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Review

Aquaculture and conservation of the common snook *Centropomus undecimalis* in southeastern Mexico: a review of research at UMDI Sisal

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ABSTRACT. In celebration of UMDI-Sisal's 20th anniversary, the Experimental Biology group for Aquaculture and Conservation at UMDI-Sisal in southeastern Mexico has consolidated its focus on research of the common snook (*Centropomus undecimalis*) to advance aquaculture and conservation. This review focuses on research on common snook conducted at UMDI-Sisal, rather than providing a general state-of-the-art overview of the species. It analyzes bibliographic and bibliometric data on common cnook aquaculture and conservation, highlighting progress in broodstock management, breeding, digestion, dietary requirements, and osmoregulation. Research has also examined its ecological role and its impact on fisheries. The new knowledge has also helped develop strategies to mitigate adverse impacts on their natural population. The findings contribute to an understanding of the environmental and human-induced effects on marine species and support conservation efforts. UMDI-Sisal's work has been crucial in integrating government, academia, industry, and local communities for sustainable common snook management and food production technologies in southeastern Mexico.

Keywords: *Centropomus undecimalis*; common snook; aquaculture; conservation; southeastern Mexico

INTRODUCTION

There are 12 snook species in America, six from the eastern Pacific and six from the western Atlantic (Ossa-Hernández et al. 2025). The common snook, *Centropomus undecimalis*, is the most widely distributed, occurring in the western Atlantic from Florida to South America through Rio de Janeiro, including Texas, Mexico, most of the Antilles, and Central America (Robins & Ray 1986) They are euryhaline fish and can be found from saltwater to freshwater, depending on the season and the age of the fish. Adults typically inhabit water within a temperature range of 26 to 29°C, in waters and at a depth of no more than 40 m (FAO 2007 in Alvarez-Lajonchère & Tsuzuki 2008), while juveniles prefer a temperature range of 28.5 to 29.3°C

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(Tremblay et al. 2017). Snook are protandric hermaphrodites, maturing first as males and later undergoing a sex change to female. They require seawater for final maturation and spawning, as well as for embryonic development and the early larval stages (Alvarez-Lajonchère & Tsuzuki 2008). The common snook is the largest and fastest-growing member of the family in the western Atlantic (Alvarez-Lajonchère & Tsuzuki 2008, Ibarra-Castro et al. 2011), with a total length of up to 140 cm and a maximum body weight of 24.3 kg (Durruty-Lagunes et al. 2017).

According to recent national statistics, the average annual fishery harvest of snook in Mexico ranges between 2,500 and 3,500 mt, primarily originating from the Gulf of Mexico (GOM, Fig. 1) and Caribbean coastal states, including Tamaulipas, Veracruz, Tabasco, Campeche, Yucatan, and Quintana Roo (CONAPESCA 2021, 2022). This consistent harvest highlights the species' importance as a target for small- and medium-scale artisanal fisheries, which are often conducted in estuarine and nearshore environments. Economically, snook holds substantial market value, with an estimated annual economic impact of between 300 and 400 million Mexican pesos (MXN$). This valuation is driven by both the high demand in regional markets and the species' gastronomic importance. Reported prices fluctuate between MXN$100-150 per kilogram (US$5.2-7.9 kg^{-1}), depending on fish size, quality, and regional market conditions (CONAPESCA 2021, 2022). Beyond direct commercial fishing, they are also a key species in the recreational and sport fishing industry, particularly in tourist areas, contributing additional revenues to local economies through services such as guided fishing trips, lodging, and related activities.

Additionally, far from their importance in fisheries, their potential for aquaculture has also begun to be explored. The first study to assess the potential for snook aquaculture in Mexico was published in 1994 and focused primarily on common snook. The study aimed to highlight the species' potential for aquaculture, address the existing technological gaps in snook farming, and lay the foundation for developing snook aquaculture by providing initial guidelines (Muhlia-Melo et al. 1994). Since then, collaborative efforts from research institutions, government agencies, and the private sector industry have been directed towards advancing snook aquaculture in Mexico (DOF 2022).

In 1997, the Faculty of Sciences at the National Autonomous University of Mexico (UNAM, by its Spanish acronym) and the College of the Southern Border (ECOSUR, by its Spanish acronym) in Campeche State organized a workshop on developing aquaculture in the state, aligned with state priorities. The key conclusion from this meeting was to prioritize the development of marine fish aquaculture using native species, such as the common snook, striped mullet (*Mugil cephalus*), and pompano (*Trachinotus carolinus*; Sánchez-Zamora et al. 2002a). One of the primary goals of UNAM was to mitigate the shortage of hatchery-produced juveniles. A few years later, the Juarez Autonomous University of Tabasco (UJAT, by its Spanish acronym) launched a research project focusing on the reproduction of common snook. The two research directions were closely aligned, and since then, a close collaboration between UNAM and UJAT to develop snook aquaculture has been crucial. We are currently located in a new facility in Sisal, Yucatan, where we are developing the Multidisciplinary Academic and Research Unit (UMDI-Sisal, by its Spanish acronym, UNAM). This unit supports the marine fish research program (Fig. 1).

UMDI-Sisal's primary responsibility is to promote sustainable marine fish aquaculture development in southeastern Mexico, and we have confirmed common snook as a representative species. Our primary objectives have been to refine snook aquaculture, establish a pilot production facility to ensure a reliable supply of juveniles in support of research, and develop commercial-scale aquaculture technologies. It is important to highlight here that the farming technology developed for barramundi (*Lates calcarifer*) in the Indo-Pacific region (Schipp et al. 2007, Kibenge, 2022) has served as a benchmark for establishing snook aquaculture in Mexico (Muhlia-Melo et al. 1994, Alvarez-Lajonchère & Tsuzuki, 2008, Ibarra-Castro et al. 2009). The reproductive strategy, early life history, and grow-out requirements of the two species share many similarities (Alvarez-Lajonchère & Tsuzuki 2008, Ibarra-Castro et al. 2009, Alvarez-Lajonchère et al. 2013, Contreras-Sánchez & Mendoza-Carranza 2025). This review focuses on research on common snook conducted at UMDI-Sisal, rather than providing a general state-of-the-art overview of the species, reviewing highlights of the foundational and technical research, key studies, significant results, and future perspectives on common snook aquaculture and conservation after two decades of research at the UMDI-Sisal, UNAM, Mexico.

MATERIALS AND METHODS

This document presents a bibliometrics analysis (Scopus©, Elsevier) and a bibliographic review. The bibliometric methodology was limited to English-

Figure 1. Geographic distribution of the common snook range in southeastern Mexico, including the location of UMDI-Sisal in Sisal, Yucatan State, Mexico.

language publications available for download in any format that allows full readability; however, for the bibliographic review process, we considered some Spanish-language materials accessible, as the focus of the common snook study at UMDI-Sisal has been significantly regionalized (southeastern Mexico).

Bibliometric analysis

A bibliometric analysis was limited to English-language publications available for download in any format that allows full readability on July 24, 2024. The data quest was conducted using TITLE-ABS-KEY (centropomus AND undecimalis) AND (LIMIT-TO (AFFILCOUNTRY, "Mexico") AND (LIMIT-TO (AF-ID, "UNAM - Campus Sisal" 60172562) as an advanced query. The selected publications were restricted to original articles, and bibliometric line-drawing mapping and keyword network visualization were elaborated using VOSviewer software (Van Eck & Waltman 2010). These networks illustrate the relationships between various items in scientific literature.

The number of documents that referred only to UMDI-Sisal was 13, involving 57 different individuals. Sixty-five keywords were obtained, with 13 considered principal words (Fig. 2a). Three clusters show the relationship between these keywords. They were divided into four groups (Fig. 2a). Group 1 comprises keywords such as genetic diversity and microsatellite, group 2 focuses on dietary lipids, a metabolic enzyme, dietary protein, protein-sparing effect, and digestive enzyme, group 3 displays words such as pilot-scale, reproduction, and juvenile production, and group 4 includes dietary carbohydrate and glucose metabolism. The frequency of articles featuring specific keywords over time provides valuable information to explore the progression of our research, i.e. our focus began with group 3 (pilot-scale and juvenile production) and, more recently, has shifted to focus on dietary research included in groups 2 and 4 (Fig. 2a). Additionally, we were able to rank all authors to determine contributions and frequency of contribution over the years (Fig. 2b). For example, Rosas C. has five articles, the most by an individual author, and a total citation count of 107, reflecting the high impact of his research on common snook. A visual distribution of keywords related to the *C. undecimalis* and UMDI-Sisal bibliometric analysis is also included (Fig. 2c).

Bibliographic review

The bibliographic review was conducted in both Scopus, a product of Elsevier, and Google Scholar to improve the results. The explorer was limited to

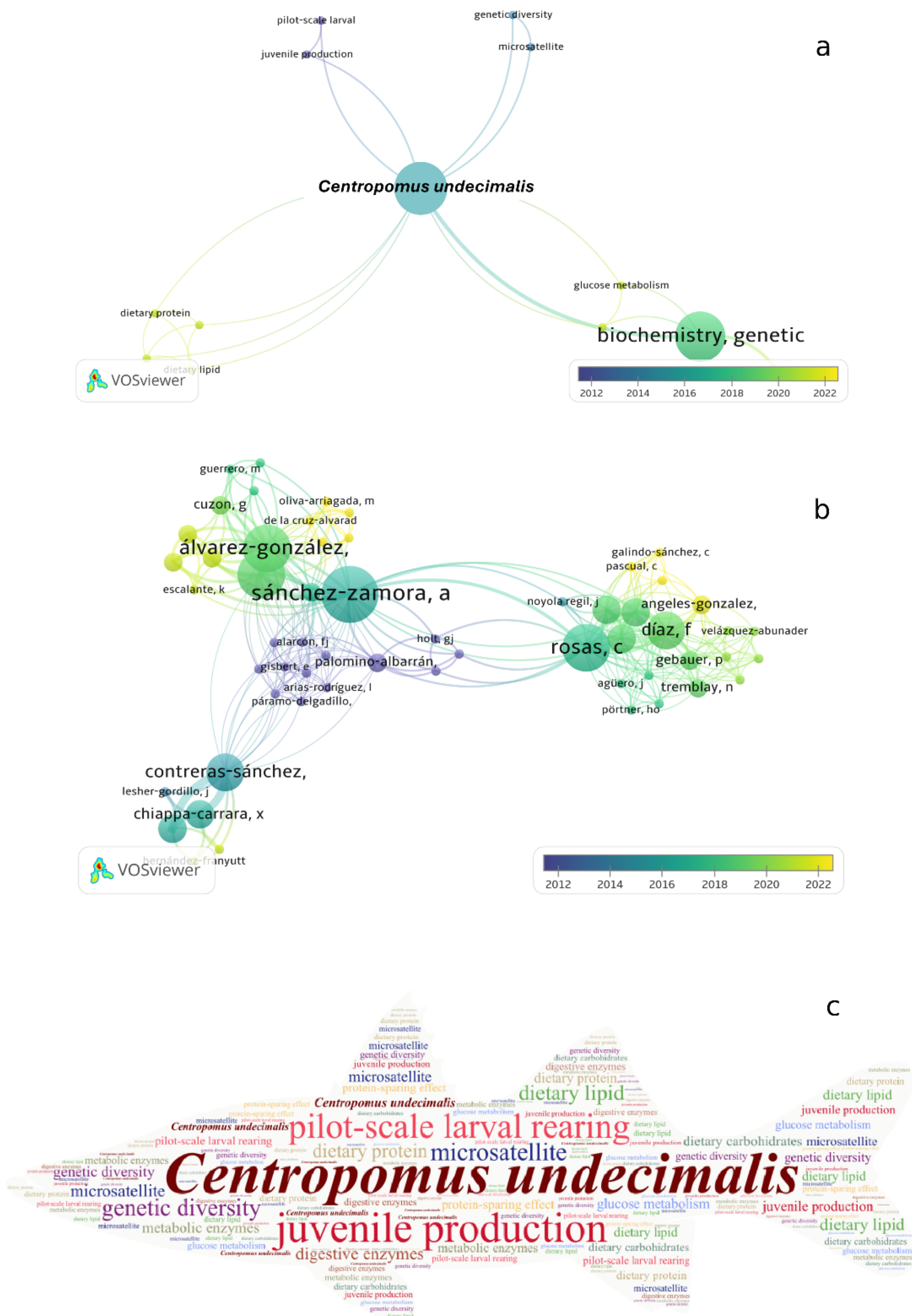

Figure 2. VOS viewer network visualization map of a) common snook and 13 principal keywords divided into four major groups and how our research focus has shifted throughout the years, b) common snook and authors, illustrating individual contribution and frequency of contribution over the years, c) distribution of keywords related to *Centropomus undecimalis* and UMDI-Sisal bibliometric analysis. Bibliometric analysis was conducted in Scopus©, a product of Elsevier.

conducted between October 1, 2023, and October 1, 2024.

The bibliographic analysis shows that most publications on the aquaculture and conservation of common snook originated from institutions in the state of Florida, USA, where extensive management and conservation programs for these species are established (Fig. 3a). However, UMDI-Sisal is also one of the six institutions with the most research published (13 documents; Fig. 3a). These studies are primarily related to Agricultural and Biological Sciences (54.5%), Biochemistry, Genetics and Molecular Biology (22.7%), and Environmental Science (9.1%, Fig. 3b), according to the source categories.

The specific studies regarding common snook aquaculture from UMDI-Sisal have included: maturation and spawning (Sánchez-Zamora et al. 2002b), salinity effects on juveniles physiological conditions (Gracia-López et al. 2006), digestive capacities of juveniles (Jiménez-Martínez et al. 2012, Concha-Frías et al. 2016, 2022, Lemus et al. 2017), dietary protein requirement in juveniles reared in marine and brackish water (Concha-Frías et al. 2018), effects of dietary carbohydrates on growth performance (Arenas et al. 2021a), physiological and metabolic protein-sparing effects of dietary lipids (Arenas et al. 2021b), genetic variability in connected marine and rivers environments (Hernández-Vidal et al. 2014), thermal metabolic scope (Paschke et al. 2018), thermal biology (Noyola-Regil et al. 2015), resilience to thermal oscillations (Tremblay et al. 2017), and improvements in the hatchery protocols (Ibarra-Castro et al. 2011).

UMDI-sisal aquaculture facilities, procedures, and research

Aquaculture facilities

UMDI-Sisal, located in Yucatán State, has facilities for broodstock management, larviculture, live feed, production, and a nursery stage, where various research programs on common snook are developed. It is now called the Laboratory of Reproduction and Marine Finfish Hatchery. Additionally, we have support from laboratories conducting specific studies, including reproduction, live feed, ecophysiology, nutrition, and fish growth. The research unit is in Yucatan State, approximately 25 km from Hunucmá and 63 km northwest of Merida, on the southeastern coast of Mexico (21°09'50"N, 90°02'53"W; Fig. 1). The Marine Finfish Hatchery comprises two sections: an indoor workroom section including offices and dry and wet laboratories (including our live feed area, 4.45×3.88 m). At the same time, the outdoor greenhouse includes both broodstock tanks (10.52×22.6 m) and laviculture tanks (10.52×7.8 m) shaded by sailcloth.

The seawater is driven from two pump rooms, with one 1.6 hp pump used in the broodstock area (northwest facing) and one 1.6 hp pump used in the larviculture area (north facing). Seawater is taken from a beach well (22 m deep). To release solids and ground organic acids mixed with the water, the solids are sedimented in three open reservoirs (each with a capacity of 200 m^3) before the water is sent to the greenhouse facility. In contrast, the inorganic gas (sulfuric acid, H_2SO_4) mixed with the groundwater is released into the atmosphere. From the reservoirs, seawater is then sent to three vertical black reservoir tanks (each with a capacity of 10 m^3), set on a 2 m-high, north-facing platform, where it is filtered through a sand filter (SD80 W/2, 75 gpm, Pentair©).

The broodstock area consists of eight cylindrical fiberglass tanks, 1.2 m high and 4 m in diameter (10 m^3 in operation), covered with a gray liner. Seawater is introduced into the tanks at a flow rate of 3 tank volumes per day through a 50-mm pipe from an aerial branch that terminates in a jet-type outlet. The air supply is provided by a 1 hp, oil-free air blower (Sino Aqua, Model RB40-520), producing an airflow rate of 3 m^3 min^{-1} at approximately 180 mbar.

In the larviculture area, seawater passed through a sand filter (SD80 W/2, 75 GPM, Pentair), then through a 20 µ cartridge filter, and subsequently to an ultraviolet water sterilizer (UVA-24B, Polaris Scientific) with a flow rate of 80 L per minute. Two larviculture tanks (5 m^3) are equipped with recirculation aquaculture systems, coupled to a chiller (CW1000, 1 HP, 800-1800 L, Resun) for temperature control.

Photoperiod has generally been natural, with 14 h of light and 10 h of darkness in summer and the opposite in winter. However, for some evaluations, fiberglass covers were placed on the broodstock tanks, and lamps were placed for illumination and to create controlled photoperiods. Currently, the tanks do not have lids, but they do have a blue canvas covering 1.5 m above the water level to reduce the intensity of daylight.

In the live feed area, the room temperature is maintained between 26 and 28°C, and illumination is provided by daylight fluorescent tube lamps (40 klux) for zooplankton production. This room has air, oxygen gas, freshwater, and seawater supplies. Only rotifers (*Brachionus* sp.) and brine shrimp (*Artemia* sp.) are produced for snook larviculture. Regarding rotifers, batch (every 3-4 days) and semi-continuous (daily harvests of 10-25% of the culture volume) rotifer cultures and enrichment are performed in 500-L cylin-

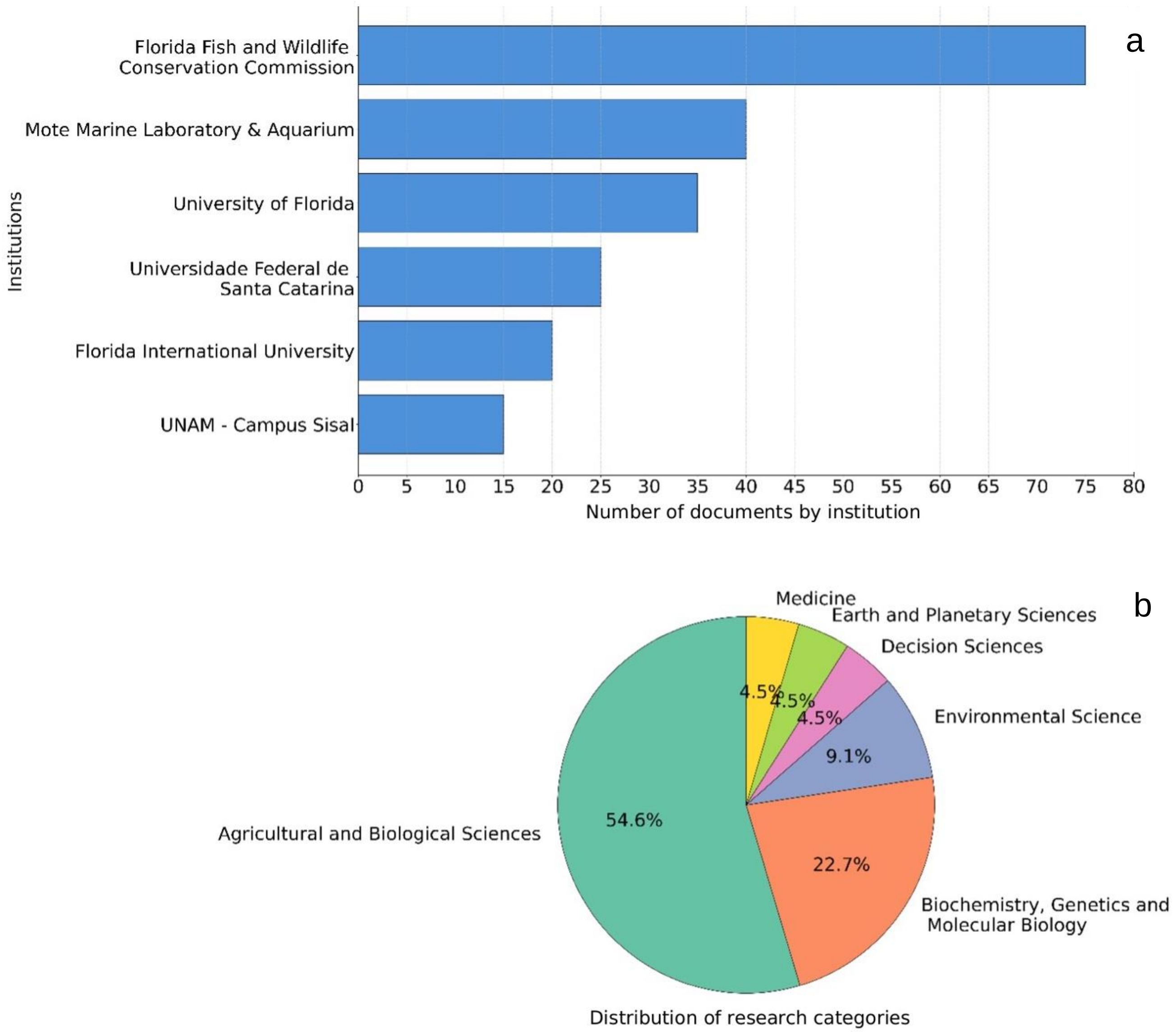

Figure 3. Bibliometric analysis conducted in Scopus© of Elsevier and Google Scholar showing a) publications by affiliation, and b) publications by subject area.

droconical fiberglass tanks. Microalgae paste (*Nannochloropsis* sp., Nanno 3600©) is used to feed rotifers, with the feed supplied by peristaltic pumps (~12.5 mL min^{-1}). Sodium hydroxymethanesulfonate (ClorAm-X©, AquaScience Research Group, Inc., USA) is used to reduce the ammonium concentration. The brine shrimp procedures depend on the supplier's instructions. Brine shrimp nauplii and metanauplii enrichment are produced in three 500-L cylindroconical fiberglass tanks.

Breeding, larviculture, and juvenile grow-out

Wild broodstocks are housed at Ciudad del Carmen (ECOSUR) and UMDI-Sisal (UNAM; Sánchez-Zamora et al. 2002a,b). Commercial production of common snook juveniles requires the creation of broodstock groups selected from wild populations, followed by the development of breeding programs. Initially, wild adult common snook were captured offshore using traditional fishing gear such as gill nets. However, fish survival is low, and they often die during transportation to the laboratory. In addition, this method was expensive. Therefore, we switched to catching large immature common snook in the coastal lagoons of Sisal and Celestún, Yucatán. Briefly, night fishing was conducted from 20:00 to 12:00 h using a monofilament gill net with a 1¾-in mesh size and an approximate depth of 4 m. A 150-m long section, equivalent to the length of the net panels, was enclosed from shore to shore. Fish within the enclosed area were driven into the net by striking the water to startle them, after which the net was retrieved with the entangled fish. The captured fish were placed in 500-L circular containers aboard the boat, which were aerated by 12V air pumps (Sánchez-Zamora et al. 2002b). After the quarantine and adaptation to captivity in 20 m^3 tanks, an electronic PIT tag, implanted intramuscularly on the left side of the fish's body near the anterior dorsal fin, is used to identify the individual common snook selected for the future breeding program.

Once the broodstock collection and handling were established, we developed the procedures for juvenile production. The program's priority has been to solve the unavailability of juvenile production supplies; as such, our goal here was to induce maturation and spawn in captivity. During our first decade of work, in UMDI-Sisal facilities, female common snook generally began developing from July to September, with some earlier maturation observed in May (Sánchez-Zamora 2009, Ibarra-Castro, *pers. comm.*). In this second decade, we continue to evaluate and adjust the reproductive period across annual seasons with varying temperatures. However, like other fish in captivity, our broodstock present characteristic reproductive dysfunctions: a) females do not continue into the final maturation process, and b) males produce low sperm or do not fertilize eggs during the natural spawning behavior (Mañanós et al. 2008). Furthermore, snook are protandric hermaphrodites, and once they are in captivity, they spend long periods undergoing sex change. Therefore, understanding gametogenesis and reproductive patterns and identifying reproductive dysfunctions as early as possible is essential for developing snook aquaculture. To induce common snook spawning, various hormone treatments are used, including HCG (500-1100 IU kg^{-1}) and GnRHa in cholesterol pellets (Sánchez-Zamora et al. 2002b). For example, Ibarra-Castro et al. (2011) induced snook broodstock (kept for five years in a hatchery) to spawn using sGnRHa implants (Ovaplant®, Syndel Laboratories Ltd., Vancouver, Canada). The hormone dosage to females was 121 ± 31 µg kg^{-1} for 402 ± 15 µm vitellogenic oocyte diameter, and to males was 83 ± 6 µg kg^{-1}. Ten voluntary spawns were recorded with 4.33×10^6 eggs (18.5% floating) in total.

In our larviculture protocol, embryos and larvae are reared in temperatures of 26.7 ± 0.9°C, salinity of 38, dissolved oxygen of 5.4 ± 0.2 mg L^{-1} (saturation: 85.4 ± 3%), pH of 8.2 ± 0.2, and NH_3 less than 0.6 mg L^{-1}, with photoperiod maintained at 14:10 h light:dark. As a result, more than 70,000 juveniles were harvested (34,021 and 36,915 per 5 m^3 tanks) with a survival rate of 17.7% from hatching to 45 days after hatching (dah). Larval growth increased from 0.34 mm d^{-1} during the first 28 dah to 0.58 mm d^{-1} until larviculture was completed. Juvenile biomass was 0.479 kg m^{-3} with 7.1 juveniles L^{-1}. Moreover, the incidence of deformities was low (<2%), with principal lordosis reported in the nursery stage (Ibarra-Castro et al. 2011).

Despite the knowledge generated over the past two decades and the highest larval rearing survival reported to date for the species, the consistent commercial-scale production of common snook juveniles has not yet been achieved. While it is important to highlight that the challenges related to juvenile production are linked to the reproductive process, the issue may also be due to a lack of continuity in implementing these procedures. It has been challenging to retain key personnel and maintain facilities that replicate our best results, due to limited economic resources for conducting research and building new facilities.

Nutrition and digestive metabolism

To evaluate the development of digestive enzymes in larvae using biochemical and electrophoretic techniques, Jiménez-Martínez et al. (2012) employed sGnRHa (Ovaplant) to induce final maturation and spawning in broodstock. The embryos obtained were collected, and the larvae were fed using *Nannochloropsis* sp. and S-type rotifers (*B. rotundiformis*) for the first 10 dah. The co-feeding was then switched to rotifers and *Artemia* nauplii until 25 dah. Finally, from 25 to 36 dah lipid-enriched (Selco©) *Artemia* metanauplii were supplied to the larvae. The authors report changes in enzymatic activities associated with morphophysiological changes in the larval gut. As this organ differentiates into hind, mid, and foregut, enterocyte microvilli mature, and the type of food, whether live or artificial, changes during larval growth. Common snook larvae exhibit classic digestive enzyme development like that of other marine fish in captivity, and the weaning process for this species may begin at 34 dah or later (Jiménez-Martínez et al. 2012).

Most nutrition studies at UMDI-Sisal, such as those focused on digestive metabolism, are centered on the juvenile stage (>3 g), characterized by the onset of more complex physiological and behavioral features closer to the adult form. These studies examine the physiological and metabolic protein-sparing effects of dietary lipids, juvenile digestive capacities, and dietary protein requirements in marine or brackish water environments. Additionally, the impact of dietary carbohydrates on growth performance has been investigated. Digestive protease characterization was partially explored in common snook juveniles using electrophoretic and biochemical techniques (Concha-Frías et al. 2016). In this study, the authors considered diverse aspects to demonstrate that a single acidic protease is sufficient for digestion. However, this protease is inhibited by variations in pH and temperature. However, alkaline protease digestion is more stable, indicating robust alkaline protease activity for hydrolyzing various protein sources.

While common snook is a carnivorous fish, vegetal protein as a fish meal replacement has been one of the goals of its aquaculture, with the primary question being ¿what benefit do common snook obtain from plant sources? To answer the question, Lemus et al. (2017) investigated the digestion potential (*in vitro*) and absorption (*in vivo*) of vegetable and animal protein sources in juveniles. The authors observed that native wheat gluten produced a high degree of hydrolysis and ADC protein. Surprisingly, the canola and soybean meals were similarly digested. Hence, despite carnivorous preferences, the common snook maintained some digestive capacity for vegetable sources, with wheat gluten > soybean meal > canola meal > soy protein concentrate when included at 30% of the diet. This information is relevant and should be considered when selecting ingredients and formulating dry diets for juveniles to promote growth. Moreover, this study establishes guidelines for assessing the final cost of common snook feed (Lemus et al. 2017).

In natural conditions, common snook juveniles typically eat crustaceans and fish, indicating a significant demand for protein. The maximum growth rate of carnivorous fish is dependent on the consumption of proteins that provide the necessary amino acids. Therefore, understanding the dietary protein requirements of juveniles and their effects on growth and survival is relevant, especially across different salinities (5 and 36), as tested by Concha-Frías et al. (2018). In this research, protein sources (sardines, poultry, and pork meal) given to juveniles in seawater (36 of salinity) required a 54% protein content, whereas they required a protein content of >60% in the diet in brackish water (<5 of salinity) to achieve the same growth and survival. This requirement is due to the energy costs of osmoregulation in brackish water. The authors note that while rearing common snook in brackish and seawater is feasible, the dietary protein requirement is large (Concha-Frías et al. 2018).

Arenas et al. (2021a) studied the dietary requirements of carbohydrates in two species, the common snook and yellowtail snapper (*Ocyurus chrysurus*), which share similarities in thermal physiology and feeding habits. The main variables tested were glucose metabolism, performance, glycemia response, digestive enzymes, and liver enzymes. The research determined that common snook could take more advantage of diets with high carbohydrate content (20%) than yellowtail snapper, because they have a greater capacity to utilize and store carbohydrates.

While the previous study focused on carbohydrate effects, Arenas et al. (2021b) and Concha-Frías et al. (2022) researched the lipid requirements of common snook. The capacity of common snook juveniles to utilize lipids as an energy source remains poorly understood. However, protein and lipid levels in diets were assessed to determine their effects on growth, feed utilization, and digestive and hepatic enzyme activities (Arenas et al. 2021b). This study reports a protein-sparing effect associated with an increase in dietary lipids (60 to 120 g kg^{-1}), although it promoted the deposition of excess lipids throughout the whole body. Nevertheless, a reduction in protein levels (from 500 to 400 g kg^{-1}) is possible when lipid levels are increased, along with 20 g kg^{-1} of carbohydrates (corn starch), without any adverse effects on growth and efficiency. The authors suggest this combination for effective protein utilization of common snook juveniles (Arenas et al. 2021b).

Concha-Frías et al. (2022) presented the characterization of digestive lipase to know bile-salt-activated lipase in the intestine, and as it exerts its catalytic activity. Characterization of the lipase is important for assessing enzyme activity and its response to variation in temperature and pH. The lipase has a molecular weight of 43.8 kDa, an optimal temperature of 35°C, an optimal pH of 9, and exhibits sensitivity to inhibitors. The authors determined that Ebelactone A is their principal inhibitor. The authors recommend conducting further studies to identify suitable lipid sources to meet the lipid requirements of common snook juveniles.

UMDI-Sisal growth-out and physiological responses

Understanding the common snook's physiology and behavior, using both hatchery- and wild-caught fish, is crucial for its survival, growth, reproduction, fisheries management, and conservation through aquaculture.

Growth-out evaluation

Growth in wild common snook has been assessed in various settings and salinities. First, we used wild juveniles weighing 20-25 g. They were maintained in single 20 m^3 cylindrical tanks connected in a seawater flow-through system and fed with dry feed twice daily. The juvenile reached an average of 300 g in 6 months, and the specific growth rate ranged from 1.14 to 1.17%. After 12 months, 800 g of fish were harvested, with a growth rate of 2.7 g d^{-1}, yielding an average of 4-5 t yr^{-1} (Sánchez-Zamora et al. 2002b). Finally, a growth trial was conducted at the freshwater fish farm "Agrosistemas Yaxchilam" for 136 days (October-January 2016, Yucatan), in a single 350 m^3 raceway tank, with water at 2 of salinity and 29°C. A 7 mm rainbow trout pelleted with 40% protein was used as feed. The initial average hatchery fish weight was 422 g (n = 309), and the stocking density was 1 ind. m^{-3} (0.4 kg m^{-3}). At the end of the trial, a survival rate of 82% was recorded, with an increase in average weight to 802 g and a growth rate of 2.8 g d^{-1} reported (Biol. Sergio Monroy, company manager, *pers. comm.*).

Osmoregulation capacity

Snook exhibits a high capacity for osmoregulation and can maintain its internal osmotic pressure practically independent of external salinity. However, osmoregulation incurs energetic costs, affecting a key aspect of its aquaculture management. Future common snook culture and aquaculture diversification (e.g. tilapia and shrimp farms) at UMDI-Sisal will occur in both fresh- and brackish-water environments. Gracia-López et al. (2006), therefore, tested the effect of different salinities on the metabolic costs of wild juveniles (13.7 ± 6.3 g wet weight). Specifically, they assessed the oxygen-to-nitrogen ratio and, as a factor, the apparent heat increment.

Oxygen consumption was dependent on salinity in fasting and feeding regimens, with juveniles in 0, 25, and 35 of salinity consuming more energy than juveniles in 12. Thus, snook juveniles can adjust their energy substrate based on salinity, using a mix of proteins, lipids, and carbohydrates at 35 of salinity, and show a stronger preference for proteins at 12 of salinity. The results demonstrated the high energetic cost and preferential catabolic substrate for osmoregulation of common snook juveniles. The authors suggest that energy from feed should lead to maximum growth, independent of the culture system conditions, such as salinity.

Reproductive variability in environments of contrasting salinities

In southeastern Mexico, the high commercial value of snook drives intensive fishing; however, declining yields highlight the need for conservation strategies to protect local populations. Spawning aggregations along the coast and seasonal migrations to those aggregations increase snook vulnerability to catch. Hernández-Vidal et al. (2014) studied the reproductive cycle across freshwater and marine environments in the Grijalva-Usumacinta basin. Surprisingly, mature, capable gonads were found in freshwater, though active spawning only occurred in marine habitats. These findings suggest a previously undocumented reproductive strategy in which common snook synchronize reproduction and reach advanced gonadal maturity in freshwater. This knowledge is essential for sustainable management, as the fisheries heavily catch large females.

Ecophysiology and relationships with other species in southeastern Mexico

Aquatic environments exhibit temporal and spatial thermal variability, requiring organisms to develop behavioral and physiological mechanisms to survive within specific limits. Ectothermic species rely on metabolic and behavioral adjustments to cope with temperature fluctuations, which influence their activity and metabolism at all life stages. While temperatures within an optimal range enhance physiological functions, extreme variations can be fatal. Mobile species respond by seeking preferred temperatures and avoiding harmful extremes. Noyola-Regil et al. (2015) studied the thermal biology of prey and predators, including common snook, in the vicinity of *Octopus maya* habitats on the Yucatán Peninsula. Their findings showed that prey species preferred temperatures between 23.5 and 26.0°C, while predators preferred temperatures between 26.4 and 28.5°C. Notably, common snook exhibited the broadest thermal tolerance of 11 to 42°C. The study suggests that rising temperatures could drive prey species to migrate in search of optimal conditions, potentially altering the community structure of the continental shelf. However, predators like snook are already near their preferred temperatures and are likely to remain in the area despite warming trends.

Similarly, Trembaly et al. (2017) present results from studies conducted to understand the resilience of two crustacean species, three mollusks, and two marine fish of ecological and fishery importance for the Yucatan Peninsula to thermal oscillations. The most resilient to thermal oscillations were the two fish species (*C. undecimalis* and *O. chrysurus*) and the snail *M. corona bispinosa*, including those likely associated with global warming (+3°C). Considering this thermal niche, it is expected that the two species of crabs (*C. similis* and *L. dubia*), the nolón snail (*S. pugilis*), and the octopus (*O. maya*) will prefer cooler environments, possibly associated with the eastern zone of the Yucatan Peninsula, where the seasonal summer upwelling limits the increase in temperature above 26°C. The thermal sensitivity of snook should be used to assess their resilience and inform management strategies in the event of increased temperatures in the GOM, with special attention to the western zone of the Yucatan Peninsula.

Finally, Paschke et al. (2018) compared a new method, temperature-induced metabolic rate (TIMR), with traditional approaches such as swim flumes and chasing, using the common snook as a focal organism to estimate metabolic rates and oxygen consumption. Fish are the most-studied ectothermic aquatic species, making them ideal for such research. The first experiment tested the TIMR method against swim-flume respirometry on juvenile snook, acclimated to optimal (28°C) and sub-optimal temperatures (32 and 35°C). The second experiment evaluated the effect of acclimation temperature on snook, yellowtail (*O. chrysurus*), and clownfish (*Amphiprion ocellaris*) using both TIMR and the chasing method. Results showed that both methods yielded similar maximum metabolic rates (MMR) for snook and yellowtail, but diverged for clownfish. In clownfish, TIMR produced a significantly higher thermal metabolic scope than chasing, suggesting that chasing might not accurately reflect the aerobic capacity in this species. The MMR of common snook measured in the swim-flume respirometer did not change significantly with acclimation temperature (28°C), and was 20.4, 7.5, and 10.5-fold higher than corresponding routine metabolic rate values for treatments at 28, 32, and 35°C, respectively. Further, when common snook were forced to swim in a seawater flow of 13 cm s^{-1}, lactate values increased significantly in comparison with those obtained when swimming between 2 and 9 cm s^{-1} seawater flow. In seawater flow rates between 0-15 cm s^{-1}, the average oxygen consumption was between 3-24 (mg O_2 h^{-1} g WW^{-1}). The study concluded that TIMR offers a useful alternative for estimating differences in metabolic activity across varying temperatures. Although it does not exactly measure aerobic scope, it allows standardized estimation, particularly for this species, where swimming-based measurements are impractical. This method could be valuable for comparing aerobic scopes in common snook and similar species.

Welfare

In the Academic Group of Experimental Biology for Aquaculture and Conservation of Aquatic Organisms at UMDI-Sisal, we are concerned with the welfare of aquatic organisms, and an internal ethics committee oversees our experiments. The ethics committee establishes guidelines for appropriate management practices for aquatic organisms, based on the norms of conduct (Paschke et al. 2018), including ethics and welfare during catch, transport, and laboratory captivity protocols, for common snook. In the laboratory, research is conducted in accordance with the established Mexican standard NOM-062-ZOO-1999 (DOF 1999, Conchas-Frías et al. 2022) for the welfare of laboratory animals. When necessary, fish are euthanized in accordance with the Helsinki Convention (Arenas et al. 2021a,b).

DISCUSSION

Mexico (Government of Mexico 2021) established an implementation strategy for a sustainable ocean economy (2021-2024), highlighting the importance of sustainable ocean foods, which play a fundamental role in feeding the world's population. Seafood is an important source of animal protein and micronutrients, particularly in developing countries and during economic or environmental crises (Costello et al. 2019). By applying management strategies and advanced technology, while always respecting human rights, the oceans could provide more than six times the amount of food they currently supply. It must involve greater transparency in ocean governance and global supply chains, as well as the removal of inefficiencies and harmful incentives that undermine the sustainability of the food we derive from the ocean (Government of Mexico 2021). We must take advantage of the opportunities this government initiative offers and follow up on strategies to sustainably increase the productivity of the fishing industry and the common snook aquaculture sector.

Although we have made significant advances in knowledge of aquaculture management and snook conservation in the Americas, several challenges remain, and several objectives still need to be achieved. In addition, emerging problems include climate change, declining fisheries, and food security. Specific to southeastern Mexico, future research and conservation perspectives for the common snook are outlined below.

Snook is a popular commercial and sport fish in the Yucatan Peninsula, and its catch has been regulated in Mexico since 1933 (DOF 2014). Nevertheless, common snook has been declared overfished for decades, and conservation programs have been proposed to control catch and boost common snook stocks. Basic regulations, such as temporary fishing bans, were adopted in Tamaulipas, Veracruz, and Tabasco, Mexico (DOF 1994). Still, the rest of the states in the GOM and the Caribbean Sea do not have seasonal closures. Conservation research in southeastern Mexico should focus on wild stocks of common snook and adopt management approaches similar to those of the Florida Fish and Wildlife Conservation Commission (https://myfwc.com/fishing/saltwater/recreational/snook), which employs a holistic view to management decisions. That agency uses multiple metrics (e.g. spawning potential ratio, relative abundance, habitat, harmful algal blooms, fishing effort, temperature, and stakeholder feedback) to assess wild common snook stocks at a smaller regional scale. Regional metrics may also be necessary in the Yucatan Peninsula due to similar fisheries and environmental effects (e.g. no rivers, sport fishing, increased temperatures, northern events, and sargasso blooms) to establish additional regulations, such as temporary fishing bans, on a more regional scale.

Additionally, UMDI-Sisal's ongoing efforts to understand how rising ocean temperatures affect species of socioeconomic importance, such as *O. maya*, can provide valuable insights into the resilience and adaptability of common snook under similar conditions (Escamilla-Aké et al. 2024).

Management of wild fisheries and environmental issues is not the only alternative; aquaculture-based improvements are a viable option that could make fisheries such as snook sustainable (Lorenzen et al. 2010). The availability of juvenile snook from hatcheries is essential for conservation programs (stock enhancement and restocking) and aquaculture management (mariculture and land-based farming). Therefore, the research, development, and innovation marine fish program at UMDI-Sisal needs a pilot-level commercial demonstration unit to lead the development of common snook aquaculture management in the Government of Mexico, which requires addressing knowledge gaps in biotechnology and implementing technical adaptations to facilities to enhance capacity and produce snook juveniles consistently each year. Staff, technology, and equipment are required to turn the Laboratory of Reproduction and Marine Finfish Hatchery into a Production Models Unit (UMPRO, by its Spanish acronym).

Aquaculture-based fisheries enhancement encompasses various management strategies that involve releasing hatchery-raised organisms to support, conserve, or restore fisheries (Lorenzen et al. 2010, Caldentey et al. 2021). This concept includes a range of enhancement systems such as sea ranching, stock enhancement, and restocking (Bell et al. 2006, Lorenzen 2008). Different objectives and conditions lead to variations in system design. For instance, near Sisal in Celestún, Yucatán, fishermen use community surveillance and the maritime culture of the Fishing Refuge Zone (FRZ, https://www.alianzakanankay.org/en/fishery-refugee-zones) to combat illegal fishing. They have established a committee with rotating shifts to monitor the FRZ daily and have set up floating cages -12 m in diameter and made of PVC pipes- to cultivate yellowtail snapper (*O. chrysurus*), florida pompano (*Trachinotus carolinus*), and spotted seatrout (*Cynoscion nebulosus*). These kinds of aquaculture-based fisheries with community involvement are becoming increasingly important in southeastern Mexico, and more FRZ are emerging and will require juvenile, hatchery-reared marine fish such as common snook.

Furthermore, upwelling zones, on the northern side of the Yucatán Peninsula, maintain relatively stable temperatures and may serve as refugia for marine species impacted by climate change. Such areas could optimally support the aquaculture of species such as common snook (Angeles-Gonzalez et al. 2024). Another possibility for common snook production may be to combine the growth-out of juveniles with tilapia or shrimp farm facilities, or with aquaponic systems for vegetable production. This approach not only diversifies aquaculture but also produces protein-rich foods and essential micronutrients, such as iron, copper, and zinc, which are crucial for combating malnutrition in vulnerable communities (Zuluaga & Campo 2017, Pinho et al. 2021).

As a case in point, the white snook (*Centropomus viridis*) grown out in floating cages in the Pacific subtropical zones has demonstrated significant growth rates, making it a profitable aquaculture species. Studies have shown that under optimal temperature conditions and with larger juveniles, survival and efficiency in early growth-out stages can be improved (Baldini et al. 2022). Economic models suggest this approach is viable, with market prices exceeding US\$10 kg^{-1}, making it an attractive alternative for diversifying food production and increasing the availability of high-quality protein in Mexico.

The research we have conducted on common snook holds significant potential to contribute to food security in Mexico and other tropical and subtropical regions. Furthermore, the inclusion of common snook in aquaculture and mariculture programs aligns with Mexico's blue economy strategies and supports sustainability goals. By integrating local communities into resource management and implementing aquaculture systems based on native species, both conservation and the sustainable use of resources are promoted (Mendoza-Carranza et al. 2013, Dávila-Camacho et al. 2019). The common snook culture in closed systems could complement fish refuge zone efforts, enabling controlled, consistent production that contributes to food security, reduces conflicts over access to fishing resources, and provides economic alternatives for vulnerable coastal regions. These efforts also benefit from UMDI-Sisal's broader research initiatives addressing climate change impacts on fisheries, ensuring that aquaculture strategies are both adaptive and resilient.

Credit author's contribution

A. Rojo: conceptualization, validation, methodology, formal analysis, writing-original draft; L. Ibarra & A. Trotter: supervision, review, and editing; C. Rosas: project administration; Á. Escamilla & H. Cruz: conceptualization, data curation, formal analysis, review, and editing; C. Pascual : review and editing. All authors have read and accepted the published version of the manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

Ethics statement

This review presents research that for all experiments and animal husbandry, we followed established guidelines for good management practices for aquatic animals, in accordance with the conduct standards of the National Autonomous University of Mexico.

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