PESQUERÍA ARTESANAL POR BUCEO DE PECES DE ROCA EN EL CENTRO NORTE DE CHILE: DIAGNÓSTICO DEL SISTEMA SOCIAL - ECOLÓGICO Y LOS DESAFÍOS PARA SU SUSTENTABILIDAD

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Resumen

En esta Tesis se abordó el problema de la pesquería artesanal por buceo de peces litorales de roca, no regulada, desde una perspectiva de un sistema social-ecológico marino. El estudio incluyó una combinación de elementos empíricos y teóricos derivados de principios ecológicos aplicados para diagnosticar y comprender el funcionamiento de este sistema. El estudio se desarrollo en la costa centro-norte de Chile (ca.18° S – 33° S) donde opera la pesquería. Las capturas de peces litorales de roca las realizan buzos artesanales que utilizan equipo snorkel (resuello) y hookah (compresor de aire) La pesquería cuenta con información sobre desembarques y esfuerzo pesquero, a nivel de especie. Sin embargo, información sobre composición de las capturas, estrategias de pesca, mercado y los potenciales efectos de la pesca por buceo sobre el ensamble de peces, no está disponible. Actualmente no existe ninguna regulación sobre la pesquería por buceo y las poblaciones de peces muestran claros signos de sobre-explotación. Así, para mejorar la comprensión de ésta pesquería artesanal esta tesis incluyó una combinación de elementos empíricos y teóricos aplicados en el diagnostico de la pesquería. Se analizaron aspectos básicos de la pesquería como composición de las capturas de buzos artesanales en un gradiente latitudinal, su valorización económica y el mercado local. Además, se exploraron los factores relacionados con la toma de decisión de los buzos sobre dónde y cuanto tiempo pescar. Finalmente, aplicando teoría ecológica se analizó la dinámica poblacional de dos especies de peces litorales *Graus nigra* (“vieja”) y *Semicossyphus darwini* (“pejeperro”) y la influencia del precio de mercado y el clima como factores exógenos. Los resultados señalan que la pesquería por buceo es una actividad rentable que opera sobre gran parte de la distribución geográfica y hábitats del ensamble de peces litorales de roca. Se registraron variaciones en la composición de las capturas de buzos artesanales por efecto del gradiente latitudinal y el tipo de equipo de buceo utilizado en las capturas. Además, se observó una alta sobre posición de las principales especies capturadas. También las capturas por buceo fueron caracterizadas por la baja representación de especies emblemáticas de mayor tamaño y una alta representación de especies menos emblemáticas y de menor tamaño. Por otra parte, los resultados del capítulo dos muestran que las estrategias de pesca de buzos artesanales fueron influenciada principalmente por las restricciones que les impone el ambiente costero como estado del mar, visibilidad y accesibilidad por sobre el tiempo de viaje y permanencia en los campos de pesca. Finalmente, y de acuerdo a los

resultados la dinámica poblacional de *G. nigra* y *S darwini* estarían influenciados por una combinación de procesos endógenos (e.g. competencia intra-específica) y por efectos de factores exógenos como la pesquería, el mercado y fluctuaciones climáticas. Los modelos predicen que perturbaciones climáticas de gran escala como el evento el Niño influencian de forma positiva y el precio de mercado de forma negativa los índice de abundancia relativa de ambas especies. En conclusión, los múltiples indicadores utilizados en esta Tesis orientan la implementación de estrategias de manejo y conservación para la importante diversidad íctica costera del centro-norte de Chile.

I. Introducción General

Introducción

La pesca artesanal es una importante actividad para las economías locales de países en vías de desarrollo, siendo fuente de ingresos y alimento para millones de personas (Berkes y cols., 2001). Las pesquerías artesanales operan en zonas del intermareal y submareal de ecosistemas costeros. Se describen como pesquerías multí-específicas donde se utilizan una variedad de artes y aparejos de pesca en las capturas. Entre ellos se incluye el buceo, las redes de enmalle, espineles y trampas y el uso de embarcaciones menores (Castilla, 1994, Castilla y Defeo, 2005). A pesar de su importancia socio - económica los problemas de sobreexplotación de recursos que enfrentan las pesquerías artesanales en el mundo y en Chile han sido ampliamente reconocidos (Defeo y Castilla, 2005, Caddy y Seijo, 2005, Andrew y cols., 2007, McClanahan y cols., 2009). Actualmente, numerosas pesquerías costeras se ven enfrentadas al colapso de sus principales recursos, afectando directamente los estilos de vida de las comunidades de pescadores artesanales y adicionalmente el funcionamiento de los ecosistemas (Allison y Ellis, 2001). Esta situación, representa un importante desafío para la planificación de estrategias de manejo y conservación que se adapten a las necesidades del sector artesanal (Johannes, 1998, Castilla y Defeo, 2005).

El manejo de este tipo de pesquería es un proceso complejo que requiere de la integración de información sobre el sistema ecológico (e.g. biología y clima) con los factores socio-económicos e institucionales que afectan al comportamiento de los usuarios (pescadores) y a los responsables de su administración (Seijo y cols., 1997, Defeo y Castilla, 2012, Ortega y cols., 2012). Esta visión holística del sistema, donde los ecosistemas marinos costeros y las sociedades humanas son dos componentes interrelacionados de un sistema social-ecológico marino único, surge en respuesta al desafío de equilibrar el uso y la conservación de los recursos marinos costeros. Tales sistemas incluyen al sub-sistema ecológico (aspectos ecológicos y físicos) y social (aspectos culturales, económicos, políticos y éticos), que operan a través de interacciones y retroalimentaciones interdependientes (Berkes y Folk, 1998, Berkes y cols., 2001). Las pesquerías artesanales operan en zonas costeras interiores las que son reconocidas como áreas de gran relevancia ecológica y económica, pero también como ecosistemas altamente vulnerable al asentamiento humano y al desarrollo de actividades extractivas (Halpern y cols., 2008).

Esta visión del sistema pesquero artesanal como un sistema social-ecológico (Berkes, 2003) incluye metodologías y aproximaciones que permiten acceder a información básica sobre el funcionamiento de la pesquería (e.g. tipos de artes de pesca y el rol del mercado) y sus potenciales efectos sobre el ecosistema, esto último inferido a través del análisis de la composición de las capturas (McClanahan y Mangi, 2004). Este tipo de información enriquecen las inferencias obtenidas del sólo análisis de series de tiempo de índices de abundancia relativa (e.g. capturas por unidad de esfuerzo, CPUE) o desembarques. Por lo tanto, la integración de un amplio rango de consideraciones y fuentes de información (e.g. conocimiento local) mejoran nuestra comprensión del sistema social-ecológico y tienen el potencial de guiar hacia estrategias de manejo sustentables (Berkes y cols., 2001, McClanahan y Cinner, 2008).

En Chile, existe una pesquería artesanal costera interior por buceo de peces litorales de roca que ha operado por lo menos en las últimas cuatro décadas sin ningún tipo de regulación pesquera, a pesar de los diferentes llamados de atención de los científicos sobre su estado de conservación (Moreno, 1972, Fuentes 1981, Fuentes 1985, Pequeño y Olivera, 2005, Godoy y cols., 2010). Las especies explotadas que componen el ensamble de peces litorales habitan principalmente los sectores rocosos del submareal entre los 0 y 30 m. de profundidad, asociados principalmente a bosques de *Lessonia trabeculata* (Villouta y Santelices, 1984, Nuñez y Vasquez, 1987, Perez-Matus y cols., 2008), con una distribución en Chile desde ca. 18° S a 40° S. Este grupo de especies son denominados comúnmente como “peces de roca”, donde se incluyen especies carnívoras y micro-carnívoras tales como la “vieja negra” o “mulato” (*Graus nigra*), “pejeperro” (*Semicossyphus darwini*), “apañao” (*Hemilutjanus macrophthalmos*) y “bilagay” o “pintacha” (*Cheilodactylus variegatus*); omnívoros como el “acha” (*Medialuna ancietae*) y “baunco” (*Girella laevifrons*) y el herbívoro “jerguilla” (*Aplodactylus punctatus*) (Moreno, 1972, Fuentes, 1981, Fuentes, 1982, Cáceres y cols., 1993, Palma y Ojeda, 2002, Medina y cols., 2004, Godoy, 2008). Las especies más emblemáticas del litoral chileno son tres; la vieja negra o mulato, el pejeperro y el acha debido a que alcanzan grandes tamaños y valor comercial (Godoy y cols., 2010).

La pesquería en Chile opera en el centro - norte de Chile (18° S y 30° S) e involucra esencialmente a un subconjunto de buzos artesanales que utilizan arpón de bandas elástica como aparejo de pesca y embarcaciones pesqueras artesanales menores a 10 metros de eslora, equipadas con un sistema de aire comprimido generado por medio de compresor o hooka (Castilla, 1994) y además por un subconjunto de buzos artesanales a snorkel o resuello que operan desde la costa (Godoy, 2008). Actualmente, la pesquería está definida bajo un régimen de libre acceso o acceso abierto y sin restricciones. En Chile el 98% de los desembarques de las principales especies de peces litorales de roca provienen de buceo con arpón de bandas elásticas, aparejo de pesca que no está definido en la Ley General de Pesca y Acuicultura. Un estudio reciente de Godoy y cols. (2010), sugiere que la pesquería por buceo en Chile muestra muy claras señales de sobrexplotación.

La pesquería por buceo de peces litorales de roca cuenta con información sobre desembarques y esfuerzo pesquero, por especie, y precios de mercado desde el año 1992. Sin embargo, esta información no ha sido analizada con el objetivo de evaluar los efectos de la pesquería, el precio de mercado y el clima sobre las dinámicas poblacionales de las especies capturadas, objetivo que fue parte de esta tesis. A pesar de la utilidad de esta información los registros pesqueros oficiales informan los desembarques por especie siendo ésta una pesquería artesanal multí-específica (Godoy, 2008, Godoy y cols., 2010). Por lo tanto, los esfuerzos por mejorar nuestra comprensión de esta pesquería requieren necesariamente de la integración de información empírica sobre el funcionamiento de la pesquería por buceo, que permitan inferir los potenciales impactos sobre el ensamble de peces litorales de roca y enriquecer las inferencias obtenidas desde el análisis de las series de tiempo.

En consecuencia, esta tesis tuvo como objetivo general mejorar el conocimiento de la pesquería por buceo desde una perspectiva holística del sistema. Para ello el estudio incluyó una combinación de elementos empíricos y herramientas teóricas aplicadas en el diagnóstico de ésta pesquería. Un primer análisis evalúo las capturas por buceo artesanal snorkel y hookah "*in situ*" que permitió conocer las especies objetivo de la pesquería e inferir los potenciales impactos del buceo artesanal sobre el ensamble de peces litorales de roca (McClanahan y Mangi, 2004, McClanahan y Cinner, 2008). Esta evaluación también permitió conocer algunos de los aspectos sociales y económicos básicos de la pesquería, tales como: costos y retornos asociados por salida de pesca, precios de mercado y los principales componentes de la demanda local, información útil para conocer la rentabilidad de la actividad pesquera y el rol del mercado en este sistema social – ecológico marino. Por último, esta información fue útil para validar de forma independiente las tendencias observadas en las series de tiempo de desembarques y precio. El área de estudio incluyó un gradiente latitudinal que abarco el centro y norte de Chile. Un segundo análisis incluyó la evaluación de los factores que subyacen en la toma de decisión de los buzos artesanales, en términos de donde y cuanto tiempo bucear. Estudio que fue desarrollado en el norte de Chile y que además incluyó, factores tales como capturas, estado del mar, tiempo de viaje y permanencia en los sitios de pesca (Aswani, 1998, Begossi, 2009). Y finalmente, un tercer análisis que incluyó el diagnostico y modelación de los efectos de la pesquería, los precios de mercado y el clima sobre la dinámica poblacional de dos especies emblemáticas del litoral *G. nigra* y *S. darwini.* Análisis basado en teoría ecológica de dinámica de poblaciones (Lima, 2011, Lima y Naya, 2011) y en series de tiempo de índices de abundancia relativa. El estudio fue divido en tres capítulos:

Capitulo 1: Evaluación empírica de la pesquería artesanal por buceo de peces litorales en el centro-norte de Chile

Hipótesis 1

En el centro-norte de Chile la pesca artesanal por buceo es una actividad pesquera rentable que actualmente opera sobre gran parte de la distribución biogeográfica y hábitats de las especies que componen el ensamble de peces de roca. En consecuencia, se espera que las capturas de buzos artesanales, snorkel y hookah, provenientes de áreas de libre acceso a la pesca incluyan la mayor parte de las especies que componen el ensamble de peces de roca y que la composición de las capturas este influenciada principalmente por efecto regional y por la técnica de buceo empleada. Por último, se espera que la composición de las capturas, se caracterice por la baja representación de las especies emblemáticas mayormente extraídas, y por una mayor representación de especies de menor tamaño, como consecuencia de la sobre-pesca.

Objetivo especifico 1

Evaluar la composición de las capturas obtenidas por buceo artesanal snorkel y hookah, en términos de abundancia y biomasa relativa por especie, en un gradiente regional (latitudinal) en el centro-norte de Chile. Además, de explorar el rol del mercado en el sistema social-ecológico a través de valorizar las capturas e identificar variables tales como origen de la demanda local, costos y retornos económicos asociados a la actividad pesquera.

Capitulo 2: Explorando los factores que subyacen a las conductas de pesca de buzos artesanales en el norte de Chile

Hipótesis 2

La variabilidad observada en las capturas de buzos artesanales (kg por salida de pesca) estaría influenciada principalmente por variables cómo el tiempo de viaje y el tiempo de permanencia en los campos de pesca. Campos de pesca lejanos al lugar de origen del buzo (e.g. ciudad o caleta) mantendrían mayores abundancias de peces litorales que lugares cercanos por efecto de sobre-pesca. En consecuencia, el tiempo de permanencia en los campos de pesca es dependiente del tiempo de viaje. Además, se espera que factores como altura de la ola (estado del mar), claridad del agua de mar y la accesibilidad a los campos de pesca también expliquen parte de la variabilidad observada en las capturas de buzos artesanales. Los buzos artesanales se enfrentan a una geomorfología de la costa norte de Chile que es caracterizada por una alta exposición al oleaje.

Objetivo especifico 2

Evaluar los factores que subyacen en las tomas de decisión de los buzos artesanales snorkel y hookah sobre dónde y cuanto tiempo bucear. Variables tales cómo tiempo de viaje y permanencia en los campos de pesca, altura de ola, claridad del agua de mar y accesibilidad a los campos de pesca serán registradas en cada salidas de pesca.

<u>Capitulo 3:</u> Efectos de la pesquería por buceo, el precio de mercado y el clima sobre la dinámica poblacional de dos especies de peces litorales de roca capturados por buceo artesanal *Graus nigra* (Kyphosidae) and *Semicossyphus darwini* (Labridae) en la costa centro – norte de Chile

<u>Hipótesis 3</u>

La dinámica poblacional de *G. nigra* y *S darwini* estarían influenciados por una combinación de procesos endógenos (e.g. competencia intra-específica) y por efectos de factores exógenos como la pesquería, el mercado y fluctuaciones climáticas. Se espera que las dinámicas de ambas especies exhiban dinámicas dominadas por un proceso de retroalimentación negativa de primer orden, como consecuencia de procesos de competencia intra-específica por alimento y/o territorio. Además, se espera que perturbaciones climáticas de gran escala como el evento el Niño afecten positivamente la tasa per cápita de crecimiento poblacional, dada la afinidad subtropical de ambas especies. Finalmente, se espera que el aumento del esfuerzo pesquero afecte negativamente la tasa per cápita de crecimiento poblacional por la remoción directa de individuos de la población y por los rasgos de historia de vida de las especies.

<u>Objetivo especifico 3</u>

Determinar la influencia de la pesquería por buceo, los precios de mercado y de variables climáticas en las fluctuaciones poblacionales de dos especies emblemáticas de peces de roca en Chile: *Graus nigra* y *Semicossyphus darwini*, mediante el uso de modelos basado en teoría de dinámica poblacional. Los modelos serán parametrizados con series de tiempo de captura por unidad de esfuerzo (CPUE), y que incluyen además, factores exógenos como el clima y los precios de mercado, como proximal del esfuerzo pesquero.

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CAPÍTULO I

II. Evaluación empírica de la pesquería por buceo de peces litorales de roca en la costa centro-norte de Chile

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An assessment of artisanal spearfishing from temperate coastal ecosystems in Chile.

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Abstract

This paper provides a current assessment of the artisanal reef multi-species spearfishery by examining catches of snorkel and hookah divers and basic aspect on local reef fish market in central-north of Chile (18° S -32° S). We assessed 415 snorkel and hookah spearfihing trips between springs 2010 - summer 2011. Results show that artisanal spearfishing activities targets ca. 90% of the most common species in dominant kelp forests, mainly carnivorous fishes. This result suggest that spearfishery in Chile operates over the whole fish assemblage, depth range, body size and the full range of accessibility refuge in the near shore rocky subtidal habitats The analysis of the composition of catches showed that latitude (regional scale) and dive gear type explain most variation observed. The catches show high overlap of reef fish target between gears with a high representation of small fish species and low representations of emblematic large long lived species and high fishing efficiency for hookah gear. Our result showed that artisanal spearfishing is an activity which provides important livelihood alternatives for spear divers. The prices paid by the main local consumers (domestic, middleman and restaurant market) show that spearfishing is a profitable activity. In Chile, during the last four decades the spearfishery has operated without legal regulations despite local scientific awareness that the most important reef fish species are declining or over-exploited. Our result reinforces the need to implement a reef fish management and conservation program. This study provides the first building block in developing a simple gear based management guideline for this South-Eastern Pacific endemic reef fish assemblage. Our aims is that fisheries managers, policymakers and scientist kick-start the discussion on how such a scheme may be designed.

Key words:
Rocky reef fishes; Conservation; Management; Speargun; Local knowledge.

Introduction

Small-scale artisanal fisheries are globally recognized to provide important livelihood opportunities for millions of people in coastal communities (Allison and Ellis, 2001, Berkes et al., 2001, Andrew et al., 2007, Castilla and Defeo, 2001, McClanahan et al., 2009). However, many coastal small-scale fisheries face resource declines that lead to social-ecological problems. In general, in marine artisanal fisheries there is a low level of investment in monitoring and enforcement (Defeo and Castilla, 2005) and so there is a challenge to gather the information needed to develop sustainable management schemes (Salas et al., 2007).

Small-scale artisanal reef/rocky fisheries are generally multispecific and use fishing gears, such as spearguns, hook and line, gill nets and traps (McClanahan and Cinner, 2008). It is important to understand the effects of different fishing gears on coastal reef assemblages because it opens the possibility to integrate catch composition data with scientific monitoring and traditional ecological knowledge, as a way to develop adaptative management tools (McClanahan and Cinner, 2008, and Cinner et al., 2009). In many countries artisanal spearfishing is an important component of the overall reef fishing effort (Bohnsack, 1982, Guillet and Moy, 2006, Meyer, 2007, Godoy, 2008).

Spearfishing usually targets fish species that are long living, top predators, and have low reproductive output (Dulvy et al., 2003, Sadovy et al., 2003 and Cheung et al., 2007). Additionally, some reef fish species show complex life history traits, such as, hermaphroditism (Hamilton et al., 2012) and spatial aggregations for spawning (Cowen, 1990, Sala et al., 2001, and Hamilton et al., 2007), which may increase its vulnerability to visual fishing gear. Recent studies on coastal reef fish have shown that spearfishing has the potential to diminish fish abundance, alter fish behaviour, and modify age-structure, which may induce severe changes in fish communities (Sluka and Sullivan, 1998, Harmelin et al., 1995, Jouvenal and Pollard, 2001, Lowry and Suthers, 2004 Cinner et al., 2006, Lloret et al., 2008 and Feary et al., 2011).

The effects of speargun on fish diversity, richness, functional groups and size structure of catches, has provided the basic understanding of the impacts on fish assemblages and ecosystems (Sluka and Sullivan, 1998, Guillet and Moy, 2006, Meyer, 2007, and McClanahan and Mangi, 2004). In this way, information on catch compositions , coupled with the natural history of reef fishes, market access, human population density and governance rules, have represented the starting point for developing management policies (McClanahan and Cinner, 2008, Brewer et al. 2012). Information on catch composition of artisanal spearfishing in the South-Eastern Pacific temperate coastal ecosystems is scarce (Godoy et al., 2010). For instance, in Chile an unregulated spearfishery has operated for more than 40 years with no published information on speargun catch composition or on the possible impacts on rocky fish assemblages and coastal ecosystem (Godoy et al., 2010).

In this context, this study presents the first thorough analysis of the Chilean artisanal rocky reef spearfishery, aimed to assess the basic aspect of social-ecological system. Currently, artisanal spearfishing operates on most the biogeographic distribution and habitats of reef fish species. Therefore, we expected that artisanal composition catches include a high number of species that composite the reef fish assemblage. The artisanal spearfishing catch composition is influenced mainly by regional effect and dive technique used in fishing activities. Finally, we expected that catch composition is characterized by the low representation of emblematic reef fish species, and higher representation of smaller species as a result of overfishing. Overall, this study provides basic information on the magnitude and impact of spearfishing on reef fishes in Chile as a way to initiate policy discussions aimed to set the bases for management policies.

Materials and methods

Research setting

Small-scale artisanal fishers in Chile are organized around coastal areas, which are officially designated as "caletas" (coves). These are strips of land above the high tide market that are granted to fisher communities as a concession by the State and provide the rights for users to have access to the landing of boats and to erect certain buildings (Gelcich et al., 2005). Artisanal spearfishing is mainly conducted in central and northern Chile, along *ca*. 2015 km of coastline (Fig. 1), where currently located there are 115 caletas. The Chilean National Artisanal Fishery Registry (Registro Pesquero Artesanal, RPA) shows that currently there are 2978 registered spear divers. Inshore coastal ecosystems in the temperate region of Chile support spearfishing activities with the use of snorkeling and hookah (semi-autonomous) diving equipment to extract reef fishes. Snorkel divers operate from the shore, while hookah divers operate from small wooden or fiberglass boats. The spearfishery operates upon an endemic southern temperate Pacific fish assemblage (Ojeda et al., 2000), without management regulations on minimum size limit, sexual maturity or reproductive periods. Seven species of reef fishes are mainly extracted in Chile (Godoy, 2008). The three largest and more emblematic are: the "vieja negra", *Graus. nigra*; the "pejeperro" or sheephead, *Semicossyphus darwini*; and the "acha", *Medialuna ancietae*. In the last decade, artisanal speargun was the dominate gears over total landing (TL) of *S. darwini* (98%, TL) , *G. nigra* (98%, TL), *M. ancietae* (99.1%, TL), *Pinguipes chilensis* (92%, TL); *Aplodactylus punctatus* (53%, TL) and; *Cheilodactylus variegatus* (66 %, TL). (SERNAPESCA 1997-2010; north-central Chile). Thus, the Chilean spearfishery provides a unique scenario to assess selectivity of artisanal speargun on reef fish assemblage in a temperate coastal ecosystem.

Sites selection and sampling.

We conducted fieldwork during springs 2010 and summer 2011, covering the XV (18°S) and V administrative Regions (30°S) of Chile, where most of the spearfishing activities occur (Fig. 1). Catch composition and basic reef fish market information were obtained by direct evaluation of artisanal spearfishing catches and interviews of spear divers returning from fishing trips. We followed a total of 415 snorkel and hookah spearfihing trips. On these trips spear divers collected 6188 fish specimens. Artisanal catch composition was evaluated as fish species richness, size, length, weight and abundance of target fish species. Fish length was obtained using a measuring board (cm) and weight was estimated with a dynamometer (10 ± 0.2 kg). Each fish was identified to species level (Moreno and Castilla, 1975). The entire hookah and snorkel catches were sampled and when this was not possible, the information was eliminated for further analysis. Additionally, frequency of trips, diving time, depth, cost and income per trip (1 US$ ~ 500 Chilean peso) and fish demand, also were registered. Fishing activities were generally undertaken in shallow-water (< 30 m depth) mostly in *Lessonia trabeculata* kelp-forest dominated ecosystems. Catches recorded were obtained exclusively from open-access areas. Catch data from partially protected areas managed through Territorial User Right for Fisheries (TURFs) policies (Gelcich et al., 2009) were not sampled in this study. Artisanal spearfishing activity is not common inside MEABRs as fisher organizations restrict diving to stop illegal poaching of *Concholepas concholepas* and key-hole limpets. This restriction is due to the lack of trust between fishers, as spear-gun divers could poach on benthic resources. This establishes very strict de facto diver access regulations (Gelcich et al., 2008).

Two approaches were used to quantify information of the spearfishery: (1) Hookah data: We used official reef fish landing information (SERNAPESCA 1992-2011) to select the study sites and identified two coves in each Region with relatively high reef fish landings, except in Arica were only one cove was sampled. Selected coves were: Caleta Camarones (Arica); Caleta Los Verdes and Puerto Iquique (Iquique); Caleta La Chimba and Caleta Constitución (Antofagasta); Caleta Pan de Azúcar and Caleta Chañaral de Aceituno (Caldera); Caleta Hornos and Caleta Los Choros (Coquimbo) and; Caleta Algarrobo and Caleta Maitencillo (Valparaiso). Initially we visited each cove to explore the fishery system and also to identify local active hookah spear divers. Once identified, we asked for permission to conduct our assessments based on their catches. Data was collected over 2-3 week periods in each cove. In some cases, this time was extended up to 4 weeks because sea conditions did not allow fishing trips. A total of 183 hookah spear fishing trips were assessed (2) Snorkel data: We identified snorkel artisanal divers through the Federación Chilena de Deportes Subacuáticos (FEDESUB), since many of these divers also compete in recreational championships. In Chile, there are approximately 600 registered recreational snorkel divers. We visited each regional association affiliated to FEDESUB and identified potential artisanal snorkel divers for our study. Once identified, we asked for permission to conduct assessments based on their catches. We assessed ten snorkel fishers in each Region. Snorkel divers operate from the shore and usually move in groups of 3-4 divers by land, using vehicles, to reach fishing grounds. Data were collected over 2-3 week periods for each site selected and a total of 232 trips from snorkel divers were assessed. Artisanal catch records were taken by a group of field assistants (2-4) who visited each region included in this study. This group was subdivided in 2 teams which, in each region, recorded simultaneously a) snorkel and b) hookah divers catch.

Statistics analysis

Multivariate analysis

The similarities between composition catches in latitude and dive gear (based of relative abundance and biomass of reef fish in catches) were assessed with multivariate approaches. We used the statistical software P.R.I.M.E.R. (Plymouth Routines in Multivariate Environmental Research; Clark & Warwick, 2001) to perform multivariate analysis on spear catch compositions. We applied the Bray-Curtis index for similarity to untransformed data set to conduct a cluster analysis. The group average linkage technique was used to form clusters of similar catch that gave similar responses. Subsequently, we used a similar matrix derived from the data set to generate a multidimensional scaling (MDS) ordination plot that represented in two dimensions the similarity between catch compositions made by latitude. Differences in the catch compositions made for latitude and dive gear were tested *a priori* for significance with the PERMANOVA procedure (two-way analysis for similarity; Clarke, 1993). We used similarity percentages analysis (SIMPER) to identify those reef fish species accounting for the largest differences in catch composition.

Univariate analysis

Differences between dive gear aspect, such as, capture per unit effort, composition of catch, number of fish per species, fishing effort, depth and time of diving, cost per trip and income per trip, were compared using *t* test methods and non parametric Mann-Whitney U test (Sokal and Rolf, 1995).

Results

Catch Composition

Relative fish abundance contribution

The artisanal reef spearfishing catch composition included 22 fish species from 15 families (Fig 2). The families Cheilodactilidae, Serranidae and Pinguipidae were the best represented in the catches. Two target species, *Seriola lalandi,* was truly pelagic, while the rest were inner-shore rocky or demersal fish species. The rocky fishes *Seriola lalandi*, *Cilus gilberti*, *Anisotremus scapularis*, *Medialuna ancietae* and *Paralichthys microps*, were exclusively captured by snorkel fishers. Three carnivorous fishes made up 50% of the total catch with both dive gears: *Cheilodactylus variegatus* (34.14%), *Pinguipes chilensis* (20.5%) and *Paralabrax humeralis* (14.3%). On the other hand, hookah divers catches were composed mainly by *Cheilodactylus variegatus* (39%), *Pinguipes chilensis* (17 %) and *Hemilutjanus macrophthalmos* (13.3%). The emblematic species, *Graus nigra*, *Semicossyphus darwini* and *Medialuna ancietae* showed low representation in catches (< 5.8%).

Relative fish weight contribution

The species showing the major contribution by snorkel divers, in terms of weight, were the carnivorous *Ch. variegatus* (23.8%), *P. chilensis* (17.3%), *G. nigra* (13.2%) and *P. humeralis* (11.6%). The hookah divers catches were composed mainly by the carnivorous fish species *Ch. variegatus* (25.6%), *S. darwini* (14.3%), *G. nigra* (12.7%), *G. chilensis* (12,7%), *P. chilensis* (11.8%), and *H. macrophtalmos* (10.5%).

Comparison of catches compositions based in relative abundance

Catch composition, in term of relative abundance, differed significantly between latitude (MDS: R^2= 0.32, PERMANOVA: F= 18.21, P < 0.001, Fig. 3) and dive gear (MDS: R^2= 0.26, PERMANOVA: F= 33.74, P < 0.001, Fig. 3). The interaction between latitude and dive gears were significant (F = 0.12, P < 0.001). SIMPER analysis showed that five species accounted for ~ 70% of the differences: *Ch variegatus, P. chilensis, H. macrophthalmos*, *P. humeralis* and *S. darwini.* The relative abundance of *H. macrophthalmos*, *P. humeralis* and *S. darwini* in catches showed a decrease toward high latitude. *Ch. variegatus* remain similar abundance through latitudinal range. Finally, relative abundance of *P. chilensis* increase to high latitude (Fig 4).

Univariate analysis showed that with the exception of *P. humeralis* and *P. chilensis*, the relative abundance of all targeted species showed significantly differences between dive gears. The hookah diver catches showed higher densities of all five reef fish species analyzed (Table 1).

Comparison of catches compositions based in relative biomass

Catch composition, in term of relative biomass, differed significantly between latitude (MDS: R^2= 0.24, PERMANOVA: F= 14.4, P < 0.001, Fig. 5) and dive gear (MDS: R^2= 0.29, PERMANOVA: F= 38.05, P < 0.001, Fig. 5). The interaction between latitude and dive gears was not significant (P > 0.05). SIMPER analysis revealed that five fish species accounted for ~ 68% of the difference: *Ch. variegatus*, *S. darwini*, *G. chilensis*, *P. chilensis* and *G. nigra*. The relative weight contribution of *S. darwini*, *Graus nigra* and *Genypterus chilensis* in catches was high at 27° S (Caldera, Atacama Region). *Ch. variegatus* remain similar weight contribution through latitudinal range and *P. chilensis* increase to high latitude (Fig 6).

Univariate analysis showed that the relative biomass of targeted species were significantly different between dive gears. Hookah divers catches showed the greatest biomass for seven fish species analyzed (Table 1).

Spear fishery parameters

Catch per Unit Effort

Catch per unit effort (CPUE), measured as kilograms of rocky fish extracted per hour was significantly greater for hookah than for snorkel divers (t = 3.6, P < 0.001). A total of 183 fishing trip of hookah divers extracted 10.89 ± 4.56 kg^{-1} hr^{-1}, compared with 6.98 ± 3.11 kg^{-1} hr^{-1} for 232 trip of snorkel divers (Fig 7A).

Richness of catches

The average of fish richness did not show significant differences between diving gears (t = 1.23, P > 0.05): hookah divers caught 4.9 ± 1.9 different fish species per trip while the snorkel divers caught 4.58 ± 1.72 species per trip (Fig. 7B).

Effort (spearfihing trip month^{-1}) and depth performance.

The average number of trips per month by hookah fishers showed no significant differences when compared with snorkel divers (t = 0.68, P > 0.05): hookah divers showed 12.12 ± 5.2 $trip^{-1}$ $month^{-1}$ and snorkel divers 15.02 ± 6.4 $trip^{-1}$ $month^{-1}$ (Fig. 7C). On the other hand, hookah divers fished 4.7 ± 1.3 hours per trip, while snorkel divers fished 4.5 ± 1.5 hours per trip (t = 1.04, P > 0.05; Fig. 7D). The depth at which both type of divers fished was significantly different (t = 4.11, P < 0.01): hookah dive at depths of 23.9 ± 3.60 m^{-1} $trip^{-1}$, while snorkel at depths of 13.93 ± 2.88 m^{-1} $trip^{-1}$ (Fig 7E).

Fish price, income and cost

The local commercial value of rocky fishes ranged between US$ 2,5 and US$ 6 per kilograms, with an average the US$3.5 kg^{-1} $fish^{-1}$ Locally, the fish species that are considered of higher quality is called "*fino*" and includes: *G. nigra*, *S. darwini*, *M. ancietae*, *H. macrphtalmos*, *O. insignis, G. chilensis* and *P. adpersus*. The lower quality fish species are locally called "*molido*" and includes: *C. variegatus*, *P. chilensis*, *P. humeralis*, *A. scapularis* and *A. punctatus*.

Average economic income per cápita per fishing trip was not significantly different between both diving gears (*t* = 2.57, *P* > 0.05; Fig. 7F): Hookah divers earned 103 to 243.1 ± US$ gross per trip; this income is generally divided into three parts: a) one for vessel owner, b) one for the diver c) one for the diving assistant (details in Castilla 1994). Therefore, hookah divers earned 91.3 ± 75.4 US$ per cápita per trip. Snorkel divers earned 85.4 ± 66.3 US$ gross per trip. This income is individual. Costs associated with the fishing trip showed not significant differences between dive gears (*t* = 3. 16, *P* > 0.05; Fig. 7G). The costs associated with hookah divers included fuel, oil lubricants for outboard engine and air compressor. Snorkel divers only have the costs of fuel for terrestrial transport. In this study the maintenance cost of vessel and vehicle were not considered. Hence, the cost associated per cápita per trip for hookah divers was 28.01 ± 9.11 US$ per trip, and for snorkel divers was 20.11 ± 8.54 US$ per trip (Fig 7G).

Local reef fish buyers

Results show that local fish buyers for rocky fish catches is concentrated by restaurants and middlemen (Fig 7H). Hookah divers generally sell their catch to middlemen (89%), and about 11% is directly sold to restaurants. The middleman reduces the time and effort needed by hookah divers to market their catches. For snorkel divers the pattern is the opposite, since they sell catch mainly to restaurants (61%) and 39% to the middlemen. Further, snorkel divers often filleted fish catches to sell it to restaurants with an additional value over the price of middlemen.

Total length, weight and Catch per Unit Effort for fish species

The snorkel spear fishing in Chile caught fishes with mean length of 34.1 cm for *Ch. variegatus* to 87.1 cm for *G. chilensis*. For hookah divers the fish mean length was 32.9 cm for *Ch. variegatus* to 83.3 cm for *G. chilensis* (Table 2). The main difference were observed in *G. nigra* which averaged a length of 48.1 ± 10.7 cm for snorkel and 57.6 ± 9.9 cm for hookah (*t* = - 3.05, *P* < 0.001); *H. macrophthalmos*: 38.2 ± 8.2 cm for snorkel and 29.4 ± 3.9 cm for hookah (*t* = 2.98, *P* < 0.001); and *P. adpersus*: 56.6 ± 32.2 cm for snorkel and 70.8 ± 9.0 cm for hookah (*t* = - 4.21, *P* < 0.001; Table 2).

For snorkel divers, the fishes mean weight ranged from 0.67 kg for *C. variegatus* to 3.18 kg for *G. chilensis*. For hookah divers mean weight ranged from 0.55 kg for *P. chilensis* to 4.04 kg for *G. nigra*. The main difference were observed in *G. nigra*: 2.73 ± 1.60 kg for snorkel and 4.04 ± 1.64 kg for hookah divers (t = - 4.01, $P < 0.001$); *H. macrophthalmos*: 1.12 ± 0.76 cm for snorkel and 0.56 ± 0.24 cm for hookah divers (t = 3.19, $P < 0.001$); and *P. adpersus*: 2.2 ± 1.12 cm for snorkel and 3.4 ± 0.92 cm for hookah divers (t = - 3.52, $P < 0.001$ (Table 2).

For snorkel divers, the CPUE for species fluctuates between 0.08 k $fisher^{-1}$ hr^{-1} for *M. ancietae* and 1.68 k $fisher^{-1}$ $trip^{-1}$ (*C. variegatus*). For hookah divers, the CPUE ranged from 0.002 kg $fisher^{-1}$ hr^{-1} for *G. laevifrons* to 3.96 kg $fisher^{-1}$ hr^{-1} for *C. variegatus* (Table 2). The main differences were observed for *G. nigra* (U = 1773, $P < 0.001$); *S. darwini* (U = 1832, P = 0.02); *H. macrophthalmos* (U = 1345, $P < 0.05$); *Ch. variegatus* (U = 1467, $P < 0.001$) and; *G.chilensis*: (U = 1237, $P < 0.001$, Table 2)

Discussion

This is the first study assessing the Chilean artisanal reef fish spearfishery by examining selectivity of snorkel and hooka speargun divers. The study provides insights on the potential impact of the fishery on reef fish assemblages. Our results show that in Chile spearfishing is an activity which provides important livelihood alternatives for fishers along ~ 2000 km of coast. In addition, this fishery exploits almost 90% of the species in coastal reef fish assemblages (Villouta and Santelices, 1984, Nuñez and Vásquez, 1987, and Perez-Matus et al., 2007).

The analysis of catch composition suggests that spearfishery in Chile operates over the most biogeographic distribution of fish assemblage, sizes and depth ranges in near shore reef subtidal habitats. Our results suggest that variability of composition catches would be influenced mainly by latitude and dive gears. The composition caches showed a latitudinal trend. Some reef fish species with warm affinities as *S. darwini*, *H. macrophthalmos*, *and P. humeralis* (Ojeda et al. 2010) show a decrease in their abundance toward high latitude. Probably due to the southern limits of distribution these fish species (Ojeda et al, 2010). On the other hands, relative abundance in the catches of reef fish species whose distributions extends to 40 ° S as *P. chilensis* and *Ch. variegatus* showed an increase and maintained toward high latitude. Our results suggest that the biogeographic affinities of these warm - temperate reef fish assemblage would be explain in part the variability observed in catch composition.

Our results also suggest that dive gears would be influence the composition of catches. Some specific differences among the two diving gears were observed. Hookah divers caught reef fishes in deeper water (e.g. *G. maculatus*) and snorkel divers in shallower water (e.g. *M. ancietae*). This suggests that there is currently a moderate bathymetric partitioning of resources among the different diving gears (McClanahan and Cinner 2008). However, our result also show a consistent pattern between gears with a high representation of small fish species and low representations of emblematic large long lived species. We hypothesize that this tendency in catch compositions is a symptom of the population decline of the emblematic reef fish species, which as Godoy et al (2010) suggested have been substituted by smaller sized reef fish species. This tendency has been reported for reef fisheries elsewhere (Jennings and Polunin, 1996, Pauly et al., 1998, and McClanahan and Hicks, 2011). Anecdotal evidence for Chile indicates that in the past *O. insignis* was the substitute of higher economic value reef fish such as *M. ancietae*. Currently, *Ch variegatus* would be a substitute for most of the other high value reef fish species (i.e. *G. nigra, S. darwini*).

Species richness of catches was relatively low when compared with the high diversity of landings reported for tropical coastal ecosystems (McClanahan and Cinner, 2008 and Gillet and Moy, 2006). However, the mean of artisanal CPUE in Chile (hookah divers 10.89 ± 4.56 k^{-1} hr^{-1} and 6.98 ± 3.11 k^{-1} hr^{-1} for snorkel divers) was higher than the mean artisanal spearfishing findings from elsewhere on tropical coastlines, such as Pacific Island (2.20 ± 0.17 k^{-1} hr^{-1} by SCUBA divers and 0.64 ± 0.10 k^{-1} hr^{-1} by snorkel divers, [Page, 1998] and 1.2 k^{-1} hr^{-1}, [Dalzell, 1996]), Hawaiian reef (1.13 k^{-1} hr^{-1}, [Meyer, 2007]), and the mean spearfishing CPUE in Mediterranean reef (1.36 k^{-1} hr^{-1}, [Lloret et al., 2008]). Importantly, the impact of relatively high CPUE associated with market pressures can lead to the overexploitation of reef fish populations (Cinner and McClanahan 2006, McClanahan 2006). Although this study did not investigate the specific factors that lead people to engage in fishing as a livelihood strategy, our assessment suggests that artisanal spearfishing would play an important economic and social role in the artisanal fisheries sector. The prices paid by the consumers (domestic, middleman and restaurant markets) show that spearfishing is a profitable activity. We estimate that the net economic revenue of spearfishing ranges between US\$800 $month^{-1}$ and US\$1400 $month^{-1}$. Thus the income received by a spear fisher is two to three times higher than the Chilean current minimum wage (US\$ 400 $month^{-1}$). These results suggest the need to improve our understanding of reef food fish trade and the development of local markets with artisanal speargun catches in order to design management strategies for reef fish assemblages.

During the last four decades, spearfishing in Chile had operated without legal regulations despite of local awareness that the most important reef fish species are declining (Moreno, 1972, Fuentes, 1981, Fuentes, 1985, Pequeño and Olivera, 2005, and Godoy et al., 2010). For example, our estimates of CPUE for the sheephead *S. dawini* in the northern Chilean was around 0.47 kg^{-1} hr^{-1} and 2.22 kg^{-1} hr^{-1} for snorkel and hookah fishers, respectively; while 25 years ago the CPUE for snorkel divers ranged from 10 to 15 kg^{-1} hr^{-1} (Fuentes, 1985). Unfortunately, subtidal ecological information in Chile is scarce, which makes it very difficult to assess the historical effects of reef fish harvest activities. However, spear fishing in Chile has the potential to change reef fish abundance (Gelcich et al., 2008; Gelcich et al 2012), body size and behavior (Jouvenel and Pollard, 2001, Feary et al., 2011, and Januchowski-Hartley, et al., 2011) and could drive some species toward local extinction (Sadovy et al., 2003). Also, spear fishing could potentially reduce rates of carnivore predation and lead towards a dominance of the benthos by invertebrate prey (Ory et al., 2012). Theoretical based models and experimental approaches will be needed to include these factors for determining the relative importance of spear fishing and environmental factors in shaping the dynamics of these fish populations.

Despite spatial and temporal sampling limitations, our results are in close agreement with previous studies assessing the current state of the spear fishery based on local ecological knowledge and other sources of information which signal overfishing through spearfishing (Godoy et al., 2010). The empirical evidence presented in this study reinforces the need for implementing in Chile a reef fish management program. A starting point could be the development of an adaptive gear based management framework (McClanahan and Mangi, 2004, and McClanahan and Cinner, 2008). This approach has been shown to have high compliance and significant effects on improving reef fish biomass on tropical ecosystems (Cinner et al., 2005). Results presented in this paper provide the first building block to develop a simple gear based management guideline for this South-Eastern Pacific endemic reef fish assemblage. It is critical that fisheries managers, policymakers and scientist start the discussion of how such a scheme could be designed.

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Tables

Table 1. Comparison between diving gears on the relative abundance and relative weight for species in the catches.

	Relative Abundance (n° fishes per trip)				Relative Weight (kg per trip)			
	Average (SD)				Average (SD)			
Species	Snorkel	Hookah	U-test	*p*-value	Snorkel	Hookah	U-test	*p*-value
Graus nigra	1.5 (1.79)	2.35 (1.71)	1702.5	**0.001**	3.74 (4.01)	7.85 (6.10)	1445	**<0.001**
Semicosyphus darwini	0.5 (0.91)	3.51 (4.03)	1367	**<0.001**	1.88 (3.50)	8.89 (9.58)	1464	**<0.001**
Hemilutjanus macrophthalmos	2.42 (3.76)	8.03 (12.98)	1992.5	**0.044**	2.58 (4.24)	6.48 (10.12)	1981	**0.039**
Cheilodactylus variegatus	9.84 (7.69)	22.72 (18.71)	1421	**<0.001**	6.75 (4.80)	15.88 (13.97)	1531.5	**<0.001**
Aplodactylus punctatus	0.78 (2.22)	2.32 (4.34)	2121.5	**0.044**	0.67 (1.90)	1.56 (3.40)	2242	0.180
Medialuna ancietae	0.08 (0.28)	0.00 (0.00)	-	-	0.33 (1.51)	0.00 (0.00)	-	-
Oplegnathus insignis	0.28 (0.97)	0.30 (1.78)	2316	0.167	0.23 (0.85)	0.36 (2.38)	2316	0.167
Acanthistius pictus	1.07 (3.16)	1.41 (4.72)	2301	0.299	1.20 (3.95)	1.26 (4.50)	2326.5	0.378
Genypterus chilensis	0.14 (3.16)	2.65 (3.33)	1181	**<0.001**	0.39 (1.75)	7.85 (9.60)	1162	**<0.001**
Genypterus blacodes	0.12 (0.76)	0.48 (2.80)	2348	0.263	0.27 (1.62)	0.36 (1.51)	2384	0.437
Paralabrax humeralis	4.11 (5.76)	4.94 (10.24)	1942	**0.018**	3.31 (4.14)	3.03 (6.69)	1829.5	**0.004**
Paralichthys adpersus	0.45 (1.59)	0.38 (0.73)	2357.5	0.601	0.58 (1.38)	1.16 (2.46)	2324	0.466
Paralichthys microps	0.07 (0.26)	0.00 (0.00)	-	-	0.14 (0.66)	0.00 (0.00)	-	-
Pinguipes chilensis	5.91 (3.94)	10.25 (10.51)	2087.5	0.128	4.91 (3.35)	7.29 (7.00)	2147.5	0.206
Girella laevifrons	1.28 (2.94)	0.01 (0.12)	1812	**<0.001**	1.23 (3.02)	0.02 (0.16)	1849	**<0.001**
Anisotremus scapularis	0.14 (0.49)	0.00 (0.00)	-	-	0.07 (0.26)	0.00 (0.00)	-	-
Labrisomus philippii	0.07 (0.31)	0.00 (0.00)	-	-	0.09 (0.35)	0.00 (0.00)	-	-

Table 2. Average total length,weight and CPUE for reef fish species caught by spearfishers.

	TOTAL LENGTH (cm)		TOTAL WEIGHT (kg)		CPUE (kg fisher^{-1}hr^{-1})	
	Average (SD)		Average (SD)		Average (SD)	
Species	Snorkel	Hookah	Snorkel	Hookah	Snorkel	Hookah
Graus nigra	48.12 (10.70)	57.64 (9.88)*	2.73 (1.60)	4.04 (1.64)*	0.93 (1.0)	1.96 (1.52) *
Semicossyphus darwini	50.71 (10.83)	47.86 (8.11)	2.93 (1.74)	2.04 (1.16)	0.47 (0.87)	2.22 (2.39) *
Hemilutjanus macrophthalmos	38.19 (8.20)	29.36 (3.85)*	1.12 (0.76)	0.56 (0.24)*	0.64 (1.06)	1.61 (2.52) *
Cheilodactylus variegatus	34.08 (3.83)	32.89 (3.15)	0.67 (0.21)	0.56 (0.15)	1.68 (1.2)	3.96 (3.49) *
Aplodactylus punctatus	35.17 (3.56)	37.11 (1.36)	0.77 (0.18)	0.78 (0.13)	0.16 (0.47)	0.39 (0.84)
Medialuna ancietae	56.8 (16.09)	NR	4.5 (3.71)	NR	0.08 (0.37)	NR
Acanthistius pictus	36.00 (1.41)	39.04 (2.58)	0.89 (0.07)	1.08 (0.14)	0.30 (0.98)	0.31 (1.25)
Genypterus chilensis	87.12 (28.74)	83.33 (22.98)	3.18 (2.05)	3.07 (1.64)	0.09 (0.43)	1.96 (2.39) *
Paralabrax humeralis	39.53 (0.98)	37.56 (3.34)	0.98 (0.43)	0.81 (0.19)	0.82 (1.03)	0.75 (1.67)
Paralichthys adpersus	56.57 (32.22)	70.80 (9.00)*	2.2 (1.12)	2.9 (0.92)	0.14 (0.34)	0.29 (0.61)
Pinguipes chilensis	38.48 (3.64)	34.67 (4.77)*	0.79 (0.25)	0.55 (0.26) *	1.22 (0.83)	1.82 (1.74)
Girella laevifrons	36.90 (2.05)	40.00 (1.63)	1.13 (0.21)	1.33 (0.28)	0.30 (0.75)	0.002 (0.03)

Figures

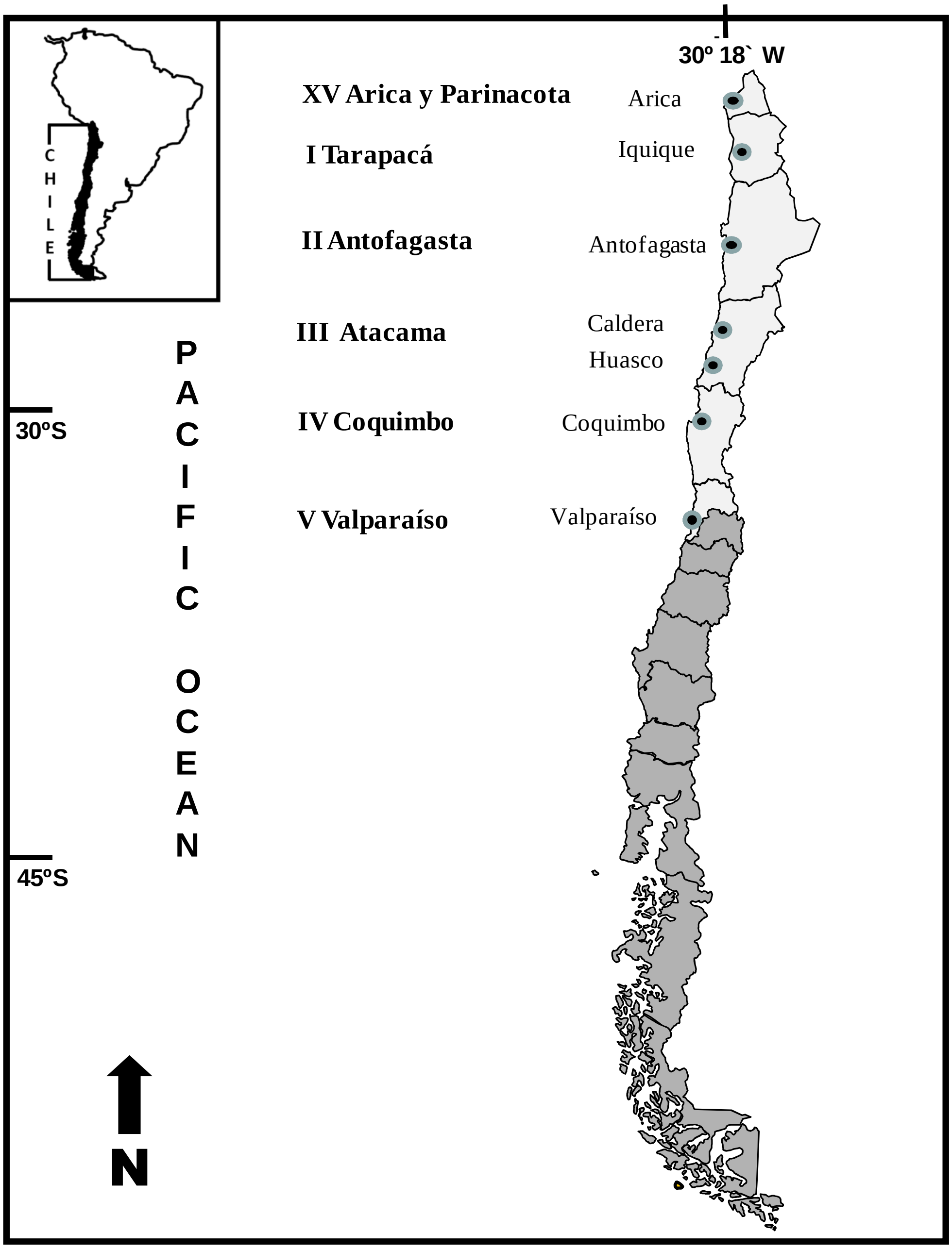

Fig. 1. Map of the study area in central – north Chile showing the administrative region and cities where assessments were made.

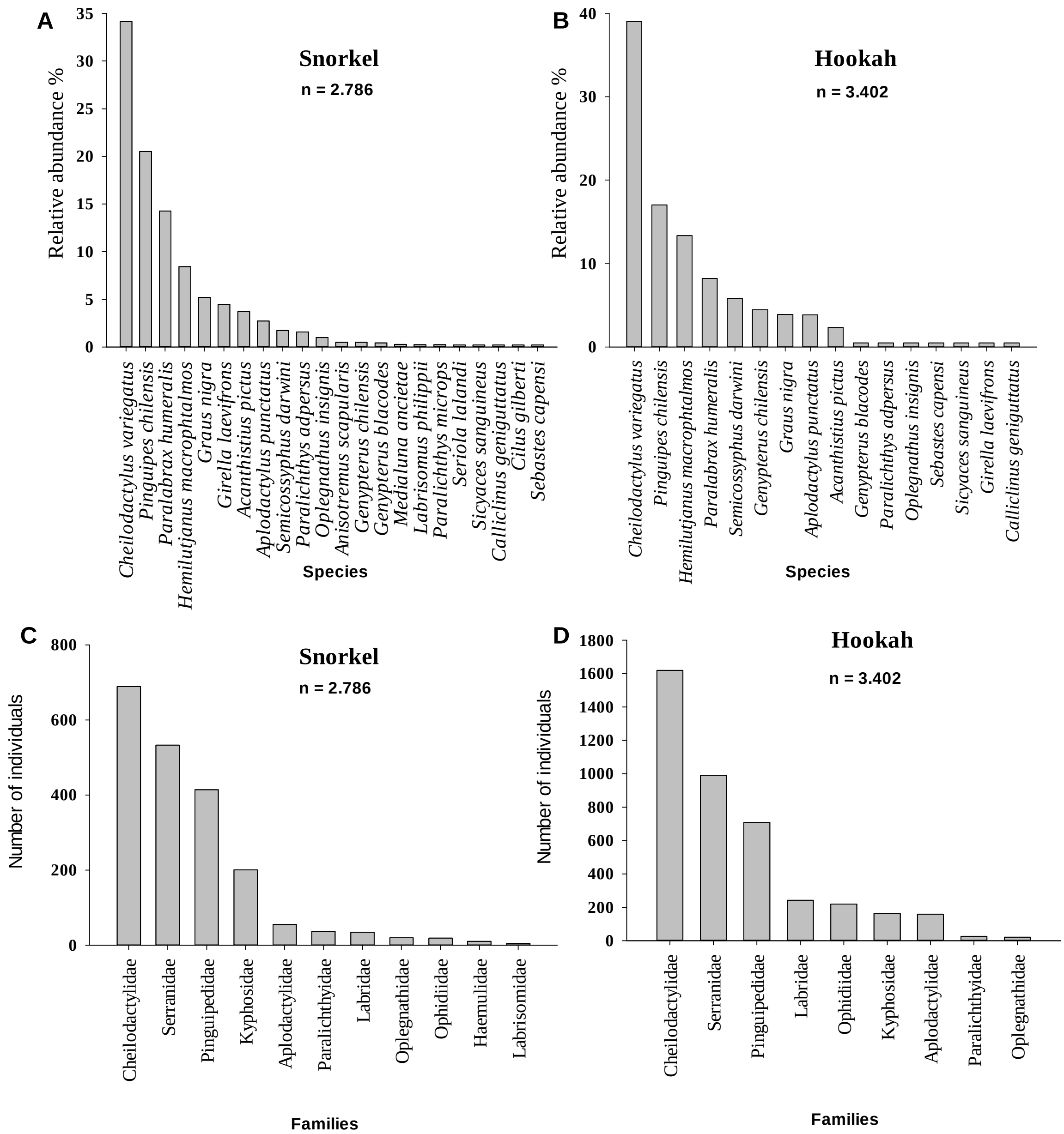

Fig. 2. Relative abundance of species (A-B) and families (C-D) targeted by each dive gear.

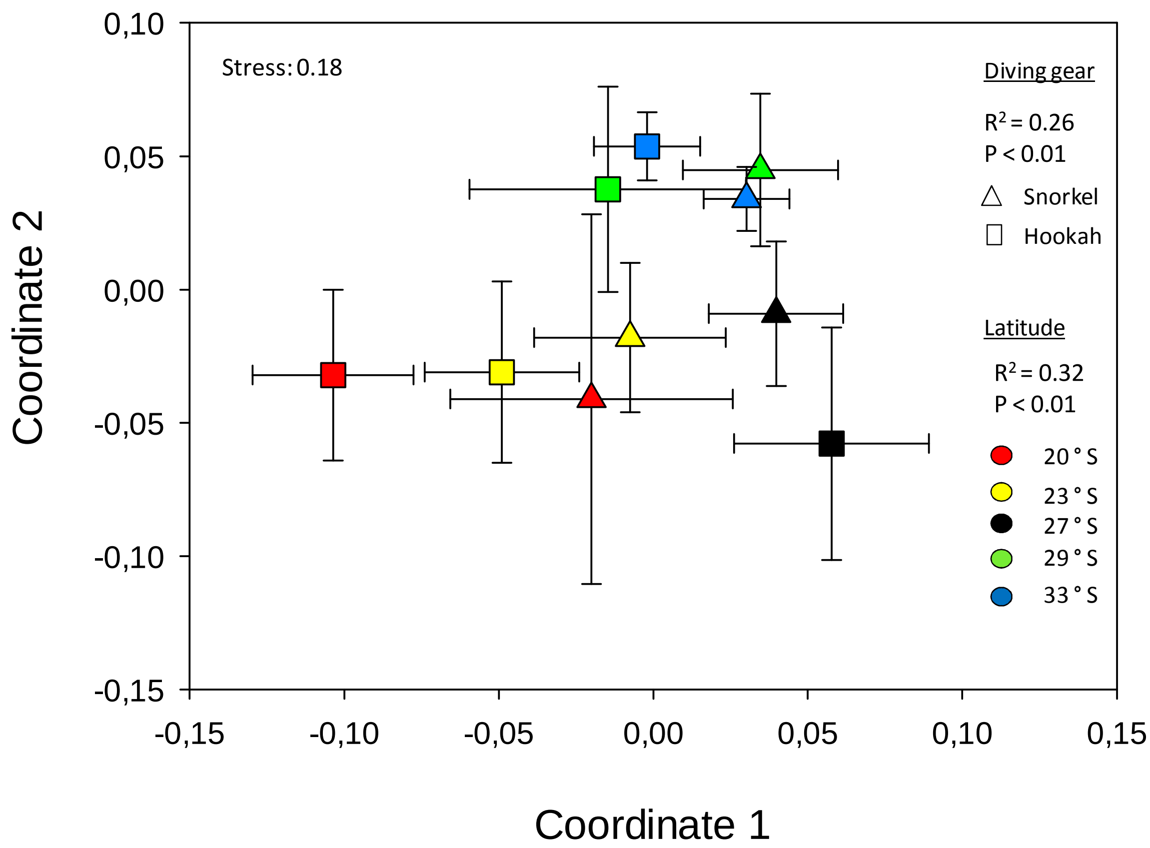

Fig. 3. A nonmetric multidimensional scaling (MDS) plot of relative similarities in composition catch, in terms of relative abundance of reef fishes by latitude and dive gears.

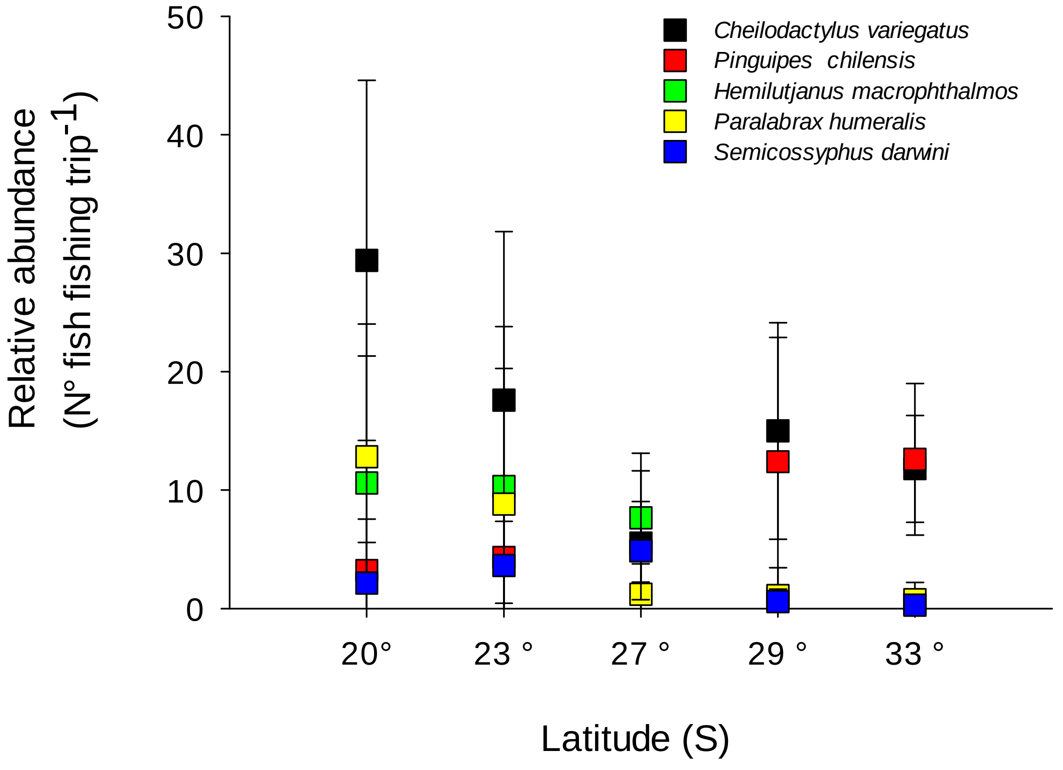

Fig. 4. Averages (±SD) of the relative abundance of reef fish in artisanal catches which account for 70% of the observed differences between latitude.

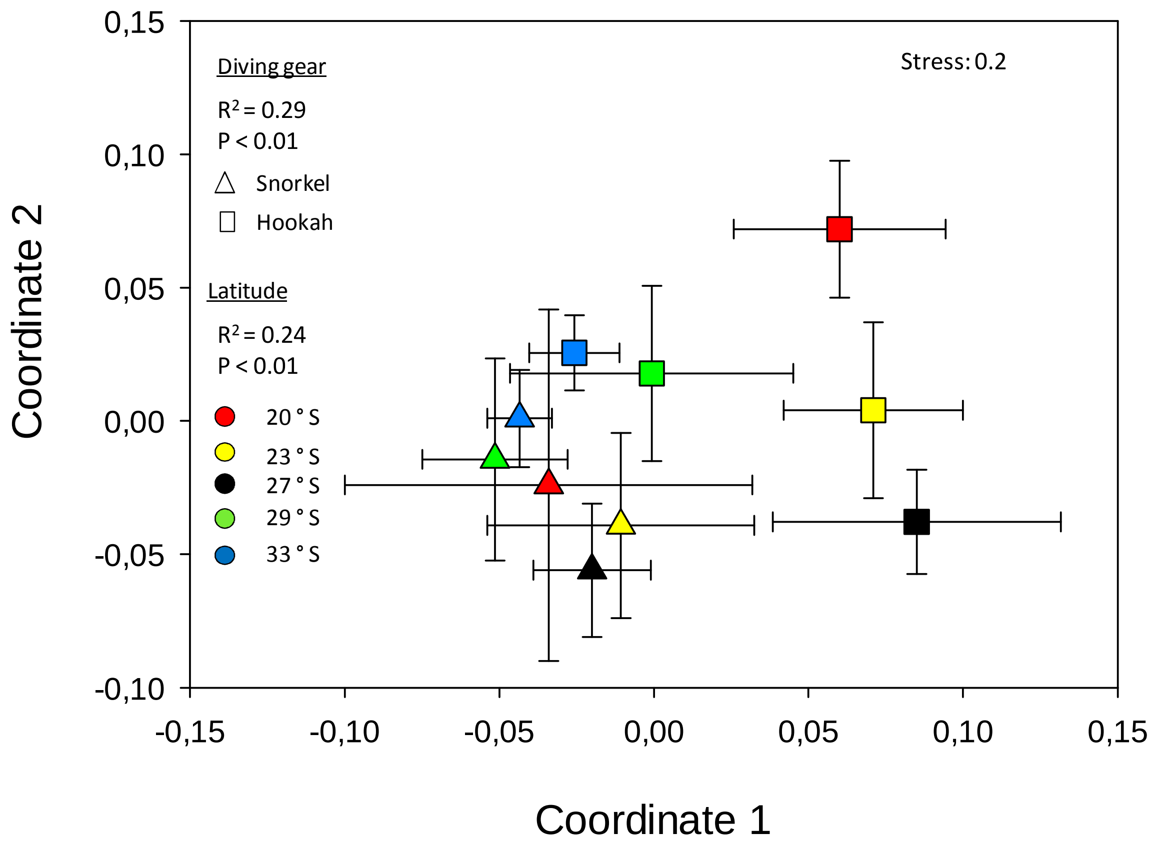

Fig. 5. A nonmetric multidimensional scaling (MDS) plot of relative similarities in composition catch, in terms of relative weight of reef fishes by latitude an dive gears.

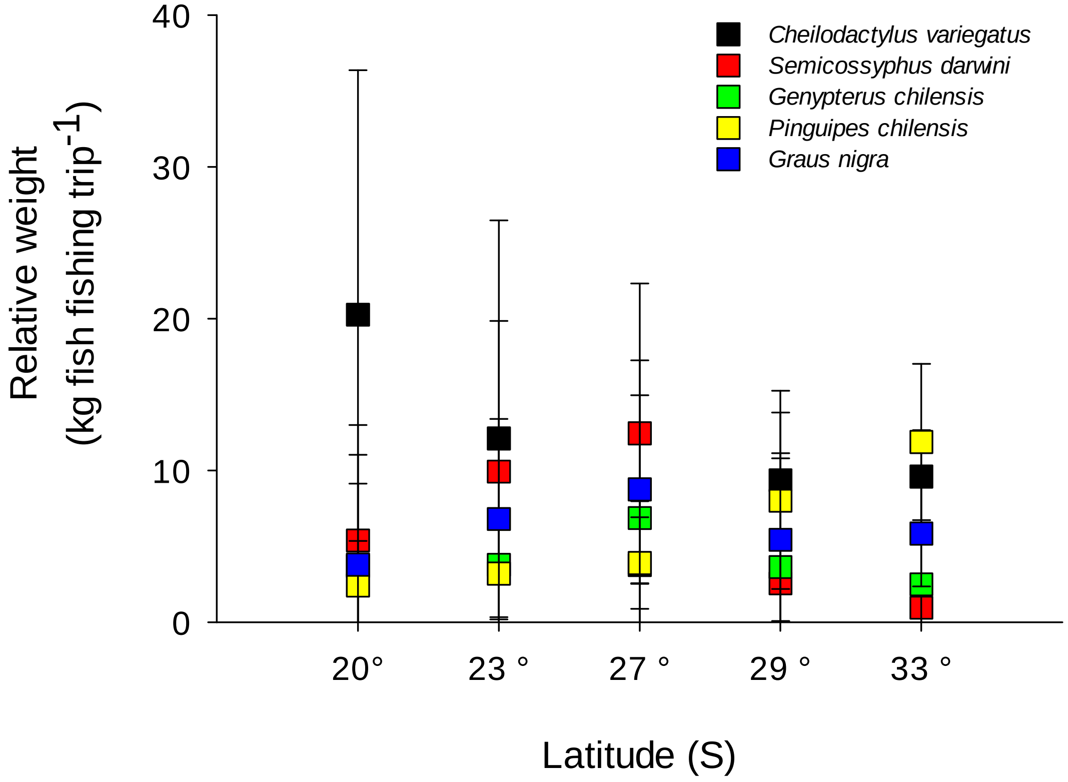

Fig. 6. Averages (±SD) of relative weight of reef fish in the catches which account for 68% of the observed differences between regions or latitude.

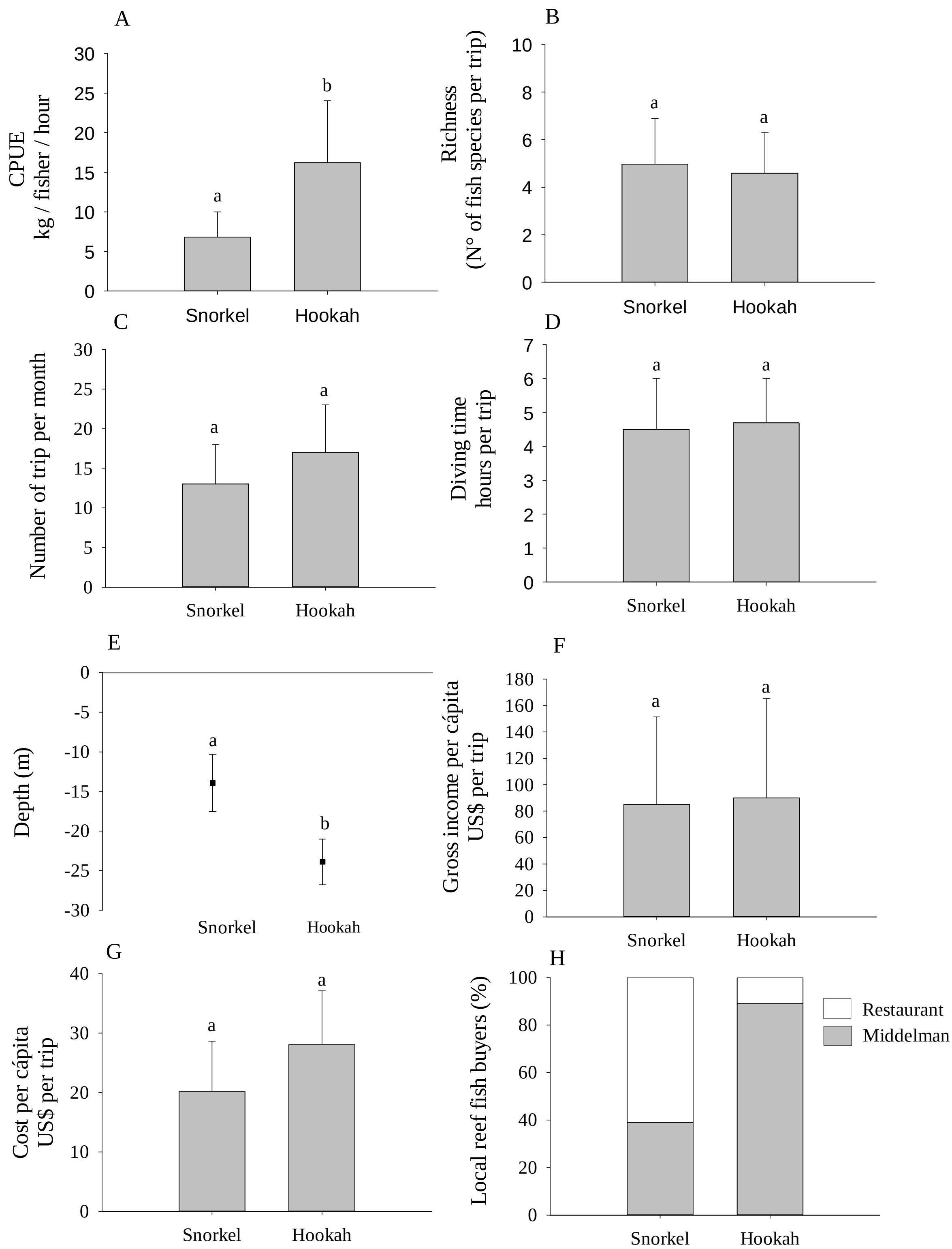

Fig. 7. Comparison between fishing parameters to snorkel and hookah spear fishers: A) CPUE; B) Richness; C); Number of trip for month; D) Diving time; E) Diving depth F) ; G) Income per cápita per trip; G) Cost per cápita per trip; H) Local reef fish buyers.

III. El uso de teoría ecológica en la exploración de las conductas de pesca de peces litorales por buzos artesanales en el norte de Chile.

Godoy N, Gelcich S, Castilla J.C., Smith A., Lima M. Ecological theory in the exploration of fishing behavior of artisanal spear divers in north of Chile (Submitted).

Ecological theory in the exploration of fishing behavior of artisanal spear divers in north of Chile

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Abstract

Understanding how people operate in the fishery system helps to understand how the system works. We used the central place optimal foraging theory (CPF) and diver local knowledge as a framework to understand the mechanisms underlying fishing site selection and fishing time by artisanal spear divers exploiting reef fish species. Two CPF predictions are tested based on daily artisanal spearfishing catches data: 1) A diver who travels to more distant fishing fields should return to the central place with more fish. Assuming depletion in fishing field closed to central place; 2) consequently, the fishing time is dependent on the travelling time, additionally, and four environmental variables associated to fishing trip were assessed based on local knowledge: wave height (m), degree of accessibility of fishing grounds and sea water clarity. Our results show that the travel time and fishing time explain few of catch variability for both dive gears (11%-12%). The findings indicate that artisanal spear divers are dealing with the particularities of Chilean coastal geomorphology, environmental constraints or “sea condition phenomena”. These variables explain most of variability observed from artisanal spearfishing catches. The aim of this study was to improve our understanding of fishing strategies used for artisanal spear divers and their interaction with the marine environment. Management can reflect more accurately on the reality if we know the variables that influence fishers' decision-making processes.

Key words:
Rocky fishes, management, speargun, spearfishery, local knowledge.

Introduction

Many coastal small-scale fisheries are facing the decline of exploited population and the difficulty in sustaining fishing activities (Defeo and Castilla, 2005). In addition, there is a challenge gathering the basic information needed to sustainably manage small-scale fisheries (Salas et al., 2007). Analyses of this sort require interdisciplinary and integrated studies using multiple information sources, innovative methodologies and the recognition of fisher´s tactics and strategies (Salas and Gaertner, 2004). In particular, small scale fisheries have generally been managed by rules of 'how much can be taken' rather than by evaluating and controlling 'how, when and where' people fish (Gaertner et al 1999, Castilla and Defeo, 2001, Salas et al. 2004). In this sense, Hilborn (1985) suggested that the collapse of many fisheries can best be explained as the result of misunderstanding fisher behavior, rather than a lack of knowledge of fishery resources. Although a number of studies have emphasized the need for understanding fisher behavior (Salas and Gaertner 2004, Hilborn and Walters 1992, Wilen et al. 2002), few of them report sound basic information (Begossi 1998, Lopes and Begossi 2011). In fact, the literature is even more limited in the case of small - scale fisheries (Cabrera and Defeo 1997, Salas 2000).

Optimal foraging theory has been used as a theoretical framework for exploring fishermen behavior (Begossi 1992, Aswani 1998, Begossi et al., 2009, Lopes and Begossi 2011). The utility of foraging models to analyze coastal foragers is assessed by applying two related models: the patch choice (MacArthur and Pianka, 1966), and the marginal value theorem (Charnov, 1976) patch time allocation models. These are employed to generate predictions on the daily and seasonal movement of marine foragers and to assess their possible impact on the marine environment. Optimal foraging can then bring insights about when, where and why users go fishing and to what extent they are optimizing their fishing returns (Lopes et al., 2011). Management can reflect more accurately on the reality if we know the variables that influence fishers' decision-making processes (Béné and Tewfik 2001).

One of the most used optimal foraging models for predicting fishermen behavior is the "Central Place Foraging Theory" (CPF, Orians and Pearson 1979), a version of the marginal value theorem (Beggossi et al., 2009). This theory describes through a set of functional hypotheses and models how is the foraging behavior of fishermen located in a fixed point (e.g. city, village). Therefore, quantitative tests of optimal foraging models require measurements of different situations of itinerant fishing foragers (e.g., travel time, time of fishing and rate of fish capture). An optimal forager should maximize the rate of energy delivered to the central place, including the expenses involved in the round trip to the foraging ground. The major predictions are: 1) A diver who travels to more distant fishing fields should return to the central place with more fish, assuming depletion in fishing field closed to central place; 2) Consequently, the fishing time is dependent on the travelling time (Lopes et al., 2011).

The present study examines two major predictions of foraging theory (outlined above) using empirical data of foraging behavior by the artisanal spear divers in north of Chile. In addition, we are interested to understand how sea conditions, such as, accessibility to fishing grounds and seawater clarity can be relevant factors to define the behavior adopted by spear divers. Therefore, we think that this study contribute to the basic knowledge of fishermen behavior and it can be used as an important element to guideline effective management rules of the endemic of Pacific South-Eastern rocky fish assemblage.

Research setting

The coasts from northern Chile support multi-species artisanal spearfishing activities with the use of snorkeling and hookah (semi-autonomous) diving equipment to extract rocky fish species, without management regulations, and showing clear signal of overexploitation (Godoy et al., 2010). Snorkel divers operate from the shore and usually move in groups of 3-4 divers by land, using vehicles, to reach fishing grounds. This spear divers return to a “central place” represented by towns/cities where they sell their catches and live. On the other hands, the hookah spear divers operates from small wooden or fiberglass boats organized around coastal areas which are officially designated as "caletas" (Castilla 1994) or “central place”. These are strips of land above the high tide market that are granted to fisher communities as a concession by the State and provide the rights for users to have access to the landing of boats and to erect certain buildings (Gelcich et al., 2005).

Site study and sampling

We conducted fieldwork during 2011 in north of Chile, where artisanal spearfishing activities occur. We explored the spear fishers behaviors based in Iquique city (20° 13’ S - 70° 08’ W) and “caleta” Los Verdes (20° 25’ S - 70° 09’ W), placed 24 kilometers at south of Iquique city (Fig 1). We followed a total of 124 snorkel spearfihing trips. The snorkel divers were identified through the Federación Chilena de Deportes Subacuáticos (FEDESUB), since many of these divers also compete in recreational championships. We visited regional association affiliated to FEDESUB and identified potential artisanal snorkel divers for our study. Once identified, we asked for permission to conduct assessments based on their catches. On the other hand, 93 artisanal hookah fishing trip were directly evaluated in “caleta” Los Verdes, prior spear divers permission.

Spear divers were asked about the distance (in minutes) travelled to the fishing ground for each trip, the time spent fishing. Additionally, spear divers were consulted by the degree of accessibility of fishing grounds. Accessibly scale was built based on local knowledge and ranged between 1 at 5, where: (1) accessible in all sea conditions (e.g. bays) and; (5) accessible only with very good sea conditions (e.g. heavy exposed coastal zone). Finally, spear divers were consulted by sea water clarity when their performance fishing activities.

Sea water clarity scale was also built based on local knowledge and ranged between 1 at 3, where: (1) Clear sea water, (2) intermediate clarity, and (3) turbid sea water. Sea conditions were registered as daily mean of wave height (m) for Iquique port through www.buoyweather.com. We considered that these factors can affect the predictive power of the models used. Diver's experience and fishing power can also affect capture (Prince 1998). By including only samples of professional diver's, we assume that the variability in experience among divers should not cause a significant effect. Also, we assume vessels sampled did not differ in their fishing power, as they presented similar features in the geographical range in which this study was conducted.

Catches recorded were obtained exclusively from open-access areas. Catch data from partially protected areas managed through Territorial User Right for Fisheries (TURFs) policies (Gelcich et al., 2009) were not sampled in this study. Artisanal spearfishing activity is not common inside MEABRs as fisher organizations restrict diving to stop illegal poaching of *Concholepas concholepas* and key-hole limpets. This restriction is due to the lack of trust between fishers, as spear-gun divers could poach on benthic resources. This establishes very strict de facto diver access regulations (Gelcich et al., 2008).

Statistical analysis

In order to test the "central place" predictions simple linear regression analysis were performed. Additionally, to exploring the predictor variables that could explain the artisanal speargun catches we used partial least squares regression analysis (PLSR). This statistical technique is particularly well suited to analyzing a large array of related predictor variables (no truly independent, i.e. sea condition, accessibility and seawater clarity), with a sample size not large enough compared to the number of independent variables, and cases in which an attempt is made to approach complex phenomena or syndrome that must be define as a combination of several variables obtained independently (Carrascal et al., 2009). Also, possible correlations between the predictor variables were analyzed using Pearson product-moment correlation.

Some aspects of the foraging behavior of spear fishers

Observed spear fishing activities showed some difference in features of foraging behavior for both diving gear. The foraging range extends for about 30 and 150 kilometers for hookah and snorkel divers, respectively (Fig. 1). Fishing activities by snorkel divers on the northern of Iquique City were not performance because the coastal geomorphology does not allow access by land (Fig. 1). There was no difference in the time spear divers spent fishing, while the travel time varied according to diving gear. The travel time spent for snorkel divers is longer that hookah divers (Table 1). Also, the catches were higher for hookah divers than for snorkel divers. Artisanal speargun catches were collected from 20 and 9 fishing grounds, for snorkeling and hookah, respectively (Table 1).

"Central place" predictions

The first hypothesis proposed in this study and one of the core questions in the central place foraging model states that a forager who travels further must bring back home a higher energetic return than when foraging closer to the central place. This assumption had significant regression coefficients, but it showed that only 11 % and 12% of the return in kilograms of fish caught was explained by the distance travelled by the spear divers (Table 2). If the result demonstrated above was the consequence of an optimal strategy by divers, then it is expected that the divers stayed shorter in the more distant patches in order to catch more fish. However, this pattern is not consistently with empirical data. The result did not show a travel time as significant predictor for fishing time for both diving gear (P>0.05; R^2=0,00; Table 2).

Partial Least Squares Regression analysis

Significant correlations between sea conditions with accessibility of fishing ground and sea water transparency were observed (Table 4). These results showed that choice of PLSR seem adequate to estimate of relative contribution of no truly independent predictor variable on the artisanal spearfishing catches. Results of the PLSR analysis provide two significant components explaining 62% and 66% of the original variance in the response variable, for snorkel and hookah divers, respectively (Table 5). The first component accounts for a major proportion of the explained variance, while the second component accounts for a marginal, but significant, 0.7 and 0.2 %. The meaning of the components was interpreted considering the weights attained by the variables. Component 1 mainly associates sea condition, accessibility of fishing ground and sea water transparency for both diving gear. This means that these predictor variables cannot be seen as independent variables, but they comprise a ‘sea condition phenomena’ affecting spear fishing catches. These three variables alone retain 76% and 78% of the information content of the first component for snorkel and hookah divers respectively (Table 5). The variable that most explain snorkel catches was the accessibility of fishing ground (28%), while the sea conditions (32%) was to hookah catches (Table 5). Time fishing and travel fishing were predictor variables that accounts for 24% and 25% of the explained variance for snorkel and hookah divers.

Discussion

Our results show that an increase in the distance of the fishing grounds from the central place did not increase the amount of rocky fish caught neither the fishing time by artisanal spear divers. These results would indicate a 'non-optimal' behavior, as it was not explained by the foraging models (Lopes et al., 2011). However, several studies show that most of the time, artisanal fishermen are not acting as “catch maximizer” (Begossi, 1992, Begossi 1999). Non-optimal behavior may occur due to several reasons such as open access situation, overexploitation and changes in behavior due to seasonality, climate variability, foraging gear and habitat variability (Lopes et al. 2011). The results presented here indicate that artisanal spear divers, instead of optimizing, are dealing with particular ecological factors, such as coastal geomorphology, environmental constraints or “sea condition phenomena” and the depletion of rocky fish stocks.

The geomorphology of the northern Chilean coastal is fairly continuous, almost straight line, fully exposed to stronger south prevailing winds and waves, with open sandy beach and few sheltered bays (Santelices 1990). Wave expose and semi-exposed rocky surface are common sub-tidal habitat that can be observed in few kilometers of coastal line. These habitats may have positive effects on the abundance of target rocky fish, by restricting "naturally" access to fishing, similar to effects observed by the fishing restrictions imposed of Territorial User Right for Fisheries in Chile (TURFs, detail in Gelcich et al., 2008, 2012). Artisanal spear divers should catch more fish from wave expose and semi-expose fishing ground closed to central place, when sea condition allowed, than more distant fishing ground. However, we cannot ignore that part of the observed variability in the catches was significant explained by the travel time, which suggests some degree of depletion of fishing ground nearest to the central place. Consequently, our results suggest that artisanal spear divers stay longer time foraging when sea conditions are favorable for diving. Effective time fishing in more distant fishing ground may be limited by the time of return to central place, particularly for snorkel divers, which travel longer distances.

The ‘sea condition phenomena’ explain most of variation observed on artisanal spear divers catches. However, some specifics differences were evident in terms of the importance of predictor’s variables on the spear diver behaviour’s. The accessibility of fishing ground for snorkel divers were the main predictor variable for explaining most of catch variability, but it was much less important for hookah divers. This pattern is consistent independent of the method used by spear divers to access to fishing grounds. Snorkel divers need better sea conditions for access to fishing ground because they literally jump from the littoral rocks into the shallow sea water. Instead, hookah diver access fishing ground using boats equipped with semi-autonomous diving equipment allowing them access to deeper rocky fish habitat away from the surf zone (Castilla, 1994). Our results also show that sea water clarity explain similar variability of the spear diver behavior’s. It is reasonable to suppose, because spear divers are visual-oriented aquatic predator that depends upon light and/or clarity to localize prey (Abrahams and Kattenfeld, 1997), both artisanal spear divers are faced a similar visual constraints when performance spearfishing activities.

Beyond the limitations of our predictor variable (some based on local knowledge) and temporal-spatial sampling, our empirical study has been helpful in clarifying the variables involved in decision processes concerning where to artisanal spear divers fish and how long to stay fishing in a ground. Note that results were obtained exclusively from open access areas. These patterns could be modify by including TURFs as fishing ground were highest fish abundance has been reported (Gelcich et al., 2008) and its proximity of central place. Finally, the simple theoretical models were useful in the formulation of hypotheses to account for patterns of artisanal spear divers and their interaction with the marine environment. Management can reflect more accurately on the reality if we know the variables that influence fishers' decision-making processes (Béné and Tewfik 2001). Artisanal spearfishery currently show clear signals of overexploitation (Godoy et al. 2010), thus this information could be used in combination with quantitative ethnographic fieldwork and target fish population dynamics information to develop an adaptive management framework.

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Tables

Table 1. Some aspects of the foraging behavior of artisanal spear fishers form north of Chile.

Diving gear	Sample size	Time fishing (min) (±SD)	Travel time (min) (±SD)	Catch (kg)(±SD)	Fishing ground
Snorkel	124	4.5 (± 1.5)	65.9 (± 47.5)	31.87 (± 46.4)	20
Hookah	93	4.7 (± 1.3)	46.8 (± 55.2)	57.74 (± 72.34)	9

Table 2. Simple linear regressions using capture as the dependent variable and travel time and sea condition phenomena as the independent variable.

Artisanal diving gear	**Dependent variable**	**Independent Variable**	**Regression line**	**R^2**	**F**	**P**	**n**
Snorkel	Capture (kg fishing trip^{-1})	Travel time (min)	C = 19.83 + (0.118 * Tt)	0.11	15.51	< 0.001	124
Hookah	Capture (kg fishing trip^{-1})	Travel time (min)	C = 34.12 + (0.124* Tt)	0.12	34.02	< 0.001	93

Table 3. Simple linear regressions and PLRS using spear fishing time as the dependent variable and travel time and sea condition phenomena as the independent variable.

Artisanal diving gear	Dependient variable	Independient Variable	Analysis	R^2	F	P	n
Snorkel	Fishing time (min)	Travel time (min)	Linear Regression Non significant	0.0	0.30	0.585	124
Hookah	Fishing time (min)	Travel time (min)	Linear Regression Non significant	0.0	0.01	0.90	93
Snorkel	Fishing time (min)	Sea condition	PLSR	0.09	-	< 0.001	124
Hookah	Fishing time (min)	Sea condition	PLSR	0.16	-	< 0.001	93

Table 4. Pearson's correlation coefficients for relationship between sea conditions and accessibility of fishing ground and sea water clarity.

Pearson's correlation coefficients					
Diving gear	Variables	t	df	p-value	R^2
Snorkel	Sea condition Accessibility	8,39	122	< 0,001	0,39
	Sea condition Clarity	5,31	122	< 0,001	0,19
Hookah	Sea condition Accessibility	5,25	91	< 0,001	0,18
	Sea condition Clarity	5,42	91	< 0,001	0,21

Table 5. Results of the partial least squares regression analysis (PLSR) carried out with the artisanal spear fishing catches from north of Chile (response variable) and five predictor variables.

PLSR Models				
Snorkel				
	Component 1		Component 2	
	$R^2 = 0.61$	$P < 0.001$	$R^2 = 0.007$	$P < 0.001$
Hookah				
	Component 1		Component 2	
	$R^2 = 0.66$	$P < 0.001$	$R^2 = 0.002$	$P < 0,001$
Variable importance				
Predictor variable			R	R^2
Snorkel				
Accessibility of fishing ground			0,53	0,28
Sea condition			0,49	0,24
Sea water transparency			0,48	0,23
Fishing time			0,40	0,16
Travel time			0,29	0,08
Hookah				
Sea condition			0,57	0,32
Sea water transparency			0,49	0,24
Accessibility of fishing ground			0,46	0,21
Fishing time			0,38	0,15
Travel time			0,28	0,10

Figures

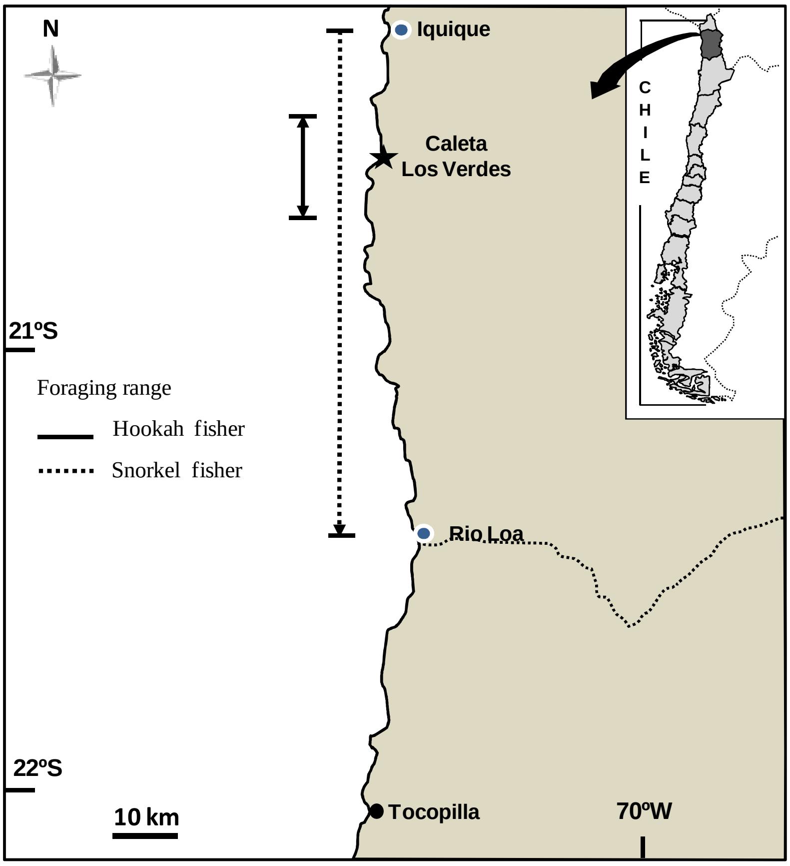

Figure 1. Map of the study area in north Chile showing sites where assessments were made and foraging range of the artisanal spear fishers.

CAPÍTULO III

IV. Efectos de la pesquería por buceo, el precio de mercado y el clima sobre la dinámica poblacional de dos especies de peces litorales de roca capturados por buceo artesanal *Graus nigra* (Kyphosidae) and *Semicossyphus darwini* (Labridae) en la costa centro – norte de Chile

Godoy N., Gelcich S., Castilla J.C., Lima M. Effects of artisanal spearfishing, market price, and climate on population dynamics of two targets rocky fish species *Graus nigra* (Kyphosidae) and *Semicossyphus darwini* (Labridae) in central-north of Chile.

Effects of artisanal spearfishing, market price, and climate on population dynamics of two targets rocky fish species *Graus nigra* (Kyphosidae) and *Semicossyphus darwini* (Labridae) in central-north of Chile.

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Abstract

In Chile, the unregulated artisanal spearfishery faced the dilemma of the negative trends in the abundance of two main charismatic rocky fish species, *Graus nigra* and *Semicossyphus darwini*. Traditional approaches for fisheries management use complex models that need a large amount of data to be parameterized, which are not available for this spear-fishery. Population dynamic theory arises as an alternative approach for modeling small-scale fisheries in order to understand the underlying mechanism of these fish populations. Our aim was to test the effects of endogenous and exogenous factors on numerical fluctuations for both species. Using long term relative abundance index data of Capture Per Unit Effort (CPUE), we fitted theoretically-based models including the exogenous effects of climate (ENSO) and fish market price trends. Our analyses showed that intra-specific processed and the combined effects of climate and market prices are the key factors for determining fish population fluctuations. We find that there is a direct and three-year lagged positive ENSO effects and a direct negative fish market price effects, that were needed to explain most of annual variation of relative abundance index for *G. nigra* and *S. darwini*, respectively. The life history trail of these fish species probably explains the differential responses observed to exogenous factor. These results highlight the need to address species-specific guidelines to the management and conservation of artisanal speargun targeted rocky fish species. This article is an example of how theoretical simple models may be used as a proper diagnostic tool to analyzed fish population dynamics in artisanal fisheries.

Keywords
Speargun**,** rocky fish, theoretical model, conservation, management

Introduction

The small scale fisheries have faced the decline of main fish population during the last several decades [1]-[3]. Additionally, most of these fisheries share the problems of data poor/less situations where information is insufficient to estimate appropriate reference points and relative fish population status [4]. This situation difficult to applies classical fisheries management models [5]. Thus, there is increasing call to develop and apply new tools to address the challenges posed by small- scale fisheries management [6], [7].

Population dynamics theory arises as an alternative approach for models in fisheries [8]. This approach offers an objective way to develop simple, non-structured populations models that are useful to understand and predict the causes of population changes [9], [10]. Royama [11]-[13] and Berryman [9] provides a simple and complete theoretical framework to evaluate the influence of endogenous and exogenous factors on population dynamics. Theory helps understand the dynamics of populations and their interactions in the context of environmental circumstances. Such understanding emphasizes the essential importance of ensuring that such insight is taken into account in fisheries management [8]. In this context, population dynamics theory has been an essential tool for deciphering and proposing the ecological mechanism underlying dynamics of fish populations [14].

In Chile, since the 70's, operates an unregulated artisanal spearfishery; despite of there is information about official landings and fishing effort for the last two decades and scientific awareness for population declines and the potential negative effects of spearfishing on reef fish populations and ecosystems have been reported [15]-[17]. Two of the most exploited rockfish species in Chile are the large and charismatic *Graus nigra* and the *Semicossyphus darwini*. Both are heavily targeted by spear fisher because they reach large sizes, weights and market value [18]. In fact, 98% of the total landing of these species comes exclusively from artisanal spearfishery [19], thus providing a unique scenario for modeling the dynamics of spearfishery effects on both population;, without the confounding effects of gill nets or hook and line [18]. In addition, the role of climatic variability in the Humboldt ecosystem have been previously studied across the coastal communities of Chile [20], [21] but so far no study has addressed the effect of climate on population dynamics of exploited rock fish species.

In this article, we used population dynamics theory to elucidate the effects of endogenous and exogenous factors on relative abundance index of these reef fish species which show clear signal of overexploitation [18]. This study aims to provide the basic needed knowledge and population dynamics approaches to guide a sustainable management and conservation strategy of these species. Our analysis of the fish populations is based in four sequential steeps: a) standardizing of Capture per Unit Effort (CPUE), b) a diagnostic approach to determine what kind of population dynamic model is most appropriated [9], c) the modeling of the observed dynamic through a simple theoretically-based model, c) the use of a theoretical framework to analyze exogenous perturbations [13]. We hypothesized that the population dynamics of *G. nigra* and *S. darwini* would be influenced by a combination of endogenous processes (eg intra-specific competition) and exogenous factors such as the fishery, market and climate (ENSO).

Materials and methods

Reef fish species, artisanal spearfishery, and abundance data

Artisanal spearfishery

The black wrasse *Graus nigra* (Kyphosidae) and the sheephead *Semicossyphus dawini* (Labridae) are two endemic southern temperate Pacific largest dwellers of the upper sublittoral zone in temperate Chilean coast [25]. These species has been described as a benthophagic carnivorous occupying the third and four levels in the trophic change [20], [26]-[27]. Biological and ecological aspects of the fish such as reproduction, growth, ecological relationship have been recently explored [28]. The evidence suggests that both species show signal of overexploitations in the artisanal spearfishery [23]. Artisanal spearfishing is mainly conducted in central and northern Chile, along ca. 2000 km of coastline (Fig. 1). The Chilean National Artisanal Fishery Registry (Registro Pesquero Artesanal, RPA) shows that currently there are 2978 spear-fishers registered. The spear fisher can only access to catches via authorization by the Chilean Administrative Regions, where they are officially registered. Inshore coastal ecosystems in the temperate region of Chile exhibit spear-fishing activities mainly with the use of hookah (semi-autonomous) diving equipment from undocked small deck-less wooden or fiberglass boats (usually less than 10 m long). In Chile, maximum fish reef landing were observed between 1986 - 1990 periods and reached approximately 900 tons/years; with *G. nigra* and *S. darwini* accounting for up 80% of that total landing. At present, reef fish landing for both rocky fish species fluctuates around just 50 tons per years [23]. The artisanal fleet and fishing equipment such as speargun, wetsuit and hookah system have not undergone major changes during the study period.

CPUE data

CPUE data for both reef fish species were provided by National Fisheries Services (Servicio Nacional de Pesca, SERNAPESCA) (Fig. 2 A-B). The CPUE data set consisted of 14.231 observations for *G. nigra* and 7.732 observations for *S. darwini* from capture of fishing trips (Fig. 2 C), for the period 1992-2012. CPUE data for *G. nigra* come from regions III and VI and II, III and IV for *S. darwini*. These regions determine trends in data series for both species. In our case spearfihing CPUE estimates may provide a better estimate of fishes abundance than those used for others fishing gear because artisanal spear divers have the ability to visual search crevices and among boulders to detect fish.

Standarized CPUE rate

The use of CPUE data for analyzing population dynamics of fish present some problems, since CPUE data is not a reliable estimator of population abundance or biomass and is influenced by several factors that change the catchability of fish [29]. Among other, the factors that commonly affect CPUE are efficiency of a fleet, targeting by a fleet, environmental factors, dynamics of a population or fleet [1], [30]. Therefore, in this paper spearfishing CPUE was standardized to remove these types of effects, so to construct the index of abundance for the applications of Generalized Linear Modeling (GLM, [31], [32]. Standard GLM analyses based on log-transformation of the data require that no CPUE observation in a strata equal zero [33]; therefore, we add a constant to the data set to avoid bias in the analysis. The relationship between the *i*th catch rate data point and biomass is generalized to multiplicative model expressed as:

$$\text{CPUE}_i = q_i \; Bt \; e^{\varepsilon I} \qquad (1)$$

where *qi*, the catchability coefficient for CPUE data point *i*, is related to both categorical and continuous variables, and ε_i is the independent error component assumed to have a normal distribution. Factors considered as possible influences on the CPUE for both species included the independent variables year, trimester and Regions. The general linear equation can be expressed as:

$$\ln(\text{CPUE}_{ijk}) = \mu + \text{Year}_i + \text{Quarter}_j + \text{Region}_k + (\text{Quarter*Region})_{jk} + \varepsilon_{ijk} \qquad (2)$$

were,

CPUE_{ijk} = CPUE per trip (kg fisher^{-1} fishing trip^{-1}) for *i* th year, for *j* th quarter, and for *k* th Region

μ = model constant

Year_i = effects *i* th level by year factor (20 levels)

Quarter_j = effects *j* the level by quarter factor (4 levels)

Region_k = effects *k* the level by Region factor (5 level)

For each GLM, we used a stepwise approach to quantify the relative importance of the factors. We selected the best model for estimating the CPUE index including all factors and first order interactions using the F statistics associated with a probability less than or equal to 0.001 [31]. Finally, the model was adjusted again considering the selected factors. Models were fitted with log-normal distributions and identity link functions using the R programs [34]; R Development Core Team, 2004, available at http://www.r-projet.org).

Population dynamics modelling

Given that these fish species are carnivorous generalist and top predator in subtidal system, their populations dynamics are expected to be dominated by a first order density-dependent feedback [13]. Hence we used a simple model of intra-specific competitions, Ricker's equation [35], to model the basic structure of the influence of endogenous and exogenous forces.

Logarithmic representation the Ricker's equation based in Royama [17]:

$$R_t = R_{\max}\left(1 - \left(\frac{N_{t-1}}{k}\right)^a\right) \qquad (3)$$

Factoring (3)

$$R_t = R_{\max} - \frac{R_{\max}}{k^a} * N_{t-1}^a \qquad (4)$$

Applying e and log the second term of equation (4)

$$R_t = R_{\max} - e^{\log\left(\frac{R_{\max}}{k^a} * N_{t-1}^a\right)} \qquad (5)$$

$$R_t = R_{\max} - e^{\log\left(c * N_{t-1}^a\right)} \qquad (6)$$

Where C = $\frac{R_{\max}}{k^a}$

$$R_t = R_{\max} - e^{(c + a * X_{t-1})} \quad (7)$$

Were c = log C, and X = log N_{t-1} = log $CPUE_{t-1}$

$$R_t = R_{\max} - e^{[(a * X_{t-1}) + c]} \quad (8)$$

Where X_{t-1} is the logarithm of CPUE at time t-1, ($a*X_{t-1}$) + c represent density dependence effects on X_{t-1}; R_t is the realized per capita growth rate Rt_log($CPUE_t$/$CPUE_{t-1}$); R_{max} is the maximum per capita growth rate estimated for each fish species. For both species models were fixed the maximum per capita rate of 2.6 and 1.0 for *G. nigra* and *S. darwini* respectively, taking into account that maximum observed from time series.

Exogenous factors

Fish market price

To investigate the influence of market prices (expressed in Chilean Pesos, CP$) as proxy for human impact on the dynamics of *G. nigra* and *S. darwini*, we used time series of price to both species as exogenous factor. The time series were provided by National Fisheries Services (Servicio Nacional de Pesca, SERNAPESCA). The data consist in the annual mean of price estimate for SERNAPESCA from direct assess in site fishing landing (Fig 2 A-B). The data set were corrected by inflation index of 2011 (IPC). We use a linear regression to predict the data that were not available (*G. nigra*: Price=74.338(year)-147709, R^2=0.85 and; *S. darwini*: Price=71.2564(year)-141564, R^2=0.82).

The relationship between the market price with CPUE and fishing effort was evaluated through simple regression models. To explore relationship between price and CPUE was calculate the price rate of change (PR=$Price_t$ – $Price_{t-1}$).The first regression included PR as dependent variable and CPUE as the independent variable. The result show that CPUE data explain low percentage of variations in price change rate for *G. nigra* (R^2=0.05; PR=-2.52(CPUE)+128.83) and *S. darwini* (R^2=0.02; PR=0.057(CPUE)+25.75). The second regression included RP as dependent variables and price as independent variables. The result show that price data also explain low percentage of variations in price change rate for *G. nigra* (R^2=0.00; PR=-0.084 (price)+83,283) and *S. darwini* (R^2=0.02;

PR=0.0471(price)+32.25). The third regression included fishing effort (FE) as dependent variables and price as independent variables. The result show that price data explain most of observed variations in price change rate for *G. nigra* (R^2=0.77; FE=260.8 ln(price)-1432.7) and *S. darwini* (R^2=0.73; FE=575.72ln(price)-3364.9). These results guide the inclusion of price as exogenous factor in general models.

If the market price variable is symbolized by Pj, then the model representing the vertical (9) and lateral (10) perturbation are:

$$R_t = R_{\max} - e^{[(a*X_{t-1})+c]} + Pj \tag{9}$$

$$R_t = R_{\max} - e^{[(a*X_{t-1})+c+Pj]} \tag{10}$$

Climate data

To evaluate the effect of El Ñino Southern Oscillation (ENSO) on population dynamics of two reef fish were used four climate indices. Three broad-scale climate indices represent large-scale processes that may influence reef fish dynamics: the Oceanic Niño index (ONI), Southern Oscillation index (SOI) and Pacific Decadal Oscillation (PDO). The ONI and SOI were taken from. www. esrl. noaa. gov/ psd/ data/ climateindices/ list/. PDO was taken from Ortega et al. (2011) for northern bioclimatic unit which coincides with our area of study. The annual mean SSTA was also determined in northern biogeographic unit and take form Ortega et al. (2011) (Fig. 2E).

Here, we included in the models the effects of climate as vertical or lateral effect on populations' dynamics of reef fishes, since ENSO is the most important climatic disturbance in the temperate coasts of Chile [36]. If the climatic variable is symbolized by Vi, then the model representing the vertical (11) and lateral (12) perturbation are:

$$R_t = R_{\max} - e^{[(a*X_{t-1})+c]} + CVi \tag{11}$$

$$R_t = R_{\max} - e^{[(a*X_{t-1})+c+CVi]} \tag{12}$$

Where, C is a coefficient of scale. Models were fitted by using the nls library in the r program [34]; R development Core team, 2004, available at http://www.r-proyect.org) and ranked according to the Bayesian Information Criterion (BIC or Schwarz Criterion; [37]), and the minimum BIC values were selected to determine the best model.

Scenarios and predictions

In order to estimate the expected equilibrium dynamics (R=0), we can forecast future changes in equilibrium density related to changes in fish market price and best climate indices. The price and climate predictions were made under three defined scenarios as follows: a) price increase (50 and 100%); b) climate change (25% warmer and colder than average) and; c) price increase (50%) and climate change (25% warmer and colder than average).

Results

Abundance index

General Lineal Model analysis showed that the adjusted model for *G. nigra* and *S. darwini* seems adequate to estimate a relative abundance index based on CPUE. The adjusted general model for both species takes the form:

$$\ln(CPUE_{ik}) = \mu + Year_{\ i} + Region_{\ k} + \varepsilon_{\ ijk} \qquad (13)$$

The fitted models explain approximately half of the variations of the logarithm of the CPUE for *G. nigra* (R^2=0.52), and more than half of the variation of the logarithm of the CPUE for *S. darwini* (R^2=0.76) (Table 2). The distribution of standardized residuals can be assumed to be normal for all models (Figure S1).

The values of *G. nigra* CPUE standardized by the GLM method oscillated around the mean of the series with maximum in 1993 (~49 k fishing trip^{-1}) and minimum in 2002-2003 (~2 k fishing trip^{-1}). In 1992, the values increased drastically and recorded the historically-highest level in 1993. After 2005, CPUE showed a gradual decreasing trend until 2011 with some fluctuations (Fig 2A). For *Semicossyphus darwini*, the values of CPUE standardized by the GLM method showed steep decline for 1994-1997with two notable peaks in 1994 and 1996. The value of CPUE slightly increased in 2001 and 2004 and showed gradual declining trend in the 2006-2011 (Fig 2B). The value for 2011 was about 7% of that in 1994.

Population dynamics modelling

The analysis showed that ONI is the indices that most of variation explains of the fish abundance index (Table 3 and 4). The best model according to BIC for *Graus nigra* population growth rate was one that incorporates density dependence (Fig. 3A), vertical positive ENSO effects with three time lagged, and vertical negative perturbations of fish market price (Table 3). The model explains 81% of the variance in fish population growth rate. According to our analysis, the logistic model without exogenous effects accounts for 26% of the observed variation in R-values (Table 3). However, model predictions were noticeable improved with the simultaneous inclusion of vertical additive lagged effects of ONI and direct effects of market price (Table 3). For *Semicossyphus darwini* the logistic model incorporates density dependence (Fig. 3 B) accounts for 38% of the observed variation in R values (Table 4). Our second step was to look for the ONI effect to explain the residual variation of the logistic model. Direct effects of ONI showed a positive lateral perturbation on population growth rate. The Bayesian Information Criterion indicates a very strong support for the role of fish market price as the main exogenous perturbation effect for this rocky fish species (Table 4). The addition of the fish commercial price as an exogenous perturbation effect increases the explained variance from 57% to 74% (Table 4).

Predictions

In order to estimate the expected equilibrium density (N_{t-1}=K*), we set the value of R=0, V*i*= ONI average and P*i*= fish market price average in models selected and then re-arrange it to solve for the value of K*. The parameters used for modeling the different scenarios are show in Table 5. K* is then expressed as:

$$K^{*}_{G.nigra} = \frac{\ln(R_{\max}) - c + \ln(b * ONI_{t-1}) + \ln(d * \Pr ice_{t})}{a} \tag{14}$$

$$K^{*}_{S.darwini} = \frac{\ln(R_{\max}) - c - (b * ONI_{t-3}) + \ln(d * \Pr ice_{t})}{a} \tag{15}$$

Equation (14) and (15) allows us to obtain the expected K* given different scenarios and the parameter estimates of the best models for both fish species. Fig. 4 shows the result of the predictions for three scenarios. For *G. nigra* under Scenario 1 (price): 50 - 100% increase of market price, it is expected that K* will show decrease of 46% and 75%, respectively; under Scenario 2 (climate): 25% warmer and colder, it is expected that K* will show increase of 78% and decrease 71%, respectively, with a similar variation on R_{max}, and; under Scenario 3 (price+climate): 50% increase of market price more 25% warmer and colder, it is expected that K* decrease 7% and 67%, respectively, with a similar variation on R_{max}. For *S. darwini* under Scenario 1 (price): 50 and 100% increase of market price, it is expected that K* will show decrease of 10% and 32%, respectively, with a similar variation on R_{max}; under Scenario 2 (climate): 25% warmer and colder, it is expected that K* will show increase of 9% and decrease 8%, respectively and; under Scenario 3 (price+climate): 50% increase of market price more 25% warmer and colder, it is expected that K* decrease 5% and 19%, respectively, with a similar variation on R_{max}.

Discussion

Our analyses of these two spearfishing targeted rocky fish species in the temperate coastal of Chile showed that intra-specific competitions and the combined effects of climate and market price, as proxy of artisanal fishing effort, are the key factors determining population fluctuation for both species. Our results are consistent with studies showing that target reef fish population variability are closely linked to climate dynamics and fish trade and developing fish market [36]-[40].

We found a negative first order feedback effects on the per capita grown rate for both rocky fish species. Negative feedback may be associated with intra-specific competition for food and/or territory [41]. For example, the adults of the species *S. pulcher* are characterized by a strong territorial behavior [42]-[43]. Large males defend their spawning territories and they are able to monopolize a group of breeding females [44]. Although, there is no information about the social structure of adult the *G. nigra*, juveniles that inhabiting tide – pool showed territoriality behavior [45], and this likely to remains in adult stage. Additionally, several studies has suggest that food may have been limiting in an assemblage of rocky intertidal fishes inferring intra and inter competition for food resources [46]-[48].

In Chile, the ENSO effects on rocky fish assemblage are still poorly understood [34]. Some fish species are able to colonize southern areas during warm ENSO anomalies [49]. In fact, *Graus nigra* is the most austral Kyphoside species and their southern records could be related with warm ENSO anomalies [50]. This fish recruits in the intertidal zone and migrate toward the subtidal zone after 3-4 years to complete its life-cycle [51]. The three-lagged year positive effects of warm climate events detected in this study is consistent with the hypothesis that warm anomalies in the Humboldt ecosystem have positive effects on recruitment [21].Our modeling results also suggest that this species is more influenced by climate that *S. darwini*. This species will be sensitive to climate for ontogenetic variation of habitat. In tide-pool habitat the temperature is an important factor in explaining segregation of habitat by metabolic costs associated with changes in water temperature [45], [52]. Our best model for sheephead *S. darwini* show moderate lateral positive effects of warm period, it is consistent with the fish recruitment rate from California coastal and that was positively influenced by warm ENSO anomalies [53]. Moderate response of *S.*

darwini to climate could be explained by vertical migration to reach appropriate temperature conditions [54].

One interesting result is that our simple models were also able to decipher the role of the fishing and market pressure on both rocky fish population dynamics. Our result showed that the market prices explain most the observed variation to fishing effort for *G. nigra* and *S. darwini*, suggesting a close relationship between variables. Fishing pressure is predominantly driven by both market access and local population density, and has a clear negative effect on the diversity and function of reef fishes [40]. The positive feedback between market access and fishing pressure makes clear the importance of understanding social-ecological linkages in the context of increasingly connected societies [38]. The best models showed vertical negative effects of market price on per capita growth rate (particularly stronger for *S. darwini*), poses new and interesting challenges for understanding as fish trade and the socio-economic growth of fish market shaping the population dynamics and persistence of these two rocky fish species. The population dynamics of *S.darwini* is strongly influenced for price/effort. The results of this study also suggest that in the last fifteen years artisanal spearfishery pressure forced the dynamics of *S. darwini* at low population densities. Proper fisheries management require measure to prevent sex ratio skew, sperm limitations, and reproductive failure because fish population of sequential hermaphrodites, as *Semicossyphus*, are more sensitive to selective harvest, as speargun, than separate-sex fish species [55], [56], such as *G. nigra* [25]. Our results point out the importance of understanding the consequences of the fish market price on rocky fish dynamics.

The predictions advanced by this study were ecologically interpretable showing differential effects of exogenous factors on the dynamics of rocky fish species. Our predictions suggest that cold climate anomalies associated with an increase in the market price/fishing effort could be affecting negatively the fish per capita population growth rate. These results are relevant in a context of climate change. It has been suggested that global warming may be associated with an intensification of upwelling-favorable winds over the Peru-Chile upwelling region [57], [58]. This cold scenario could magnify the effect of spear diving on fish population, particularly in the case of *G. nigra*, that showing greater sensitivity to climate variations. In the case of *S. darwini* the predictions suggest that the market play a key role on the dynamics of this species highly vulnerable to fishing by diving for their life history traits more that climate change.

This study highlights the need to address gear based management on Chilean temperate rocky fish assemblage [59]. The management strategies should also focusing on the linkages between distal drivers (population density, socioeconomics development and market access) and proximate divers (fishing pressure) to quantify the relative importance of these social drive on rocky fish population dynamics and fish diversity in this time of rapid global social and environmental change [40]. Like other studies [8], [14], this article is other example that very simple models can offer reasonable explanations and accurate predictions of fish populations provided they are based on population dynamic theory. Our aim is that the article represents a step toward understanding such a complex social-ecological system of artisanal small scale spearfishery in Chile, helping to build the necessary discussion for the management and conservation of this critical endemic Southeastern Pacific rocky fish assemblage.

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Tables

Table 1. Estimates General Linear Model parameters for standardized CPUE analysis to *G. nigra* and *S. darwini*. More details in Table S1.

GLM	**Factors**						
Graus nigra	**Y**	**R**	**Q**	**R*Q**	**Multiple R^2**	**Adjusted R^2**	**p-value**
Time series 1992-2012							
ln(CPUE)~Year (Y)+Region(R)+Quarter(Q)+R*Q+ ε	1.10e-14	2.71e-05	0.053	0.81	0.62	0.53	1.5e-13
ln(CPUE)~Year (Y)+Region(R)+ε	4.43e-15	2.70e-05	-	-	0.59	0.52	2.7e-16
ln(CPUE)~Year (Y)+ε	4.75e-13	-	-	-	0.51	0.44	4.7e-13
Semicossyphus darwini							
Time series 1992-2012							
ln(CPUE)~Year (Y)+Region(R)+Quarter(Q)+R*Q+ ε	2.2e-16	5.9e-13	0.470	0.627	0.82	0.78	2.2e-16
ln(CPUE)~Year (Y)+Region(R)+ε	2.2e-16	1.98e-13	-	-	0.80	0.77	2.2e-16
ln(CPUE)~Year (Y)+ε	2.2e-16	-	-	-	0.67	0.63	2.2e-16

Table 2. Estimated parameters for each model and data set for *Graus nigra*. Bayesian Information Criterion are show, the best model selected is in bold face.

	Parameters						
	R_{max}	a	b	c	d	R^2	BIC
Graus nigra							
Endogenous							
$R = R_{max} - \exp(a*X_{t-1} + c)$	2.6	0.21	-	1.98	-	0.26	70.03
Exogenous: Climate							
Oceanic Niño Index (ONI)							
$R = R_{max} - \exp(a*X_{t-1} + c) + b*ONI_{t-1}$	2.6	0.21	-0.14	1.96	-	0.26	72.92
$R = R_{max} - \exp(a*X_{t-1} + c + b*ONI_{t-1})$	2.6	0.21	0.04	1.97	-	0.26	72.96
$R = R_{max} - \exp(a*X_{t-1} + c) + b*ONI_{t-2}$	2.6	0.20	0.82	1.93	-	0.38	69.24
$R = R_{max} - \exp(a*X_{t-1} + c + b*ONI_{t-2})$	2.6	0.20	-0.28	1.91	-	0.37	69.43
$\mathbf{R = R_{max} - \exp(a*X_{t-1} + c) + b*ONI_{t-3}}$	**2.6**	**0.31**	**1.66**	**2.45**	**-**	**0.71**	**53.79**
$R = R_{max} - \exp(a*X_{t-1} + c + b*ONI_{t-3})$	2.6	0.33	-0.57	2.52	-	0.71	54.99
Southern Oscillation Index (SOI)							
$R = R_{max} - \exp(a*X_{t-1} + c) + b*SOI_{t-1}$	2.6	0.25	-0.21	2.10	-	0.28	72.22
$R = R_{max} - \exp(a*X_{t-1} + c + b*SOI_{t-1})$	2.6	0.23	0.06	2.05	-	0.28	72.42
$R = R_{max} - \exp(a*X_{t-1} + c) + b*SOI_{t-2}$	2.6	0.28	-0.67	2.24	-	0.50	65.02
$R = R_{max} - \exp(a*X_{t-1} + c + b*SOI_{t-2})$	2.6	0.25	0.21	2.10	-	0.47	65.77
$R = R_{max} - \exp(a*X_{t-1} + c) + b*SOI_{t-3}$	2.6	0.43	-1.20	2.95	-	0.69	55.65
$R = R_{max} - \exp(a*X_{t-1} + c + b*SOI_{t-3})$	2.6	0.45	0.47	3.08	-	0.69	56.32
Pacific Decadal Oscillation (PDO)							
$R = R_{max} - \exp(a*X_{t-1} + c) + b*POD_{t-1}$	2.6	0.28	0.10	2.23		0.31	66.31
$R = R_{max} - \exp(a*X_{t-1} + c + b*POD_{t-1})$	2.6	0.28	-0.03	2.24		0.31	66.32
$R = R_{max} - \exp(a*X_{t-1} + c) + b*POD_{t-2}$	2.6	0.23	0.39	2.07		0.29	69.39
$R = R_{max} - \exp(a*X_{t-1} + c + b*POD_{t-2})$	2.6	0.24	-0.16	2.10		0.31	69.01
$R = R_{max} - \exp(a*X_{t-1} + c) + b*POD_{t-3}$	2.6	0.25	0.58	2.16		0.36	70.12
$R = R_{max} - \exp(a*X_{t-1} + c + b*POD_{t-3})$	2.6	0.24	-0.20	2.10		0.33	70.72
Sea Superficie Temperature (SST)							
$R = R_{max} - \exp(a*X_{t-1} + c) + b*SST_{t-1}$	2.6	0.23	-0.03	2.04		0.26	70.42
$R = R_{max} - \exp(a*X_{t-1} + c + b*SST_{t-1})$	2.6	0.22	0.12	2.02		0.25	70.51
$R = R_{max} - \exp(a*X_{t-1} + c) + b*SST_{t-2}$	2.6	0.21	1.23	1.92		0.36	69.88
$R = R_{max} - \exp(a*X_{t-1} + c + b*SST_{t-2})$	2.6	0.21	-0.48	1.92		0.34	70.33
$R = R_{max} - \exp(a*X_{t-1} + c) + b*SST_{t-3}$	2.6	0.18	-0.84	1.72		0.30	71.72
$R = R_{max} - \exp(a*X_{t-1} + c + b*SST_{t-3})$	2.6	0.19	0.22	1.87		0.29	71.93
Exogenous: Market Price							
$\mathbf{R = R_{max} - \exp(a*X_{t-1} + c) + b*ONI_{t-3} + d*Price}$	**2.6**	**0.55**	**1.53**	**3.07**	**-0.00008**	**0.82**	**49.83**
$R = R_{max} - \exp(a*X_{t-1} + c + d*Price) + b*ONI_{t-3}$	2.6	0.38	1.45	2.30	0.00003	0.79	50.55

Table 3. Estimated parameters for each model and data set for *Semicossyphus darwini*. Bayesian Information Criterion are show, the best model selected is in bold face.

	Parameters						
	R_{max}	a	b	c	d	R^2	BIC
Semicossyphus darwini							
Endogenous							
$R = R_{max} - \exp(a^*X_{t-1} + c)$	1.0	0.84	-	2.62	-	0.38	46.17
Exogenous: Climate							
Oceanic Niño Index (ONI)							
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ ONI_{t-1}$	1.0	0.89	0.34	2.75	-	0.44	45.26
$\mathbf{R = R_{max} - \exp(a^*X_{t-1} + c + b^*\ ONI_{t-1})}$	**1.0**	**1.32**	**-0.82**	**3.91**	**-**	**0.57**	**40.78**
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ ONI_{t-2}$	1.0	0.85	0.15	2.66	-	0.39	47.01
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*ONI_{t-2})$	1.0	1.05	-0.49	3.25	-	0.46	44.74
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ ONI_{t-3}$	1.0	0.89	0.20	2.80	-	0.40	46.72
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*ONI_{t-3})$	1.0	0.98	-0.26	3.01	-	0.42	46.59
Southern Oscillation Index (SOI)							
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ SOI_{t-1}$	1.0	0.96	-0.19	2.92	-	0.46	44.98
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*\ SOI_{t-1})$	1.0	1.20	0.21	3.58	-	0.50	43.42
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ SOI_{t-2}$	1.0	0.90	-0.11	2.78	-	0.40	46.70
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*SOI_{t-2})$	1.0	1.04	0.16	3.21	-	0.44	45.60
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ SOI_{t-3}$	1.0	0.90	-0.08	2.80	-	0.39	47.17
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*SOI_{t-3})$	1.0	0.84	0.002	2.63	-	0.38	47.42
Pacific Decadal Oscillation (PDO)							
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ POD_{t-1}$	1.0	0.80	0.19	2.55	-	0.42	44.10
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*\ POD_{t-1})$	1.0	0.80	-0.07	2.53	-	0.39	44.97
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ POD_{t-2}$	1.0	0.81	-0.06	2.53	-	0.39	46.17
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*POD_{t-2})$	1.0	0.93	-0.08	2.92	-	0.39	46.14
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ POD_{t-3}$	1.0	0.85	0.05	2.66	-	0.39	47.32
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*POD_{t-3})$	1.0	1.11	-0.26	3.40	-	0.44	45.68
Sea Superficie Temperature (SST)							
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ SST_{t-1}$	1.0	0.84	-0.37	2.65	-	0.42	45.41
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*\ SST_{t-1})$	1.0	0.83	0.25	2.62	-	0.39	46.11
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ SST_{t-2}$	1.0	0.81	-0.24	2.54	-	0.39	47.00
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*SST_{t-2})$	1.0	0.76	0.25	2.40	-	0.39	47.24
$R = R_{max} - \exp(a^*X_{t-1} + c) + b^*\ SST_{t-3}$	1.0	0.84	-0.11	2.64	-	0.38	47.34
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*SST_{t-3})$	1.0	0.88	0.26	2.76	-	0.39	47.08
Exogenous: Market Price							
$R = R_{max} - \exp(a^*X_{t-1} + c + b^*ONI_{t-3}) + d^*Price$	**1.0**	**7.11**	**-4.07**	**17.03**	**- 0.19**	**0.74**	**34.43**
$R = R_{max} - \exp(a^*X_{t-1} + c + d^*Price + b^*ONI_{t-3})$	1.0	1.21	-1.07	6.39	-0.41	0.60	41.81

Table 4. Parameters used for predicted equilibrium densities under different scenarios.

		Price (CP$)			Climate (ONI)		
		Average	50%	100%	Average	(25% warm) +	(25% cold) -
Scenario 1 (Price)	*Graus nigra*	1215	1823	2430	0.05	-	-
	Semicossyphus darwini	1091	1636	2182	0.01	-	-
Scenario 2 (Climate)	*Graus nigra*	1215	-	-	0.05	0.075	0.025
	Semicossyphus darwini	1091	-	-	0.01	0.015	0.005
Scenario 3 (Price+Climate)	*Graus nigra*	1215	1823	-	0.05	0.075	0.025
	Semicossyphus darwini	1091	1636	-	0.01	0.015	0.005

Figures

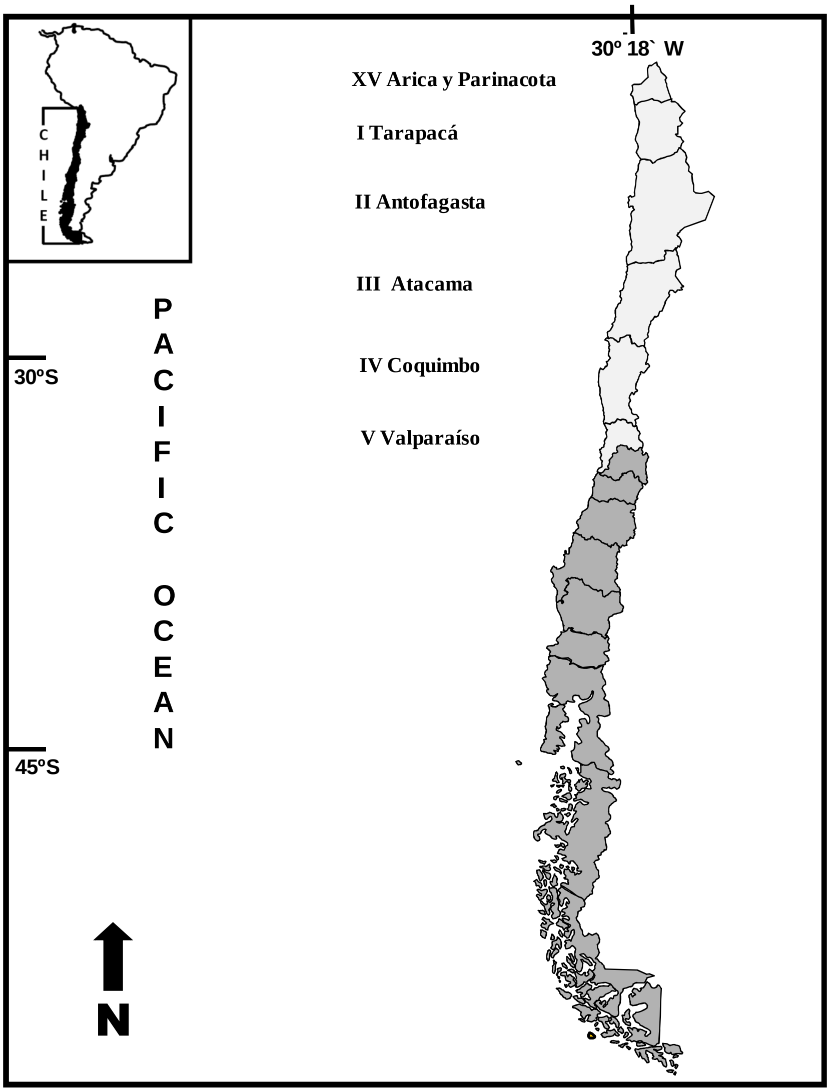

Figure 1. Map of site study.
Map covering the XV (18° 27’ S – 70° 20’ W) and V administrative Regions (30° 54’ S – 71° 31’ W) of Chile, where most of the artisanal spear fishing activities occur.

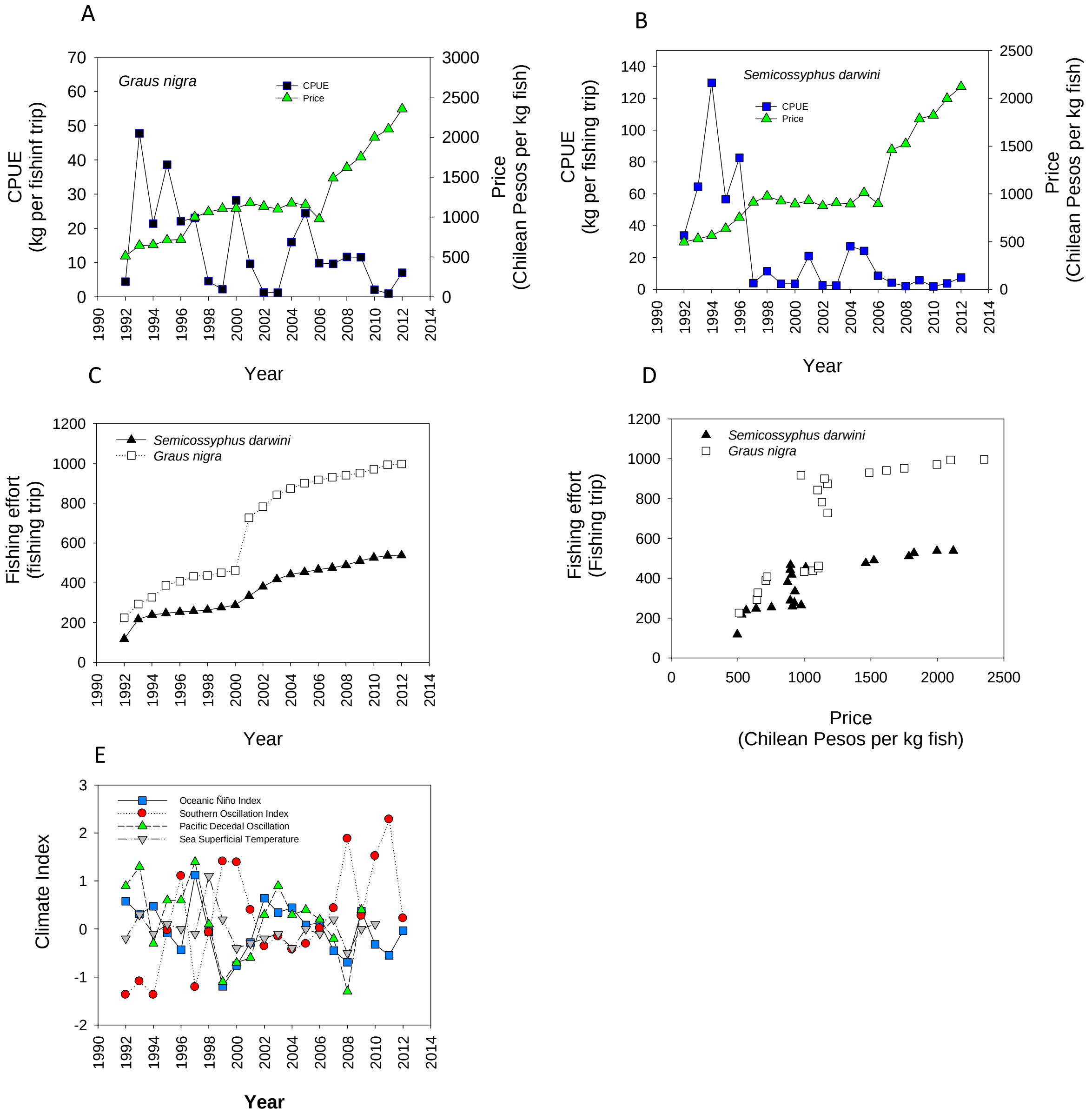

Figure 2. Time series data used in the theoretical analysis.

Capture per United Effort (CPUE) and fish market price for *Graus nigra* (A) and *Semicossyphus darwini* (B), fishing effort (C) relationship between fish market price and fishing effort (D) and, climate indices (E)

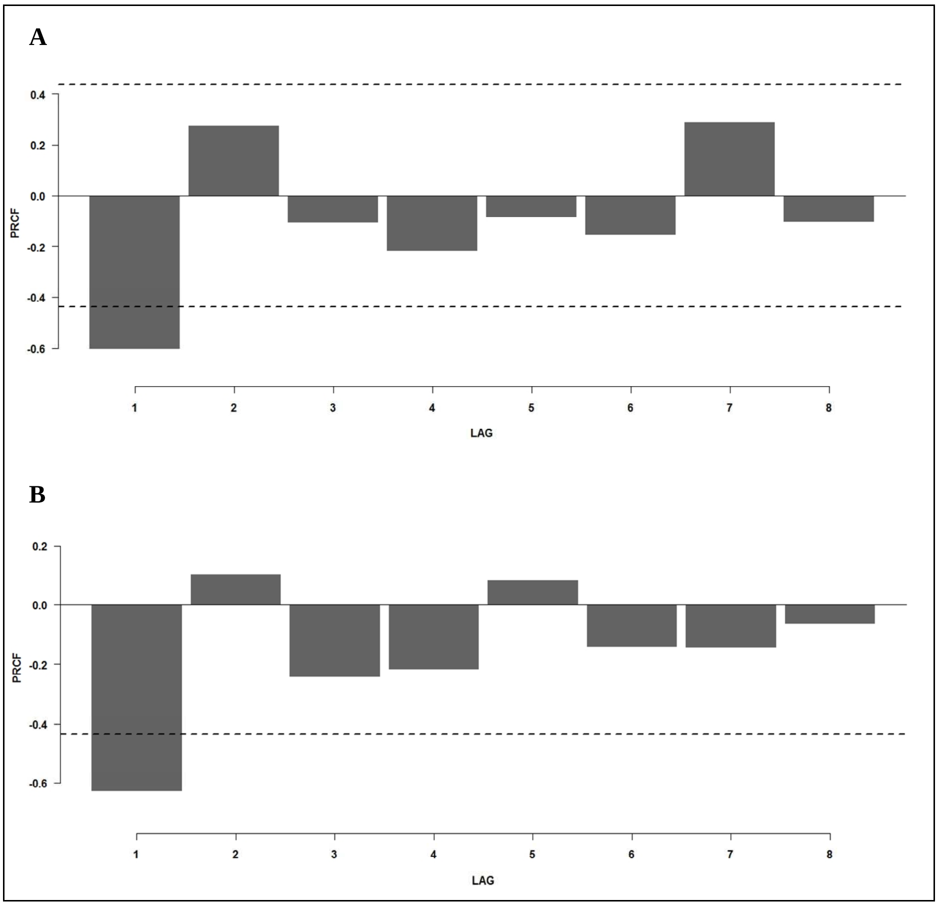

Figure 3. Partial correlation rate function (PRCF).
PRCF plots for the two rocky fish species. *Graus nigra* (A) and *Semicossyphus darwini* (B).

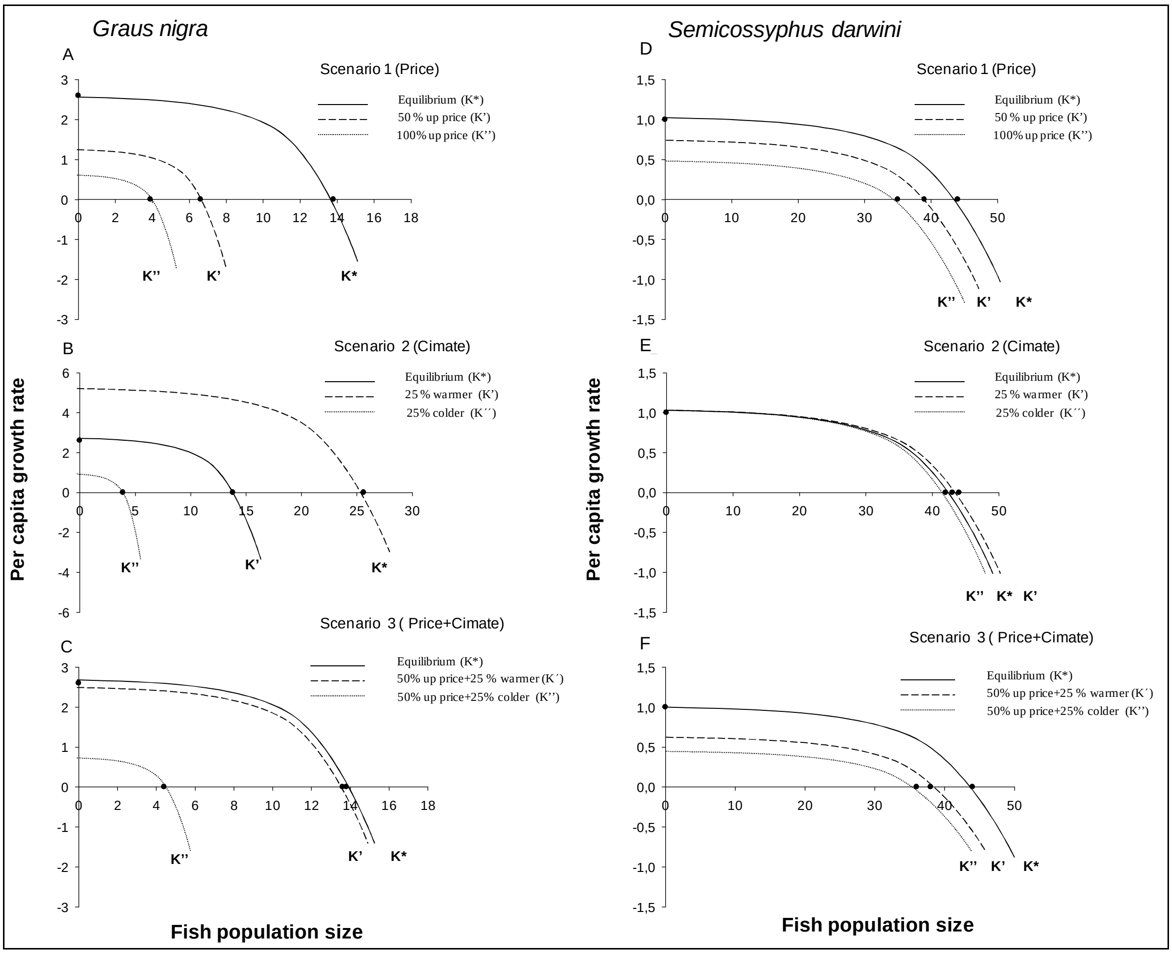

Figure 4. Reproductive curves or R-functions under different scenarios.
G. nigra (A-B-C) and *S. darwini* (D-E-F), according to equation (14) and (15).

Supporting Information

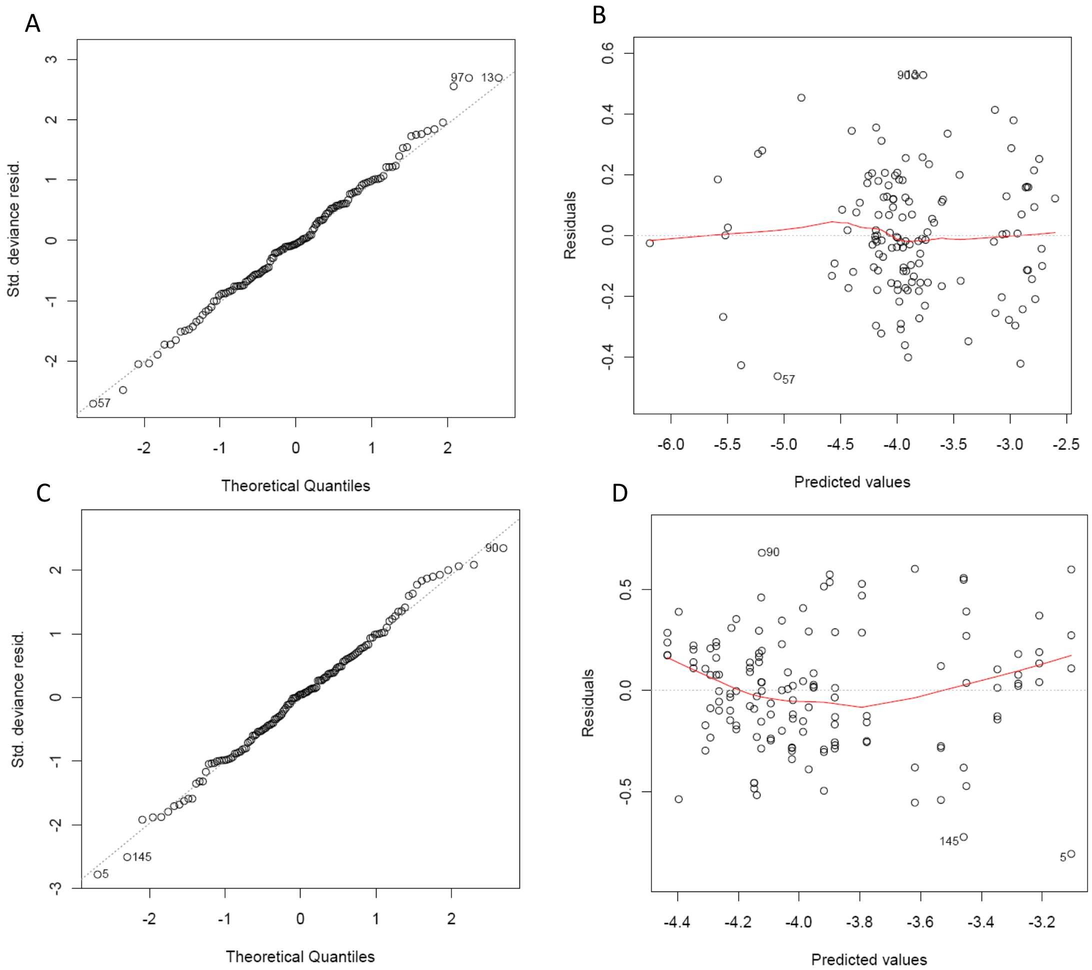

Figure S1. Distribution of theoretical quantiles and standarized residual of CPUE analysis. *Graus nigra* (A-B) and *S. darwini* (C-D).

Table S1. Summary of ANOVA for standardized CPUE analysis

Graus nigra					
	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Year	19	52.627	2.770	8.53	1.1e-14 *
Region	3	8.517	2.839	8.74	2.7e-05 *
Quarter	3	2.566	0.855	2.63	0.052
RxQ	9	1.695	0.188	0.58	0.811
Residuals	120	38.952	0.325		

Semicossyphus darwini					
	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Year	19	156.548	9.209	24.32	2.2e-16 *
Region	3	29.800	9.933	26.23	5.9e-13 *
Quarter	3	0.963	0.321	0.848	0.4704
RxQ	9	2.687	0.299	0.788	0.6274
Residuals	113	42.784	0.379		

(* significant codes: < 0.001 [31])

Conclusiones

Chile es un país de contrastes en términos de manejo y conservación de recursos marinos costeros. Es destacado a nivel mundial por la institucionalización de conceptos ecológicos y pesqueros, a través de prácticas de manejo de recursos bentónicos, en la ley de pesca y acuicultura (Castilla y Defeo 2001). No obstante, en la destacada institucionalidad pesquera chilena no existe, por ejemplo, regulación sobre la captura de peces litorales por buceo; esto a pesar de la disminución de los desembarques y los diversos estudios que advierten sobre las señales de sobre-explotación y los potenciales efectos negativos de la pesca por buceo sobre el ensamble de peces y posibles efectos en cadena sobre los ecosistemas costeros someros (Moreno, 1972, Fuentes 1981, Fuentes 1985, Pequeño y Olivera, 2004, Godoy et al. 2010). Teniendo en consideración estos aspectos, los principales resultados obtenidos en esta Tesis resultan ser una contribución para mejorar nuestra comprensión del funcionamiento de estas pesquerías y sus potenciales efectos negativos sobre el ecosistema costero somero. Esta visión holística de la pesquería permito identificar los componentes del sistema socio-ecológico y conocer sus interrelaciones.

Los resultados presentados en el primer capítulo fueron consistentes con un estudio reciente, basado en conocimiento ecológico local por los buceadores, que sugiere que esta pesquería muestra ya señales claras de sobre-explotación (Godoy et al., 2010). Los resultados de esta Tesis confirman y apoyan la existencia de signos de sobre-explotación, por ejemplo: a) una baja representación de las especies emblemáticas, b) una reducción en los tamaños corporales promedios y c) una alta representación de especies de menor tamaño y valor comercial. La pesca por buceo con snorkel y con equipo hookah es una actividad rentable que opera en su conjunto sobre la mayoría de las especies que componen este ensamble de peces, rangos de profundidad, tamaños corporales, hábitats y refugios en el submareal costero. Se registraron variaciones en la composición de las capturas de buzos artesanales por efecto del gradiente latitudinal y el tipo de equipo de buceo utilizado en las capturas. Además, se observó una alta sobre posición de las principales especies capturadas por ambas técnicas de buceo. También las capturas por buceo fueron caracterizadas por la baja representación de especies emblemáticas de mayor tamaño y una alta representación de especies menos emblemáticas y de menor tamaño. Estos resultados confirman la necesidad de planificar estrategias de manejo y conservación para este ensamble de estas especies.

Los resultados del segundo capítulo de esta Tesis sugieren que las estrategias de pesca de buzos artesanales, en relación a que sitios visitar y cuanto tiempo permanecer buceando, estarían influenciadas por una serie de restricciones ambientales impuestas por el “estado del mar”, por sobre el tiempo de viaje y tiempo de buceo en los campos de pesca. Por lo tanto, este análisis permitió mejorar nuestra comprensión sobre las estrategias de pesca de los buzos artesanales y su interacción con los peces litorales de roca.

Por otra parte, el uso de modelos de dinámica poblacional, para el análisis de información pesquera artesanal, permitió deducir la estructura endógena poblacional. Además, de informar de la importancia de los efectos exógenos, como ENSO y precios de mercado, y como la pesquería por buceo influencian las dinámicas observadas. Esta información es clave para el manejo de estas pesquerías. Por lo tanto, la Tesis es un ejemplo de cómo la aplicación de elementos teóricos puede aportar información relevante para resolver problemas prácticos de manejo y conservación de pesquerías artesanales. La teoría ecológica de dinámica de poblaciones fue una herramienta útil en descifrar los factores exógenos (Oceanic Niño Index y precios de mercado) y endógenos (competencia intraespecífica) que subyacen a las fluctuaciones observadas en *G. nigra* y *S. darwini*.

El estudio sugiere efectos positivos de periodos climáticos cálidos (El Niño) y negativos del precio de mercado (utilizado como proximal del esfuerzo pesquero) sobre los índices de abundancia relativa, para ambas especies. Sin embargo, los efectos del clima explicaron la mayor parte de la variación de los índices de abundancia, para *G. nigra* y el precio de mercado fue el principal predictor para *S. darwini*. Estos resultados son relevantes en un escenario de cambio climático, donde se espera que en las costas de Chile--Perú se intensifiquen los vientos sur – oeste, favoreciendo los eventos de surgencia de aguas frías (Garreaud y Falvey, 2009, Goubanova y cols., 2011). Este escenario podría magnificar el efecto de la pesca por buceo, particularmente, en el caso de *G. nigra* que muestra mayor sensibilidad a variaciones climáticas. En el caso de *S. darwini* los resultados sugieren que el mercado jugó un rol importante sobre la dinámica de esta especie, altamente vulnerable a la pesca por buceo por sus rasgos de historia de vida. Se ha descrito en la literatura que el acceso al mercado de peces puede determinar en gran medida la abundancia y diversidad del ensamble de peces litorales (Cinner y McClanahan, 2006, Brewer et al., 2012).

Los resultados de este estudio sugieren para Chile una pesquería por buceo con claras señales de sobre-explotación, y donde el mercado estaría determinando gran parte del esfuerzo pesquero. Estos antecedentes en combinación con estudios previos dan cuenta de la necesidad de implementar estrategias de manejo y conservación para estas pesquerías. Particularmente cuando estudios recientes sugieren que zonas templadas serian nuevos "hotspots" de diversidad funcional de peces costeros. (Stuart-Smith y cols., 2013). Una estrategia de manejo simple, es la implementación de restricciones al buceo como arte de pesca (McClanahan y Mangi, 2004, McClanahan y Cinner, 2008), regulando, por ejemplo, el numero maximo de ejemplares por especies que pueden ser capturados, y las tallas mínimas de madurez sexual (Flores y Smith, 2010). Esta tesis es un aporte más al conocimiento de estas pesquerías y los efectos sobre el ensamble de peces litorales, tal que futuras aproximaciones pueden ser orientadas a:

- Determinar si los patrones aquí observados se mantienen al incorporar antecedentes sobre capturas provenientes desde AMERBs, donde se han descrito mayor abundancia de estas especies (Gelcich y cols, 2008)

- Determinar como el acceso a los mercados o cercanía a centros urbanos y el desarrollo socio-económico pueden explicar la diversidad y biomasa del ensamble de peces litorales.

- Evaluar los patrones de conducta de escape de peces litorales con y sin importancia comercial, ante la presencia de buzos artesanales, como indicador de impacto de la pesca.

- Evaluar las propiedades de las redes de interacciones tróficas entre los peces capturados por la pesquería y sus presas, en distintos regímenes de acceso a la pesca (Libre acceso - AMERBs - Reservas Marinas).

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