in the mussel *Mytilus galloprovincialis*. *Aquatic biology*. 4, 225-233. doi:10.3354/ab00109

Larsen, R., K.-E. Eilertsen & E. O. Elvevoll. 2011. Health benefits of marine foods and ingredients. *Biotechnology Advances.* 29, 508-518. doi:10.1016/j.biotechadv.2011.05.017

Le Moullac, G., C. Soyer, J. Vidal-Dupiol, C. Belliard, J. Fievet, M. Sham Koua, A. Lo-Yat, D. Saulnier, N. Gaertner-Mazouni & Y. Gueguen. 2016. Impact of $pCO_2$ on the energy, reproduction and growth of the shell of the pearl oyster *Pinctada margaritifera*. *Estuarine, Coastal and Shelf Science*. 182, 274–282. doi.org/10.1016/j.ecss.2016.03.011

Logan, C.A. 2010. A review of ocean acidification and America's response. *BioScience* 60, 819–828.

Marshall, N. A. 2010. Understanding social resilience to climate variability in primary enterprise and industries. *Global Environmental Change*. 20, 36-43. doi:10.1016/j.gloenvcha.2009.10.003

Matson, P. G., P. C. Yu, M. A. Sewell & G. E. Hofmann. 2012. Development under elevated $pCO_2$ conditions does not affect lipid utilization and protein content in early life-history stage of the purple sea urchin *Strongylocentrotus purpuratus*. *Biological Bulletin*. 223, 312-327 (2012). doi:10.1086/BBLv223n3p312

McClintock, J. B., R. A. Angus, M. R. Mcdonald, C. D. Amsler, S. A. Catledge & Y. K. Vohra. 2009. Rapid dissolution of shells of weakly calcified Antarctic benthic macroorganisms indicates high vulnerability to ocean acidification. *Antarctic Science.* 21, 449–456. doi:10.1017/S0954102009990198

Michaelidis, B., C. Ouzounis, A. Paleras & H. O. Pörtner. 2005. Effects of long-term moderate hypercapnia on acid-base balance and growth rate in marine mussels *Mytilus galloprovincialis*. *Marine Ecology Progress Series*. 293, 109–118. doi:10.3354/meps293109

Moore, C. 2015. Welfare estimates of avoided ocean acidification in the US mollusk market. *Journal of Agricultural and Resource Economics*. 40(1), 50-60.

Moussa, R. M., M. ElSalhia & A. Khalifa. 2014. Energy storage and allocation of pearl oyster *Pinctada radiata* (Leach, 1814) in relation to timing of pearl seeding. International Journal of Biology and Biological Sciences. 3(5), 53–66.

Mozzaffarian, D. & J. H. Y. Wu. 2011. Omega-3 fatty acids and cardiovacular disease: effects on risk factors, molecular pathways, and clinical events. *Journal of the American College Cardiology.* 58(20), 2047-2067. doi:10.1016/j.jacc.2011.06.063

Narasimhulu, K. V. & J. L. Rao. 2000. EPR and IR spectral studies of the sea water mussel *Mytilus conradinus* shells. Spectrochimica Acta Part A. Molecular and Biomolecular Spectroscopy. 56, 1345-1353. doi:10.1016/S1386-1425(99)00259-0

Narita, D. & K. Rehdanz. 2017. Economic impact of ocean acidification on shellfish production in Europe. *Journal of Environmental Planning and Management*. 60, 500–518. doi:10.1080/09640568.2016.1162705

Navarro, J. M., C. Duarte, P. H. Manríquez, M. A. Lardies, R. Torres, K. Acuña, C. A. Vargas & N. A. Lagos. 2016. Ocean warming and elevated carbon dioxide: multiple stressor impact on juvenile mussels from southern Chile. *ICES Journal of Marine Science*. 73(3): 764-771. doi.org/10.1093/icesjms/fsv249

Orban, E., G. Di Lena, T. Nevigato, I. Casini, A. Marzetti & R. Caproni. 2002. Seasonal changes in meat content, condition index and chemical composition of mussels (*Mytilus galloprovincialis*) cultured in two different Italian sites. *Food Chemistry*. 77, 57–65.

Osores, S. J. A., N. A. Lagos, V. San Martin, P. H. Manriquez, C. A. Vargas, R. Torres, J. M. Navarro, M. J. Poupin, G. S. Saldias & M. A. Lardies. 2017. Plasticity and inter-population variability in physiological and life-history traits of the mussel *Mytilus chilensis*: A reciprocal transplant experiment. *Journal of Experimental Marine Biology and Ecology*. 490, 1-12. doi.org/10.1016/j.jembe.2017.02.005

Plan de Acción Nacional de Cambio Climático (PANCC) 2017-2011. Ministerio del Medio Ambiente.

Penney, R. W., M. J. Hart & N. D. Templema. 2007. Shell strength and appearance in cultured blue mussels *Mytilus edulis*, *M. trossulus*, and *M. Edulis* X *M. trossulus* hybrids. *North American Journal of Aquaculture*. 69, 281–295.doi: 10.1577/A06-044.1

Racotta, I. S., J. L. Ramirez, S. Avila, & A. M. Ibarra. 1998. Biochemical composition of gonad and muscle in the catarina scallop, *Argopecten ventricosus*, after reproductive conditioning under two feeding systems. *Aquaculture*. 163, 111 – 122. doi: 10.1016/S0044-8486(98)00226-9

Reimer, O. & S. Harms-Ringdahl. 2001. Predator-inducible changes in blue mussels from the predator-free Baltic Sea. *Marine Biology*. 139, 959–965. Doi:10.1007/s002270100606

Reimer, O. & M. Tedengren. 1996. Phenotypical improvement of morphological defences in the mussel *Mytilus edulis* induced by exposure to the predator *Asterias rubens*. *Oikos.* 75, 383–390.

Ries, J. B., A. L. Cohen & D. C. McCorkle. 2009. Marine calcifiers exhibit mixed responses to $CO_2$ -induced ocean acidification. *Geology*. 37(12), 1131–1168. doi:10.1130/G30210A.1

Rodolfo-Metalpa, R., F. Houlbrèque, È. Tambutté, F. Boisson, C. Baggini, F. P. Patti, R. Jeffree, M. Fine, A. Foggo, J.-P. Gattuso & J. M. Hall-Spencer. 2011. Coral and mollusk resistance to ocean acidification adversely affected by warming. *Nature Climate Change*. 1, 308-312 . doi:10.1038/NCLIMATE1200

Rodríguez-Astudillo, S., M. Villalejo-Fuerte, F. García-Domínguez & R. Guerrero-Caballero. 2005. Biochemical composition and its relationship with the gonadal index of the black oyster *Hyotissa hyotis* (Linnaeus, 1758) at Espiritu Santo Guld of California. *Journal of Shellfish Research*. 24(4), 975–978. doi:10.2983/0730-8000(2005)24[975:BCAIR]2.0.CO;2

Rossoll, D., R. Bermúdez, H. Hauss, K. G. Schulz, U. Riebesell, U. Sommer & M. Winder. 2012. Ocean acidification-induced food quality deterioration constrains trophic transfer. *PlosOne*. **7**(4): e34737. doi:10.1371/journal.pone.0034737

San Martin, V. A., S. Gelcich, F. Vásquez Lavín, R. D. Ponce Oliva, J. I. Hernández, N. A. Lagos, S. N. R. Birchenough & C. A. Vargas. 2019. Linking social prefences ad ocean acidification impacts in mussel aquaculture. *Nature Scientific Reports*. 9:4719. doi.org/10.1038/s41598-01941104-5

Sarkar, A. & A. Costa. 2008. Dynamics of open innovation in the food industry. Trends in Food Science & Technology. 19(11), 574-580. doi:10.1016/j.tifs.2008.09.006

Sezer, N., Ö. Kılıç, M. Metian & M. Belivermiş. 2018. Effects of ocean acidification on $^{109}$Cd, $^{57}$Co, and $^{134}$Cs bioconcentration by the european oyster (*Ostrea edulis*): biokinetics and tissue-to-subcellular partitioning. *Journal of Environmental Radioactivoty.* 192, 376–384. doi:10.1016/j.jenvrad.2018.07.011

Simard, C., & J. West. 2006. Knowledge networks and the geographic locus of innovation. In Chesbrough, H. W., W. Vanhaverbeke, & J. West (Eds.), Open innovation: Researching a new paradigm (pp. 220-240). Oxford: Oxford University Press

Soto, R. E., J. C. Castilla & F. Bozinovic. 2004. Conducta de forrajeo del gastrópodo *Acanthina monodon* Pallas, 1774 (Gastropoda: Muricidae) en el intermareal rocoso de Chile central. Revista Chilena de Historia Natural. 77(1), 157–175. doi:10.4067/S0716-078X2004000100012.

Soto, R. 1996. Estructura gremial de un ensamble de depredadores de la zona intermareal rocosa en Chile Central. *Investigaciones Marinas*. 24, 97–105.

Shaw, A., S. Sheppard, S. Burch, D. Flanders, A. Wiek, J. Carmichael, J. Robinson & S. Cohen. 2009. Making local futures tangible-Synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. *Global Environmental Change* 19(4), 447-463. doi:10.1016/j.gloenvcha.2009.04.002

Tate, R. D., K. Benkendorff, R. Ab Lah & B. P. Kelaher. 2017. Ocean acidification and warming impacts the nutritional properties of the predatory whelk, *Dicathais orbita*. *Journal of Experimental Marine and Ecology*. 493, 7-13. doi.org/10.1016/j.jembe.2017.03.006 0

Timmins-Schiffman, E., W. D. Coffey, W. Hua, B. L. Nunn, G. H. Dickinson & S. B. Roberts. 2014. Shotgun proteomics reveals physiological response to ocean acidification in *Crassostrea gigas*. *BMC Genomics.* 15, 951- 968. doi.org/10.1186/1471-2164-15-951

Vargas, C. A., N. A. Lagos, M. A. Lardies, C. Duarte, P. H. Manríquez, V. M. Aguilera, B. Broitman, S. Widdicombe & S. Dupont. 2017. Species-specific responses to ocean acidification should account for local adaptation and adaptive plasticity. *Nature Ecology and Evolution.* 1, 84-90. doi:10.1038/s41559-017-0084

Valles-Regino, R., R. Tate, B. Kelaher, D. Savins, A. Dowell & K. Benkendorff. 2015. Ocean warming and $CO_2$-induced acidification impact the lipid content of a marine predatory gastropod. *Marine Drugs*. 13, 6019-6037. doi:10.3390/md13106019

Watson, S. A., P. C. Southgate, P. A. Tyler & L.S. Peck. 2009. Early larval development of the Sydney Rock Oyster *Saccostrea glomerata* under near-future predictions of $CO_2$-driven ocean acidification. *Journal of Shellfish Research* 28(3), 431–437. doi: 10.2983/035.028.0302

Welladsen, H. M., P. C. Southgate & K. Heimann. 2010. The effects of exposure to near-future levels of ocean acidification on shell characteristics of *Pinctada fucata* (Bivalvia: Pteriidae). Molluscan Research. 30(3), 125-130.