UNIVERSIDAD DE COSTA RICA
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VARIABILIDAD ISOTÓPICA DE PECES LOROS Y MACROALGAS EN EL PACÍFICO NORTE DE COSTA RICA: UNA HERRAMIENTA POTENCIAL PARA EL MANEJO DE LA PESQUERÍA CON COMPRESOR

"Isotopic variability of parrotfish and macroalgae in the North Pacific of Costa Rica: A potential tool for compressor fishery management"

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Tesis sometida a la consideración de la Comisión del Programa de Posgrado en Gestión Integrada de Áreas Costeras Tropicales para optar al grado y título de Maestría en Gestión Integrada de Áreas Costeras Tropicales

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DEDICATORIA

Dedico este trabajo de investigación a todas las personas conectadas al mar: investigadoras, investigadores, comunidades costeras y personas pescadoras. Al mismo tiempo, quiero enfatizar que estos logros pueden ser alcanzados por personas independientemente de su edad, género, orientación sexual, etnia o capacidades. Este logro representa un tributo a nuestra pasión compartida por la conservación de nuestros océanos, la investigación incansable y la contribución a posibles soluciones para las comunidades costeras y la sostenibilidad de nuestros valiosos recursos marinos. Espero que nuestras fortalezas y "debilidades" continúen inspirándonos en este camino conjunto hacia un futuro más sostenible y equitativo en relación con el mar y las personas que dependen de él.

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LISTA ABREVIATURAS

A

A. *Actors*

B

BSE. *Bahía Santa Elena*

E

EAM. *Epilithic algae matrix*

F

FAO. *The Food and Agriculture Organization of the United Nations*
FL. *fishing landings*

G

GLIER. *Great Lakes Institute for Environmental Research*
GS. *Governance Systems*
GSE. *Golfo Santa Elena*

I

I. *Interactions*
IM. *Islas Murciélago*

M

MAXQDA. *MAX Qualitative Data Analysis*
MPA. *Marine Protected areas*

O

O. *Outcomes*

R

RS. *Resource Systems*
RU. *Resource Units*

S

S. *Social, Economic, and Political Settings*
SD. *Standard Deviation*
SEA. *Standard Ellipse Area*
SEAc. *Sample Size Corrected Standard Ellipse Area*
SESF. *Social Ecological System Framework*
SIA. *Stable isotope analysis*
SIBER. *Stable Isotope Bayesian Ellipses*
SINAC. *Sistema Nacional de Áreas de Conservación*
SSF. *Small-scale fisheries*

T

TL). *total length*

INTRODUCTION

Coastal development and increasing global demand for fisheries resources are key factors that have contributed significantly to the overexploitation of many marine species in recent decades, which could have ecological consequences of great relevance to the health of marine ecosystems (Brander, 2007; Jackson, 2008; Telesca, 2017). It is important to recognize that while artisanal fisheries account for about half of these catches, they also play a key role in generating about 90% of employment in the sector (FAO, 2020). In this global context, many countries are implementing policies aimed at balancing environmental and social benefits through a more sustainable use of natural resources (Madrigal-Ballestero et al., 2017). However, effective management of marine resources can be difficult, with challenges ranging from lack of equipment and training to limited funding (Arias et al., 2014). In this scenario, marine protected areas (MPAs) are presented as a fundamental tool for the management and conservation of fishery resources, although their effectiveness largely depends on compliance by local communities (Campbell et al., 2012).

On the northern Pacific coast of Costa Rica, artisanal fishing, particularly diving fishing using air compressors, is an important source of employment and economic livelihood for local communities (Villalobos-Rojas et al., 2015). Historically, this fishery was based on free diving, but the introduction of air compressors has changed the dynamics of the fishery. In addition, night fishing with compressors has significantly increased landings of several species, including parrotfish (Ebisawa et al., 2016). Parrotfish, in turn, represent an economic resource of great importance in this Costa Rican region (Villalobos-Rojas et al., 2014), contributing significantly to the species landed, in some cases up to 48% (Espinoza et al., 2020). It should be noted that parrotfish play a key role as consumers of marine primary production on reefs, contributing significantly to the energy flow that underpins the resilience of these ecosystems (Adam et al., 2018; Durán & Claro, 2009; Rodríguez-Barreras et al., 2015; Bonaldo et al., 2014).

The lack of essential data on the dynamics of compressor fishing, ranging from information gaps on fishing effort to the status of affected populations such as parrotfish, hinders the implementation of effective monitoring and management strategies (Villalobos-Rojas et al., 2014; García, 2013). Furthermore, the establishment of the Islas Murciélago MPA near the fishing community in the Gulf of Saint Helena has led to an increase in illegal activities, posing a significant threat to marine resources (Sánchez Jiménez et al., 2014; SINAC, 2019; Madrigal-Mora et al., 2022). Although illegal parrotfish fishing has not been documented in this area, it is a known practice among local fishermen and occurs mainly at night (M. Lara, pers. comm.). In this sense, the traceability of the geographical origin of seafood products is crucial to ensure sustainable fishing practices (Saiki 2015, de Aquino Ferreira et al., 2021, del Rio-Lavín et al., 2022).

Stable isotope analysis (SIA) is emerging as a cost-effective and powerful ecological tool for tracking the diet and trophic interactions of marine species (Hobson, 1999). In recent years, SIA has been used to distinguish between production methods and to trace the geographical origin of fishery products (Gamboa Delgado et al., 2014; Gopi et al., 2019). In coastal areas, this approach has the potential to trace the origin of fishery products from different geographical locations (Kim et al., 2015; de Aquino Ferreira et al., 2021; del Rio-Lavín et al., 2022). It is important to recognise that artisanal fisheries in tropical coastal areas have considerable complexity due to the temporal and spatial variability of landings, the diversity of species and the variety of fishing techniques used (Naranjo and Salas, 2006; Naranjo et al., 2015). The introduction of new technologies, such as air compressors, has the potential to significantly alter these complex socio-ecological systems. Consequently, a comprehensive understanding of the social and ecological dynamics of these fisheries provides a sound basis for improving fisheries management in a more sustainable and transparent procedures.

Recognition of the importance of incorporating social and human dimensions in fisheries research and management (Chuenpagdee et al., 2005). Our study takes two complementary approaches to recommending management measures for compressor fisheries. First, we use Ostrom's SESF to analyze the adoption of air compressors by Cuajiniquil fishermen. Second, we investigate one of the main management challenges in this area, illegal fishing in the Islas Murcielago MPA. To this end, we used stable isotope analysis (SIA), specifically $\delta13C$ and $\delta15N$, to trace the geographic origin of parrotfish fisheries along the Pacific coast of Costa Rica. The results of our study highlight the need for a comprehensive ecosystem-based management strategy for air compressors in the Cuajiniquil FSS, emphasizing collaboration between fishers, local leaders, government agencies and other key stakeholders. Addressing the challenges of implementing closed MPAs requires a balanced approach and the promotion of collaborative dialogue between fishers and government authorities. This holistic approach considers not only the state of fish stocks, but also the behavior of fishers, which can lead to more effective and sustainable regulations (Letschert et al., 2023).

Introducción

El desarrollo costero y la creciente demanda global de recursos pesqueros son factores cruciales que han contribuido significativamente a la sobreexplotación de numerosas especies marinas en las últimas décadas, lo que podría resultar en consecuencias ecológicas de gran relevancia para la salud de los ecosistemas marinos (Brander, 2007; Jackson, 2008; Telesca, 2017). Es fundamental reconocer que la pesca artesanal, aunque contribuye aproximadamente con la mitad de estas capturas, también desempeña un papel fundamental al generar alrededor del 90% de los empleos en este sector (FAO, 2020). En este contexto global, numerosos países están implementando políticas orientadas a equilibrar los beneficios ecológicos y sociales a través de un uso más sostenible de los recursos naturales (Madrigal-Ballestero et al., 2017). Sin embargo, la gestión efectiva de los recursos marinos puede resultar difícil, con desafíos que van desde la falta de equipamiento y capacitación hasta la limitación en términos de financiamiento (Arias et al., 2014). En este escenario, las áreas marinas protegidas (AMP) se presentan como una herramienta fundamental para la gestión y conservación de los recursos pesqueros, aunque su efectividad depende en gran medida del cumplimiento de las reglas por parte de las comunidades locales (Campbell et al., 2012).

En la costa del Pacífico norte de Costa Rica, la pesca artesanal, y en particular la pesca de buceo con compresores de aire, es una fuente vital de empleo y sustento económico para las comunidades locales (Villalobos-Rojas et al., 2015). Históricamente, esta pesquería se basaba en pesca a pulmón, pero la introducción de compresores de aire ha transformado la dinámica pesquera. Además, la pesca nocturna con compresores ha incrementado significativamente los desembarques de diversas especies, incluido el pez loro (Ebisawa et al., 2016). Los peces loro, por su parte, representan un recurso económico de gran importancia en esta región costarricense

(Villalobos-Rojas et al., 2014), contribuyendo de manera considerable a las especies desembarcadas, llegando a representar hasta el 48% en algunas ocasiones (Espinoza et al., 2020). Es necesario destacar que los peces loro desempeñan un papel fundamental como consumidores de la producción primaria marina en los arrecifes y contribuyen significativamente al flujo de energía que sustenta la resiliencia de estos ecosistemas (Adam et al., 2018; Durán & Claro, 2009; Rodríguez-Barreras et al., 2015; Bonaldo et al., 2014).

La falta de datos esenciales sobre la dinámica de la pesca con compresor, abarca desde vacíos de información sobre el esfuerzo pesquero hasta el estado de las poblaciones afectadas, como el caso de los peces loros, lo cual obstaculiza la aplicación de estrategias efectivas de seguimiento y gestión (Villalobos-Rojas et al., 2014; García, 2013). Además, la creación de la AMP Islas Murciélago cerca de la comunidad pesquera del Golfo de Santa Elena ha dado lugar a un aumento en la actividad ilegal, lo que constituye una amenaza significativa para los recursos marinos (Sánchez Jiménez et al., 2014; SINAC, 2019; Madrigal-Mora et al., 2022). Aunque no se ha documentado la pesca ilegal de peces loro en esta zona, es una práctica bien conocida entre los pescadores locales, y tiende a ocurrir principalmente durante las horas nocturnas (M. Lara, com. pers.). En este sentido, la trazabilidad del origen geográfico de los productos marinos se vuelve crucial para garantizar prácticas pesqueras sostenibles (Saiki 2015, de Aquino Ferreira et al., 2021, del Rio-Lavín et al., 2022).

El análisis de isótopos estables (SIA) emerge como una herramienta ecológica rentable y poderosa para rastrear la dieta y las interacciones tróficas de las especies marinas (Hobson, 1999). En los últimos años, el SIA ha sido utilizado para discernir entre métodos de producción y rastrear el origen geográfico de productos pesqueros (Gamboa Delgado et al., 2014; Gopi et al., 2019). En entornos costeros, este enfoque tiene el potencial de rastrear el origen de productos pesqueros procedentes de diferentes ubicaciones geográficas (Kim et al., 2015; de Aquino Ferreira et al., 2021; del Rio-Lavín et al., 2022). Es importante reconocer que las pesquerías artesanales en zonas costeras tropicales presentan una complejidad considerable debido a la variabilidad en los desembarques en términos de tiempo y espacio, la diversidad de especies y la variedad de técnicas de pesca utilizadas (Naranjo y Salas, 2006; Naranjo et al., 2015). La introducción de nuevas tecnologías, como los compresores de aire, tiene el potencial de alterar de manera significativa estos sistemas socio ecológicos complejos. En consecuencia, comprender de manera integral la dinámica social y ecológica de estas pesquerías proporciona una base sólida para mejorar la gestión pesquera de manera más sostenible y transparente.

Reconociendo la importancia de incorporar dimensiones sociales y humanas en la investigación y gestión pesquera (Chuenpagdee et al., 2005). Nuestro estudio aborda dos enfoques complementarios para recomendar medidas de manejo de la pesca con compresor. En primer lugar, utilizamos el SESF de Ostrom para analizar la adopción de compresores de aire por parte de los pescadores de Cuajiniquil. Segundo, exploramos uno de los principales desafíos de gestión en esta área, la pesca ilegal en la AMP Islas Murciélago. Para ello, aplicamos el análisis de isótopos estables (SIA), específicamente δ13C y δ15N, para rastrear el origen geográfico de la pesca de peces loro a lo largo de la costa del Pacífico de Costa Rica. Los resultados de nuestro estudio resaltan la necesidad de una estrategia de gestión integral basada en el ecosistema para los compresores de aire en el SSF de Cuajiniquil, enfatizando la colaboración entre pescadores, líderes locales, organismos gubernamentales y otros actores clave. Abordar los desafíos de la implementación de AMP de veda requiere un enfoque equilibrado y el fomento de un diálogo colaborativo entre pescadores y autoridades gubernamentales. Este enfoque integral no solo considera el estado de las poblaciones de peces, sino también el comportamiento de los pescadores, lo que puede llevar a regulaciones más efectivas y sostenibles (Letschert et al., 2023).

CHAPTER I. Social-ecological drivers of air compressor use in an artisanal fishery on the Pacific coast of Costa Rica

Factores socio ecológicos del uso de compresores de aire en una pesquería artesanal de la costa del Pacífico de Costa Rica

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I. ABSTRACT

Coastal areas are a vital source of resources and livelihoods for millions of people around the world. Small-scale fisheries (SSF) play an essential role in supporting coastal communities and their economies. However, the introduction of new technologies has the potential to reshape these complex social-ecological systems. This study uses Ostrom's Social Ecological System Framework (SESF) to analyze the adoption of air compressors by fishers in Cuajiniquil, a coastal community on the North Pacific coast of Costa Rica. By combining quantitative and qualitative data, the study identified key environmental and social factors influencing the use of air compressors. The shift from traditional fishing methods to compressor fishing has led to changes in target species, landings and fishing dynamics. Challenges related to fishers' safety and the dynamics of market shifts highlight the need for comprehensive management strategies. The application of the SESF framework in this study contributes to a deeper understanding of the adoption of innovative practices in a small-scale fishery.

Resumen

Las zonas costeras son una fuente vital de recursos y medios de subsistencia para millones de personas en todo el mundo. La pesca artesanal desempeña un papel esencial en el sustento de las comunidades costeras y sus economías. Sin embargo, la introducción de nuevas tecnologías puede alterar estos complejos sistemas. Este estudio utiliza el Marco de Sistemas Socio ecológicos (SESF) de Ostrom para analizar la adopción de compresores de aire por los pescadores de

Cuajiniquil, una comunidad costera del Pacífico Norte de Costa Rica. Combinando datos cuantitativos y cualitativos, el estudio identificó los principales factores ambientales y sociales que influyen en el uso de compresores de aire. La transición de los métodos de pesca tradicionales a la pesca con compresor ha provocado cambios en las especies objetivo, los desembarques y la dinámica pesquera. Los retos relacionados con la seguridad de los pescadores y la dinámica de los cambios del mercado resaltan la necesidad de estrategias de gestión integrales. La aplicación del marco SESF en este estudio contribuye a una comprensión más profunda de la adopción de prácticas innovadoras en una pesquería artesanal.

II. INTRODUCTION

Tropical coastal areas support the ecological, economic, cultural, and social interests of more than 775 million people through a wide variety of marine ecosystems and resources (Selig et al., 2018). Small-scale fisheries (SSF) provide several important benefits to coastal communities, including food security, nutrition, community resilience, employment, and local empowerment (Veitayaki, 2021). According to a report by the United Nations Food and Agriculture Organization (FAO), global fisheries production has already reached its highest level on record (FAO, 2018). SSF produce almost half of the fish consumed in low- and middle-income countries and directly employ 60 million people, with a further 53 million fishing for subsistence (FAO, 2020). Small-scale fisheries (SSFs) in tropical coastal areas exhibit considerable complexity due to their variable landings over space and time, diverse species, and diverse fishing gears and techniques (Naranjo Madrigal & Salas Márquez, 2014; Naranjo-Madrigal et al., 2015). This complexity is compounded by the limited information available to fisheries management on their historical evolution, responsiveness to regulation, and overall fishing dynamics. In particular, understanding of fishers' behavior in the context of change is primarily focused on larger commercial fleets (Branch et al., 2006). By addressing these gaps, a deeper understanding of the social-ecological factors that drive fishers' behavior during dynamic change can significantly improve the effectiveness of management (Villasante et al., 2022).

Over the last few decades, the catch rates and profitability of SSF have improved considerably as a result of major technological advances in fishing gear (Boopendranath, 2012). Fishers often seek out innovations in fishing gear based on their perceived needs, knowledge, and the advantages/disadvantages of adopting or rejecting new practices (Halim, 2002). Adapting new innovations can have positive and negative impacts on social-ecological systems. For example, the use of air compressor diving for fishing, raises both ecological and human safety concerns, as fishers typically target multiple reef species, which can lead to overfishing, and this practice can also have serious implications divers' health (Ennis & Aiken, 2014; Pavlowich & Kapuscinski, 2017; Villalobos-Rojas et al., 2015). Compressor-based fishing is known to occur only in tropical regions and appears to have a different dynamic that allows the fishers to adopt a unique fishing behavior than other artisanal gears (Dirgantara et al., 2019). This activity is conducted underwater, breathing air supplied by a compressor (via a hose) on a vessel, and fishers typically target multiple reef species from different trophic levels (Indra et al., 2019). There is often limited information on the target species, fishing locations and social dimensions of compressor-based fisheries (Barbosa-Filho et al., 2020), consequently, these fisheries are still poorly understood and difficult to manage (Young, 2015).

Compressor fishing could face challenges other than those affecting the well-being of reef ecosystems and fishers. The drivers that lead to the adoption of an innovation have been shown to be influenced by a wide range of social and environmental factors. Research on social-ecological systems (SES) in SSF has helped to sort out the complexity of these interactions (Basurto et al., 2013; McGinnis & Ostrom, 2014), but little work has been done to understand the drivers of innovative fishing gear adoption and their impacts in the context of SSF (Torres Cañete et al., 2022). The application of Social-Ecological System Framework SESF has been useful as a diagnostic tool to structure data collection (McGinnis & Ostrom, 2014, Chavez Carrillo et al., 2019 & Partelow, 2023). This approach allows to analyze interactions and outcomes related to the resource system and resource units, as well as the governance systems and actors involved in the system. The SESF consists of several variables organized into different tiers and categories (Fig. 1) (Anderies et al., 2004; Ostrom, 2007). This tool also provides a common vocabulary for communication between scientists from different disciplines, facilitating the communication of results across research communities and enabling comparison and information sharing.

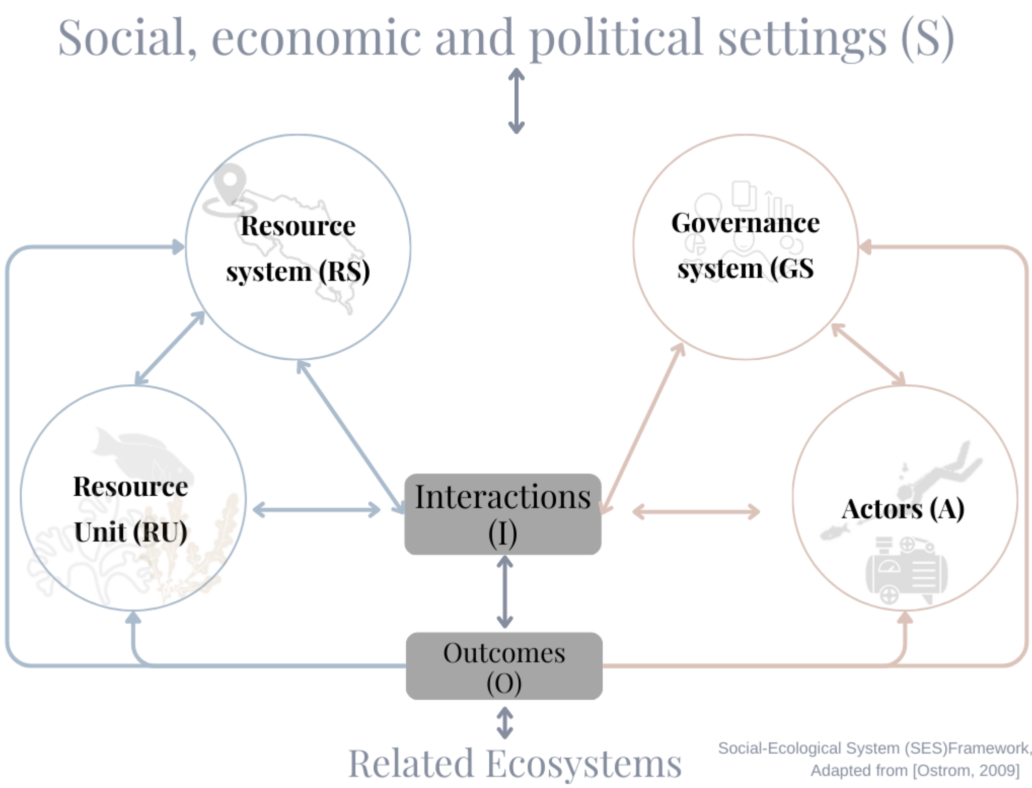

Fig 1. Social Ecological (SES) framework adapted from Ostrom (2009).

On the north Pacific coast of Costa Rica, SSF is one of the most important sources of work and economic livelihood (Villalobos-Rojas et al., 2015). The compressor-based fishery is an important fishery in this region, specifically within the Gulf of Santa Elena. A wide range of reef species are caught in this region by the compressor-based fishery, with parrotfish (Scaridae) accounting for 48% of landings (SINAC, 2020). Parrotfish are among the largest consumers of primary marine production on reefs and contribute significantly to the energy flow energy and resilience of coral reefs worldwide (Bonaldo et al., 2014; Duran et al., 2018). Parrotfishes have been utilized as important food resources in tropical and subtropical region (Ebisawa et al., 2016). One of the main gears for capturing parrotfishes is mostly nets and speargun through diving. Historically, this fishery was based on freediving, but the introduction of air compressors changed the fishing dynamics. Moreover, the introduction of night spear fishing significantly increased the landings of several groups, including parrotfish (Ebisawa et al., 2016). In Costa Rica compressor fishing is permitted but not fully regulated and there are no records of this fishery or catch statistics (Villalobos-Rojas et al., 2015). This results in limited information about the possible human and ecological impacts of the adoption of air compressors into the fishery. Addressing these challenges requires that social and human dimensions be explicitly incorporated into fisheries research and management frameworks (Chuenpagdee et al., 2005). This can lead in the development of regulations that not only consider the status of fish stocks but also the behavior of fishers. Such an integration would help policymakers to support effective management (Letschert et al., 2023).

In this study, we argue that the adoption of air compressors for fishing in the Gulf of Santa Elena is influenced by a combination of socio-economic factors, cultural norms, and ecological considerations. We expect that the introduction of air compressors has changed the fishing dynamics in the community, leading to shifts in target species, catch volumes, and fishing behavior. To explore these arguments, we analyzed compressor dive fishing in the Gulf of Santa Elena on the north Pacific coast of Costa Rica. Our study aims were to (i) investigated the social-ecological drivers behind the adoption of air compressors for fishing in Cuajiniquil, and (ii) evaluated how fishing dynamics changed with the use of the compressor. Our study provides recommendations for improving the ecological status of this fishery and the well-being of local villagers who depend on it.

III. METHODOLOGY

Study area

Cuajiniquil is the main fishing community from La Cruz, Guanacaste, and it is located inside the Gulf of Santa Elena (10°57'58.26"N, 85°44'12.48"W), north Pacific coast of Costa Rica (Fig. 2). This location benefits from a variety of marine habitats and is characterized by strong seasonal upwelling, which increases the overall productivity of the surrounding waters (Amador et al., 2006), lifting colder water from the sub thermocline and bringing in nutrient-rich water from the bottom (Alfaro & Cortés, 2015; Rodríguez et al., 2021). These biological and oceanographic characteristics have led to the establishment of important protected areas around Cuajiniquil, such as the Murciélago Islands no-take Marine Protected Area (MPA) stablished in 1987, followed by Bahia Santa Elena Marine Management Area stablished in 2018 (SINAC, 2009 & SINAC, 2020)

Cuajiniquil was historically a ranching community, but with the creation of the Santa Rosa National Park in the 1970s, it lost access to the surrounding land and gradually became a fishing community. There are approximately 2000 people in Cuajiniquil, and it is now one of the main fishing communities in the Pacific coast of Costa Rica. (SINAC 2017; INE, 2011). The port of Cuajiniquil contributes a significant amount to the production of local and export fishing. The main types of SSF are compressor-diving, nets and handlines, used to target multiple inshore species such as snapper (*Lutjanus guttatus*, *Lutjanus peru*, *Lutjanus* spp.), grouper (*Epinephelus* spp) octopus (*octopus* spp.), lobster, parrotfish (*Scarus ghobban*) among others (Farías-Tafolla et al., 2022). There is also a semi-industrial fishery within the types of medium-scale commercial and advanced commercial fishing that use drifting longlines and target pelagic species offshore such as mahi-mahi – dorado (*Coryphaena hippurus*), Silky shark (*Carcharhinus falciformis)*, Indo-Pacific sailfish, (*Istiophorus platypterus) swordfish* (*Xiphias gladius)*, yellowfin tuna (*Thunnus albacares) and* bigeye tuna (*Thunnus obesus)* (Villalobos-Rojas et al., 2015). Both groups (artisanal and semi-industrial) have different dynamics and regulations. For example, landings are only monitored in the semi-industrial and ornamental dive fisheries, and the remaining artisanal fisheries are not covered.

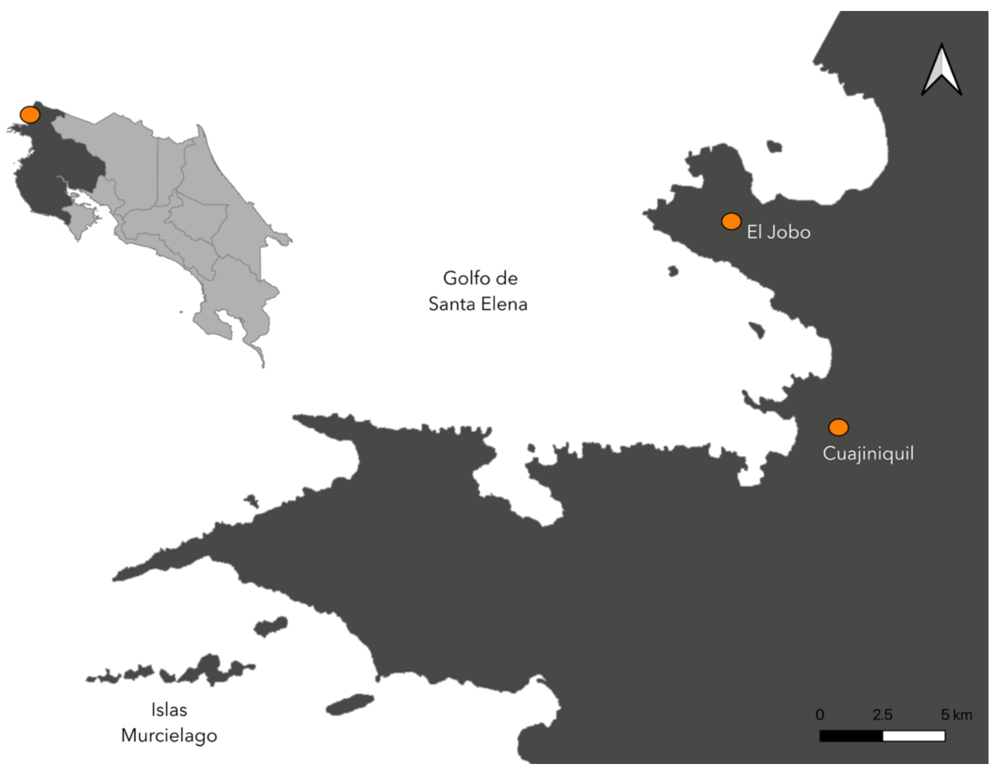

Fig 2. Study area: the fishing community of Cuajiniquil, located in the Gulf of Santa Elena on the north Pacific coast of Costa Rica.

Data collection

Using a mixed methods approach, we collected qualitative and quantitative data on the compressor fishery in Cuajiniquil to address our research questions (Table 1). This paper focused on two key areas of the compressor fishery that would benefit from further research. Specifically, we (i) investigated the social-ecological drivers behind the adoption of air compressors for fishing in Cuajiniquil, and (ii) evaluated how fishing dynamics changed with the use of the compressor. To do this, we conducted surveys to active fishers (appendix A), ex-fishers (appendix B) and semi-structured interviews (appendix C) and) in the community of Cuajiniquil from March 2021 to July 2022. To gain a comprehensive understanding of compressor fishing, given the limited available information, we adopted a dual approach. We conducted interviews with both key informants and fishers. Key informants were defined as individuals with practical knowledge of compressor fishing, including roles such as fish receivers, coastal rangers, and government representatives. This group included both former fishers and active fishers (those currently involved in compressor fishing). Our key informant interviews contributed to a holistic insight into practice, while surveys were conducted with both categories of fishers to further enrich our understanding.

Semi-structured interviews with key informants

We conducted 12 semi-structured interviews in Spanish with key informants that allowed us to collect historical data, track shifts in fishers' behavior, assess catch composition, and establish a trajectory of compressor fishing trends, resulting in an official description of this activity which had not previously been documented (Table 1). Our interview questions were designed to capture the timeline of changes in the fishery, provide detailed descriptions of (i) the compressor fishing operating in the Gulf of Santa Elena, (ii) the equipment used, (iii) target species, (iv) social changes, and (v) the social-ecological drivers of compressor use in the SSF. Data were collected through a snowball sampling, where participants are initially chosen based on existing connections, and then they refer additional participants. The interviews lasted between 45 and 60 mi, during which all participants provided informed oral consent prior to the discussions.

Structured survey with compressor fishers

To determine how compressor fishing is currently carried out, we conducted 30 surveys with active fishers. We apply surveys to active fishers who sells their catch to fish landing receivers and fishers who sell their product on the beach to independent buyers. To compare this data with data from previous years and the early stages of the introduction of air compressor, we also surveyed former fishers. Our aim was to build trust with the fishermen and identify ideal survey times, for example, we observed that the most active fishermen often unload their catches at landing sites. We made our first contact with the owners of fish landing sites to introduced ourselves and scheduled monthly visits; additional observations were made on the independent beach landing sites. This was carried out mainly in the morning (6 to 8am) when they have returned from overnight fishing or from longer trips, but also when fishers were preparing their equipment. For both surveys, the questions were structured around the dynamic of compressor fishing in the present to compare how evolved with the time, as the (i)fishing sites, (ii) target species, (iii) knowledge of regulations, (iv) motivations behind using compressors and (v) the current situation of parrotfish fishing (table 1). The interviews typically lasted 25-30 min; our focus was on obtaining a comprehensive profile of the experiences and personal histories of compressor fishers. Field notes were taken each time we visited fish landing sites.

Table 1. Research aims, questions and the data sources used to address the data

Research aims	**Research questions**	**Surveys and Interview questions**	**Data sources**
social- ecological drivers behind the adoption of air compressors	How are they fishing?	Description of the fishing practice with compressor	Key informant interviews (semi-structured)
	Who is fishing?	Years of experience	Active fisher surveys
	How many boats?	Which boats are active	Key informant interviews (semi-structured)
	What is the fish from this fishery used for?	Who buy the product	Key informant interviews (semi-structured)
	What regulation exists for this fishery?	Regulations Perceptions Illegal behavior	Key informant interviews (semi-structured) Surveys active fishers

		Participation in rules establishment	
	What are they targeting?	Target species present and past	Active fisher surveys Surveys ex-fishers
	What are the major challenges of compressor fishers?	Reasons of using air compressors for fishing	Active fisher surveys Surveys ex-fishers
	What is the history of the fishery?	Past Target species	Surveys ex-fishers
Changes in fishing dynamics with the use of the compressor	How it starts?	Target species in the past	Surveys ex-fishers
		Past Fishing sites	Surveys ex-fishers
		Past dynamic fishing	Key informant interviews (semi-structured)
	How is in the present?	compressor usage learning process	Key informant interviews (semi-structured)
		Changes in the equipment	Key informant interviews (semi-structured)
		Changes in fish size and abundance	Active fisher surveys

IV. DATA ANALYSIS

In the first stage, we analyzed quantitative and qualitative data from surveys and interviews. This data was then codified using the software MAX Qualitative Data Analysis (MAXQDA Plus 2022). We applied the Social Ecological System Framework (SESF) (Ostrom., 2014) to categorize the data into various sections, facilitating organized analysis (Table 2). The second stage involved a thematic analysis of the codified data. Each section of the SESF was carefully examined to uncover insights, adjustments were made to the descriptions while ensuring alignment with the system's characteristics. In the third stage, the outcomes were derived from the analysis of interactions within the SESF's categories and subcategories. This stage aimed to answer the research questions by assessing social and ecological drivers of the use of air compressors in an SSF. The analysis progressed methodically through each stage, ensuring a comprehensive understanding of the complex interplay between social factors and ecological dynamics. The analysis within each stage remained dynamic, with codes continually reviewed and re-coded where necessary. As we review the information, we condense the data into memos and refine our analysis. This iterative process ensures a comprehensive understanding of the complex interactions between variables, resulting in robust documentation of our findings.

Table 2. 1st- and 2nd-tier variables of the SESF for analyzing the drivers in the use of air compressors in an SSF. Adapted from McGinnis and Ostrom (2014)

Category	Subcategories		
Social, Economic, and Political Settings (S)	S1- Economic development		
	S2- Demographic trends		
	S3- Political stability		
	S4- Other governance systems		
	S5- Markets		
	S6- Media organizations		
	S7- Technology		
Resource Systems (RS)	RS1- Sector (e.g., water, forests, pasture)	**Resource Units (RU)**	RU1- Resource unit mobility
	RS2- Clarity of system boundaries		RU2- Growth or replacement rate
	RS3- Size of resource system		RU3- Interaction among resource units
	RS4- Human-constructed facilities		RU4- Economic value
	RS5- Productivity of system		RU5- Number of units
	RS6- Equilibrium properties		RU6- Distinctive characteristics
	RS7- Predictability of system dynamics		RU7- Spatial and temporal distribution
	RS8- Storage characteristics		
	RS9- Location	**Actors (A)**	A1- Number of relevant actors
Governance Systems (GS)	GS1- Government organizations		A2- Socioeconomic attributes
	GS2- Non-governmental organizations		A3- History or past experiences
	GS3- Network structure		A4- Location
	GS4- Property-rights systems		A5- Leadership/entrepreneurship
	GS5- Operational rules		A6- Norms (trust-reciprocity/social capital)
	GS6- Collective choice rules		A7- Knowledge of SES/mental models
	GS7- Constitutional rules		A8- Importance of resource (dependence)
	GS8- Monitoring and sanctioning		A9- Technologies available
Interactions (I)	I1- Harvesting	**Outcomes (O)**	O1- Social performance measures
	I2- Information sharing		O2- Ecological performance measures
	I3- Deliberation processes		O3- Externalities to other SESs
	I4- Conflicts		
	I5- Investment activities		
	I6- Lobbying activities		
	I7- Self-organizing activities		
	I8- Networking activities		
	I9- Monitoring activities		
	I10- Evaluative activities		

V. RESULTS

The use of the social-ecological systems framework facilitated our understanding of the complex factors driving the adoption of air compressors in fishing activities since the beginning of this innovation and the overall dynamics of compressor fishing. According to the fishers, fishing is an important source of income for Cuajiniquil. The fishers shared their personal histories and how their livelihoods have evolved over time; they recalled the community's earlier days as cattle ranchers before transitioning to a fishing-based livelihood and provided information on key events influencing the fishing dynamics (Fig. 3). According to local fishermen, the proximity of their community to the Nicaragua-Costa Rica border has led to an influx of foreign fishermen and the adoption of new fishing techniques (A4). In particular, former fishers recall that the traditional practice for all was initially free diving; however, they mention that in the 1980s the emergence of a new market, mainly driven by Chinese demand for sea cucumbers, influence the transition from free diving to compressor diving (A3). Currently, official records indicate the existence of 43 compressor boat licences, but during our field visits to fishing sites and beach observations, we documented a total of 13 active compressor boat licences.

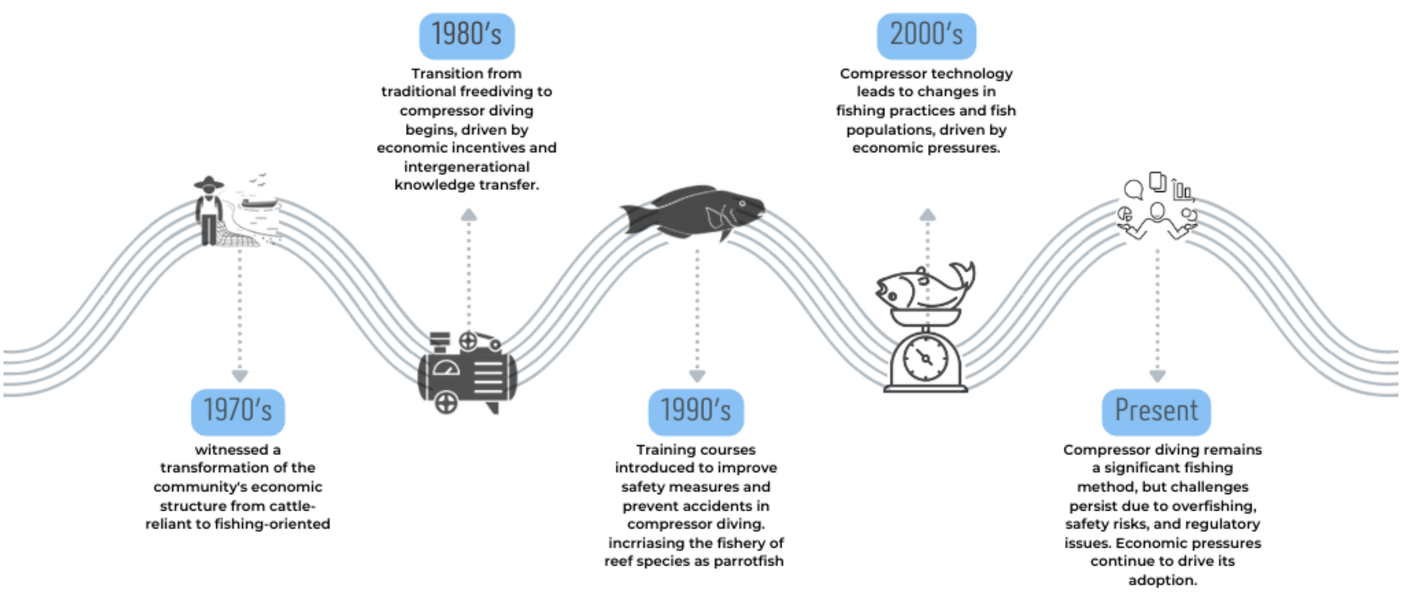

Fig 3. Dynamic of the use of Air Compressor fishing in Cuajiniquil community since 1970 to present.

The resource system is around the marine ecosystem encompassing coral reefs and rocky coastal areas. Interviewees highlighted the exceptional attributes of this environment, including clean water quality and rocky and coral reef substrates conducive to a productive fishing system (RS1).

The marine ecosystem in Cuajiniquil is characterized by diverse of reef species (RU1). Fishers are well aware of the dynamics of this seasonality and, in line with their perspectives, mention how these seasonal patterns and species behaviour significantly influence their choice of target species, their choice of fishing locations and their ability to discern favourable and unfavourable months for economic income generation. These characteristics play an important role, the interviewees mention the demand for fish fillets has led to increased opportunities for selling reef species caught, as more restaurants now buy fish, which has had an impact on the economic development of the SSF in Cuajiniquil.

The benefit of the introduction of air compressor that most recall on the interviews is how allowed fishers to access habitats that were inaccessible by freediving, such as deeper areas of the reef, thus increasing the overall catch (S1). The survey found that 66% of former fishers used compressor-based fishing to obtain more product, which fits with the narrative of economic incentives driving adoption of the technology (A9). The adoption of this practice allows fishers to target a wide range of species, often emphasizing high-value species, and has led to changes in species behavior and distribution (RS3). Historically, all respondents (100%) expressed a preference for catching lobster and 83% for octopus in surveys of former fishermen (Fig. 4). However, the introduction of air compressors has gradually changed the target species preferences of active fishermen. Based on the survey data, active fishers have shown an increased interest in other species such as parrotfish, triggerfish and a category referred to as "chatarra", which includes various reef fish of limited economic value (see Table 3). It is noteworthy that they mentioned that 'chatarra' is mainly sold to restaurants for use in a traditional dish known as 'ceviche'.

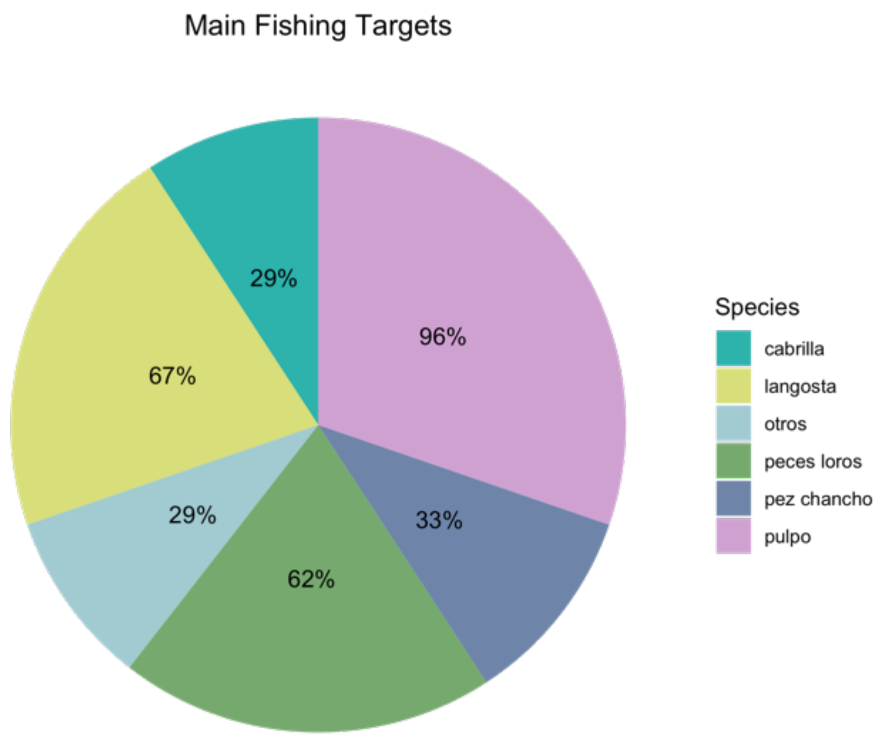

Fig 4. Main target species preferred by fishers using air compressors along the year (2021-2022)

Table 3. List of species capture by compressor fishers in the fish landing receivers; data collected through fieldnotes in the period of (2021 -2022)

Species Group	**Species Name**
Parrotfish /Peces loros	- *Scarus ghobban*
	- *Scarus perrico*
	- *Scarus rubroviolaceus*
	- *Scarus compressus*
Pacific Lobster/ Langosta del pacifico	- *Panulirus gracilis*
Grunts/ Roncadores	- *Orthopristis chalceus*
	- *Haemulon steindachneri*
Octopus/ Pulpos	- *Octopus vulgaris*
Snappers/ Pargos	- *Lutjanus guttatus*
	- *Lutjanus peru*
	- *Hoplopargus guentherri*
Triggerfish/Pez chancho	- *Balistes polylepis*
Surgeon fish/Cirujanos	- *Acanthuridae*
Wrasse fish/ Viejas-señoritas	- *Bondianus diplotaenia*
	- *Halichoeres nicholsi*
Groupers/Cabrillas	- *Epinephelus* sp (Cabrilla pequeña)
	- *Hyporthodus acanthistius* (Cabrilla de profundidad)
Tiger fish/ Pez tigre	- *Cirrhitus rivulatus*
Pez piedra	- *Scorpaena mystes*

Parrotfish was not a target species according to the fishers, as they believed it to be poisonous for its particular colours, this changed when they realised that parrotfish were edible (RU4), making it one of the species of greatest interest to compressor fishers, with 66% mentioning it as a preferred target species. Parrotfish catches varied with seasons, with 79% of fishers stating that they prefer to catch parrotfish in the rainy season when conditions are favorable. However, the growth or replacement rate of parrotfish has decreased over time (RU2), key informants mention that parrotfish sizes of up to 6 kg were common, but now they are smaller than 1 kg. Overall, 80% of the active fishers reported that the parrotfish fishery had declined, with 45% attributing this decline to overfishing (RU2).

Economic incentives of the target species, often drives fishers to explore even during challenging conditions. Some fishers were prepared to move to more distant areas during strong winds, a strategic response to unfavorable conditions around Cuajiniquil. Others, mention that during cold water periods, pursue deep water seasonal species that move closer to shore such as the cabrilla *Hyporthodus acanthistius*. The health risks are significant, with many divers reporting accidents and injuries due to improper decompression practices when catching deep water species, or due to multiple dives on the same day at different depths. There were at least 14 reported deaths attributed to diving with compressors between 80s and the present. In addition, accidents resulting in injury or disability were common, with around 25 people reportedly affected. It is important to note that this information is based solely on the informants' recollection of events and not on formal statistics.

The description by the fishers of the equipment used in the diving fishing, employed an air compressor where they adapt a hose, usually 100 m long, which allows them to reach deeper water. This hose has a “T” shape where two fishers can dive simultaneously using regulators; some use wetsuits for cold water, spearguns, fins, mask, belts, and special tools such as "bicheros" to catch octopus, flashlight for night diving (U9.1) (Fig. 5). The boat operator plays a critical role in compressor-based fishing, ensuring that there is enough fuel in the compressor during the dives and making decisions about dive locations. They are also responsible for the timing the dives and sending out the sings to call the fisher out, but generally the times and depths do not carry adequately planned to avoid decompression accidents. Some sources indicated that the main causes of these incidents are irresponsible fishing techniques, driven by the need to increase income due to limited economic opportunities (U10).

Fig 5. Equipment used in compressor fishing; A. Air compressor with adapted hose and regulator, B. Fishers catching parrotfish with a spear gun, C. Compressor fisher explaining the operation of the compressor.

The practice of compressor fishing also interacts with regulatory measures and economic considerations, influencing fishing patterns (GS3). The governance system in Cuajiniquil is shaped by multiple stakeholders, including governmental institutions, active/ex-fishers, and community leaders (GS2). Regulatory measures aim to ensure resource sustainability and manage conflicts among users. Despite possessing knowledge about the established rules, the lack of effective patrolling and enforcement has contributed to instances of illegal fishing (GS4). Overall, 79% of active fishers are willing to comply with new regulations on compressor fishing. Enforcement of the rules requires attention, as 66% of active fishers claim to avoid prohibited fishing areas and 33% admit to being involved in illegal fishing. More concerningly, when asked if they know other fishers who fish in prohibited areas, 62% answered affirmatively, demonstrating the prevalence of such activity (Fig. 6). Some concerns have been raised about the coordination of governmental institutions, information sharing and effective enforcement. According with the governmental informants the limited budget allocated to these institutions was identified as one of the main factors contributing to these challenges (GS1). The data also revealed a need for improved inclusivity, as 75% of respondents feel they were not consulted during the creation of the protected area Islas Murcielago, suggesting the potential for more participatory and collaborative approaches to shaping collective-choice rules (GS6).

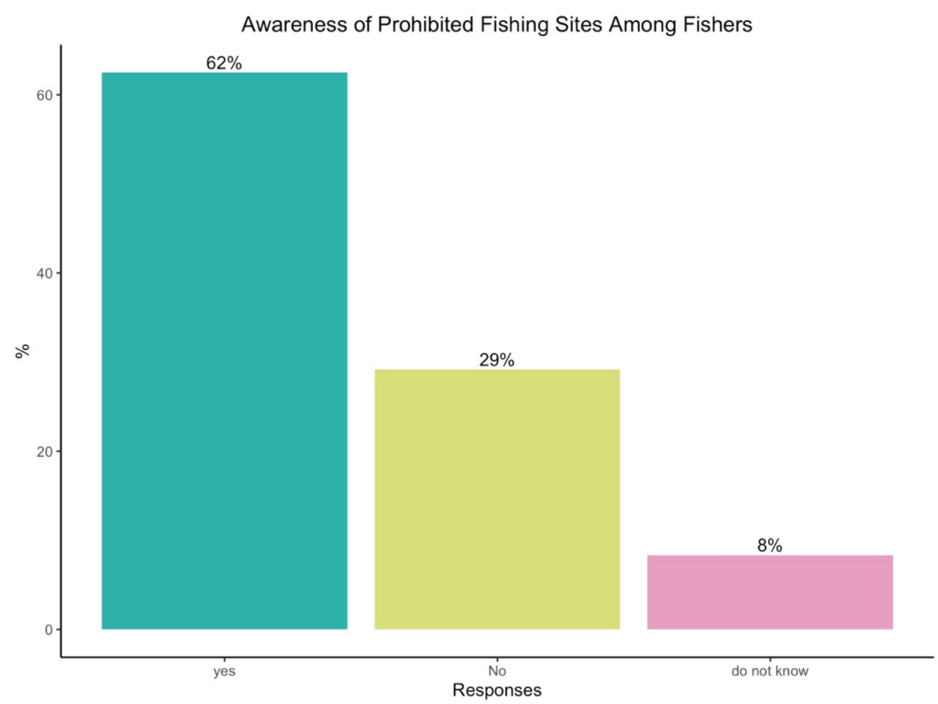

Fig 6. % of Illegal behavior in an MPA (Islas Murciélago) and the awareness among fishers

VI. DISCUSSION

Using SESF, this study gained a comprehensive understanding of SSF in Cuajiniquil. The transition from traditional to compressor fishing marked a major shift, with foreign divers and technological advances driving this change. Parrotfish have become a major target species and concerns over overfishing have led to a decline in their abundance, affecting both the ecological balance and the economic dynamics. The adoption of this technology also poses challenges to the well-being of fishers, resulting in accidents and deaths as they explore and dive at different depths and locations to meet the demands of changing market dynamics. These market fluctuations, in turn, result from changes in resource availability. The dynamics of the practice have evolved with the economic incentives, changing markets and regulatory governance that have shaped fishing practices. While the dominance of the practice has brought economic benefits, it has also raised questions about sustainability. This research, underpinned by a mixed-source thematic analysis, provides a descriptive understanding of how social-ecological factors have shaped the trajectory of compressor fishing practices.

Factors influencing the adoption of air compressors in fisheries

The adoption of air compressors for fishing in Cuajiniquil is driven by a combination of social and ecological factors. In the social aspect, economic considerations play a crucial role, giving that, the transition from traditional free diving to compressor-based, which offered higher economic returns with valuable species as parrotfish, octopus, lobster, cabrilla and other reef species valued for their fillets. The introduction of innovations in fishing gear technology, such as compressors, is perceived positively by fishers because they increase fishing mortality as a result of improved catchability by increasing the time fishers can stay underwater (Dirgantara et al., 2019). However, it's important to recognise that increased fishing effort, often supported by technological innovation, can exacerbate overfishing and lead to changes in fishers' behaviour (Eigaard et al., 2014). Fishers often cite changes in reef conditions and species composition over time, which they attribute to overfishing. It is crucial to recognise this fishery as a direct result of the technological innovation introduced. This recognition serves as a basis for more precise and effective management strategies.

Although marine habitat and fishing effort are better understood, few studies have quantified spatial-temporal changes in fisheries or their drivers. (Stephenson et al., 2018). Frameworks had been used to undertint how these drivers impulse or change the dynamic of SSF this. For example, (Basurto et al., 2013), analyzed governance processes and outcomes in SSF based on the general framework to diagnose sustainability of SES, emphasizing that the use of frameworks is a starting, not an ending, point for inquiry on governance of SESs. This highlight the importance, to explore deeply this outcomes to assess the biological, social and economic impacts of these innovations in order to effectively mitigate any negative consequences (Pita et al., 2019).

The overall adoption of air compressors for fishing in Cuajiniquil is influenced by a mixture of economic motives, geographical dynamics, historical context, and environmental considerations. The decision-making process involves a mix of family traditions, generational practices, economic pressures, and the search for alternative livelihoods. Economic pressures stem from limited opportunities and the need to secure income for families, which motivate fishers to adopt innovative technologies (Torres Cañete et al., 2022). In addition, external factors such as the influx of outside fishers and changes in market demand contribute to the diversification of fishing practices within Cuajiniquil. As we have seen, the decision to adopt an innovation is not simultaneous, the adoption of new practices involves sequential events over time, several factors influence adoption, such as evolving learning and perceived benefits (Halim, 2002).

Understanding How the Fishing Dynamic Changed with the Use of the Compressor:

The introduction of air compressors for fishing brought about significant changes in the fishing dynamics of Cuajiniquil. This change allowed fishers to target species that were previously out of reach, changing the composition of the and contributing to changes in the distribution of species within the ecosystem. The dynamics of fishing have also changed in terms of safety and risks. While the use of compressors increased catch rates, it also brought health and safety risks due to inadequate decompression practices, leading to accidents, injuries, and even fatalities. Compressor diving is often described as not being properly trained to modern standards. The equipment used is considered to be outdated and the decompression procedures used by these divers are either based on experience or inappropriate for the conditions in which they work, resulting in a significant incidence of decompression sickness (Astari et al., 2021; Baňez, 2019). These safety concerns created complexities within the fishing dynamic, highlighting the need for improved awareness, training, and regulation to ensure the well-being of divers (Gold et al., 2000). The fishing dynamics became more efficient but also more complex and loaded with social-ecological trade-offs. Overall, these interconnected interactions underscore the complex interplay between outcomes and the varied mechanisms through which stakeholders engage with and influence the social-ecological system of Cuajiniquil fishery.

The transition from free diving to compressor-based fishing brought with it a range of impacts that require comprehensive approaches to policy. For example, the adoption of compressor-based techniques appears to coincide with an increase in illegal behaviour. These fishers, motivated by the pursuit of lucrative catches such as parrotfish, may be encouraged to venture into no-take MPAs such as Islas Murciélago, area where illegal fishing has previously been a concern (Alvarado et al., 2021; Madrigal-Mora et al., 2022; Naranjo-Madrigal et al., 2015). This particular pattern of behaviour is consistent with the displacement of 60-70 divers who previously worked in these waters before the establishment of the MPA (Rowe, 2011). Unfortunately, these fishers have not been offered any form of compensation or assistance in transitioning to alternative livelihoods. As a result, some continue to operate in protected waters, even in the face of potential consequences. This context highlights the need to understand how the dynamics of the fishery have evolved with the integration of compressors, a critical basis for designing effective conservation and regulatory strategies. Understanding how the dynamics of the fishery have changed with the use of the compressor is, therefore, essential for designing effective regulations and conservation strategies.

Insights and Recommendations from Compressor Fishing management

The rapid spread of technological advances that increase fishing effort, coupled with inadequate government capacity to assess the sustainability of fisheries can lead to rapid levels of exploitation (Eigaard et al., 2014). We recommend implementing an ecosystem-based management strategy for air compressors in Cuajiniquil SSF, emphasizing collaborative governance structures that engage active fishers, local leaders, government bodies, and other key actors. Addressing the challenges of enforcing no-take MPAs requires a balanced approach. Despite the current complexities, promoting a collaborative dialogue between fishers and government authorities is crucial. Acknowledge the mutual concern for ecosystem vitality and the livelihoods of fishing communities. This participatory engagement can lead to positive outcomes such as inclusive decision-making processes, empowering stakeholders to, for example, shape regulations and encourage market diversification. Adaptive management strategies, continuous research, and capacity building for data analysis are vital for effective resource management (Lengnick-Hall et al., 2011).

Compressor fishers are one of the SSF practices with highly concern leading to many accidents and even deaths of fishers (Barbosa-Filho et al., 2020), hence, prioritizing safety training for divers is crucial. It would also have been valuable to review hospital records, but this was not possible in this study due to logistic constraints. Therefore, we recommend strengthening safety protocols by using official accident data and exploring fisher's experiences and perceptions of to identify key areas of concern. The most significant impact of compressor fishing is the significant number of accidents and fatalities associated with this practice (Astari et al., 2021; Cha et al., 2019; Huchim-Lara et al., 2015). In addition, government involvement is crucial in providing guidance on health issues related to diving activities, thereby increasing the awareness and knowledge of divers for the implementation of effective occupational disease prevention programmes (Astari et al., 2021). An important percentage of fishers claimed to do this activity due to economic dependence and lack of opportunities, therefore, embracing sustainable tourism practices and diversifying livelihoods can further reduce dependency on fishing. However, it is still crucial to prioritize capacity-building to ensure that this transition is successful. Developing training courses focused on the local ecological knowledge, hospitality skills, and business management, while seeking financial support for skill development and infrastructure could be effective. Partner with experienced tourism entities to ensure a well-prepared and sustainable transition that safeguards the community's livelihoods.

VII. CONCLUSSION

The SESF approach has proved to be an adaptable tool, this framework allows us to understand the dynamic drivers behind the adoption of air compressors in fishing innovations. Through its application, a clearer understanding emerges of the complex interplay between social-economic factors, ecological attributes and technological changes driving the transition to compressor fishing. In addition, the SES framework not only synthesises research findings, but also provides insights and recommendations from the management of compressor fishing. By analysing the complex interactions that drive compressor adoption, this approach provides a structured way to identify target areas for intervention. Small-scale fisheries are complex and achieving an in-depth understanding of these systems can be challenging due to the diverse social and ecological dynamics. This study highlights a broader knowledge and understanding of the adoption of innovative practices within a small-scale fishery. These findings were essential to improve knowledge of the fishery resources, to better understand the dynamics of the fishery and to guide the development of management strategies to maintain the sustainability of this fishery.

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CHAPTER II. Using stable isotopes to track fishing of parrotfish inside and outside a Marine Protected Area in the Pacific coast of Costa Rica

Uso de isótopos estables para rastrear la pesca de peces loro dentro y fuera de un Área Marina Protegida en la costa del Pacífico de Costa Rica

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I. ABSTRACT

Understanding the geographical origin and traceability of seafood is essential to promoting sustainable fishing practices. This study used stable isotope analysis ($\delta^{13}C$ and $\delta^{15}N$) to trace the geographic origin of parrotfish fishing along the north Pacific coast of Costa Rica. Stable isotopes provide valuable insights into both dietary preferences and geographic origins. By analyzing different fishing grounds, we identified distinct isotopic variability that allowed identifying parrotfish origins, including inside a no-take marine protected area. Based on our findings, stable isotopes have the potential to become a valuable tool for fisheries management and stakeholders involved in the enforcement of sustainability standards and the prevention of illegal fishing activities. We recommend using both $\delta^{13}C$ and $\delta^{15}N$ for source attribution of commercially important species. This approach provides insights into fishery dynamics and resource tracking, including the potential to detect illegal activities. However, to improve accuracy, we recommend the integration of complementary techniques, such as the analysis of isotopic ratios of additional elements. Despite its limitations, this approach provides valuable insights into fishery dynamics and resource management.

Resumen

La comprensión del origen geográfico y la trazabilidad de los productos del mar es esencial para promover prácticas pesqueras sostenibles. Este estudio utilizó el análisis de isótopos estables ($\delta^{13}C$

y $\delta^{15}N$) para rastrear el origen geográfico de la pesca de peces loros en la costa norte del Pacífico de Costa Rica. Los isótopos estables proporcionan valiosas perspectivas tanto sobre las preferencias alimenticias como sobre los orígenes geográficos. Al analizar diferentes áreas de pesca, identificamos una variabilidad isotópica distintiva que permitió identificar los orígenes de los peces loros, incluso dentro de una zona marina protegida sin extracción. Según nuestros hallazgos, los isótopos estables tienen el potencial de convertirse en una herramienta valiosa para la gestión pesquera y las partes interesadas involucradas en la aplicación de estándares de sostenibilidad y la prevención de actividades pesqueras ilegales. Recomendamos utilizar tanto $\delta^{13}C$ y $\delta^{15}N$ para la atribución de origen de especies de importancia comercial. Este enfoque proporciona información sobre la dinámica de la pesquería y el seguimiento de los recursos, incluida la capacidad de detectar actividades ilegales. Sin embargo, para mejorar la precisión, recomendamos la integración de técnicas complementarias, como el análisis de las relaciones isotópicas de elementos adicionales. A pesar de sus limitaciones, este enfoque proporciona valiosas perspectivas sobre la dinámica de la pesquería y la gestión de recursos

II. INTRODUCTION

Knowledge of the geographic origin and traceability of seafood is crucial to ensure sustainable fishing practices (Ferreira et al., 2021). However, this information is often lacking or unreliable, making traceability a critical step in ensuring the sustainability of fish stocks and preventing overexploitation of marine resources (Kim et al., 2015). Stable isotope analysis (SIA) has become a cost-effective and powerful ecological tool for quantifying diet and trophic interactions of marine species (Hobson, 1999); however, in recent years SIA has also been used to discriminate between production methods to trace the origin of farm products (Gamboa-Delgado et al., 2014; Gopi et al., 2019). In coastal environments, this approach has the potential for tracing the origin of fisheries products from distinct geographical locations without the need of on-board observers, tag/recapture programs, or other approaches that are often more expensive and difficult to implement (Del Rio-Lavín et al., 2022; Ferreira et al., 2021; Kim et al., 2015). Therefore, assessing the effectiveness of SIA as tracer of seafood origin remains crucial to inform fisheries management and develop sustainable fishing practices (Dempson et al., 2010; Tulli et al., 2020).

Stable isotopes of carbon $\delta^{13}C$ are commonly used to track the movement of aquatic species between isotopically distinct habitats (Post, 2002). Biogeochemical processes and fixation by primary producers in the ocean (e.g., phytoplankton, macroalgae, etc.) regulate carbon input into different ecosystems (Fry, 2006), influencing the presence and variation of $\delta^{13}C$ (Hobson et al., 1993). Carbon sources are then transferred to consumers that move between isotopically distinct food webs as these retain information from consumed carbon sources that have been integrated into their tissues over time (Jardine et al., 2003). In contrast, $\delta^{15}N$ indicate the trophic level of an organism relative to other species in the food web (Newsome et al., 2007; Vander Zanden et al., 2015). Both $\delta^{13}C$ and $\delta^{15}N$ values can determine the relative proportions of isotopically distinct resources incorporated into an animal's tissues (Newsome et al., 2007; Post, 2002). This can provide important information about possible feeding sites or regions (Gaston & Suthers, 2004; Hobson, 1999). Therefore, SIA could be a useful tool to improve the management of ecologically important species or species that are currently overfished by verifying traceability and authenticating their origin. This approach can contribute to the sustainable management of coastal fisheries, in particular small-scale fisheries (SSF), a sector that is susceptible to environmental, economic, and political changes, even though they play a crucial role to human nutrition and social and economic progress (FAO, 2020)

Most coastal fisheries have traditionally target large, predatory species that typically occupy high trophic levels (Zhou & Smith, 2017). However, illegal, unreported, and unregulated (IUU) fishing activities have resulted in the overexploitation of common coastal resources, which has led to disruption in food webs and potential trophic cascades (Essington et al., 2006; Petrossian, 2015). For example, tropical reefs have experienced significant declines of large predatory fishes mainly due to overfishing, which is exerting new pressures on low trophic level consumers such as parrotfish (Scaridae), an ecologically important group of coral reef fish that is now being harvested in many tropical and subtropical areas (Ebisawa et al., 2016; Taylor, 2014). Low trophic level species account for over 30% of global fisheries production and make a significant contribution to global food security (Smith., et al., 2012). Such pressures have led to negative impacts on reef communities, such as reduced species diversity and biomass, loss of resilience, and phase shifts (Zamborain et al., 2023)

Parrotfish are among the largest consumers of the primary marine production of reefs and contribute to the energy flow that help maintain their resilience (Adam et al., 2011; Bonaldo et al., 2014; Duran et al., 2018). Isotopic studies have shown that the main source of carbon in the diet of Parrotfish comes mainly from Epilithic algae matrix (EAM), which is a complex structure of living and non-living resources, including turf-forming filamentous algae, microalgae, microbes, detritus, and invertebrates (Gerona & Evacitas, 2013). This consumption helps to limit the excessive growth of algae on corals, maintaining the reef structure and biodiversity (Mumby, 2006; Nemeth & Appeldoorn, 2009). Parrotfishes are primarily target by small-scale fisheries with a wide range of fishing gears, including gillnets, handlines and spearguns (Ebisawa et al., 2016; Taylor, 2014). However, our understanding of the effect of small-scale fisheries on parrotfish dynamics is still limited in most tropical areas (Roos et al., 2016).

In the north Pacific coast of Costa Rica, parrotfish are an important economic resource for local communities (Villalobos-Rojas et al., 2015). Parrotfishes are primarily caught through compressor fishing and their catches constitute a significant portion of the species landed, which can represent up to 48% (SINAC, 2020). However, essential data on fishing grounds, effort, species-specific landings, and population status is still lacking, which is concerning given the recognized ecological significance of parrotfishes to the health of reef ecosystems. Effective monitoring and management of marine resources require detailed knowledge of fisheries dynamics (de Juan et al., 2020; Villalobos-Rojas et al., 2015). Common spatial management approaches such as Marine Protected Areas (MPAs) can improve the protection of key habitats and species with high fisheries value, but in some areas the lack of resources for surveillance has limited the overall benefits of MPAs to fisheries production (Arias et al., 2014). Moreover, the effectiveness of MPAs not only depends on regulatory compliance but also on the availability of comprehensive ecological and social information (Campbell et al., 2013; Chavez Carrillo et al., 2019). Although illegal fishing of parrotfish has not been documented in the north Pacific coast of Costa Rica, there are reports indicating its occurrence in some areas (SINAC, 2019). Hence, proper protocol implementation, to track fishery product is crucial to determining fishing activities within MPAs to ensure the proper management and sustainability of the harvested resource.

Given the economic and ecological importance of parrotfish, it is crucial to ensure their traceability and authentication of origin to promote sustainable fisheries management. In this study, we used SIA as a potential tool to trace the geographic origin of parrotfish caught inside and outside a no-take MPA located in north Pacific coast of Costas Rica. We employed $\delta^{13}C$ and $\delta^{15}N$ values to assess the isotopic variability originating from EAM sources at several reef sites with different types of management (from completely open to no-take areas). This allowed us to establish a distinct fingerprint of different geographic areas, to later assign it to parrotfish samples of known and unknown origins. We discussed the implications of our findings, limitations of our sampling method, and explored complementary methodologies going forward. This research contributes to advancing the understanding of the use of SIA as a tool that could inform fisheries management.

III. METHODOLOGY

Study region

Our study was conducted in the Santa Elena Gulf and the Islas Murciélago Archipelago (here after referred to as Islas Murciélago), which are located in the north Pacific coast of Costa Rica (Fig. 1). In this region, we considered two locations that are open to fishing (Golfo de Santa Elena and Bahía Playa Blanca), a marine management area (Bahía Santa Elena), where fishing is restricted to specific areas and gears (SINAC, 2020), and a no-take MPA (Islas Murciélago). Golfo de Santa Elena is characterized for having a wide range of habitats, including mangroves, rocky and coral reefs, small islets and underwater pinnacles, and soft-mud and sandy bottoms in estuarine areas (Bassey Fallas, 2010). Golfo de Santa Elena also has a significant contribution to the production of local fisheries products given the proximity of the main ports and fishing landings. Bahía Santa Elena is a relatively large (7.5 km^2), semi-enclosed embayment that also has a variety of habitats available (e.g., mangroves, rocky and coral reefs, islets and underwater pinnacles, and soft-mud and rubble bottoms). Bahía Playa Blanca is characterized by a large cover of mangrove forest along the coastline and rocky reefs and small islets in the outer bay; this area is also a well-known ground for the SSF (Bassey-Fallas, 2010). Islas Murciélago was designated a no-take MPA in 1987 (SINAC, 2009), and it comprises of five main islands and several islets that are part of the Santa Rosa National Park. Islas Murciélago is characterized by having a large extent of rocky and coral reef habitats and is considered one of the most biologically diverse and productive coastal area in

Costa Rica (Cortés, 2017; Denyer et al., 2006). The creation of the Islas Murciélago MPA near the fishing community of Golfo de Santa Elena has resulted in prevailing illegal activity, posing a significant threat to marine resources (Madrigal-Mora et al., 2022; Sánchez-Jiménez et al., 2015). Although illegal fishing of parrotfishes has not been documented in this area, it is a well-known practice among local fishers that takes places mainly at night (M. Lara, pers. comm.).

The study region is influenced by a strong coastal upwelling during the dry season (December-April), which is driven by the northeast trade winds (Papagayo Wind Jet) (Amador et al., 2006). Strong winds push surface waters offshore, initiating vertical mixing of the water column, lifting colder water from the sub thermocline and bringing in nutrient-rich water from the bottom (Alfaro & Cortés, 2015; Rodríguez et al., 2021). The upwelling increases the biomass of phytoplankton and the overall productivity of the system, thus enhancing fisheries production for coastal communities (Fiedler, 2002). Seasonal changes from the upwelling result in shifts in the community structure and composition of primary producers. For example, coral reefs are dominated by algal turf, which consists of a combination of several filamentous and corticated green, red, and brown algae and usually forms carpets. During upwelling, cold waters favour the growth of macro-algae becoming more abundant (Cortés, 2017; Fernández-García et al., 2021).

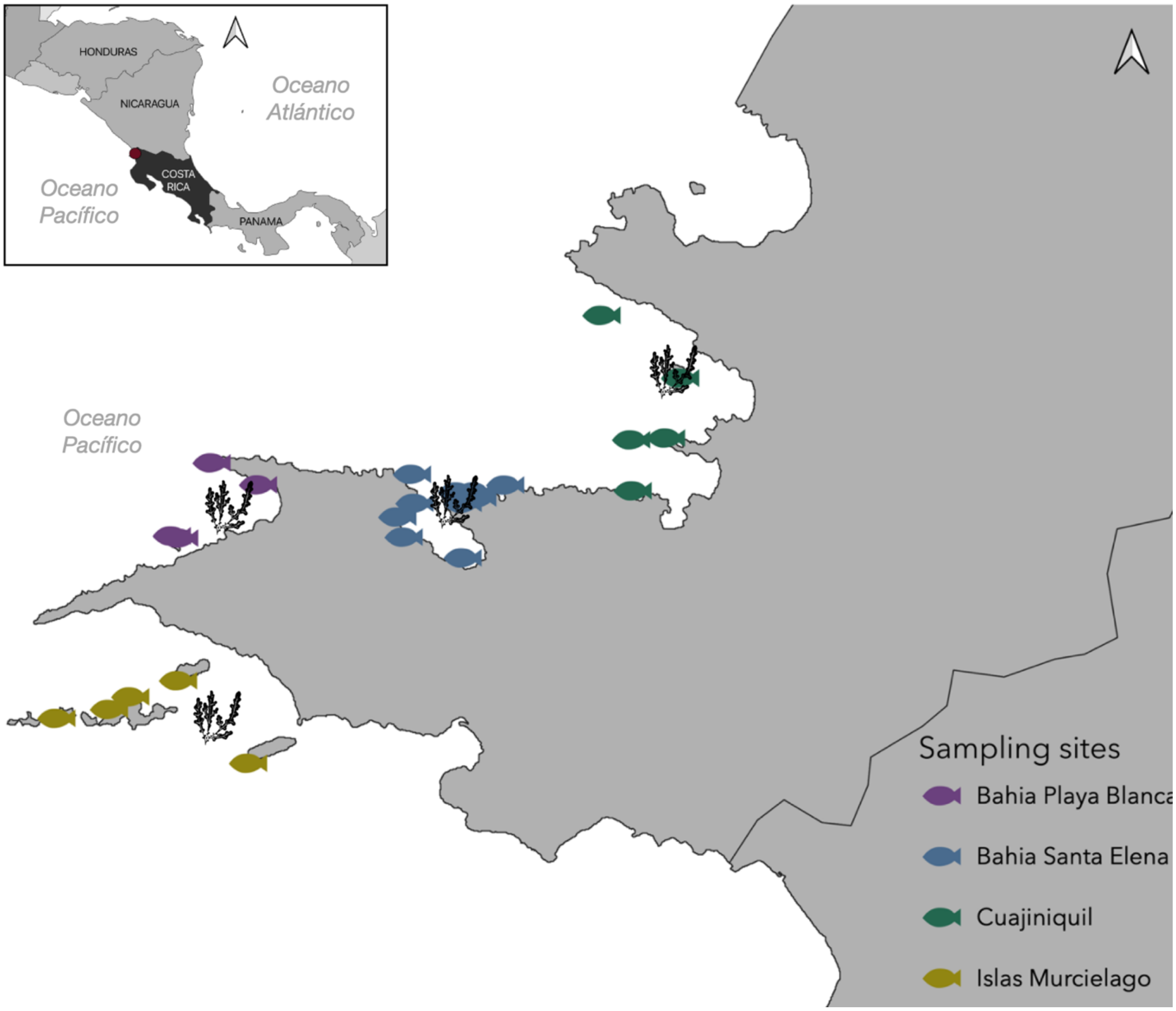

Figure 7. Map of the study region showing the sampling locations in the north Pacific coast of Costa Rica /Central America).

Sample collection

Samples were collected between March 2021 and July 2022 during the upwelling and non-upwelling seasons. The sampling was performed with a speargun during SCUBA and snorkelling surveys. The blue-barred parrotfish *Scarus ghobban* is one of the most abundant species of parrotfish in the north Pacific coast of Costa Rica, but also the main target species of compressor fishers in this region (Farías-Tafolla et al., 2022; Tresnati et al., 2021). This species feeds mainly on EAM that covers rocky/coral reef habitats (Wilson et al., 2003). We collected muscle samples of *S. ghobban* and EAM samples at depths of 2-15 m along a 40 km stretch of coast. To determine the origin of *S. ghobban*, we collected muscle tissue samples from two different sources: fishing landings, where fishermen deliver their products of unknown origin, and known field sites. In addition to the collection of tissue samples, we recorded fish total length (TL) and weight. Samples were stored in pre-labelled vials and kept at -80°C for further analysis. In addition, our collection efforts were extended to include EAM samples, not only the algae but also their associated substrates or matrices, such as rock surfaces or other platforms where algae have formed mats (TURF). This comprehensive approach also resulted in the collection of EAM samples comprising multi-species assemblages of filamentous benthic algae.

Stable isotope analysis

The treatment preparation for muscle samples collected was to freeze-dry at -80°C, homogenized and crushed each sample. Tissue samples did not require lipid extraction based on the C:N ratios were < 4.5 (Post et al., 2007). For EAM, samples were dried in an oven at 60ºC for 48 hrs and then grounded into a fine powder using a mortar and pestle. After tissue processing for each sample, between 400 and 600 µg of muscle tissue were weighed into tin capsules for SIA, and between 2800 and 3000 µg for algae. For the precision of the mass spectrometer replicate samples of four internal laboratory standards: Bovine Liver (NIST 1577c), Tilapia (Internal standard), Urea IVA 33802174, USGS 40, and then analyzed after every 16 samples in between standard sets. The $\delta^{13}C$ and $\delta^{15}N$ values were measured using the elemental analyzer Thermofisher EA IsoLink FlashIRMS System at the Chemical Tracers Laboratory, Great Lakes Institute for Environmental Research (GLIER) at University of Windsor in Canada. Stable isotope ratios were expressed in per mil (‰) in delta (δ) notation using following $\delta X = [(R_{sample}/R_{standard}) - 1]$, where X is ^{13}C or ^{15}N and R equals $^{13}C/^{12}C$ or $^{15}N/^{14}N$. The standard materials for $\delta^{13}C$ and ^{15}N values are Pee Dee Belemnite and atmospheric nitrogen, respectively.

IV. DATA ANALYSIS

Isotope signature of parrotfish & food sources values between sites

To investigate spatial and seasonal variation in isotopic values ($\delta^{15}N$ and $\delta^{13}C$) across the study region, we used muscle tissue samples of *S. ghobban* collected at different sites, seasons, and known origins (e.g., Cuajiniquil, Bahia Santa Elena, Islas Murciélago, Playa Blanca). For comparisons, we used the mean ± SD (Standard Deviation) to assess variation in $\delta^{15}N$ and $\delta^{13}C$ values between sites and seasons. To explore potential variations in stable isotope values between different sites and seasons, we assessed the normality of our data using the Shapiro-Wilk test. Initial tests indicated non-normal distribution of the data, hence Kruskal-Wallis tests were used to determine isotopic variation across sites and seasons. We conducted linear regression analyses to explore potential relationships between parrotfish total length, $\delta^{15}N$ and $\delta^{13}C$ values.

Parrotfish origins

To identify the source of parrotfish caught by the compressor fishery, we analyzed the degree of isotopic overlap between fish collected from known and unknown origins using SIBER (Stable Isotope Bayesian Ellipses), an R package used to compare isotopic niches between communities (Jackson et al., 2011). With this method, we established the percentage of overlap between our sampled sites and samples of unidentified origin from fishing landings. Using SIBER, we calculated the Standard Ellipse Area (SEAB), which provided insight isotopic niche breadth for individuals at each sampled site within each community. We evaluated data dispersion using a Standard Ellipse Area (SEA) and adjusted for variations in sample size using Sample Size Corrected Standard Ellipse Area (SEAc) to enhance the accuracy of our comparisons (Jackson et al.2011). All analyses were conducted in R version 4.2.1 (R Core Team, 2022).

V. RESULTS

A total of 153 samples of *S. ghobban* and 45 samples of EAM were collected in our study region (Table 1). We sampled four sites during the upwelling and non-upwelling season, however, due to field logistics most of the samples were collected during the non-upwelling season. At Golfo de Santa Elena it was not possible to collect data during upwelling due to limited sampling opportunities. In the case of Playa Blanca, muscle tissue collection was not possible due to its remote location and strong winds during sampling events, which limited access to the site.

Additionally, restricted site accessibility led a limited number of sampling trips, resulting in the collection of EAM samples exclusively during daylight hours. Seasonal variations, particularly during the upwelling season, also affected data collection at the other sampling sites.

Table 4Total number of parrotfish muscle and EAM samples from each of the four sampling areas (Costa Rica North Pacific coast)

origin	specie	season	n
Bahia Santa Elena	Scarus ghobban	Non upwelling	13
		Upwelling	5
	EAM	Non upwelling	2
		Upwelling	6
Cuajiniquil	Scarus ghobban	Non upwelling	17
	EAM	Non upwelling	11
		Upwelling	5
Islas Murcielago	Scarus ghobban	Non upwelling	15
	EAM	Non upwelling	16
Landing site	Scarus ghobban	Non upwelling	92
		Upwelling	11
Playa Blanca	EAM	Non upwelling	5
		Total	198

Relationships between stable isotopes and total length by season

Total length (TL) measurements of *S. ghobban* ranged from 13 to 52 cm. Among the main length classes observed, there were 16 specimens measuring between 13 and 23 cm, constituting 17.58% of the sample. Additionally, 47 specimens fell within the 23 to 33 cm range, accounting for 51.64%, while 28 specimens fell in the 33 to 43 cm range, making up 30.77% of the sample. There was no significant effect of fish TL on $\delta^{15}N$ or $\delta^{13}C$ values (Fig. 9).

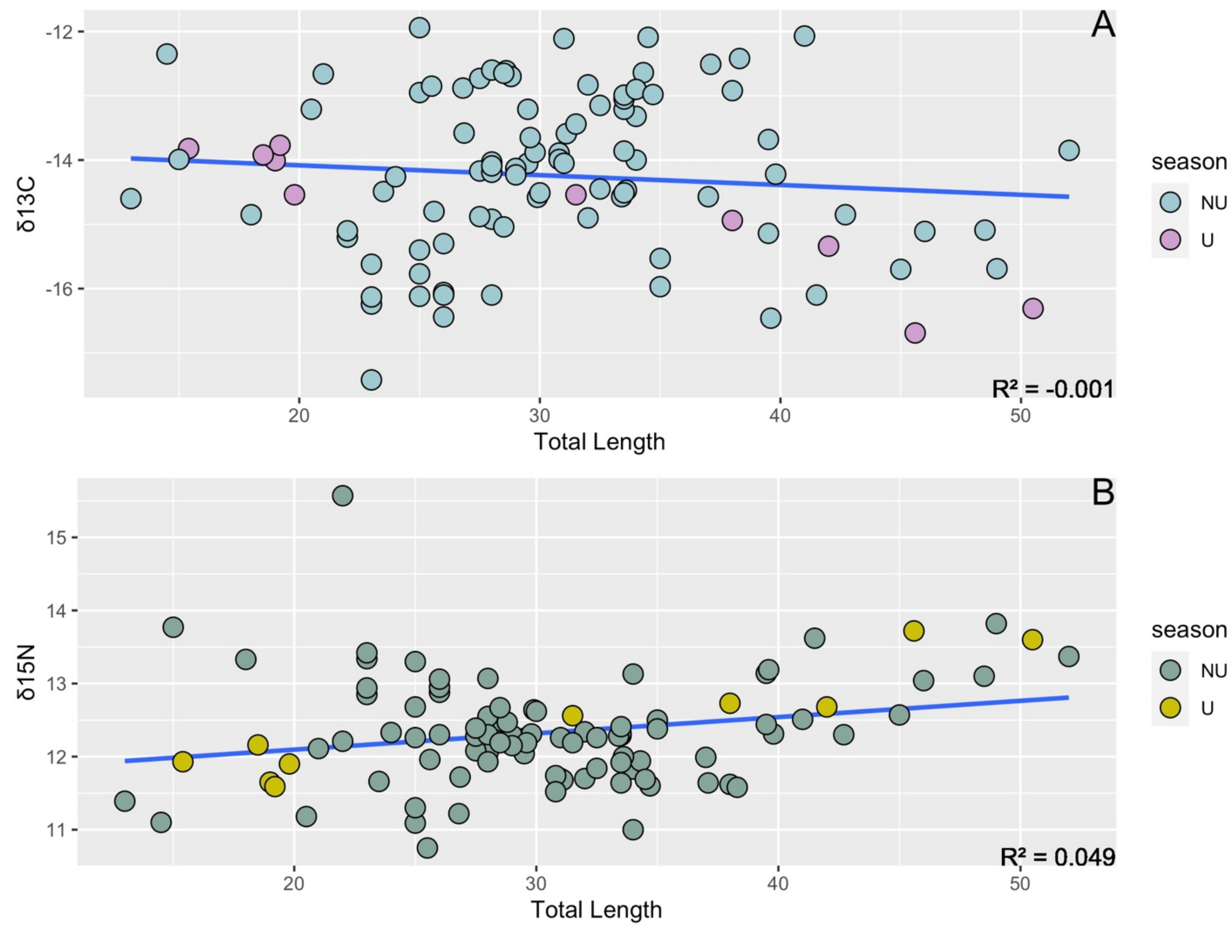

Figure 8. Relationship between isotope values with total length (A: δ13C, B: δ15N) of parrotfish across two seasons (U: upwelling; NU: non-upwelling).

Parrotfish & EAM isotopic signature x sites & seasons

Parrotfish samples exhibited higher $\delta^{15}N$ values, ranging from 11.5‰ to 13.4‰, compared to their food source, EAM samples, which exhibited $\delta^{15}N$ values ranging from 8.3‰ to 10.2‰ (Table 2), consistent with trophic enrichment. Conversely, EAM samples exhibited heavier carbon $\delta^{13}C$ values ranging from -12.3‰ to -7.4‰, in contrast to parrotfish values ranging from -15.3‰ to -13.1‰. In particular, samples from the fishing landings stood out with distinct characteristics, with higher δ15N values ranging from 11.8‰ to 13.4‰ and slightly lower $\delta^{13}C$ values ranging from -15.3‰ to -13.1‰ (Fig. 2), suggesting more pronounced isotopic variability specific to this particular site. There was no significant difference in $\delta^{13}C$ between seasons (KW: value, $p > 0.01$); however, a significant effect was found between sites (KW: value, $p < 0.01$). Similarly, for $\delta^{15}N$

values, no significant differences were observed between seasons (KW: value, $p > 0.01$), while a significant variation was found between different origins (KW: value, $p < 0.01$).

Table 5. Mean ± SDD of δ15N, δ13C & C:N of parrotfish (Scarus ghobban) muscle samples & carbon sources sustaining parrotfish (Scarus ghobban) feeding EAM from the north Pacific coast of Costa Rica

Origin	Group	Season	n	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C:N (mean)
Bahia Santa Elena	Parrotfish	Non upwelling	13	-13.1±0.8	11.5±0.4	3.1
		Upwelling	5	-14±0.3	11.8±0.2	3.1
	EAM	Non upwelling	1	-8.8	9.4	17.5
		Upwelling	5	-7.4±1.9	10.2±1.4	19.6
Golfo de Santa Elena	Parrotfish	Non upwelling	17	-13.3±1	12.2±0.5	3.2
	EAM	Non upwelling	11	-8.5±2	9.4±0.5	21.9
		Upwelling	5	-11.7±5.9	8.3±0.6	14.4
Islas Murcielago	Parrotfish	Non upwelling	15	-14±0.5	12±0.3	3.2
	EAM	Non upwelling	15	-9.5±2.5	9.1±0.6	16.3
Fishing Landings	Parrotfish	Non upwelling	92	-14.8±1.4	12.6±0.8	3.3
		Upwelling	11	-15.3±1.1	13.4±0.7	3.2
Playa Blanca	EAM	Non upwelling	5	-12.3±1.2	9.7±0.7	10.9

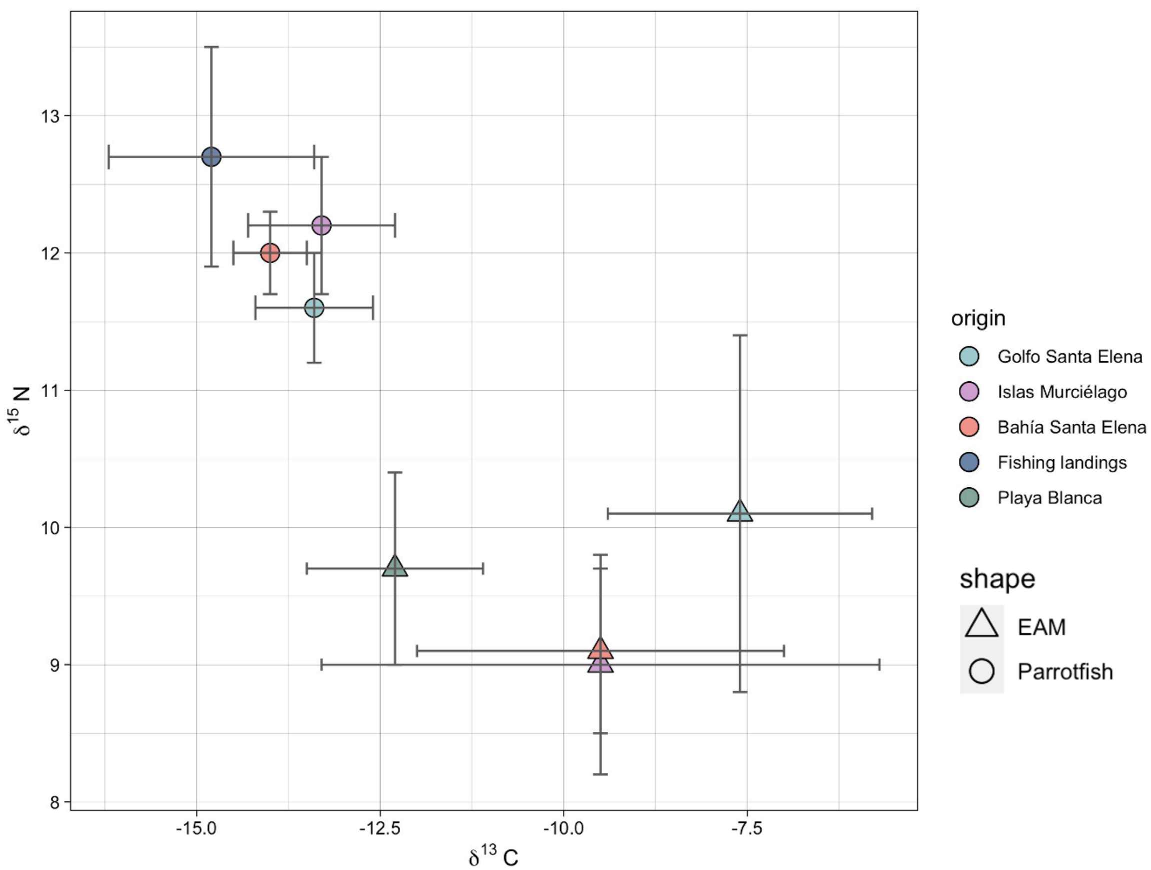

Figure 9. Fig 2. Mean ± SDD of δ15N and δ13C of parrotfish (Scarus ghobban) & EAM (source)

Origin assignment

Based on the SIBER analysis, the SEAC results showed that samples from the fishing landings had the widest SEAc value (17.3), while Golfo Santa Elena had the narrowest SEAc value (0.45) (Fig. 4). The results from overlap percentages further highlight the extent of these overlaps, low overlap percentages were observed between sites, highlighting the concept that these sites exhibit distinct isotopic variability, creating unique ecological niches. Specifically, the overlap percentages between the sites are as follows: Bahía Santa Elena (BSE) and Islas Murciélago (IM) at 4%, BSE and Golfo Santa Elena (GSE) at 22%, BSE and fishing landings (FL) at 27%, IM and GSE at 24%, GSE and LS at 25%.The highest overlap occurred between parrotfish caught at fishing landings of unknown origin and the Islas Murciélago isotopic niche at 44%.

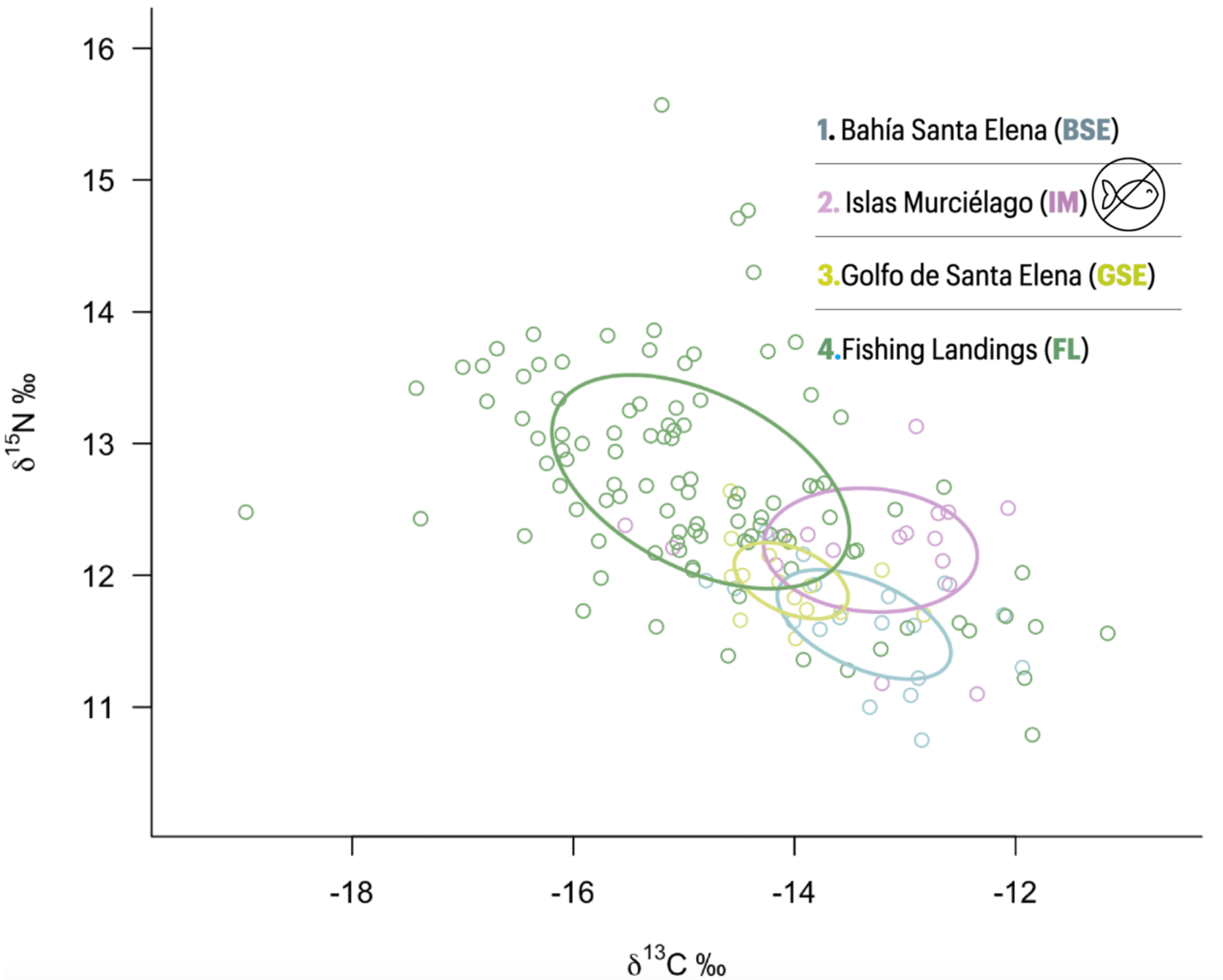

Fig. 11. *$\delta^{15}N$ and $\delta^{13}C$ plot of fish values with corrected standard ellipse areas (SEAc) representing the core niche of parrotfish by site (Ellipses): Group 1: Bahia Santa Elena, Group 2: Islas Murciélago (MPA), Group 3; Golfo Santa Elena and Group 4: Landing site". Next, the values of overlap between groups*

VI. DISCUSSION

Knowledge of the geographic origin of marine resources is key to assessing the traceability of economically and ecologically important species (Vinci et al., 2013). Here, SIA provided important information on the ecological and geographic origin of parrotfish, a key target species harvested by SSF in north Pacific coast of Costa Rica. This tool provides valuable insights for regulators, the fishing industry and stakeholders interested in preventing illegal behavior to enforce standards in sustainable fisheries management (Del Rio-Lavín et al., 2022). This study aimed not only to attribute illegal behavior to the compressor fishery, but also to assess the usefulness of the technique and, indirectly, to gain a better understanding of the spatial and temporal dynamics of the fishery. Therefore, we present the efficacy and challenges of using stable isotope analysis to determine the geographic origin of an economically important marine resource. Our findings provide insights into potential illegal fishing activities and highlight the need for more robust research to accompany this approach.

Since many basal sources (primary producers) in the system determine the isotopic variability, the values of $\delta^{15}N$ and $\delta^{13}C$ in a consumer will be given by the consumption of the type of sources, thus providing information of where a species is feeding from (Plass-Johnson et al., 2018). Here, we showed that the differences in isotopic values of *S. ghobban* between sites are indicative of different dietary preferences and potential sources. In particular, the observed variation in $\delta^{15}N$ and $\delta^{13}C$ variability between Bahia Santa Elena, Golfo de Santa Elena, and Islas Murciélago highlight the differential assimilation of carbon and nitrogen sources within their respective habitats. Both $\delta^{15}N$ and $\delta^{13}C$ values indicate different feeding behaviors and food sources among *S. ghobban* from the different sampling sites. The observed isotopic differences between parrotfish and EAM emphasized the importance of EAM as a dietary element for parrotfish. However, the differences found in $\delta^{15}N$ and $\delta^{13}C$ values, showing different degrees of enrichment or depletion within the sampled sites, imply the involvement of other food sources. This suggests that parrotfish selectively use other sources beyond the EAM. While parrotfish are known to feed on turf algae, some studies have shown that they can also ingest detritus, endolithic algae, and invertebrates (Clements et al., 2016). Furthermore, these results highlight the importance of addressing variability in parrotfish food sources, especially given the ongoing uncertainties surrounding parrotfish trophodynamics in the Pacific region (Plass-Johnson et al., 2013).

Stable isotope ratios measured in consumer tissues are closely linked to those in their diet. The isotopic values of animal tissues can be plotted in δ space and this essentially delineates an animal's isotopic niche (Newsome et al., 2007), providing ecologically relevant information about the individual, population or community. This study revealed there was a significantly high isotopic overlap (44%) between parrotfish samples of unknown origin from those collected at the no-take

MPA (Islas Murcielago). In the other sites examined, the degree of isotopic overlap was relatively low. The observed overlap makes sense, as these areas, particularly Golfo Santa Elena and Bahia Santa Elena, are well-known as important fishing grounds for the community, not only for parrotfish but also for various other fishery products (Farías-Tafolla et al., 2022). These results provide some evidence of illegal behaviour by compressor fishers in a no-take MPA. Interestingly, the ellipse of the fishing landings is clearly different from the other sites sampled. The isotopic values of parrotfish from the fishing landings site showed distinct isotopic values compared to the rest of the sites: higher $\delta^{15}N$ values and slightly lower $\delta^{13}C$ values compared to the other groups. This suggests that different environmental conditions and habitats, for which we don't have isotopic information, are shaping the isotopic signatures of a relatively high percentage of parrotfish sampled from fishing landings. There is also the possibility that some samples from the fishing landings came from other areas outside our sampling region. For example, seasonal changes are known to affect the spatial dynamics of SSF in the north Pacific coast of Costa Rica (Eisele et al. 2020), where fishers often travel far away to more suitable areas in response to changing environmental conditions, possibly targeting parrotfish from these areas. This result also suggests a potential scenario where fishers may be operating in unsampled areas, deeper environments, or fishing in locations not previously suspected.

Parrotfish have significant economic and ecological value (Espinoza et al., 2022; Farías-Tafolla et al., 2022; Tresnati et al., 2021), and consequently it is crucial to understand the fisheries dynamic in order to develop sound management and conservation approaches. Although illegal fishing behavior from compressor divers has been previously reported in the Islas Murciélago (M. Lara pers. comm.), this study used a novel ecological technique to address these issues. In this study, there were some limitations to the use of this approach. For example, although differences in δ15N and δ13C values between Bahia Santa Elena, Golfo de Santa Elena and Islas Murciélago revealed distinctive isotopic signatures for each site, it became clear that a more thorough spatiotemporal and robust sampling strategy was essential. This strategy should address the sampling gaps that occurred during upwelling events, ensure an equal number of samples from each site, and provide a clearer and more comprehensive picture of the isotopic variability of the area. Such an approach would include seasonal variations and provide a more refined characterization of isotopic sources, thereby improving the reliability of signals between sites. The incorporation of complementary techniques, such as the analysis of isotopic ratios of additional elements (Gamboa-Delgado et al., 2014; Heuvel et al., 2019), may also allow for a more precise attribution of geographic origin, as overlapping isotopic values may occur in groups of different origin. Nevertheless, this tool provides valuable information for a broader understanding of the dynamics of the fishery.

VII. CONCLUSSION

Our study highlights the effectiveness of stable isotope analysis as a valuable tool for determining the origin of marine organisms, particularly parrotfish, a key species within reef ecosystems and a valuable resource in the north Pacific coast of Costa Rica. By examining the isotopic signatures of $\delta^{15}N$ and $\delta^{13}C$ values, we gain valuable insights into dietary preferences and geographical origins. This approach allows us to discriminate between different sampling sites and even establish links between parrotfish samples collected at the fishing landings and potential source regions, such as a no-take Marine Protected Area (MPA). Based on the results obtained, we recommend the use of both $\delta^{15}N$ and $\delta^{13}C$ for source attribution of commercially important species, thereby enhancing traceability verification. Despite some inherent challenges in source attribution, stable isotopes have demonstrated their ability to provide a comprehensive understanding of small-scale fisheries (SSF) activities, where this knowledge is fundamental for effective management of marine resources.

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GENERAL CONCLUSION

Our study demonstrates the adaptability of the SESF approach as a valuable tool for understanding the dynamic drivers behind the adoption of air compressors in fishing innovations. This framework not only provides a clearer understanding of the intricate interplay between socio-economic factors, ecological attributes and technological changes driving the transition to compressor fishing, but also synthesises research findings and provides insights and recommendations for compressor fishing management. By analysing the complex interactions that drive compressor adoption, this approach provides a structured method for identifying areas for intervention within small-scale fisheries, which are often difficult to understand due to their diverse social and ecological dynamics. Furthermore, our research highlights a broader understanding of the adoption of innovative practices within small-scale fisheries, particularly in the case of parrotfish capture through compressor fishing, a key species in reef ecosystems. Using stable isotope analysis, we gain valuable insights into dietary preferences and geographical origin by examining the isotopic signatures of $\delta^{15}N$ and $\delta^{13}C$ values. This method allowed us to discriminate between sampling sites and establish links between parrotfish samples collected at landing sites and potential source regions, such as a no-take Marine Protected Area (MPA). Based on our results, we recommend the use of both $\delta^{15}N$ and $\delta^{13}C$ for source attribution of commercially important species, thereby enhancing traceability verification. Despite the inherent challenges of source attribution, stable isotopes have demonstrated their ability to provide a comprehensive understanding of small-scale fisheries (SSF) dynamic, as an informative tool, which is fundamental to the effective management of marine resources and the sustainability of these fisheries.

CONCLUSION GENERAL

Nuestro estudio demuestra la adaptabilidad del enfoque SESF como valiosa herramienta para comprender los factores dinámicos que impulsan la adopción de compresores de aire en las innovaciones pesqueras. Este marco no sólo proporciona una comprensión más clara de la compleja interacción entre factores socioeconómicos, aspectos ecológicos y cambios tecnológicos que impulsan la transición a la pesca con compresor, sino que también sintetiza los resultados de la investigación y aporta ideas y recomendaciones para la gestión de la pesca con compresor. Al analizar las complejas interacciones que impulsan la adopción de la pesca con compresor, este enfoque proporciona un método estructurado para identificar áreas de intervención dentro de las pesquerías de pequeña escala, que a menudo son difíciles de comprender debido a sus diversas dinámicas sociales y ecológicas. Además, nuestra investigación resalta una comprensión más amplia de la adopción de prácticas innovadoras dentro de la pesca a pequeña escala, en particular en el caso de la captura de peces loro mediante la pesca con compresor, una especie clave en los ecosistemas de arrecife. Mediante el análisis de isótopos estables, obtuvimos información valiosa sobre las preferencias alimentarias y el origen geográfico examinando las firmas isotópicas de los valores $\delta^{15}N$ y $\delta^{13}C$. Este método nos permitió discriminar entre los lugares de muestreo y establecer vínculos entre las muestras de peces loro recogidas en los lugares de desembarque y las posibles regiones de origen, como un Área Marina Protegida (AMP) de veda. Basándonos en nuestros resultados, recomendamos el uso de $\delta^{15}N$ y $\delta^{13}C$ para la atribución del origen de especies comercialmente importantes, mejorando así la verificación y la trazabilidad. A pesar de los retos de este estudio en a la atribución de las fuentes a los sitios muestreados, los isótopos estables han demostrado su capacidad para proporcionar una comprensión global de la dinámica de la pesca a pequeña escala (SSF), así como una herramienta informativa, que es fundamental para la gestión eficaz de los recursos marinos y la sostenibilidad de estas pesquerías.

ANEXOS

Capitulo 1: A. Encuesta a pescadores con compresor activos

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Encuesta sobre la pesca con compresor en el Pacifico Norte de Costa Rica
La información que usted escriba aquí es confidencial

En la siguiente encuesta queremos explorar más en que consiste la pesca con compresor y las percepciones de los pescadores sobre esta pesca. La información que usted nos dé es muy importante ya que queremos describir como es la pesca con compresor contada por ustedes.

¿Hace cuántos años usted vive aquí en la comunidad de Cuajiniquil? ____________

¿Hace cuánto tiempo es buzo con compresor?
1 **0-10** ☐ 2 **10-20** ☐ 3 **20-30** ☐ 4 **más de 30** ☐

1

Edad ____________

¿Es dueño de alguno de los siguientes equipos de pesca?

Compresor ☐1
Regulador ☐2
Arbaleta ☐3
Traje de buceo ☐4
Hielera ☐5
Otro (nada)
Todo ________6

2

¿Cuál es su trabajo durante la pesca?

Encargado del compresor ☐1
Carguero ☐2
Tirador ☐3
Capitan ☐4
Otro (todo, se rotan) 5

¿Cuál es la razón principal por la cual usted decidió pescar con compresor?
**marcar solo una opción*

4

Mi familia pescaba con compresor ☐1
Mi familia pescaba con buceo ☐2
Es más económico ☐3
Me gusta este tipo de pesca ☐4
Obtener más producto de pesca ☐5
Otra razón ______________________________

¿Cuáles son las tres especies que usted pesca en más cantidad durante todo el año?

5

Pulpo ☐1
Peces Loros ☐2
Langosta ☐3
Cabrilla ☐4
Peces Chancho ☐5

¿A quién vende usted lo que pesca?
**marcar solo una opción*

6

Recibidores ☐1
Otros compradores ☐2
Ambos ☐3

¿Cuál es la época que más se pesca peces loros?
**marcar solo una opción*

7

diciembre a mayo (temporada de vientos del norte) ☐1
mayo a noviembre ☐2
Semana santa ☐3
Otra temporada ______________

¿Cuáles son los mejores sitios para pesca de peces loros?

8

El hachal ☐1
Islas Loros ☐2
Islas Muñecos ☐3
Islas Murciélago ☐4
Playa Blanca ☐5
Bajo Rojo ☐6
Bahía Santa Elena ☐7
Otros (escríbalos en las siguientes líneas)
____
____
____
____

¿Cuál es la razón principal que usted pesca más en los sitios antes mencionados?
**marcar solo una opción*

Conocimiento local de lugares de pesca ☐1
Por causa de las prohibiciones ☐2
Fácil pescar ahí y se gasta poco tiempo ☐3
Costos de combustible bajos ☐4
Reducir conflictos con otros botes ☐5
Otra razón ________________________

¿Qué peso total se considera una buena pesca de peces loros en un día de pesca?
**marcar solo una opción*

10

de 50 kilos 100 kilos ☐1
de 100 kilos 300 kilos ☐2
de 300 kilos 400 kilos ☐3
Mas de 400 kilos ☐4

¿Generalmente cuantos kilos de peces loros pescan en un día?
peso: 1 0 a 1kg ☐ 2 1 a 2 kg ☐ 3 más de 2kg ☐ 1

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Encuesta sobre la pesca con compresor en el Pacifico Norte de Costa Rica
La información que usted escriba aquí es confidencial

¿Ha disminuido la pesca de peces loros a lo largo de los años?

12

Si ☐1
No ☐2
No sabe ☐3

Si contesto si a la pregunta anterior, ¿Cuál cree que sea la razón?

13

Mucha pesca de este pez que ha hecho que disminuya ☐ 1
Destrucción de las áreas en donde viven ☐ 2
Contaminación ☐ 3
Otra razón:

Existen regulaciones/prohibiciones para la pesca con compresor
**marcar solo una opción*

14

Si ☐1
No ☐2

¿Ha pescado usted en sitios prohibidos de pesca?

18

Si ☐1
No ☐2

¿Conoce casos de personas que pesquen en sitios prohibidos de pesca?

19

Si ☐1
No ☐2
No sabe 3

¿Usted piensa que las áreas marinas protegidas (específicamente los sitios de no pesca) han sido positivas o negativas en la vida de los pescadores?

20

Positiva ☐1
Negativa ☐2
Ningún efecto ☐3

En el siguiente cuadro escriba cada una de las regulaciones/prohibiciones que existen Cuajiniquil sobre la pesca con compresor y marque con una X si está o no de acuerdo con cada una de ellas

15

Regulación	Está de acuerdo con esta regulación		Porque razón si está o no de acuerdo con esta regulación
	Si ☐	No ☐	
	Si ☐	No ☐	
	Si ☐	No ☐	
	Si ☐	No ☐	
	Si ☐	No ☐	

¿Usted participo o fue consultado sobre la creación de regulaciones para la pesca de peces loros?

16

Si ☐1
No ☐2

¿Le gustaría participar en talleres sobre las regulaciones de peces loros?

17

Si ☐1
No ☐2

¿Para usted cual es la función de las áreas marinas protegidas?

____
____
____
____

¿Qué importancia cree usted que tienen los peces loros en el ambiente?

____
____
____

Capitulo 1; B. Encuesta a ex pescadores con compresor

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II. Encuesta sobre la pesca con compresor en el Pacifico Norte de Costa Rica – ExPescadores

La información que usted escriba aquí es confidencial

En la siguiente encuesta queremos explorar más en que consiste la pesca con compresor y las percepciones de los pescadores sobre esta pesca. La información que usted nos dé es muy importante ya que queremos describir como es la pesca con compresor contada por ustedes.

¿Hace cuántos años usted vive aquí en la comunidad de Cuajiniquil? ____________
Otra comunidad ______________________

¿Hace cuántos años comenzó a pescar con compresor?
1 **0-10** ☐ 2 **10-20** ☐ 3 **20-30** ☐ 4 **más de 30** ☐

¿Hace cuántos años dejo de pescar con compresor?
1 **0-10** ☐ 2 **10-20** ☐ 3 **20-30** ☐ 4 **más de 30** ☐

Edad ____________

¿Cuál es la razón principal por la cual usted decidió pescar con compresor?
**marcar solo una opción*

Mi familia pescaba con compresor ☐1
Mi familia pescaba con buceo ☐2
Es más económico ☐3
Me gusta este tipo de pesca ☐4
Obtener más producto de pesca ☐5
Otra razón ___________________________ 6

¿Cuáles son las tres especies que usted pescaba?
**marcar solo tres opciones*

Pulpo ☐1
Peces Loros ☐2
Langosta ☐3
Cabrilla ☐4
Peces Chancho ☐5

¿Cuáles eran los mejores sitios para pesca de peces loros?

El bachal ☐1
Islas Loros ☐2
Islas Muñecos ☐3
Islas Murciélago ☐4
Playa Blanca ☐5
Bajo Rojo ☐6
Bahía Santa Elena ☐7

Otros (escríbalos en las siguientes líneas)8
____
____
____
____
____

En orden de importancia ¿Cuáles fueron las razones más importantes por las que dejo de practicar la pesca como actividad comercial?

____
____
____

¿Usted consideraría volver a la pesca en el futuro?

Si ☐1
No ☐2
No sabe ☐3

Si usted marco si en la pregunta anterior ¿Cuál sería la razón?
**marcar solo una opción*

No hay otra oportunidad de trabajo ☐1
No me gusta el trabajo actual ☐2
Extraño la pesca ☐3
Otra razón ____________________________

¿Existían regulaciones para la pesca con compresor cuando usted pescaba?

Si ☐1
No ☐2
No recuerda ☐3

En caso de que existieran regulaciones en el pasado ¿estaba usted de acuerdo con ellas?

Si ☐1
No ☐2
No aplica ☐3

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II. Encuesta sobre la pesca con compresor en el Pacifico Norte de Costa Rica – ExPescadores
La información que usted escriba aquí es confidencial

En algún momento cuando usted era pescador comercial ¿pesco en lugares prohibidos de pesca?

Si ☐1
No ☐2
No existían ☐3

Si contesto si a la pregunta anterior, ¿Cuál cree que fue la razón?
**marcar solo una opción o solo contestar otra opción*

Había más peces en los sitios de no pesca ☐1
No había vigilancia ☐2
Fui multado y no lo volví a hacer ☐3

Otra razón: ____

¿Actualmente se pesca en sitios prohibidos de pesca?

No sabe ☐1
No ☐2
Si ☐3
Cuales son estos sitios:
____
____

¿Usted cree que ahora hay más/menos pesca en sitios prohibidos que antes?

Mas ☐1
Menos ☐2
No sabe ☐3

Si contesto más en la pregunta anterior ¿Cuál cree que sea la razón principal?
**marcar solo una opción*

Menos vigilancia ☐1
Mayor cantidad de pescadores ☐2
Han disminuido los peces en los sitios legales ☐3

Otra razón: ________________________________ 4

¿Usted participo o fue consultado sobre la creación de regulaciones para la pesca de peces loros?

Si ☐ 1
No ☐ 2

¿Qué importancia cree usted que tienen los peces loros en el ambiente?

____
____
____

¿Tiene sugerencias para proteger las especies de peces loros en su comunidad?

____
____
____
____

Capitulo 1: C. Entrevista a informantes claves

III. Entrevista sobre la pesca con compresor de peces loros (base line)

Grabación si___ No______ Fecha_______________

1. ¿Hace cuántos años usted vive aquí en la comunidad?

2. ¿Hace cuántos años empezó a pescar?

3. ¿Hace cuánto tiempo es buzo? o por cuanto tiempo fue buzo?

4. ¿Cómo es la pesca con compresor? De una descripción general

5. ¿Cuál es el equipo que se utiliza? ¿Puede describir para que sirve cada uno?

6. ¿Hace cuanto existe la pesca con compresor en Cuajiniquil?

7. ¿Generalmente, cuantos pescadores salen por viaje?

8. ¿Como distribuyen el trabajo?

9. ¿Planifican los sitios de pesca y de que dependen estos?

10. ¿Hay temporadas de pesca según la especie a pesca? ¿Cuáles y por qué?

11. ¿Cuáles son los principales sitios de pesca?

12. ¿Cuáles son las medidas de seguridad que se debe de tener al bucear con compresor?

13. ¿Cuánto tiempo permanecen en un día de pesca, cuantos buceos y cuanto dentro del agua? ¿Quién mide este tiempo?

14. ¿Ha tenido algún accidente de descompresión?

15. ¿Conoce a alguien que haya tenido un accidente o muerte por buceo con compresor? ¿cuántas personas y porque cree que haya ocurrido?

16. ¿Cuándo, dónde y con quien aprendió a bucear?

17. ¿Recibió algún entrenamiento antes de comenzar a bucear?

18. ¿En la comunidad se han brindado talleres sobre capacitación y medidas de seguridad en el buceo?

19. ¿Estaría a favor que se den estos talleres?

20. ¿Hace cuánto tiempo se pescan los peces loros?

21. ¿Ha disminuido la pesca de peces loros a lo largo de los años?

22. ¿Cuáles eran las tallas o pesos promedios de peces loros cuando comenzó a pescar y cuales son ahora?

23. ¿Cuál fue la talla de pez loro más grande que haya capturado?

24. ¿Cuál es su percepción de la ilegalidad antes y actualmente, ha disminuido o aumentado y porque piensa?

Capitulo 2: D. Hoja de colecta de campo

PROYECTO HERBÍVOROS - MACROALGAS, PACÍFICO NORTE CR_ UCR

Contacto: Paola Díaz **email:** lesly.diaz@ucr.ac.cr **Cel:** 70775893

CÓDIGO VIAL ____ sp	**SI-Tejid** Alga ☐	***Estómag*** si ☐ Codigo
Sitio:	Músculo ☐	no ☐
Fecha:	Hígado ☐	
Hora:	Aleta ☐	***Muestra genética*** Codigo
Latitud:	***Peso***	si ☐ no ☐
Longitud:		**Sustrato (alga)**
T° ***Prof*** Salinidad	***Medicion*** LT	
	LH	***Nombre Colectora/colector***
Uso sitio Pesca ☐ No pesca ☐ rismo ☐ tro ☐	***Sexo*** M H	
Especificar otro		***Comentarios***
	Estadío IP ☐	
	JP ☐	
	TP ☐	

CÓDIGO VIAL ____ sp	**SI-Tejid** Alga ☐	***Estómag*** si ☐ Codigo
Sitio:	Músculo ☐	no ☐
Fecha:	Hígado ☐	
Hora:	Aleta ☐	***Muestra genética*** Codigo
Latitud:	***Peso***	si ☐ no ☐
Longitud:		**Sustrato (alga)**
T° ***Prof*** Salinidad	***Medicion*** LT	
	LH	***Nombre Colectora/colector***
Uso sitio Pesca ☐ No pesca ☐ rismo ☐ tro ☐	***Sexo*** M H	
Especificar otro		***Comentarios***
	Estadío IP ☐	
	JP ☐	
	TP ☐	

CÓDIGO VIAL ____ sp	**SI-Tejid** Alga ☐	***Estómag*** si ☐ Codigo
Sitio:	Músculo ☐	no ☐
Fecha:	Hígado ☐	
Hora:	Aleta ☐	***Muestra genética*** Codigo
Latitud:	***Peso***	si ☐ no ☐
Longitud:		**Sustrato (alga)**
T° ***Prof*** Salinidad	***Medicion*** LT	
	LH	***Nombre Colectora/colector***
Uso sitio Pesca ☐ No pesca ☐ rismo ☐ tro ☐	***Sexo*** M H	
Especificar otro		***Comentarios***
	Estadío IP ☐	
	JP ☐	
	TP ☐	

Capitulo 2. E. Hoja de campo colecta de muestras en recibidores

PROYECTO HERBÍVOROS - MACROALGAS, PACÍFICO NORTE CR_ UCR

Contacto: Paola Díaz **email:** lesly.diaz@ucr.ac.cr **Cel:** 70775893

ID	recibidor	sp	estadio	TL	Tejido	fecha	hora	Field notes