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# Inferring ecosystem impacts of a small-scale snapper fishery through citizen science data, productivity and susceptibility analysis, and ecosystem modelling

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ABSTRACT

The small-scale fishery targeting snappers in the Mexican Atlantic is data-limited since the best scientific information is insufficient to determine its status. Governmental (at regional level) and citizen science data (at a local scale) were used for fishery characterisation, emphasising the red snapper (*Lutjanus campechanus*). The characterisation, along with productivity and susceptibility analysis (PSA) and ecosystem modelling (Ecopath with Ecosim), were used to infer fishery impacts on the coastal ecosystem of Campeche and Tabasco, southern Gulf of Mexico (GOM). Red snapper official annual landings indicated relative stability after 2000 in all the Mexican states, with the highest average landings in Tabasco. Citizen science data showed that the fishery is highly selective for snappers (three species accounted for 83.4%) due to the use of species-specific gears in areas far from the shore (> 50 km). Although bycatch (n = 20 species) included five species with an IUCN risk category (VU, EN, and CR) and two sharks in CITES Appendix II, they represented a low catch percentage (< 2%) of the citizen science records. PSA suggests the red snapper had a moderate and three elasmobranchs high overexploitation risk. The ecosystem had a simple trophic structure and high resilience, with a strong energy flow exchange between three food web compartments. The overall results suggest that the small-scale fishery has a relatively low ecosystem impact in Tabasco and Campeche. However, systematic fishery monitoring to understand catch composition variations and collect more information on trophic web interactions is needed for future assessments.

## 1. Introduction

The red snapper (*Lutjanus campechanus*) is distributed in the Western Atlantic, Caribbean Sea, and Gulf of Mexico (GOM). It is associated with coral reefs and hard substrates (e.g., gravel bottoms, rock outcrops, artificial reefs, and oil platforms) in depths ranging 30–130 m (Allen, 1985; Stanley and Wilson, 1997; Gallaway et al., 2009). The red snapper has early sexual maturity (2–4 years), reaches full reproductive maturity at about ten years, and is a long-lived species, surviving for 45–57 years (White and Palmer, 2004; Anderson et al., 2015). It is classified as vulnerable in the GOM by the International Union for Conservation of Nature (IUCN Red List) because it has a decreasing population trend due to heavy exploitation by recreational and commercial fisheries (Anderson et al., 2015).

The management and status of the fishery in the USA and Mexico are contrasting; fisheries management in the former has reversed the deterioration status, while Mexico has no management plan, and its fishery is overexploited. The USA fleet started fishing the red snapper between 1862 and 1892 in the northern and southern GOM, and progressively fishing areas were expanded to other regions. The fishery in the USA collapsed in the 1980 s (Cowan Jr.. et al., 2011), and presently, there is a rebuilding population plan. The last assessment indicated that the stock was not overfished, and the population was recovering (Goethel and Smith, 2018). In contrast, a population decline of at least 58% was

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inferred over the last three decades in Mexican waters (Anderson et al., 2015), where the status is overexploited. However, no fishery management plan or species-specific regulations, such as fishing licenses, catch quotas, size limits, or closed seasons, exist (DOF, 2018a).

Despite its status, the Mexican snapper fishery ranks sixteenth in landings among 185 fisheries at the national level. However, the fishery ranks eighth in economic value (SAGARPA, 2018). Snappers are commercialised in different presentations (whole or fillet, either fresh, iced or frozen) to the national market, where the average price is around USD 7.20 per kg (Fernández et al., 2011; SAGARPA, 2018). Also, snappers are exported to the international markets, mainly the USA and Canada, where they reach higher prices (Fernández et al., 2011). In this context, a snapper's elevated demand and price in national and international markets make the fishery highly profitable.

In Mexico, the snapper fishery is composed mainly of small-scale boats (outboard motorboats < 10 m long) and some medium-size boats (12–15 m long), mainly on the Yucatan coast (Monroy et al., 2004; DOF, 2018a). The fishing gear is the bottom vertical line and longline (Monroy et al., 2004; DOF, 2018a; Mendoza-Carranza et al., 2018), and it is a multi-species fishery (DOF, 2018a; Mendoza-Carranza et al., 2018). The National Fishing Chart, containing the diagnosis, assessment, and status of the Mexican fisheries used by the fishing authority for implementing management measures (DOF, 2018b), established the overexploited snapper fishery's status based only on the catch trends (DOF, 2018a) since there is a lack of fishing effort, catch rates, and catch composition data to conduct a stock assessment. This feature is common in Mexico and Latin America small-scale fisheries (Salas et al., 2007; Begossi, 2010; de Mattos and Wojciechowski, 2019). Some other features of these fisheries include multiple species, multiple gear types, landing sites widely dispersed along coasts, and an intricate relationship between fishers and money-lending fish traders (Chuenpagdee et al., 2011), making their assessment and management extremely challenging.

An emerging strategy to address the lack of data in these fisheries is citizen science, where fishers are involved in data generation (e.g., Fairclough et al., 2014; Mendoza-Carranza et al., 2018; Fulton et al., 2019). The term citizen science refers to scientific studies involving the participation of public members (Fulton et al., 2019) or scientific research and monitoring conducted by non-specialist individuals (Bonney et al., 2014). Citizen science produces reliable data and information that scientists and policymakers can use since it is generated under the same procedures as conventional science (Conrad and Hilchey, 2011; Fulton et al., 2019). Additionally, as citizen science is supported by local ecological knowledge (LEK; Giovos et al., 2019; Reyes-García et al., 2020) confers confidence in data acquisition since fishers have broad knowledge about species ecology, oceanographic conditions, fishing gears, and fishing ground characteristics (Lima et al., 2017; Martins et al., 2018). The fishers' participation throughout the management process (starting with data generation) is integrated into the ecosystem approach to fisheries (EAF).

The EAF explicitly recognises ecosystems' complexity and the interconnections among its components (García et al., 2003). Ward et al. (2002) defined it as an extension of conventional fisheries management, considering explicitly the interdependence between human well-being and ecosystem health and the need to maintain ecosystems productivity. Thus, EAF incorporates the knowledge and uncertainties of biotic, abiotic, and human components of ecosystems and their interactions (García et al., 2003). One of the objectives of the EAF is the conservation of ecosystem attributes, maintaining the energy flow, structure, functioning, diversity, and predator-prey relationships (FAO, 2015). Therefore, this approach requires the consideration of fishing impacts on habitats, bycatch species, threatened and endangered species, and associated ecological communities (Hobday et al., 2011).

One of the methods used for data-limited situations to assess the impacts of fisheries on target and bycatch species is productivity and susceptibility analysis (PSA; Hobday et al., 2011), and the most widely used approach to assess the impacts on the ecosystem is Ecopath with Ecosim (EwE) because it allows the characterisation of the food web's structure and function considering trophic relationships and fisheries extractions (Christensen and Walter, 2005). Both methods are complementary to infer fishery impacts on the ecosystem and identify priorities for research and management. The objective of the present study was the characterisation and inference of ecosystem impacts of a data-limited small-scale fishery targeting snappers in the southern GOM using governmental and citizen science data, PSA, and ecosystem modelling (EwE).

## 2. Materials and methods

### 2.1. Fishery characterisation

Three databases from the National Commission of Aquaculture and Fishing of Mexico (CONAPESCA, by its Spanish acronym) were used to describe the red snapper fishery. The first database containing annual landings records from 1980 to 2014 was used to describe the annual fishery trends by state (Tamaulipas, Veracruz, Tabasco, Campeche, Yucatán, and Quintana Roo; Fig. 1). The second database containing monthly landing records from 2006 to 2014 was used to describe monthly trends by state. Finally, the third database with annual landings from 2008 to 2018 was used to estimate the red snapper proportion among teleost fishes and elasmobranch species in Campeche and the CONAPESCA's regional office of Atasta, Campeche. Atasta is the fishing community where fishers from Nuevo Campechito report their catches to CONAPESCA. Databases represent the best available information.

Additional fishery data was generated through citizen science in Nuevo Campechito, Campeche. The data were generated by a logbook system by a fishing cooperative from that fishing port (Cooperativa de Producción de Bienes y Servicios Pescadores de Nuevo Campechito SC de RL de CV). The cooperative is implementing a Fishery Improvement Project (FIP) that is guided by the three principles of the Marine Stewardship Council (MSC) standard (sustainable stocks, minimisation environmental impact, and effective fisheries management) to achieve sustainability in their snapper fishery. The fishing cooperative was already used to make records because their landings data must be reported to the fishing authority (CONAPESCA). However, the personnel in charge of recording landings were trained on the importance of recording daily fishing data and the process of filling out the logbook, which contains 85 fishing trips carried out by six small-scale boats targeting snappers from September 13th of 2019 to October 15th of 2020. Landing records included location, depth, and bottom type in the fishing area, duration of the trip (hours), total weight (kg) per fishing trip by the target and non-target species, fishing gear characteristics, and bait used (Table 1). The species' common names recorded in the logbook were verified based on the authors' knowledge of the region's fisheries. Finally, all data recorded was carefully reviewed to detect inconsistencies.

The number of sets, hooks used by set, and soak time were variable in the regions' fisheries (Mendoza-Carranza et al., 2018) and were not consistently recorded in the logbook due to logistical issues. The most reliable variable to estimate the catch rate was the duration of the fishing trip. The duration of the trip (hours) was transformed to days to estimate a catch rate in kg/day. The catch rates by fishing gear (vertical line, longline, and longline-vertical line) and its monthly variation (enough data only for vertical line) throughout the period (September 2019 to October 2020) were compared for the red snapper and the aggregated catch of the rest of the species. Records in the logbook also included the total length (TL) of a sub-sample by species. The average TL ($\pm$ SD) is reported. The red snapper size structure variations by gear and month were also analysed, and the size structure was also described for other eight species in the catch. Beanplot graphs were used to describe the catch rate and size structure (Kampstra, 2008). These graphs are useful for identifying the individual distribution of the data

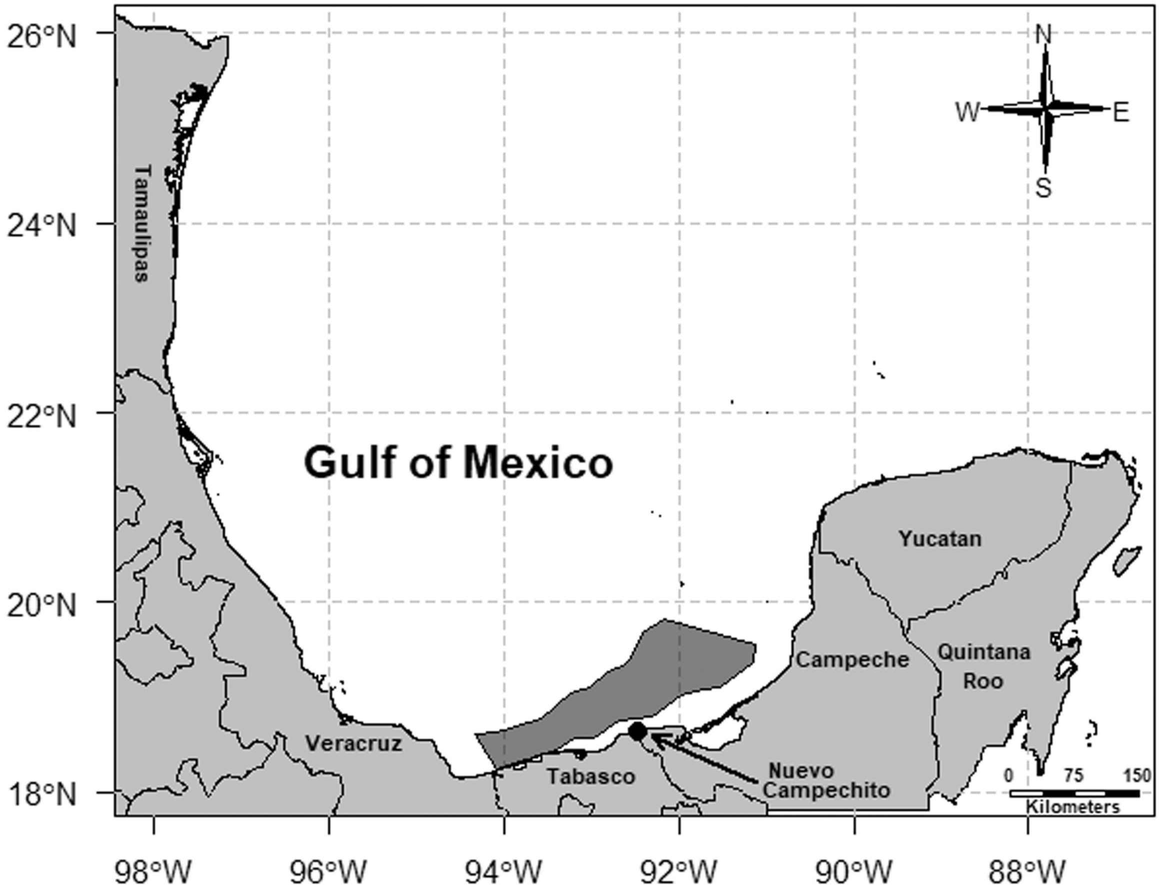


**Fig. 1.** Study area showing the states of the Mexican Atlantic (Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo), the location of Nuevo Campechito, and the application area (gray) of the Ecopath with Ecosim model. Nuevo Campechito is the fishing port where the fishing cooperative involved in the citizen science program is established.

**Table 1**
Characteristics of the small-scale fleet recorded in the logbook by the fishing cooperative from Nuevo Campechito, southern Gulf of Mexico. *IUCN category: Least Concern.

| Fishing characteristics | Description |
|---|---|
| Period of records | September 13, 2019, to October 15, 2020 |
| Boats | Six outboard motorboats ~9 m long |
| Fishers by a fishing trip | 3–4 |
| Fishing trips recorded | 85 |
| Target species | Red, vermilion, and lane snappers |
| Duration of the fishing trips (hours) | Average of 74.9 ± 25.7 |
| Fishing area | 19–20 latitude N; 91–92 longitude W; extended area northwest Nuevo Campechito's port |
| Depth in the fishing area (m) | Average of 43.9 ± 19.9 |
| Fishing gears | Bottom longline with 800–1200 circular hooks #11; vertical line with 60–120 circular hooks #9 |
| Fishing trips recorded by gears | Bottom longline = 12; vertical line = 55; bottom longline/vertical line = 18 |
| Bottom type in the fishing area | Rocky bottom in 44 fishing trips; muddy bottom in 6 fishing trips |
| Bait used | Skipjack tuna (*Katsuwonus pelamis**) and tropical arrow squid (*Doryteuthis plei**) |

(Mendoza-Carranza et al., 2018), providing a kernel density profile based on the Sheater-Jones method (Venables and Ripley, 2002). Unbalanced permutation two-way ANOVA and pairwise permutation *t*-test (900 permutations) (Kherad-Pajouh and Renaud, 2010; Oksanen et al., 2013) were used to compare the catch rate and size by fishing gear and month. These analyses are relevant to infer potential impacts on the ecosystem by the catch rate of specific population sections due to the selectivity of the fishing gears.

### 2.2. Productivity and susceptibility analysis (PSA)

The species vulnerability ($v$) was estimated through a PSA following Patrick et al. (2010) in the coast of Campeche and Tabasco, where the small-scale fleet studied operated. The PSA included two indices, the biological productivity (P) index, based on the species' life-history characteristics, and the susceptibility (S) index, based on the species' interaction with fishing operations. The set of attributes and rankings for productivity (n = 10) and susceptibility (n = 12) are shown in Annex A. The productivity and susceptibility of species were determined by providing a score ranging from 1 (low) to 3 (high) for the set of attributes related to each index by using data from a literature review, citizen science data, and authors' opinion (Annex B). A default weight of 2 for all attributes was used, missing attributes were not considered, and the uncertainty was estimated through a data quality index (Patrick et al., 2010). Species having a low productivity score and high susceptibility score are at a high risk of becoming depleted. In contrast, stocks with a high productivity score and low susceptibility score are at a low risk of becoming depleted (https://nmfs-fish-tools.github.io/PSA/). The three targeted snappers and the seven most recorded non-target species in the logbook of the fishing cooperative were included in the PSA.

Once P and S indices were calculated for each species, the results were classified into three categories according to Patrick et al. (2010): low (1–1.6), moderate (> 1.6–2.3), and high (> 2.3–3). The vulnerability ($v$) was calculated using the Euclidean distance to the point of origin in an x-y scatter plot. This graph combined P (X-axis, with values from 3.0 to 1.0) and S (Y-axis, with values from 1.0 to 3.0) with the following equation (Patrick et al., 2010):

$$v = \sqrt{\left[(P-3)^2 + (S-1)^2\right]}$$

where $v$ is vulnerability, P is biological productivity, and S is susceptibility.

The vulnerability scores were classified into four categories: low ($v \leq$ 1.8), moderate ($v > 1.8$ and $\leq 2.0$), high ($v > 2.0$ and $\leq 2.2$), very high ($v > 2.2$), according to the Framework for Integrated Stock and Habitat Evaluation (FISHE). Indices were calculated using the FISHE Spreadsheet available at http://fishe.edf.org/framework/step-4-stock-vulnerability-assessment.

The data quality to determine the uncertainty of the estimates was evaluated according to Patrick et al. (2010). Each attribute was assigned a value from 1 to 5, where one is the highest data quality and five when there are no data on which to make even an expert opinion. In this situation, a score was not provided to the specific attribute to not bias the productivity or susceptibility indices. The average quality value was classified into three categories: poor (> 3.5), moderate (2.0–3.5), and good (< 2.0; Patrick et al., 2010). Scoring data quality may help determine species of interest for further data collection and particular data gaps across species (https://nmfs-fish-tools.github.io/PSA/).

### 2.3. The red snapper ecosystem model

A trophic model built with Ecopath with Ecosim (EwE) software (version 6.6.5) evaluated trophic interactions and energy flow in the ecosystem. This model represents an ecosystem within a predetermined area based on trophic interactions between functional groups, including one or more species. The inputs and outputs of each functional group were balanced, which implies that their productivity was equal to the losses due to predation or other mortality sources (natural or fishing), migration, or biomass accumulation. Furthermore, functional groups were linked through their diets, where each group, except for primary producers, must feed on other groups (Christensen and Walters, 2004).

The role of the red snapper in the ecosystem was evaluated by modifying a trophic model generated by Zetina-Rejón and Arreguín-Sánchez (2003) in a southern GOM's subarea (Fig. 1). The red snapper functional group was added using input parameters from Abascal-Monroy et al. (2016), and the biomass of the group was estimated from the EwE model. The species diet composition from the study area (Pérez-Díaz et al., 2007) was included, considering the organic matter as detritus. The mean landing data from CONAPESCA databases (2008–2017) for the red snapper was also included. The ecosystem trophic structure was characterised, emphasising the red snapper group, its role in the ecosystem, and its interactions with other food web members (25 functional groups). Input data of the ecosystem model are shown in Annex C.

#### 2.3.1. Functional analysis

The structure and function of the ecosystem were described with the indices calculated from the Ecopath model. The total consumption, exports, respiration, and flow to detritus, which is the sum of all energy flows and is related to the total throughput of the food web, were estimated. Additionally, connectance and system omnivory indices were examined to determine the structure of trophic connections. In addition, the ascendency ($A$), development capacity ($C$), and overhead ($O$) ecosystem flow indices (Ulanowicz, 1986) were calculated to describe the growth and development of the ecosystem. The upper limit of $A$ is the development capacity ($C$) and measures the system's growth potential. The difference between $A$ and $C$ is the overhead ($O$), which expresses the system's reserve potential to respond to external disturbances.

#### 2.3.2. Topology analysis of the food web

In addition to the analysis described by Zetina-Rejón and Arreguín-Sánchez (2003), the food web topological structure and the role of the red snapper in the ecosystem were assessed through structural indices and modularity analysis.

*2.3.2.1. Structural indices.* The centrality indices for each functional group were calculated from the consumption flow matrix obtained in the Ecopath model. These analyses are based on the network topology to determine and quantify the node's connections to each other and their importance in the food web. The following indices were estimated with the 'igraph' package (Csárdi and Nepusz, 2006) in R software.

The degree centrality index ($D_i$) calculates the network connections per node and is determined by the sum of all prey and their predators. The closeness centrality index ($CC_i$) defines the node capacity to transmit its effect to all network elements, under the assumption that the most central members are at a shorter distance from the rest:

$$CC_i = \frac{N-1}{\sum_{j=1}^{N} dij}$$

where N corresponds to the number of nodes (functional groups) in the network; $\sum_{j=1}^{N} dij$ is the sum of the geodetic distances between nodes i and j. High values indicate greater easy access to the network members (Jiang and Zhang, 2015).

Finally, the betweenness centrality index ($BC_i$) quantifies how frequently a node ($i$) occurs in the short paths between each pair of nodes $j$ and $k$. It gives an approximation of the functional group's importance as a connector within the network.

$$BC_i = \frac{2 - \sum_{i \neq j} \cdot g_{jk}(i) \Big/ g_{ik}}{[(N-1)(N-2)]}$$

where $g_{jk}$ is the shortest number of trophic paths between groups $j$ and $k$; and $g_{ik}$ is the number of short routes where group $i$ has influence; and $N$ is the number of total nodes. Nodes with a high value are key because they are in the network centre or link different subgroups (Izquierdo and Hanneman, 2006).

*2.3.2.2. Modularity analysis.* Modularity is a measure of structure that consists of dividing and identifying subsystems or modules in the food web. The members (species or functional groups) of these modules present a greater trophic interconnection between them than with the rest of the network members to isolate disturbances in the entire food web (Zetina-Rejón et al., 2015). Therefore, modules or compartments in trophic networks formed by groups of species with strong trophic interactions play a key role in transferring energy in the food web (Stouffer and Bascompte, 2011). Thus, the modularity of the food web is relevant for ecosystem stability and resilience.

The fast greedy community finding algorithm (Newman and Girvan, 2004) included in the 'igraph' package (Csárdi and Nepusz, 2006) for R software was used. The algorithm quantifies the food web division in modules based on the notion that there should be more intense connections within modules than between them. Modularity measures the quality of divisions in network compartments. For weighted networks, such as food webs, the modularity ($M_w$) is calculated as (Guimerà et al., 2007):

$$M_w = \sum_{s=1}^{N_M}\left[\left(\frac{w_s^{in}}{W}\right) - \left(\frac{w_s^{all}}{2W}\right)^2\right]$$

where $W$ is the sum of the weights (biomass flows) of all predator-prey interactions, $w_s^{in}$ is the sum of the weights of predator-prey interactions within the module $s$, and $w_s^{all}$ is the sum of weights of interactions involving group $i$ within module $s$ and all other groups. Values of $M_w$ can be either negative or positive, with positive values indicating a deviation from randomness (Newman and Girvan, 2004; Newman, 2006). The functional and structural indices obtained by the ecosystem model provide the red snapper ecological role and the species influence on other organisms due to flow interactions.

## 3. Results

### 3.1. Red snapper fishery in the Mexican Atlantic

The highest red snapper landings in 1980–2014 were recorded before 2000, with an average ( ± SD) of 3919.2 ± 1570.61 t, and the highest values in 1992 (6748 t) and 1993 (7205 t). From 1994–1999, an accelerated decline in landings was observed, with an average annual decrease of 322 ± 316 t. After 2000, the landings stabilised at an annual average of 2845 ± 326 t. The state with the highest average landings in 1980–2000 was Yucatan (1346 ± 547 t), followed by Veracruz (766 ± 258 t), Tamaulipas (674 ± 141 t), Campeche (625 ± 581 t), and Tabasco (469 ± 315 t). However, from 2001 to 2014, Tabasco was the state with the highest average landings, (981 ± 137 t), followed by Yucatan (511 ± 91 t), Campeche (494 ± 128 t), Tamaulipas (489 ± 194 t), and Veracruz (346 ± 119 t). Quintana Roo maintained very low average landings (32 ± 28.4 t) throughout the period (Fig. 2). Overall total monthly red snapper landings had the highest values in January (2838 t), February (2614 t), November (2429 t), and December (2636 t). The least total landings were recorded in June (1918 t), July (1839 t), and August (1863 t; Annex D).

#### 3.1.1. Red snapper proportion in landings in Campeche

From 2008–2017, 24 teleost fishes and elasmobranch species were reported in the Campeche landings. The species with the most landings were the gafftopsail sea catfish (*Bagre marinus*), jacks (*Caranx* spp.), and common snook (*Centropomus undecimalis*). The red snapper proportion was one of the lowest throughout the period, fluctuating between 5.2% (232 t) in 2014 to a maximum of 7.64% (1308 t) in 2013 (Annex E). Landings by fishing gear in the CONAPESCA's regional office of Atasta (2008–2018), where the studied fishing cooperative reports its catches, indicated that the red snapper proportion was higher in the vertical line than in the bottom longline. The proportion in the vertical line was higher than 40%, except in 2008 (26%), with the highest values recorded in 2018 (80%) and 2014 (93%). In contrast, the proportion in the longline was smaller than 10%, except in 2018 (20%) and 2012 (45%; Annex E).

#### 3.1.2. Catch composition of Nuevo Campechito's fishing cooperative

Twenty-three species were recorded in the fishing's cooperative logbook, including 19 teleost fishes and four elasmobranchs. The total catch was 26,364.81 kg, and the red snapper and vermilion snapper, *Rhomboplites aurorubens*, accounted for 74% of the catch, followed by the lane snapper, *Lutjanus synagris* (9.26%), small sharks ('cazón/tripa'), including subadult and adults of the Atlantic sharpnose shark, *Rhizoprionodon terraenovae*, and juveniles of scalloped hammerhead, *Sphyrna lewini*, and silky shark, *Carcharhinus falciformis* (6.23%), gafftopsail sea catfish (5.30%), and southern stingray, *Hypanus americanus* (1.76%). The other 15 species accounted for 3.3% of the catch (Table 2). Among the records and following IUCN's Red List, one critically endangered (scalloped hammerhead), one endangered (Atlantic goliath grouper, *Epinephelus itajara*), five vulnerable (red and vermilion snappers, black grouper, *Mycteroperca bonaci*, yellowmouth grouper, *Mycteroperca interstitialis*, and silky shark), and three near threatened species (lane snapper, southern stingray, and greater amberjack, *Seriola dumerili*) were found. The other 13 species were classified as least concern. Additionally, the scalloped hammerhead and silky shark are included in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES; Table 2).

The overall catch rate, including all species and gears, was 47.3 ± 48.9 kg/day. For the red snapper, the highest catch rate was estimated in the vertical line (43.6 ± 41.6 kg/day), followed by the longline-vertical line (32.5 ± 18.5 kg/day), and the longline had the lowest value (27.5 ± 27.7 kg/day). Similarly, the highest catch rate by fishing gear for the rest of the species group was estimated in the vertical line (62.1 ± 65.3 kg/day), followed by the longline (48.7 ± 55.1 kg/day), and longline-vertical lines had the lowest value (45.0 ± 28.9 kg/day; Fig. 3a). The two-way permutation ANOVA reveals no significant differences ($P = 0.12$).

The monthly catch rate in the vertical line was similar between months, with an overall catch rate of 52.9 ± 55.3 kg/day. The highest red snapper monthly catch was recorded in December 2019 (69.2 ± 43.7 kg/day) and the lowest in August 2020 (7.7 ± 8.5 kg/

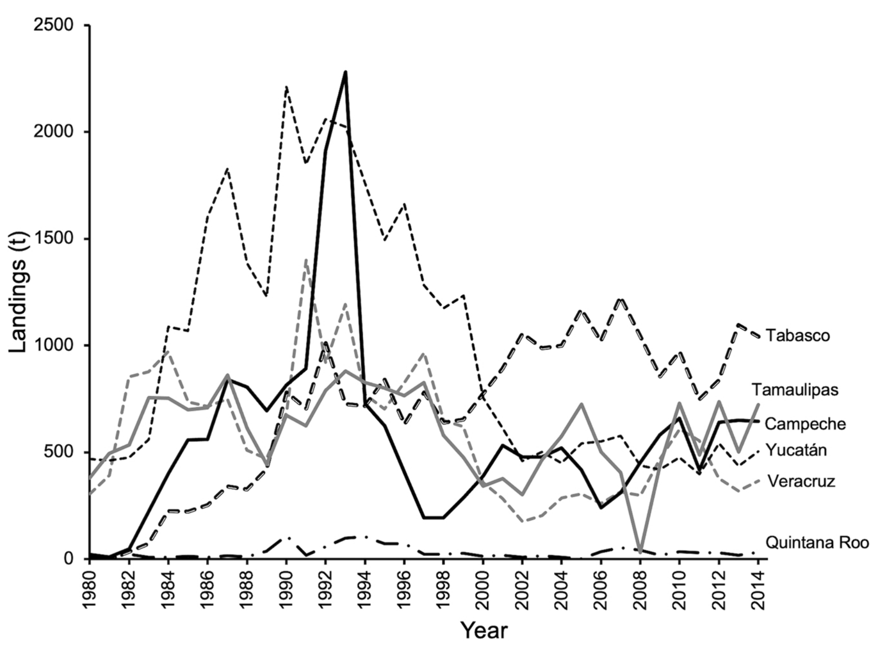


**Fig. 2.** Annual red snapper (*Lutjanus campechanus*) landings (1980–2014) by state in the Mexican Atlantic.

**Table 2**
Landing catch by species recorded in the logbook by a fishing cooperative from Nuevo Campechito, Campeche. IUCN categories are Least Concern (LC), Near Threatened (NT), Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). CITES: species listed in CITES Appendix II.

| Species | Common name | Spanish common name in the logbook | Catch (kg) | Percentage | IUCN |
|---|---|---|---|---|---|
| *Lutjanus campechanus* | Red snapper | Huachinango | 11,157.51 | 42.32 | VU |
| *Rhomboplites aurorubens* | Vermillion snapper | Besugo | 8385.8 | 31.80 | VU |
| *Lutjanus synagris* | Lane snapper | Villa jaiba | 2441 | 9.26 | NT |
| *Rhizoprionodon terraenovae* | Atlantic sharpnose shark | Cazón/tripa[a] | 1643.50[a] | 6.23[a] | LC |
| *Sphyrna lewini* | Scalloped hammerhead | Cazón/tripa | | | CR/CITES |
| *Carcharhinus falciformis* | Silky shark | Cazón/tripa | | | VU/CITES |
| *Bagre marinus* | Gafftopsail sea catfish | Bandera | 1398.5 | 5.30 | LC |
| *Hypanus americanus* | Southern stingray | Balá | 464.5 | 1.76 | NT |
| *Lutjanus jocu* | Dog snapper | Caballera | 147.5 | 0.56 | LC |
| *Caranx hippos* | Crevalle Jack | Jurel | 142 | 0.54 | LC |
| *Seriola rivoliana* | Longtail yellowfin | Extraviado | 108.5 | 0.41 | LC |
| *Ocyurus chrysurus* | Yellowtail snapper | Pargo naranja | 105.5 | 0.40 | LC |
| *Seriola dumerili* | Greater amberjack | Esmedregal | 77 | 0.29 | NT |
| *Scomberomorus cavalla* | King mackerel | Peto | 67 | 0.25 | LC |
| *Lutjanus griseus* | Grey snapper | Pargo mulato | 55 | 0.21 | LC |
| *Mycteroperca bonaci* | Black grouper | Negrillo | 41 | 0.15 | VU |
| *Rachycentron canadum* | Cobia | Bacalao | 38.5 | 0.14 | LC |
| *Brotula barbata* | Beard brotula | Rótula | 23.5 | 0.09 | LC |
| *Mycteroperca interstitialis* | Yellowmouth grouper | Cabrilla | 20 | 0.07 | VU |
| *Epinephelus itajara* | Atlantic Goliath grouper | Cherna pinta | 16.5 | 0.06 | EN |
| *Lutjanus buccanella* | Blackfin snapper | Basinico | 15.5 | 0.06 | LC |
| *Coryphaena hippurus* | Common dolphinfish | Dorado | 9 | 0.03 | LC |
| *Thunnus albacares* | Yellowfin tuna | Aleta amarilla | 7.5 | 0.03 | LC |
| | | Total | 26,364.81 | 100 | |

[a] Cazón/tripa belongs to at least four shark species according to Pérez-Jiménez et al. (2020). In the shark fisheries of the region, *R. terraenovae* accounts for 42%, *S. lewini* for 25%, *Sphyrna tiburo* for 14.5%, and *C. falciformis* for 5.3%. *S. tiburo* is caught in fisheries operating close to the shore and is not included in the snapper fishery as bycatch.

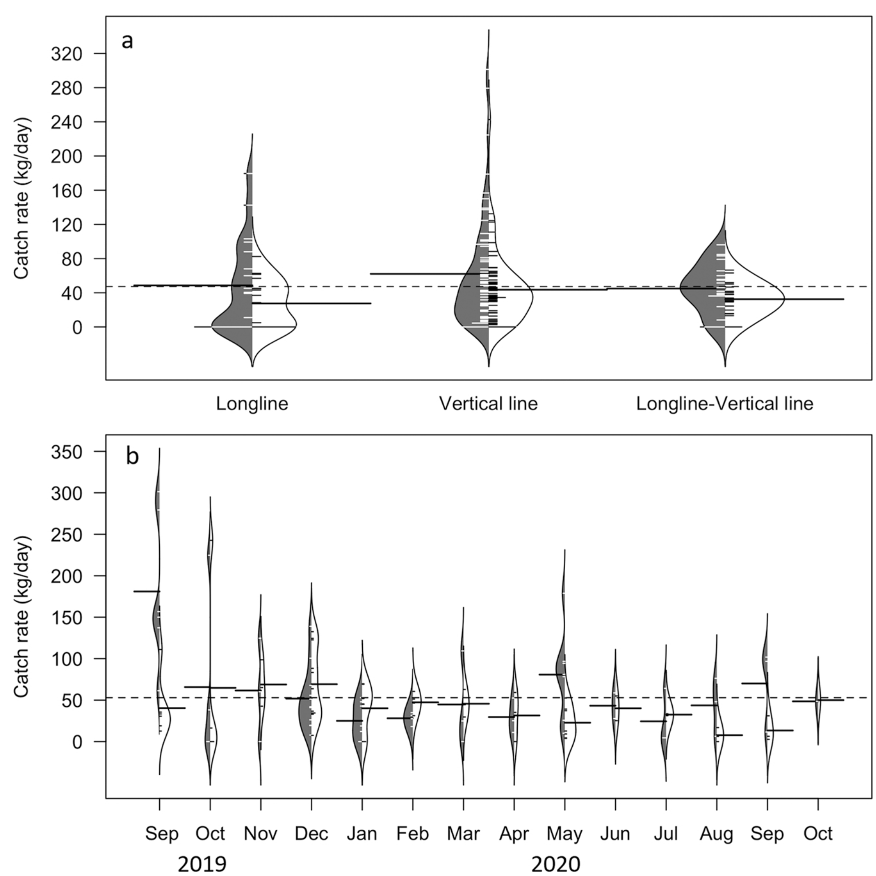


**Fig. 3.** Catch rate of the Nuevo Campechito's fishing cooperative for the red snapper (*Lutjanus campechanus*) (white/right) and the rest of the species grouped (grey/left) a) by fishing gears and b) by month with vertical line. The grey and white areas represent the kernel distribution; the small horizontal lines inside distributions are cases; the long horizontal solid lines are the average for each group; the horizontal dotted lines are the global average in each graph.

day), while the rest of the species group had the highest catch rate in September 2019 (181.0 ± 91.6 kg/day) and the lowest in July 2020 (24.4 ± 34.4 kg/day). Although the two-way permutation ANOVA reveals significant differences among monthly catch rates ($P = 0.03$), a clear seasonality was not detected due to the high data variability (Fig. 3b).

#### 3.1.3. Size structure by species

The largest average size was for the king mackerel, *Scomberomorus cavalla* (78.0 ± 10.8 cm; n = 3). The smallest size was for the lane snapper (37.5 ± 3.5 cm; n = 168). The red snapper average size was 41.6 ± 9.0 cm (n = 868), with a range of 20–86 cm, while the vermilion snapper was 37.9 ± 9.1 cm (n = 212), with a range of 19–54 cm (Fig. 4a). The average size of the red snappers was similar in the three fishing gears (longline-vertical line: 42.9 ± 9.3 cm; vertical line: 41.6 ± 9.3 cm; and longline: 40.2 ± 7.5 cm; Fig. 4b). Although the premutation ANOVA reveals significant differences in red snapper's sizes between fishing gears ($P = 0.02$; the pos-hoc permutation *t*-test for longline versus longline-vertical line was $P = 0.01$), high variability was observed, suggesting more data is required to confirm it.

The monthly average size for the red snapper, combining all gears, ranged from a minimum of 36.5 ± 8.3 cm in September 2020 to a

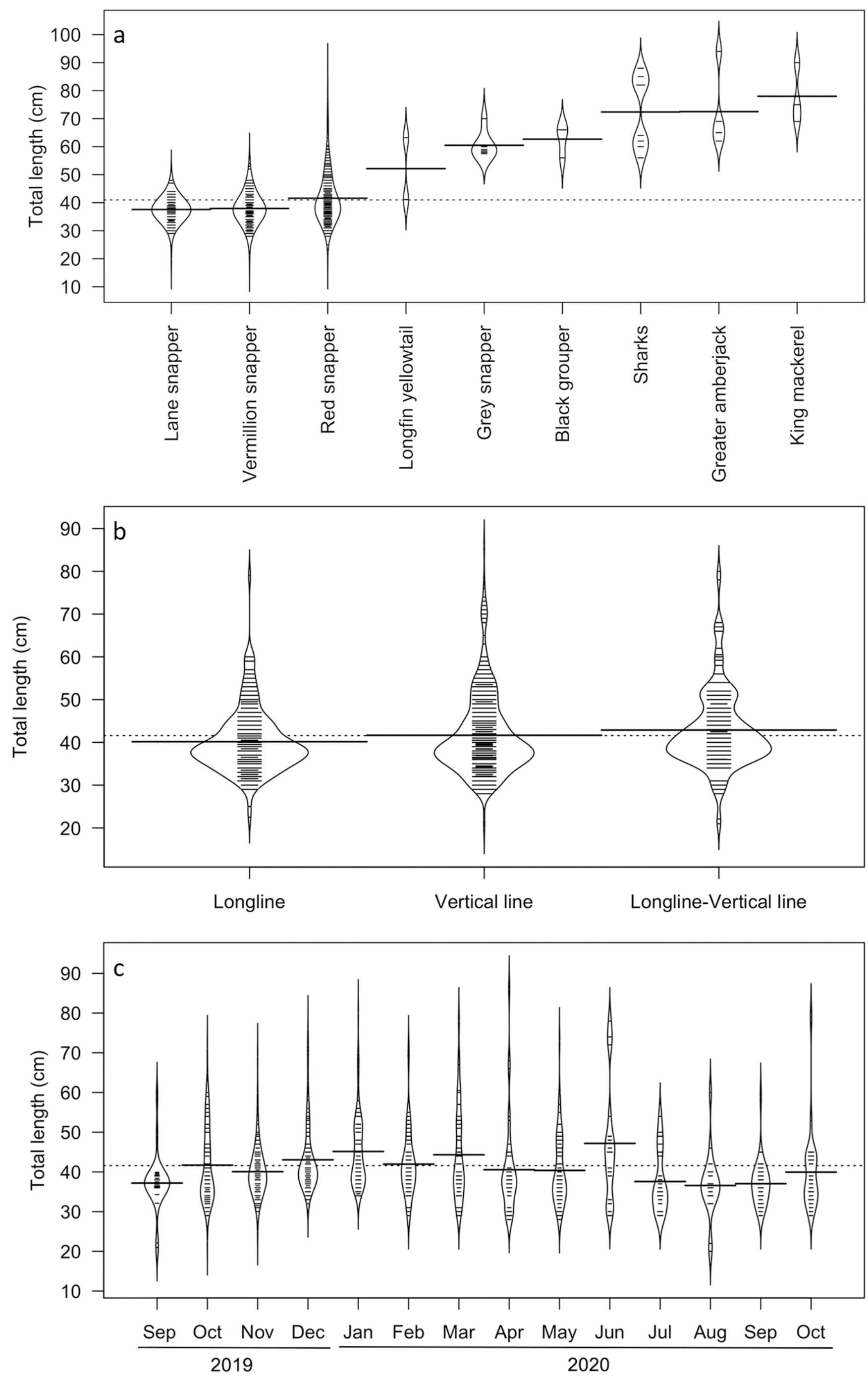


**Fig. 4.** Size frequency distribution of fishes caught by the Nuevo Campechito's fishing cooperative a) for nine species, b) for the red snapper (*Lutjanus campechanus*) by fishing gears, and c) for the red snapper by month (all fishing gears combined). The white area represents the kernel distribution; the small horizontal black lines inside the distribution are cases; the long horizontal solid lines are the average for each group; the horizontal dotted lines are the global average in each graph.

maximum of 47.2 ± 15.4 cm in June 2020 (Fig. 4c). Size differences between months were significant (permutation ANOVA, $P < 0.02$). However, differences should be interpreted cautiously because a high overlapped was observed.

### 3.2. Productivity and susceptibility analysis (PSA)

Among the species caught by the Nuevo Campechito's fishing cooperative, the silky shark ($v = 2.2$), the scalloped hammerhead ($v = 2.2$), and the southern stingray ($v = 2.2$) had high risk, and the red snapper had a moderate risk of overexploitation ($v = 1.9$, close to the high risk). The rest of the species resulted in low risk ($v \leq 1.8$) (Fig. 5; Annex F).

The Atlantic sharpnose shark had the highest overall data quality (DQ = 1.86), and the dog snapper, *Lutjanus jocu*, had the lowest data quality (DQ = 3.27). The rest of the species had moderate data quality (2.09 < DQ > 2.95; Annex F). Data quality was moderate in most species due to the lack of data for scoring some attributes. The productivity attributes used by species varied between six and nine (seven for the red snapper). The susceptibility attributes varied from 7 to 12 (8 for the red snapper). Notably, some data are absent for the red snapper, such as the intrinsic growth rate, breeding strategy, and recruitment pattern to estimate biological productivity. Additionally, there was a lack of data for the red snapper on seasonal migrations, fishing rate relative to $M$, biomass of spawners, and survival after capture and release to estimate susceptibility (Annex B).

### 3.3. The red snapper ecosystem model

#### 3.3.1. Functional analysis

Most of the energy flows in the ecosystem belong to detritus (59%). Consumption flows account for 26%, and respiration flows account for 15% of the total throughput. The connectance index indicated 27% of possible trophic connections among functional groups, and the system's omnivory index was low (0.17). Concerning ecosystem flow indices, the ascendency (A) level of the ecosystem was lower than the overhead (O), and the A/C ratio indicated that the food web organisation was 36% (Table 3). The results per functional group indicated that the red snapper had a low flow index. The primary producers, such as detritus and phytoplankton, had the highest values, indicating that the energy flows come mainly from these groups (Table 4).

**Table 3**
Summary statistics of the Campeche and Tabasco coastal ecosystem.

| Parameter | Value | Units |
|---|---|---|
| Total system throughput | 7840.46 | t/km$^2$/year |
| Total consumption | 1999.62 | t/km$^2$/year |
| Total exports | 7.57 | t/km$^2$/year |
| Total respiration | 1208.56 | t/km$^2$/year |
| Sum of all flows to detritus | 4624.71 | t/km$^2$/year |
| Total biomass/total throughput | 0.014 | t/km$^2$/year |
| Total primary production | 41.40 | t/km$^2$/year |
| Sum of all production | 5059.83 | t/km$^2$/year |
| Mean trophic level of the catch | 2.82 | |
| Connectance Index | 0.27 | |
| System Omnivory Index | 0.17 | |
| Ascendency (A) | 7624 | Flowbits |
| Overhead (O) | 13,576 | Flowbits |
| Development capacity (C) | 21,200 | Flowbits |
| *A/C* ratio | 0.36 | |

#### 3.3.2. Structural indices

The functional groups with the highest structural index values were epifauna for the degree index, detritus for the closeness index, and groupers for the betweenness index. The values for the red snapper were low in the three structural indices, suggesting that the species did not strongly connect with the other functional groups of the food web (Table 5). However, modularity analysis showed that it is well connected to other functional groups through the compartments.

#### 3.3.3. Modularity analysis

Three food web compartments were identified from the fast greedy community finding algorithm. These modules included different functional groups of distinct trophic levels and sizes (Fig. 6; Annex G). The red snapper was associated with compartment 'A,' which included six other groups (detritus, infauna, sole fish, catfish, croakers, and other fish), having a trophic level range of 1–3.63. Compartment 'B' included ten groups (benthic macrophytes, shrimp, epifauna, sea turtles, grunts,

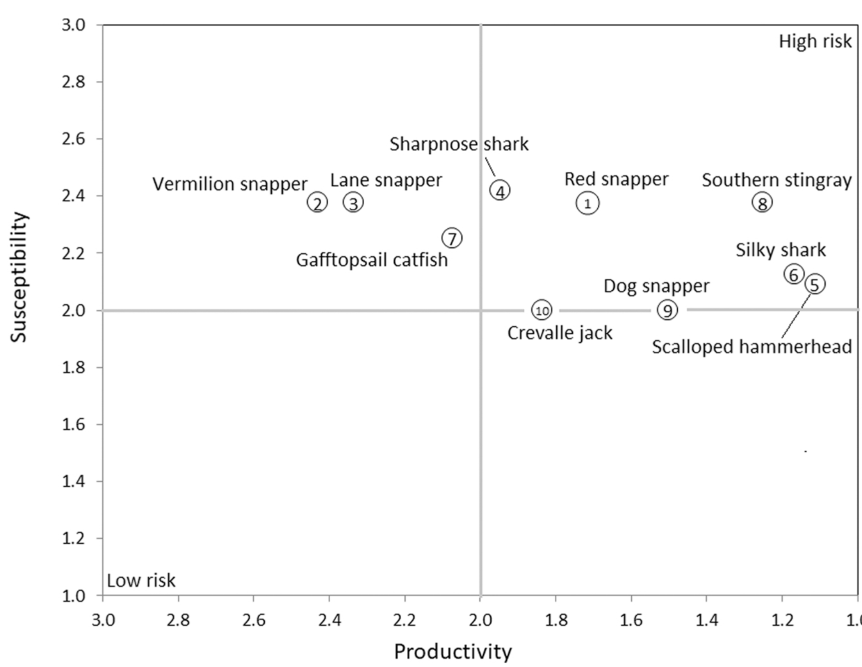


**Fig. 5.** The overall distribution of productivity and susceptibility for the ten most caught species by the Nuevo Campechito's fishing cooperative. See Annex F for scores and risk categories by species. Horizontal and vertical lines in score 2 of productivity and susceptibility are shown for reference.

**Table 4**
Ecosystem flow indices of the food web per functional group.

| Functional groups | Ascendency (t/km$^2$/year * bits) | Overhead (t/km$^2$/year * bits) | Capacity (t/km$^2$/year * bits) |
|---|---|---|---|
| Dolphins | 0.83 | 6.81 | 7.63 |
| Sharks | 1.05 | 8.18 | 9.23 |
| Sea birds | 0.13 | 1.46 | 1.59 |
| Groupers | 3.25 | 20.89 | 24.13 |
| Mackerels | 11.25 | 68.49 | 79.74 |
| Red snapper | 0.19 | 1.39 | 1.58 |
| Squids | 4.41 | 31.81 | 36.22 |
| Snappers | 0.76 | 4.67 | 5.43 |
| Jacks | 21.71 | 116.6 | 138.3 |
| Other fishes | 7 | 43.03 | 50.03 |
| Octopus | 27.34 | 94.26 | 121.6 |
| Porgies | 24.46 | 122.5 | 147 |
| Grunts | 2.67 | 18.94 | 21.61 |
| Croakers | 5.17 | 31.59 | 36.76 |
| Sardines | 156.1 | 468.2 | 624.3 |
| Catfish | 11.03 | 65.55 | 76.58 |
| Sea turtles | 1.57 | 12.32 | 13.89 |
| Sole fish | 12.93 | 76.32 | 89.26 |
| Mojarras | 25.56 | 140.2 | 165.8 |
| Epifauna | 79.05 | 331.8 | 410.9 |
| Shrimp | 114.5 | 433 | 547.5 |
| Zooplankton | 991.3 | 3111 | 4102 |
| Infauna | 913.9 | 3139 | 4053 |
| Phytoplankton | 2463 | 3563 | 6026 |
| Benthic macrophytes | 4.84 | 1.01 | 5.84 |
| Detritus | 2740 | 1665 | 4405 |
| Total | 7624 | 13,576 | 21,200 |
| (%) | 35.96 | 64.04 | 100 |

**Table 5**
Structural indices of the Campeche and Tabasco coastal food web. $D_i$= degree centrality, $CC_i$= closeness centrality, $BC_i$= betweenness centrality.

| Functional groups | $D_i$ | $CC_i$ | $BC_i$ |
|---|---|---|---|
| Dolphins | 14 | 0.002 | 4 |
| Sharks | 18 | 0.002 | 0 |
| Sea birds | 15 | 0.002 | 1 |
| Groupers | 19 | 0.003 | 69 |
| Mackerels | 15 | 0.003 | 17 |
| Red snapper | 7 | 0.002 | 2 |
| Squids | 10 | 0.003 | 12 |
| Snappers | 18 | 0.003 | 42 |
| Jacks | 13 | 0.003 | 31 |
| Other fishes | 17 | 0.003 | 51 |
| Octopus | 9 | 0.003 | 21 |
| Porgies | 10 | 0.003 | 16 |
| Grunts | 10 | 0.003 | 10 |
| Croakers | 11 | 0.003 | 5 |
| Sardines | 13 | 0.004 | 9 |
| Catfish | 16 | 0.003 | 18 |
| Sea turtles | 7 | 0.002 | 1 |
| Sole fish | 11 | 0.003 | 11 |
| Mojarras | 16 | 0.003 | 14 |
| Epifauna | 23 | 0.006 | 21 |
| Shrimp | 21 | 0.008 | 7 |
| Zooplankton | 16 | 0.01 | 22 |
| Infauna | 14 | 0.009 | 0 |
| Phytoplankton | 1 | 0.012 | 0 |
| Benthic macrophytes | 1 | 0.002 | 0 |
| Detritus | 9 | 0.018 | 0 |

porgies, octopus, snappers, groupers, and dolphins), with a trophic level range of 1–4.33. Compartment 'C' included nine groups (phytoplankton, zooplankton, mojarras, sardines, jacks, squids, mackerels, sea birds, and sharks), with a trophic level range of 1–4.22 (Annex G). The modularity value was optimal $M_W$= 0.26, indicating that the trophic relationships within each compartment were approximately 26% stronger than those expected by chance. The proportion of connections between compartments was 0.61, suggesting that the exchange of energy flows was 61%.

## 4. Discussion

The use of governmental and citizen science data allows the characterisation of a data-limited small-scale fishery that targets highly valued snappers in the southern GOM. The highest red snapper's landings in the Mexican Atlantic were recorded in 1980–2000, and there was a relatively stable trend in the last two decades (after 2000). The fishery at Nuevo Campechito fishing port is highly selective for snappers (three species accounted for 83.4%) due to the use of species-specific fishing gears in areas far from the shore (> 50 km). Although bycatch species (N = 20) included one critically endangered shark, one endangered fish, three vulnerable species (two teleost fishes and one shark), and two sharks in CITES Appendix II, they represented a low catch percentage.

PSA suggests that the silky shark, scalloped hammerhead, and southern stingray had high risk and the red snapper had a moderate risk of overexploitation in the small-scale snapper's fishery, highlighting the need for continuous monitoring of the fishery. However, although removing the missing attributes helped avoid overestimating species vulnerability (Faruque and Matsuda, 2021), data quality is moderate for most species, indicating that these results should be interpreted cautiously. Besides, Hordyk and Carruthers (2018) concluded that although the Patrick et al. (2010) approach was closest to the PSA assumptions, only the lowest and highest vulnerability scores correlate well with the risk of overexploitation, emphasizing the challenge of efficiently evaluating risk and prioritising species for management and research.

The ecosystem where the snapper fishery operates has a simple trophic structure and high resilience. The red snapper functional group has low connectivity and interaction with the rest of the food web members. However, other functional groups with significant landings in the fishery, such as snappers and catfish, have high connectivity in the food web. Additionally, three food web compartments with a strong exchange of energy flows were identified in the ecosystem.

### 4.1. The small-scale snapper fishery in the southern GOM

The National Fishing Chart (DOF, 2018a) indicates that the snapper fishery is multi-species, including around 39 teleost fishes and elasmobranchs. The official Mexican document stated a decrease of 39% in landings after 2000, resulting in a maximum sustainable yield status in Tabasco and overexploited status in the other states, except for Quintana Roo (with no status established; DOF, 2018a). However, the lack of fishing effort data and fishery indicators (DOF, 2018a) makes it a data-limited fishery. Pilling et al. (2008) indicated that the best scientific information available in data-limited fisheries is not enough to determine reference points and the current stock status concerning such reference points, as occurred with the snapper fishery.

The lack of data in Mexican fisheries is a common feature (Salas et al., 2007; Arreguín-Sánchez and Arcos-Huitrón, 2011), preventing stock assessments needed to implement management strategies. An alternative data source is the logbooks filled out by the fishing cooperatives or fishing permit owners (e.g., Russo et al., 2016; Mendoza-Carranza et al., 2018). In the present study, citizen science provides valuable data on six small-scale boats targeting snappers over 13 months. Such broad fishing survey coverage is uncommon in Mexican small-scale fisheries due to logistic and economic issues, with most monitoring programs restricted to too few days of each month. For this reason, Fulton et al. (2019) recommended the institutionalisation and adoption of citizen science by fisheries management agencies and researchers to help create national data collection networks.

Nuevo Campechito's fishing cooperative catches a high diversity of species (19 teleost fishes and 4 elasmobranchs). However, the fishery is highly selective to snappers (three species accounted for 83.4% of the catch) due to the use of species-specific gears in rocky or reef fishing areas far from the shore. The National Fishing Chart (DOF, 2018a) established that the snapper fishery in the Mexican Atlantic has three

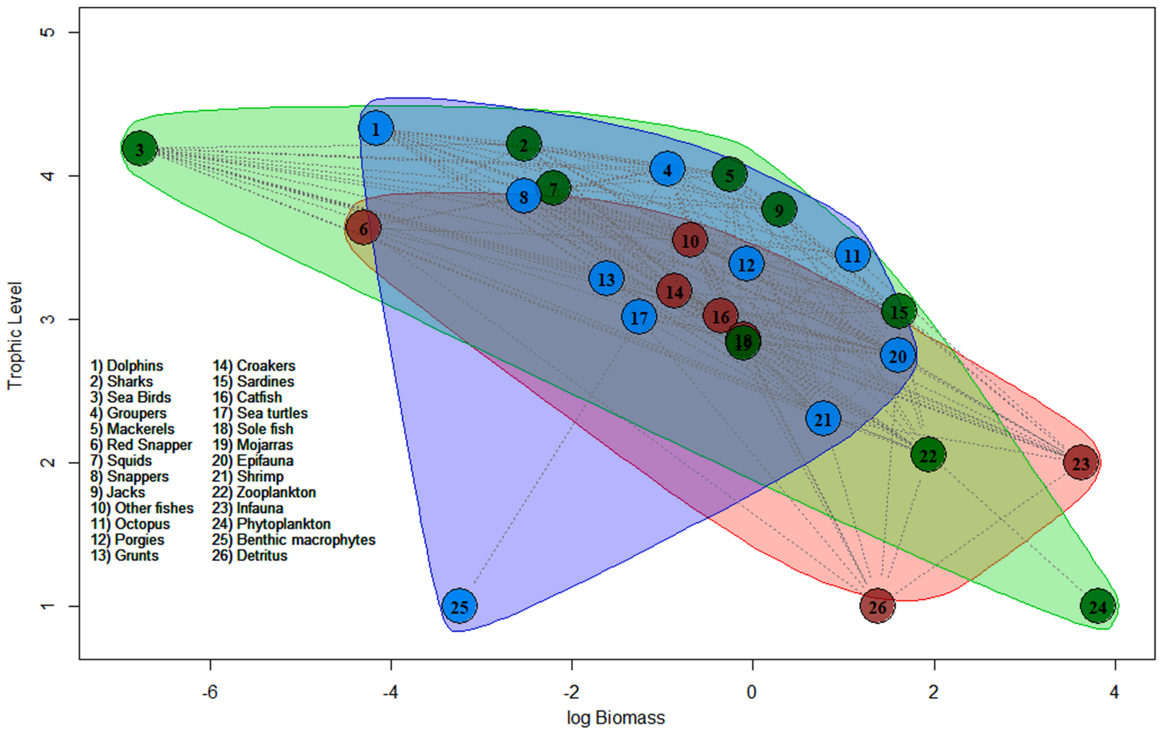


**Fig. 6.** Food web of the Campeche Bank. Trophic compartments are highlighted in colors: A is red, B is blue, and C is green. The red snapper (6) is located in compartment A. See Annex G for a description of trophic compartments.

target species, including the red, silk (*Lutjanus vivanus*), and blackfin (*Lutjanus buccanella*) snappers, and other 33 bycatch species. In comparison, the studied fishery had vermilion and lane snappers as target species instead of silk and blackfin snappers. According to the National Fishing Chart, the vermilion and lane snappers are bycatch species. In contrast, the blackfin snapper was rare in the landings recorded in the cooperative's logbook, and the silk snapper had no records. The regional differences in the target species should be considered for assessment and management because snappers may have different fishery importance along the Mexican Atlantic.

Additionally, despite the high economic value of the snappers, the fishing effort is relatively low since the fishing area is far from the coast (> 50 m). Pérez-Jiménez and Méndez-Loeza (2015) documented that only around 100 small-scale boats were targeting snappers off the coast of Tabasco and Campeche because the fishery represented a higher economic and safety risk. The safety risk is high because fishers spend several days at sea far from the shore in small boats commonly modified with a small cabin and edge enhancement (to reduce the risk) equipped with a radio and GPS. Additionally, the fishery has a higher economic risk than more coastal fisheries due to the increasing cost of gasoline and other inputs (i.e., food and ice). Saldaña et al. (2017) reported similar results for the lobster fishery in Yucatan, where searching for new fishing grounds far away from the coast increased the operational cost and the safety risk. Thus, the high operational cost and safety risk associated with the snapper fishery may be limiting the fishing effort. However, the snappers' stable seasonal catch and high value in the market incentivised some fishing cooperatives from the southern GOM to continue in the fishery. Coronado et al. (2020) found that the Atasta region, where the studied fishing cooperative is located, is characterised by low fishing effort and highly valued species, such as snappers. In addition, Peña-Puch et al. (2021) documented that in that region, other valued species were the blue swimming crab (*Callinectes sapidus*) and the seabob shrimp (*Xiphopenaeus kroyeri*).

On the other hand, the catch rate was not different among fishing gears for the red snapper and the rest of the species group, probably because of the similar hook sizes and fishing areas. Additionally, there were no conclusive significant differences in the vertical line's monthly catch, which differed from previous studies documenting a catch seasonality (Monroy-García et al., 1996; Caballero-Chávez, 2018). Monroy-García et al. (1996) estimated the lowest catch rate between July and September, and Caballero-Chávez (2018) documented a fishing season from March to October throughout the coast of Campeche and recommended protection from July to August during the reproductive season. The apparent absence of seasonality in the present study could be due to sampling coverage, fishing area, and the analysed fleet. Caballero-Chávez (2018) studied small-scale fisheries in Campeche communities with a sampling coverage of five days per month, while Monroy-García et al. (1996) studied a fleet with relatively longer boats (see below) from Yucatan, covering a more extended fishing area and having broad coverage sampling.

In the present study, the highest average catch rate for the red snapper in the vertical line (43.6 ± 41.6 kg/day) was about half of the 82.7 kg/day estimated by Monroy-García et al. (1996) in the western Campeche Bank (off Campeche coast). Although the fishing area is in a more northern region than the present study and the fishing boats from that study were relatively longer (12.2 m long) than the boats used by fishers in Nuevo Campechito (~9 m long), the fishing gears and the number of fishers per boat were similar. Nevertheless, the study by Monroy-García et al. (1996) was conducted when the Yucatan fleet recorded the highest catches in the Mexican Atlantic.

A more recent study by Mendoza-Carranza et al. (2018) based on citizen science data (2007–2012) from a small-scale fleet from Tabasco operating in the same fishing area as the fleet of the present study documented that the red snapper accounts for more than 50% of the vertical line landings, followed by vermilion snapper (25.9%). The catch rate for the red snapper was 61.9 ± 57.8 kg/day, and this species occurred in more than 95% of fishing trips. This catch rate was higher than in the Nuevo Campechito's fleet; however, continuous monitoring is needed to assess red snapper catch rate trends and determine whether variations are due to fishing or a combination of factors, including fishing. For example, Arreguín-Sánchez et al. (2017) found that the sea surface temperature explained 30% of the red snapper catches in the

Campeche Bank and established that climate change could explain changes in fish stock production and the carrying capacity of this area.

The average size (cm TL) of the three most frequent snappers in catches is above their respective size at maturity. For example, the red snapper average size was 41.6 ± 9.0, and the size at maturity was 31.4 (Brulé et al., 2010); the vermilion snapper average size was 37.9 ± 12.2, and the range size at maturity was 20–32.5 (Hood and Johnson, 1999); and the lane snapper average size was 37.5 ± 9.2, and the range size at maturity was 19.5–26.5 (Luckhurst et al., 2000). These results suggest a lower impact on the early stages of the stocks. In particular, the red snapper average size from this study was relatively smaller than that reported by Monroy et al. (2004) in the northern Campeche Bank (43.6 and 56 cm TL) in two vertical line types. Additionally, the largest red snapper recorded in the present study (86 cm TL) was smaller than the largest reported by those authors (93 cm TL). However, it was not possible to test for significant differences. The continuous records of size structure and maturity stage data by sex could help estimate fishery indicators of the species (e.g., Froese, 2004).

### 4.2. The snapper fishery impact on the ecosystem

Although the small-scale snapper fishery is highly selective to three species, other caught species included species at risk and two shark species in the CITES Appendix II. PSA indicates that the silky shark, the scalloped hammerhead, and the southern stingray had a high risk, and the red snapper had a moderate risk of overexploitation. The life history parameters, ecology, and fishery information used in the PSA (Annex B) confirm that the red snapper has low productivity and is highly susceptible to the fishery, needing continuous research and management attention. Brulé et al. (2004) established that snappers exhibit slow growth and late sexual maturity, high longevity, and low natural mortality rates, indicating that these species are close to those of the K-type. However, the vermilion and lane snappers resulted in a low risk of overexploitation due to relatively high productivity, indicating that not all snappers fit the characteristics described by Brulé et al. (2004).

The silky shark and the scalloped hammerhead are included in the small sharks' group ('cazón/tripa') of the Nuevos Campechito's landing records because the catch of these species comprises neonates and young individuals. Furthermore, the scalloped hammerhead is caught in several coastal fisheries of the region (Pérez Jiménez and Méndez-Loeza, 2015; Pérez-Jiménez et al., 2020; Cuevas-Gómez et al., 2020), and the catch rate in the snapper fishery is low. In contrast, the southern stingray is the most landed elasmobranch in Campeche and Tabasco because it is caught in several fisheries, especially in a bottom longline coastal fishery, in addition to the gafftopsail sea catfish (Pérez-Jiménez et al., 2012; Lara-Mendoza et al., 2016). In Mexico, fishing for elasmobranchs is regulated by the Official Standard NOM-029-PESC-2006 (DOF, 2007). There is a closed season for sharks on the Atlantic coast (DOF, 2014); therefore, these species receive research and management attention.

The ecosystem model (Ecopath model) indicated that the total throughput of energy flows did not change substantially from the original model by Zetina-Rejón and Arreguín-Sánchez (2003) after including the red snapper functional group. The connectance and omnivory indices' low values suggest a simple ecosystem trophic structure (Christensen et al., 2005). A similar result was reported in the same study region by Zetina-Rejón et al. (2015) and in the Yucatan continental shelf by Arreguín-Sánchez et al. (1993).

The ecosystem flow indices suggest that the study area is an immature ecosystem since ascendency represented only 36% of the energy flows, a growth level, and organisation characteristic of a developing system. Regarding stability, the overhead index indicated a high resilience (0.64), another developing system feature (Ulanowicz, 1986; Heymans et al., 2014). The flow indices suggested that the food web is based on detritus and phytoplankton as primary energy sources, coinciding with the original model by Zetina-Rejón and Arreguín-Sánchez (2003), probably due to the region's high productivity (Kemp et al., 2016).

Several authors have suggested that species with many links or a crucial position in the topological pathways might be considered a keystone species (Albert et al., 2000; Jiang and Zhang, 2015). In particular, the red snapper presented low connectivity (interaction with few groups), which implies less importance in the communication of the network's trophic flow. However, other functional groups, such as snappers and catfish, had high connectivity in the food web. These species represent a significant landing percentage in Tabasco and Campeche ports (Caballero-Chávez, 2016; Mendoza-Carranza et al., 2018).

Modularity measures are essential to understanding the ecosystem's resilience (Lorenz et al., 2011; Gilarranz et al., 2017). The results in the present study showed relevant ecosystem aspects, with a modularity value (0.26) above the median (0.2; Teng and McCann, 2004; Stouffer and Bascompte, 2011) and significantly identified compartments (Krause et al., 2003). In addition, the great energy flow exchange between compartments (0.61) is characteristic of modules with interactions among species of different trophic levels, sizes, and abundances (Brose et al., 2006). These features influence the food web's stability and resilience to perturbation (Brose et al., 2006; Levin and Lubchenco, 2008; Stouffer and Bascompte, 2011). The red snapper was linked to benthic feeding habit groups since its diet is predominantly benthivorous, feeding mainly on shrimps, squids, octopus, crabs, and fishes, and is classified as a generalist predator (Wells et al., 2008; Brewton et al., 2020). Similarly, Pérez-Díaz et al. (2007) reported that red snapper juveniles feed primarily on small crustaceans, while adults prefer fishes.

The detritus performs a key function in the system's energy throughput, which is associated with the region's high productivity (Zetina-Rejón et al., 2015; Kemp et al., 2016). In the study area, the Usumacinta/Grijava's river, which ranks second in freshwater discharge in the GOM, provides ecosystem connectivity through the shelf plume, strongly influencing fishery production in the southern GOM (Kemp et al., 2016). However, the GOM's waters are a focal point for the impacts of many anthropogenic activities, including commercial and recreational fishing, tourism, shipping, petroleum extraction, and urban use. In particular, the oil and gas extraction infrastructure includes oil refineries, petrochemical and gas processing plants, and other industry-related installations, concentrated in the northern and southern GOM (Yáñez-Arancibia and Day, 2004). In the studied area, habitat degradation and pollution are of concern due to the oil and gas industry and urban development (Yáñez-Arancibia and Day, 2004; Yáñez-Arancibia et al., 2009). In addition, there are multiple small-scale fisheries and a medium-scale shrimp fishery with a direct or indirect impact on teleost fishes and elasmobranch populations.

Brulé et al. (2004) documented that red snapper juveniles (age classes 0 and 1) exhibit high mortality in shrimp trawlers because they occur with shrimp on soft bottoms until reaching a larger size to migrate to reef areas where they are less vulnerable to trawl nets. Additionally, Wakida-Kusunoki et al. (2013) recorded red snappers in 52% of trawling sets off the Tamaulipas coast (western GOM), although they represented a low bycatch weight percentage (average 1.18%).

A potential impact reduction of shrimp fisheries has been documented in the northern GOM due to oil and gas platform installation. Everett et al. (2020) indicated that red snapper showed a high affinity to platforms and that a substantial portion of its population resides around platforms. Gallaway et al. (2009) suggested that the increased construction of oil and gas platforms and other artificial habitats has provided a new protective habitat for age two red snappers that would have otherwise suffered higher mortality in open habitats. In the southern GOM, the trawling fishing effort decreased due to shrimp fishery collapse (DOF, 2012). Additionally, all fishing fleets have restricted access to the platform fields since 2001, when maritime exclusion was established. The exclusion reduced fishing grounds considerably, creating a conflict between the fishing sector and the oil industry in

Campeche and Tabasco (Arias-Rodríguez and Ireta-Guzmán, 2009). Thus, the red snapper bycatch in the shrimp fishery is expected to be lower than in previous decades. The exclusion probably also explains the relatively low fishing effort targeting snappers.

### 4.3. Implications for management and conclusions

The PSA shows that the red snapper has a moderate risk of overexploitation due to life history characteristics and fishery interactions in the southern GOM; therefore, maintaining fishing effort at low levels is a necessary management measure. The apparent red snapper landing stability in the Mexican Atlantic after 2000 is probably explained by the relatively low fishing effort, particularly in Campeche and Tabasco, a highly selective fishery catching mainly snappers and large fishes, high ecosystem resilience, and a potential bycatch reduction in the shrimp fishery. The overall results suggest that the small-scale snapper fishery has a relatively low impact on the ecosystem's structure and function.

However, continuous monitoring fishery surveys with the fishers' participation is needed to assess the population status and establish management strategies. Training other fishing cooperatives on fishery improvement projects (FIP) and their participation in the monitoring program can strengthen the management of the fishery. The National Fishing Chart (DOF, 2018a) indicates that the elaboration of the fishery management plan and the research to establish regulations, such as size limits and a closed season, are in progress for the snapper fishery. Additionally, bycatch species are the subject of research and management regulations, including the Official Standard for Elasmobranchs (DOF, 2007) and the closed season for sharks (DOF, 2014). Another bycatch species, the gafftopsail catfish, has management considerations in the National Fishing Chart (DOF, 2018a).

Finally, the present study contributed by describing a data-limited small-scale fishery targeting snappers by using governmental and citizen science data. It makes inferences of relatively low fishery impacts on the ecosystem through catch composition data, PSA, and ecological modelling. The results highlight the need for systematic monitoring of the fishery to understand the catch rate trend, size structure, sex ratio, maturity stage ratio in the catch, and collect more information on trophic web interactions. The catch rate data of other species from the region are necessary to assess the impacts of harvest rate scenarios.

## CRediT authorship contribution statement

**Juan C. Pérez-Jiménez:** Investigation, Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. **Adrian Núñez:** Investigation, Conceptualization, Methodology, Formal analysis, Visualization, Writing – review & editing. **Mónica González Jaramillo:** Methodology, Data curation, Writing – review & editing. **Manuel Mendoza-Carranza:** Investigation, Methodology, Formal analysis, Visualization, Writing – review & editing. **Jaime Acosta-Cetina:** Methodology, Formal analysis, Writing – review & editing. **Alesa Flores-Guzmán:** Investigation, Resources, Funding acquisition, Writing – review & editing. **Lorena Rocha-Tejeda:** Investigation, Resources, Funding acquisition, Writing – review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fishres.2022.106269.

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