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Research and conservation needs of *Megalops atlanticus* (Elopiformes: Megalopidae) in Costa Rica

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ABSTRACT

Introduction: Atlantic tarpon (*Megalops atlanticus*) (Elopiformes: Megalopidae) is a tropical-subtropical species that supports fisheries throughout its geographic range. The level of scientific knowledge is greatest along the Gulf of Mexico and southeastern Atlantic coasts of the United States. There are considerable knowledge gaps on tarpon biology, fisheries, and conservation for Costa Rica.

Objective: We summarize the status of knowledge of tarpon in the western Atlantic Ocean, Gulf of Mexico, and Caribbean Sea, to provide context for examining the status of knowledge, threats, and research needs for tarpon in Costa Rica.

Methods: During September 2025, we conducted a literature review and integrated expert knowledge to evaluate the status of tarpon fisheries and conservation. Additionally, we surveyed recreational anglers and fishing guides in Costa Rica (n = 39) to obtain baseline information on the recreational fishery.

Results: We found a marked decline in tarpon abundance in Costa Rica, and substantial uncertainty regarding population connectivity, with evidence suggesting a potentially localized contingent characterized by inland river migrations. Key knowledge gaps persist for movement, nursery habitats, and fisheries dynamics, while local ecological knowledge identifies watershed-scale habitat degradation and post-release mortality as principal threats. Despite high ecological and economic value, tarpon remain largely absent from national management frameworks.

Conclusions: Tarpon in Costa Rica may represent a vulnerable, partially localized population that is insufficiently understood and inadequately managed. Critical gaps in knowledge limit effective conservation, highlighting the urgent need for ecosystem-based, policy-integrated, and regionally coordinated management.

Key words: catch and release fishery; fisheries management; habitat connectivity; migratory fish.



RESUMEN

Necesidades de investigación y conservación de *Megalops atlanticus* (Elopiformes: Megalopidae) en Costa Rica

Introducción: El sábalo atlántico (*Megalops atlanticus*) (Elopiformes: Megalopidae) es una especie tropical-subtropical que sustenta pesquerías a lo largo de toda su área de distribución geográfica. El nivel de conocimiento científico es mayor en el Golfo de México y las costas del sureste del Atlántico de los Estados Unidos. Existen considerables lagunas de conocimiento sobre la biología, la pesca y la conservación del sábalo en Costa Rica.

Objetivo: Resumimos el estado del conocimiento sobre el sábalo en el Atlántico occidental, el Golfo de México y el Mar Caribe, para proporcionar un contexto que permita examinar el estado del conocimiento, las amenazas y las necesidades de investigación para el sábalo en Costa Rica.

Métodos: Durante septiembre de 2025 realizamos una revisión de literatura e integramos el conocimiento especializado de los autores para evaluar el estado de las pesquerías y la conservación del sábalo. Además, encuestamos a pescadores deportivos y guías de pesca en Costa Rica ($n = 39$) para obtener información básica sobre la pesca recreativa.

Resultados: Encontramos una marcada disminución en la abundancia de sábalo en Costa Rica y una considerable incertidumbre con respecto a la conectividad poblacional, con evidencia que sugiere una población potencialmente localizada caracterizada por migraciones fluviales tierra adentro. Persisten importantes lagunas de conocimiento sobre el movimiento, los hábitats de cría y la dinámica de las pesquerías, mientras que el conocimiento ecológico local identifica la degradación del hábitat a escala de cuenca hidrográfica y la mortalidad posterior a la liberación como las principales amenazas. A pesar de su alto valor ecológico y económico, el sábalo permanece en gran medida ausente de los marcos de gestión nacionales.

Conclusiones: El sábalo en Costa Rica podría representar una población vulnerable, parcialmente localizada, insuficientemente comprendida y gestionada de forma inadecuada. Las lagunas críticas en el conocimiento limitan la conservación efectiva, lo que subraya la necesidad urgente de una gestión basada en el ecosistema, integrada en las políticas y coordinada regionalmente.

Palabras clave: pesca de captura y liberación; manejo pesquero; conectividad del hábitat; peces migratorios.

INTRODUCTION

The Atlantic tarpon *Megalops atlanticus* (Elopiformes: Megalopidae) is native to tropical and subtropical coastal and oceanic waters of the Atlantic Ocean, Gulf of Mexico, and the Caribbean Sea (Adams, 2017; Ault, 2007). Its geographic distribution extends to northern latitudes such as Nova Scotia and parts of Western Europe (e.g., Ireland and France), although sightings in these regions are thought to be sporadic rather than indicative of stable populations (Bañón et al., 2019; Griffin et al., 2025; Luo et al., 2020; Twomey & Byrne, 1985). Observations in southern regions, including Argentina, similarly reflect occasional occurrences rather than permanent residency (Griffin et al., 2025). These distributional dynamics are closely related to their thermal preferences, particularly their tendency to follow water temperatures around 26 °C as migratory cues—a

behavior likely amplified by climate-related ocean warming (Luo et al., 2020; A. Adams, pers. obs.). Although tarpon are also found along Africa's western coastline (Adams et al., 2014), this study concentrates on populations inhabiting the western Atlantic. Notably, the species has expanded into the eastern Pacific, likely via the Panama Canal, with confirmed captures reported as far south as Peru (Castellanos-Galindo et al., 2019; Hooker, 2025; Swanson, 1946). Overall, their distribution is constrained by temperature tolerance, with mortality observed at extremes below 14 °C and above 40 °C (Mace et al., 2018; Moffett & Randall, 1957; Robins & Ray, 1986; Zale & Merrifield, 1989).

The degree of ecological connectivity among tarpon populations varies across their range, which presents complications for coordinated conservation efforts like other highly mobile species (Game et al., 2009).

In northern areas such as the coast of North America, adult tarpon migrate seasonally over distances exceeding 1 500 kilometers to access distinct spawning and feeding zones (Griffin et al., 2022; Griffin et al., 2023a). In contrast, individuals inhabiting the Caribbean Sea and Central/South American waters tend to exhibit more restricted movements (Brown & Severin, 2008; Fernandes et al., 2023). For instance, satellite telemetry studies in Belize and Nicaragua revealed that tagged tarpon remained within national waters for several months (J. Luo, unpublished data). Despite evidence of separate movement groups, genetic analyses show low regional differentiation (McMillen-Jackson et al., 2005; Ward et al., 2004), although Costa Rica may represent an exception, possibly harboring a population that completes its life cycle locally and conducts extended migrations into river systems (Brown & Severin, 2008). Elevated genetic similarity across regions is likely due to a combination of adult vagrancy, mixing of contingents at select spawning locations (e.g., off the Mississippi River and Florida Keys; Griffin et al., 2025; Stephens et al., 2024), and larval transport mechanisms (Elmo et al., 2021; Graham et al., 2021) following offshore spawning (Luo & Ault, 2012; Luo et al., 2020). Juvenile and subadult tarpon are heavily dependent on specific nearshore habitats, including wetlands and estuaries (Bunting et al., 2024; Kurth et al., 2019; Navarro-Martínez et al., 2020; Navarro-Martínez et al., 2025). These life-stage specific habitat needs reinforce the necessity for a dual-scale approach to conservation that integrates both local protection measures and broader regional coordination (Adams et al., 2014; Stevens et al., 2024; Wilson et al., 2019).

Although research on tarpon has increased in some areas, understanding of tarpon ecology, fisheries, and conservation remains inconsistent, with significant knowledge gaps persisting throughout much of the Caribbean and Central America. This issue is especially pronounced in Costa Rica, where tarpon hold both ecological and socioeconomic significance but have received limited scientific attention. Existing evidence indicates that tarpon populations in

Costa Rica may display unique ecological traits, such as possible local residency and extensive utilization of riverine habitats (Brown & Severin, 2008), suggesting a partially isolated population with specific conservation needs. The lack of a comprehensive synthesis of current knowledge, together with insufficient empirical data on fisheries dynamics and population trends, hinders the formulation of effective management strategies.

To address these gaps, it is necessary to integrate regional scientific knowledge with locally derived information sources. In data-limited fisheries, local ecological knowledge (LEK), including information obtained from fishers and guides, can provide critical insights into population trends, habitat use, and perceived threats (e.g., Gervasi et al., 2023; Jones et al., 2024; Jones et al., 2025; Rehage et al., 2019; Shephard et al., 2021). In Costa Rica, such information remains largely undocumented, particularly in relation to the recreational tarpon fishery, which represents a key economic activity in Caribbean coastal communities.

This study synthesizes current knowledge of Atlantic tarpon across the western Atlantic Ocean, Gulf of Mexico, and Caribbean Sea and uses this regional context to evaluate current knowledge, principal threats, and research needs for tarpon in Costa Rica.

MATERIALS AND METHODS

This study is based on a literature review of Atlantic tarpon populations across the western Atlantic, Gulf of Mexico, and Caribbean Sea. We searched Google Scholar using the terms “*Megalops atlanticus*”, “tarpon”, and “sábalo”. The review was complemented by the authors’ expertise on the species.

Recognizing the historical importance of Costa Rica’s Caribbean waters for adult tarpon and the limited information available on the recreational fishery, we designed and distributed an online survey. The questionnaire was administered online during September 2025. Participation was voluntary and anonymous, respondents provided informed consent before



completing the questionnaire, and no personally identifying information was collected. The survey instrument is appropriate in this context because tarpon fisheries are data-limited, lacking long-term monitoring and standardized catch data. In such systems, LEK obtained from resource users has provided valuable insights into historical trends, spatial patterns, and emerging threats (e.g., Rehage et al., 2019; Shephard et al., 2021). Therefore, the survey was used as a complementary scientific tool to integrate experiential knowledge with existing literature and expert interpretation.

The survey followed a cross-sectional, descriptive design aimed at generating baseline information for a data-limited fishery. The instrument consisted of 25 questions grouped into five thematic areas: (1) respondent profile, (2) fishing effort and methods, (3) perceived abundance and seasonal patterns, (4) historical context and population trends, and (5) economic importance of the fishery. The questionnaire included both closed-response formats (multiple-choice questions and rating scales) and open-ended items to capture quantitative data and LEK. The survey is presented in Supplementary Material 1.

A non-probabilistic, purposive sampling approach was employed to select participants with direct experience in the recreational tarpon fishery, such as fishing guides, captains, and recreational anglers. The survey was disseminated through various channels to maximize reach within the fishing community, including online fishing groups (such as messaging platforms and community forums), social media pages focused on sportfishing, and direct email distribution to established contact lists and stakeholder databases. This multi-channel strategy aimed to capture a broad spectrum of perspectives from active participants in the fishery.

Potential differences in perception were examined by qualitatively comparing responses across experience categories (<5 years, 5–10 years, 10–15 years, and >15 years), with particular attention to perceived population trends and fishing conditions.

RESULTS

Literature review and expert knowledge

Tarpon life history

Most of what is currently known about the life history of Atlantic tarpon originates from studies conducted in North America, while empirical information from the Caribbean Sea and Central America remains comparatively limited. Nonetheless, the overall life history patterns in understudied locations are expected to be generally similar to findings from North America. Although spawning has not been directly observed and specific locations have not yet been identified anywhere within their range, spawning is presumed to occur offshore based on collection of day-old larvae (Crabtree et al., 1992; Leis & Reader, 1991, as cited in Ley, 2008), by following offshore movements of adult fish using satellite tags (Ault et al., 2008), and satellite tag-based observations of dives to > 130 m at night in offshore waters (Luo et al., 2020). This spawning behavior (offshore, deep dives) is common in the Elopiformes (Adams et al., 2014) and has been documented for bonefish (Elopiformes, Albulidae; Danylchuk et al., 2011; Danylchuk et al., 2019; Lombardo et al., 2020). During spawning season and prior to spawning, adult tarpon gather in what appear to be traditional pre-spawning aggregation areas (e.g., Florida Keys and Boca Grande Pass, Florida, USA) and migrate offshore in schools of varying size near full and new moons to spawn. In Florida, peak spawning occurs during late spring and summer (April–July) full and new lunar phases (Crabtree, 1995; Shenker et al., 2002), but the spawning season is more protracted in tropical waters such as Costa Rica (Crabtree et al., 1997) and Puerto Rico (Zerbi et al., 2001). Spawning occurs in northern areas of the range (e.g., northern Gulf of Mexico; Stein et al., 2012; Stein et al., 2016) in late summer. In Costa Rica, females appeared to be reproductively active throughout the year (Chacón-Chaverri, 1993; Crabtree et al., 1997), suggesting a year-long spawning season. However, recruitment

of leptocephalus larvae and small juveniles to Gandoca Lagoon is seasonal (July–October; Chacón-Chaverri, 1993), which, given tarpon planktonic larval duration of 20–40 days (Shenker et al., 2002), indicates that spawning likely occurs from June to September. In addition, female and larger tarpon are more common in coastal waters from November through January (Chacón-Chaverri, 1993), suggesting seasonal movements that may coincide with reproductive and foraging time periods, as observed along the North American coast (Griffin et al., 2025; Stephens et al., 2024). Tarpon is an iteroparous batch spawner (De-Menezes & Paiva, 1966; Smith, 1980; Chacón-Chaverri, 1993; Crabtree et al., 1997; Ley, 2008). Leptocephalus larvae swim or drift with ocean currents before recruiting to shallow coastal habitats (Shenker et al., 2002). Post-metamorphic juveniles are euryhaline and have been collected in waters ranging from 0 to 45 PSU (Stevens et al., 2024; Wilson et al., 2019).

The vascularized swim bladders of tarpon enable them to physiologically utilize air gulped at the surface, which allows juveniles to occupy low-oxygen habitats including stagnant pools, back waters, creeks, ephemeral coastal ponds and hurricane and storm overwashes, swales, and mangrove swamps and marshes, and man-made habitats such as mosquito impoundments and artificial wetlands (Bunting et al., 2024; Dahl, 1965; Jud et al., 2011; Robins & Ray, 1986; Stephens et al., 2024; Wade, 1962; Wilson et al., 2019; Zerbi et al., 2001). These kinds of habitats have lower predation rates and less competition for prey (Geiger et al., 2000; Schlaifer & Breder, 1940; Seymour et al., 2004) than more oxygenated waters. In Costa Rica, late-stage larvae and small juveniles were collected in the Gandoca Lagoon (Chacón-Chaverri, 1993; Chacón-Chaverri, 1994; Chacón-Chaverri & McLarney, 1992). Although unknown for Costa Rica, in other regions juveniles emigrate from backcountry areas to rivers, bays, and estuaries at 1–2 years of age (Bunting et al., 2024; Crabtree, 1995; Kurth et al., 2019). Small juvenile tarpon prey upon zooplankton, small crustaceans, polychaetes and insects that frequent

inshore nurseries (Harrington, 1958; Jud et al., 2011). Older juveniles and adults begin to inhabit deeper-water habitats such as lagoons, creeks, canals and sloughs before emigrating to coastal bays, and their diet transitions to larger crustaceans (penaeid shrimps, swimming crabs), polychaetes, and fishes (Boujard et al., 1997; Whitehead & Vergara, 1978). Similarly, research in Costa Rica's Gandoca Lagoon found copepods and notonectids as top diet items for small juveniles (Chacón-Chaverri, 1994).

Adult tarpon (>130 cm fork length (FL), Chacón-Chaverri, 1993; Crabtree et al., 1997) exhibit more extensive movements (Crabtree, 1995; Griffin et al., 2022; Kurth et al., 2019; Pusey et al., 2004) including estuaries, near-shore ocean waters, and rivers, across a wide range of salinities (fresh to hypersaline) and temperatures (17–40 °C) (Crabtree, 1995; Zale & Merrifield, 1989). Atlantic tarpon reach sexual maturity at >130 cm and 7–12 years (Chacón-Chaverri, 1993; Crabtree et al., 1997), though there is considerable variation across their geographic range. In Costa Rica, all males examined (800–1 150 mm fork length (FL)) were sexually mature, and females between 1 126 and 1 860 mm fork length (FL) were sexually mature (Crabtree et al., 1997). Females were larger than males. In the northern portion of their range (Gulf of Mexico, eastern coast of North America), adults undergo seasonal migrations (Ault et al., 2008; Drymon et al., 2021; Friess et al., 2021; Griffin et al., 2018; Griffin et al., 2022; Griffin et al., 2023a; Griffin et al., 2025; Luo et al., 2020). Tarpon reach maximum ages of 43–78 years (Andrews et al., 2001; Crabtree, 1995) and may exceed 2 m in length and 110–130 kg in mass (Crabtree et al., 1997).

Fisheries

Tarpon is an economically important recreational species (Smith et al., 2023) and occurs in cultural, subsistence, aquaculture, and small commercial fisheries in portions of its range (reviewed in Adams et al., 2014; Fernandes et al., 2023). The recreational fishery for this species developed in 1885 in Florida (White &



Brennan, 2010), and currently occurs along the southeastern United States, the Gulf of Mexico, portions of Central America and the insular Caribbean Sea, and the Atlantic coast of Brazil. Beyond recreation, tarpon support cultural traditions, subsistence practices, and commercial fisheries. For example: in Brazil, the scales are used for decorative and medicinal purposes (G. Gondolo, pers. obs.), and tarpon are targeted by an artisanal fishery (Fernandes et al., 2023); tarpon are traditionally served at Christmas in Central America (Adams et al., 2014); tarpon are consumed readily in Colombia (García & Solano, 1995) and Nicaragua, and are part of a commercial fishery in Cuba (Navarro-Martínez et al., 2024), and other locations; and subsistence and small scale commercial fisheries for roe and flesh occur in Mexico, Brazil, and other locations in the Caribbean Sea. For example, the fishery in the Parnaíba region of Brazil is primarily an artisanal fishery that harvests tarpon from 140 to 200 cm fork length, with a focus on gonads for a commercial market (Fernandes et al., 2023). Tarpon also occur as incidental catch by purse seiners, long-liners, and gill nets in Mexico and Belize, and are often brought to market (J.S. Ault, Univ. Miami, personal communication). In Costa Rica, harvest is allowed in Barra del Colorado, even with gillnets (INCOPESCA, 2019).

There has been no formal stock assessment of tarpon in any portion of the species' range; tarpon fisheries are data-poor, defined as fisheries that not only currently lack data necessary for standard fishery management (e.g., stock assessments), it is extremely unlikely that such data will be obtained. However, multiple lines of evidence suggest that tarpon populations have declined from historic levels throughout their range, which are summarized in the most recent IUCN assessment (Adams et al., 2014). For example, total commercial landings in Central and South America have undergone historical declines (Adams et al., 2014). Total global landings of tarpon declined 84.5 % between 1965 and 2007, particularly in Brazil, and mostly during the early years of that period, reflecting a drop in population size, not

a change in fishery effort (FAO, 2011). Using a generation time of 12.7 years for tarpon (Froese & Pauly, 2010), the estimated decline in United National Food and Agriculture Organization (FAO) landings over three generations (38 years) is ≥ 80 % (Adams et al., 2014).

Most data on the tarpon recreational fishery are from Florida, where recreational catches appeared to decline after the mid-1930s with a notable decrease during World War II (1941-1945) (White & Brennan, 2010). However, the fishery changed from harvest to catch-and-release during the post-war years, contributing to a decline in recorded landings (Guindon, 2011; White & Brennan, 2010). Anglers have perceived population declines in Florida waters since the 1960s (Griffin et al., 2023b), mirrored by a decline in average length as recorded by angler-collected souvenir scales through 1980 (Bortone, 2008). A similar population decline was observed in Texas in the 1960s and 1970s (Winemiller & Dailey, 2002), however, length modes did not decline over time as observed in Florida (Holt et al., 2005). Recent data show an increase in juvenile tarpon occurrence in Texas (Stephens et al., 2024), so this trend may be reversing. Less than 1 % of the total recreational catch in Florida and the USA is harvested as trophy catch (Guindon, 2011), making depredation and post-release mortality a top concern. For example, although the estimated post-release mortality is 5 % for the Gulf of Mexico coast of Florida when predators are not present, predation by sharks increases post-release mortality to 13 % (95 % CI 6 – 21 %, Guindon, 2011). Moreover, in some areas depredation and post-release predation rates can reach 15 %, depending on fight time and predator density (Casselberry et al., 2024). Estimates of post-release mortality of tarpon in Florida (using 13 %; Guindon, 2011) applied to USA catch data suggest annual recreational post-release mortality ranges from 8 000 to 16 000 individuals (Adams et al., 2014). Post-release mortality in some locations with recreational fisheries outside of the USA is likely also high due to long fight times and poor handling (Horowitz et al., 2023; A. Adams, pers. obs.).

Recreational fishing regulations for tarpon differ regionally. In the USA, for example, regulations range from catch and release only (Virginia, North Carolina, Florida, Puerto Rico, U.S. Virgin Islands) to unregulated (Louisiana) (Adams et al., 2014). There are no regulations in USA federal waters. Elsewhere, regulations include: Belize – catch and release only; Mexico – two per person per day, no minimum size; Cuba – catch and release only in recreational fishing protected areas, no regulations outside of these zones.

In Costa Rica, under the Fisheries and Aquaculture Law No. 8436 (Asamblea Legislativa, 2005) and Executive Decree No. 24.384-MAG-TUR (Ministerio de Agricultura y Ganadería & Ministerio de Turismo, 1995), tarpon is declared a species of interest for tourist and recreational fishing. This decree expressly prohibits its harvest for commercial purposes as well as its use as bait. At the regulatory level, Executive Decree No. 36782 (Regulation to Law 8436, Article 68) classifies tarpon within the group of large pelagic species, establishing that sportfishing may only land up to five specimens per trip, exclusively for personal consumption or taxidermy, while commercialization remains prohibited. Furthermore, under the Instituto Costarricense de Pesca y Acuicultura (INCOPECA) Board Agreement AJDIP/098-2017, the same limit of five specimens per trip or per day also applies when obtaining a sub-aquatic sportfishing license, reinforcing that the restriction is not limited to boat-based fishing. With regard to shore-based fishing, there is no single nationwide general limit on the number of tarpon that can be caught per day, although the Ministry of Environment and INCOPECA may set catch limits in some areas. However, INCOPECA Board Agreement AJDIP/289-2017 later declared tarpon a species of fishing and aquaculture interest, creating a legal gap and regulatory contradiction between the existing prohibition and the subsequent designation. Although more of the recreational fishery appears to be trending toward catch and release, historically high levels of harvest (followed by dramatic population declines)

and continuing harvest in some areas are cause for concern.

Threats

The life history strategy of tarpon may render it especially vulnerable to overfishing and habitat loss. Tarpon reach sexual maturity fairly late in life, are slow growing, and are long-lived (Andrews et al., 2001; Crabtree, 1995), which results in a long recovery time from population declines. Regional losses of juvenile habitat or intense fishing of adults may have impacts that are not visible for years or decades due to the storage effect (Warner & Chesson, 1985). Moreover, adult tarpon seasonal migrations may temporarily mask the local impacts of nursery habitat loss due to the influx of adults from other regions, but the lack of juvenile recruitment combined with age-related mortality in older tarpon will eventually lead to population collapse. Concurrently, intense fishing of adults may significantly reduce reproductive output, which may not become apparent for years until the lack of new recruits into the population becomes visible as the adult populations decline. For example, reduced reproductive output may result from tertiary stress effects caused by intense recreational fishing pressure, which can cause population-level effects (Guindon, 2011). In contrast, large reductions in spawning biomass may have occurred in Brazil, where an intense fishery from 1960 to the 1980s led to a severe decline in population and catch rates (Adams et al., 2014), and management of the fishery remains challenging (Fernandes et al., 2023).

The juvenile life stage of tarpon depends upon estuarine and inland habitats, which make them highly susceptible to anthropogenic habitat degradation. For example, disruption of hydrologic connectivity (Pringle, 2006) between freshwater and marine sources may alter the magnitude or dynamics of freshwater flow into estuaries (Beach, 2002; Layman et al., 2007; Sklar & Browder, 1998). Altered freshwater flows into estuaries can affect species composition (Sklar & Browder, 1998), which



can impact the diet of predatory fishes (Adams, Wolfe & Layman, 2009). Mangrove forests that serve as an important component of coastal and estuarine nurseries for tarpon are among the most threatened coastal habitats worldwide, decreasing an estimated 35 % globally over the past 50 years, with continuing annual declines of 2 % (Alongi, 2002; Valiela et al., 2001). Wetland and other coastal habitats are similarly in decline (Beck et al., 2011; Brown, 2006; Orth et al., 2006). As these habitats are lost, the amount of available essential tarpon nursery habitat declines, which may have implications for population resilience. Habitat fragmentation, which occurs when portions of a continuous habitat, or of habitat mosaics, are destroyed or degraded, creating gaps in suitable habitat, is also a significant threat. This is especially important for tarpon because ontogenetic habitat shifts.

Climate change is expected to change precipitation patterns in many regions, which will alter freshwater flows (and thus salinity structure) and delivery of nutrients, sediments, and contaminants into estuaries and other coastal areas. This will further exacerbate anthropogenic alterations already occurring in many coastal regions. Likewise, changes in temperature and seasonal flow rates may change primary production, causing phenological mismatches between first-feeding post-larval elopomorphs and their zooplankton prey that may increase mortality and reduce recruitment to subsequent life history stages (*sensu* Cushing, 1990). In some locations, freshwater flow alteration may cause a decrease in river sediment load, leading to net coastal erosion since sediments are no longer delivered from terrestrial sources, thus decreasing the extent of coastal habitats such as wetlands, which are essential to these fishes; this is presently occurring in the coastal state of Louisiana (USA) (Morang et al., 2013). In contrast, increased erosion from upland activities (e.g., development, agriculture) may increase river sediment load, causing increased turbidity and burying of coastal habitats (Restrepo & Escobar, 2018), as well as introducing additional nutrients (Wei

et al., 2020) and pesticides (Delcour et al., 2015; Polidoro & Morra, 2016; Rämö et al., 2018; Warne et al., 2022).

Since tarpon spawn in offshore waters and have an extended planktonic larval duration, changes in coastal and oceanic wind and circulation patterns associated with climate change may impact larval success and recruitment to inshore juvenile habitats. Many species of marine fishes show high levels of fidelity to spawning locations (e.g., common snook, *Centropomus undecimalis* (Carangaria, Centropomidae) (Adams, Wolfe, Barkowski et al., 2009; Adams et al., 2011); Atlantic cod, *Gadus morhua* (Gadiformes, Gadidae) (Robichaud & Rose, 2001); bonefish, *Albula vulpes* (Elopiiformes, Albulidae) (Danylchuk et al., 2011; Adams et al., 2019). Changes in ocean circulation patterns may interrupt the connectivity between spawning locations, larval transport, and nursery habitats. Climate-induced changes in currents that transport larvae to less suitable habitats could have population-level negative impacts, particularly if fewer habitats are available because of anthropogenic habitat loss and degradation.

In Costa Rica and other areas in the tropical portion of tarpon's range, climate change-induced increase in water temperature may have deleterious effects due to water temperature exceeding the tarpon thermal maximum, as well as sublethal physiological effects (e.g., respiration, metabolism; reviewed in Danylchuk et al., 2023). In addition, tarpon that are experiencing physiological stress due to high water temperature may be more susceptible to exhaustion, and thus post-release mortality, when captured in the recreational fishery (reviewed in Danylchuk et al., 2023).

Survey

Survey participants (n = 39) reported engaging in tarpon fishing across seven locations along the Caribbean coast of Costa Rica (Fig. 1): Caño Negro/Río Frío (14 %), Barra del Colorado (38 %), Barra del Tortuguero, Río Parismina/Jalova (24 %), Limón, Laguna

de Gandoca (7 %), and Río Sixaola (17 %) (Fig. 1). Fishing activity was concentrated in the northern and central regions, especially at Barra del Colorado and Río Parismína/Jalova, underscoring the spatial concentration of the recreational fishery.

Survey participants demonstrated varied fishing experience for tarpon: 60 % reported more than 15 years, 8 % between 10 and 15 years, 21 % between 5 and 10 years, and 11 % less than 5 years, indicating that the survey largely reflects long-term knowledge of the fishery (Fig. 2A; Table 1).

Most participants undertook five or fewer fishing trips per month (Fig. 2B; Table 1), reflecting moderate yet consistent fishing efforts. Tarpon fishing contributes substantially to local livelihoods, with 76 % of respondents indicating that at least part of their annual income depends on tarpon fishing (Fig. 2C; Table 1). However, among captains and guides, 54 % reported a decrease in income over time, suggesting declining fishery performance.

Tarpon fishing reportedly occurs throughout the year in most locations, with 58 % of respondents indicating year-round availability, likely reflecting the presence of both resident and migratory individuals. Indeed,

36 % of respondents identified tarpon as both resident and migratory, while 33 % considered them primarily resident and only 10 % primarily migratory (Fig. 2E, Table 1). Perceptions of migratory behavior were also consistent across respondent experience categories, with no significant association detected between years of fishing experience and whether tarpon were perceived as resident, migratory, or both resident and migratory (Fisher's Exact Test, $p = 0.411$). Seasonal variation in migratory tarpon occurrence was also reported by respondents, with mentions concentrated between September and November and peaking in October (Fig. 3). Most respondents (56 %) also indicated that tarpon size varied throughout the year, and that the fishery was perceived to be dominated by large individuals (>25 kg), whereas reports of smaller tarpon (<10 kg) were uncommon.

Overall, perceptions of declining tarpon abundance predominated among respondents (79.5 %), indicating that abundance has decreased over time (Fig. 2D; Table 1). Reports of decline were significantly more frequent than expected under an equal probability model (binomial test, $p = 0.0001$). Anecdotal accounts highlighted historical abundance, with some respondents reporting that tarpon were once



Fig. 1. Survey locations of recreational tarpon fishers in Costa Rica. / **Fig. 1.** Sitios de encuesta de pescadores recreativos de sábalo en Costa Rica.



Table 1

Summary of survey responses from recreational tarpon fishers in Costa Rica (n = 39). / **Tabla 1.** Resumen de respuestas de pescadores recreativos de sábalo en Costa Rica (n = 39).

Category	Variable	Response	%
Experience	Years fishing	>15 years	60
		10–15 years	8
		5–10 years	21
		<5 years	11
Effort	Trips/month	1–5	84
		6–10	5
		11–15	3
		>15	8
Economic dependence	Income from tarpon	All	13
		About half	37
		Small part	39
		None	11
Income trend	Change over time	Decreased	54
		Increased	24
		No change	24
Availability	Year-round fishing	Yes	58
		No	26
		Not sure	16
Behavior	Migratory/resident	Both	36
		Resident	33
		Migratory	10
		Not sure	21
Population trend	Observed change	Decrease	79
		Increase	5
		No change	8
		Not sure	8
Threats (primary)	Main factor	Agriculture	44
		Commercial fishing	15
		Recreational fishing	15
		Habitat loss	14

so numerous that nighttime navigation could become hazardous because startled fish frequently jumped near boats. Perceptions of abundance change did not differ significantly among respondent time categories (<10 years, 10–15 years, and >15 years of experience; Fisher’s Exact Test, $p = 0.225$; Table 2).

Similarly, when respondents were grouped into Caribbean and non-Caribbean regions, and responses collapsed into “decline” versus “non-decline” categories, no significant geographic differences were detected (Fisher’s Exact Test, $p = 1.0$; Table 3), indicating that

perceptions of decline were similarly widespread across regions.

Respondents identified multiple factors contributing to perceived declines in tarpon abundance. Environmental degradation, including agricultural runoff and habitat destruction, was the most frequently identified primary driver (22 of 40 responses; 55 %; Fig. 2F; Table 1). Responses were not evenly distributed among causal categories ($\chi^2 = 19.20$, $df = 3$, $p < 0.001$), with a clear predominance of environmental explanations over fishing-related and other causes (Fig. 2F). These perceived

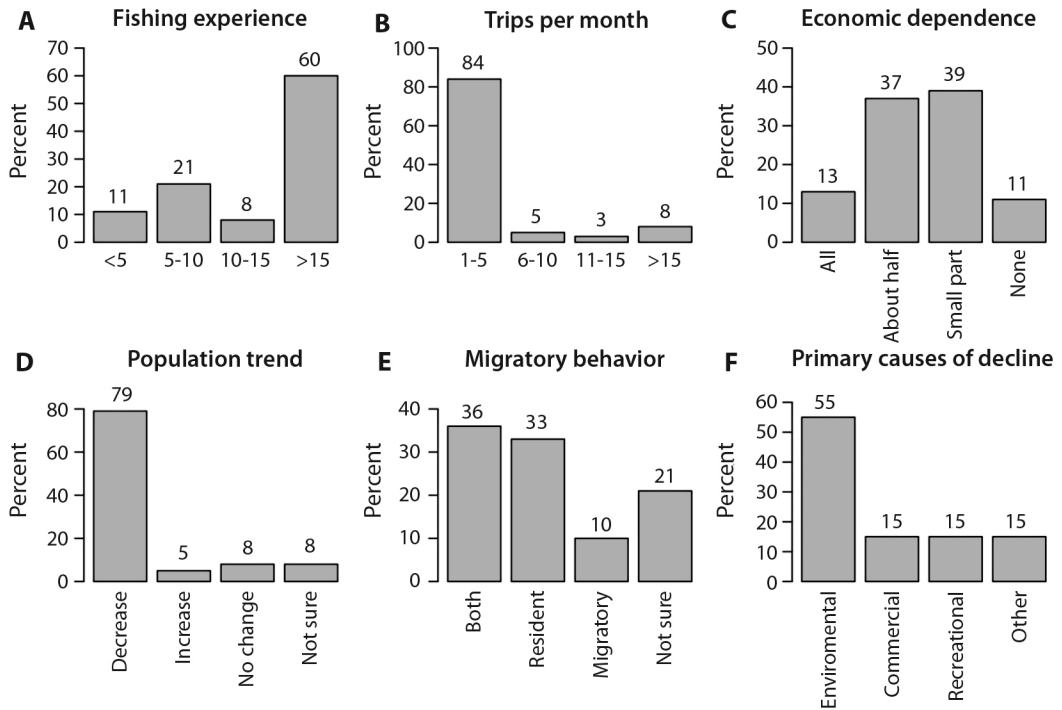


Fig. 2. Characteristics, fishing patterns, and perceptions of recreational tarpon fishers in Costa Rica. / **Fig. 2.** Características, patrones de pesca y percepciones de los pescadores recreativos de sábalo en Costa Rica.

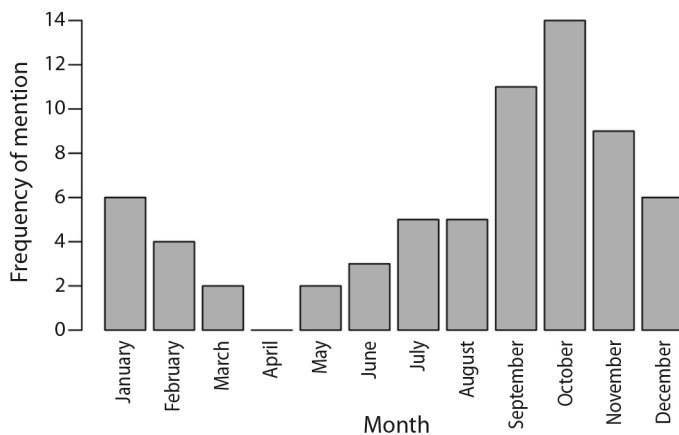


Fig. 3. Monthly frequency of migratory tarpon observations reported by recreational fishers surveyed in Costa Rica. / **Fig. 3.** Frecuencia mensual de observaciones de sábalos migratorios reportadas por los pescadores recreativos encuestados en Costa Rica.



Table 2

Perceptions of temporal trends in tarpon populations according to years of experience fishing for tarpon. / **Tabla 2.** Percepciones sobre las tendencias temporales de las poblaciones de sábalo según los años de experiencia en la pesca de esta especie.

Experience	Increased	Decreased	Uncertain	No change
<10	0	8	3	1
10–15	0	4	0	0
>15	2	19	0	2
Total	2	31	3	3

Table 3

Perceptions of tarpon population declines according to respondents’ area of residence. Non-Caribbean areas include the Pacific coast, Central Valley, and other unspecified locations in Costa Rica. / **Tabla 3.** Percepciones sobre la disminución de las poblaciones de sábalo según el área de residencia de los encuestados. Las zonas no caribeñas incluyen la costa del Pacífico, el Valle Central y otras localidades no especificadas de Costa Rica.

Region	Decline	Non-decline
Caribbean	8	3
Non-Caribbean	18	5

Primary causes of tarpon population decline identified by survey respondents classified by economic dependence on tarpon recreational fishing. In high dependence respondents, 50% or more of their income comes from the activity, whereas in low dependence respondents it is just a small percentage, nothing, or it is not applicable. Causes include commercial and recreational fishing, environmental degradation. Other include everything, nothing, unsure.

drivers were consistent with suggested management actions. The most frequently proposed solution to these issues was improved regulation of large-scale agriculture (44 %), followed by angler and community education (36 %). Perceptions of the primary cause of decline did not differ significantly between respondents with high and low economic dependence on tarpon fishing (Fisher’s Exact Test, $p = 1.0$, Table 4). Suggested management actions were broadly consistent with these perceived threats, with respondents most frequently recommending stronger regulation of large-scale agriculture (44 %) and increased education within fishing communities (36 %).

DISCUSSION

An important result of this study is the widespread perception that Costa Rican tarpon populations include both resident and migratory individuals, which may contribute to the year-round availability of tarpon fishing. Although tarpon life history has been studied in greater detail elsewhere in the Caribbean and Gulf of Mexico, where coastal migrations, off-shore spawning, and larval transport are known to drive regional connectivity (Griffin et al., 2022; Griffin et al., 2023a; Griffin et al., 2025; Luo et al., 2020), evidence from Costa Rica is consistent with the likelihood of a partially distinct contingent. Survey respondents reported contrasting perceptions of tarpon movement

Table 4

Perceived primary causes of tarpon population decline. / **Tabla 4.** Principales causas percibidas de la disminución de las poblaciones de sábalo.

Economic dependence	Environmental	Commercial	Recreational	Other
High dependence	6	1	2	1
Low dependence	16	5	4	5
Total	22	6	6	6

patterns, suggesting spatial heterogeneity in movement behavior, temporal changes in population dynamics, or both. There is evidence adult tarpon may undertake long inland migrations into river systems along the Costa Rica-Nicaragua border (Brown & Severin, 2008), suggesting the possibility of a more localized or partially closed life cycle. If a significant proportion of the population exhibits residency, as suggested by survey responses, local ecological conditions and anthropogenic pressures may have a stronger influence on population dynamics than in more connected systems. If confirmed, such isolation would have implications for conservation because a population that is less replenished by regional recruitment may be especially vulnerable to local threats (Griffin et al., 2025). Empirical movement studies using telemetry and genetic approaches are necessary to better understand residency, migration, and population connectivity in the region.

A large majority of respondents (close to 80 %) in this study perceived a significant decline in tarpon abundance. This perception was consistent across experience categories and respondent regions, suggesting that perceptions of decline are widespread throughout the country. Anecdotal accounts from respondents suggest that the magnitude of the decline may be substantial. Small tarpon were rarely reported by respondents, which may reflect fishing selectivity, habitat use, or potential recruitment limitations. Research is especially needed on small juveniles and subadults, which in other regions occupy mangrove lagoons, creeks, and estuaries before shifting into larger riverine and coastal systems (Crabtree, 1995; Jud et al., 2011; Kurth et al., 2019; Navarro-Martínez et al., 2025; Wilson et al., 2019). In Costa Rica, however, the extent of estuarine versus inland riverine dependence, which habitats function as nurseries given the relative scarcity of mangroves along the Caribbean coast, and the ecological role of inland migrations remain poorly understood. Targeted studies using telemetry, otolith chemistry, and regional genetic comparisons could be used to evaluate whether Costa Rica represents a largely self-sustaining population

or one integrated with the broader Caribbean population (Adams et al., 2014; McMillen-Jackson et al., 2005). Results from this research must directly inform national fisheries policy and protected area management plans (e.g., Tortuguero and Caño Negro).

The survey also identified perceived drivers of population decline, with environmental degradation, primarily associated with agriculture, emerging as the principal threat, followed by commercial and recreational fishing. Perceived threats did not differ between respondents with high and low economic dependence on tarpon fishing, which may indicate that perceived threats are broadly shared among fishers and tour operators across regions. These findings align with existing literature highlighting the vulnerability of tarpon to habitat degradation, particularly in estuarine and freshwater systems, where changes in water quality, sediment loads, and hydrological connectivity can affect recruitment and survival (Adams, Wolfe & Layman, 2009; Alongi, 2002; Sklar & Browder, 1998).

The prominence of agriculture as a perceived threat is particularly notable, as it points to watershed-scale processes rather than solely fishery-based impacts. This expands the scope of tarpon conservation beyond traditional fisheries management and underscores the importance of integrated land-sea management approaches. Similar linkages between land use and coastal fish populations have been documented in other tropical systems, where agricultural runoff and habitat alteration reduce nursery habitat quality and productivity (Layman et al., 2007; Restrepo & Escobar, 2018).

Survey responses also identified fishing-related pressures, including commercial harvest and recreational fishing practices, as contributing factors to population decline. Although tarpon fisheries are typically considered low-impact due to catch-and-release practices, post-release mortality can be significant, particularly under conditions of high fishing effort, long fight times, and predator presence (Guindon, 2011; Casselberry et al., 2024). This



suggests that even non-consumptive fisheries may have population-level effects if not properly managed.

Importantly, the survey revealed strong alignment between perceived threats and proposed management actions, with many respondents identifying improved regulation of large-scale agriculture and emphasizing education on best practices for catch-and-release fishing. This convergence between perceived drivers and solutions highlights the value of LEK as a tool not only for identifying problems but also for informing practical, stakeholder-supported management strategies.

From a management perspective, these findings suggest that effective conservation of tarpon in Costa Rica will require a dual approach that integrates watershed-scale environmental management with fishery-specific measures. While improvements in catch-and-release practices may reduce direct mortality, addressing land-based sources of impact, particularly agricultural runoff and habitat degradation, is likely essential for maintaining recruitment and long-term population resilience.

Together, these findings suggest that current knowledge remains insufficient to fully evaluate the ecological status and long-term resilience of tarpon populations in Costa Rica. These findings also highlight several major research and management priorities for Costa Rican tarpon conservation. The need for locally grounded research and management of tarpon has been formally recognized for more than a decade through INCOPECA initiatives (INCOPECA, 2012) and national protected area management plans but major ecological and fisheries knowledge gaps remain.

In general, a key step in the management of Costa Rican tarpon populations is to establish a biological baseline specific to Costa Rica, including the identification of critical juvenile habitats, adult movement patterns, spawning phenology and locations, and larval transport pathways. Parallel to the biological baseline, fisheries assessments are needed to evaluate

both historical and current exploitation. Recreational fisheries are increasing in importance, yet long-term catch records and systematic monitoring of angler effort remain limited. In this context, recurring LEK surveys may provide a practical tool for tracking changes in abundance, fishing effort, and fishery capacity in a data-limited recreational fishery (Gervasi et al., 2023; Jones et al., 2024; Jones et al., 2025; Rehage et al., 2019; Shephard et al., 2021). Even catch-and-release fisheries may become overcapitalized if fishing pressure exceeds the capacity of the system to maintain high catch rates, large fish size, and ecosystem quality (Post et al., 2002; Zwiern et al., 2005).

Despite Costa Rica's reputation as a global leader in marine conservation—through the expansion of marine protected areas (MPAs), the implementation of management frameworks such as Responsible Fishing Areas, and its commitment to international agreements like the Kunming-Montreal Global Biodiversity Framework – tarpon remains conspicuously absent from national conservation agendas. This oversight is particularly concerning given the species' high ecological, cultural, and economic relevance to coastal communities and the sportfishing sector. Its migratory nature, dependence on vulnerable estuarine habitats, and potential regional connectivity underscore the urgent need for a science-based, context-specific conservation strategy that explicitly includes tarpon within Costa Rica's broader marine policy and biodiversity frameworks.

These efforts should help prioritize both immediate management needs, such as identifying nursery habitats and evaluating fishery capacity, and longer-term objectives, including determining regional connectivity and mitigating watershed-scale threats. By explicitly acknowledging the uncertainties unique to Costa Rica while aligning research with regional knowledge, managers will be better positioned to protect what may represent a distinct and vulnerable tarpon contingent, and, in doing so, safeguard the broader regional fishery.

CONCLUSIONS

This manuscript contributes to the ecological and fisheries-related understanding of Atlantic tarpon by integrating previously fragmented evidence within a comprehensive regional framework, with particular emphasis on Costa Rica. The results highlight the need for an ecosystem approach that recognizes the species' high mobility, dependence on functional coastal habitats, and the diversity of fisheries throughout its range. The ecological and fisheries patterns described reinforce the need to address the conservation of this species through an ecosystem approach, explicitly recognizing its high mobility, dependence on functional coastal habitats, and the diversity of fisheries uses across its range. The study highlights the need to move toward coordinated management strategies and multi-level governance, leveraging existing regional platforms such as the Central American Fisheries and Aquaculture Organization (OSPESCA), the Central American Commission on Environment and Development (CCAD), and the Caribbean and North Brazil Shelf Large Marine Ecosystems Project (CLME+). These platforms could incorporate tarpon as a focal species to pilot integrated management models that combine habitat conservation, differentiated fisheries regulations, and stakeholder participation, consistent with international experiences in the management of highly migratory species. The conservation approach proposed for Costa Rica, based on the identification and protection of critical habitats, the incorporation of LEK, and the enhancement of governance capacities, offers a scalable, adaptable, and replicable model for other Mesoamerican countries. Finally, it is urgent to identify and characterize critical nursery habitats, conduct studies of connectivity and metapopulation structure, quantify post-release mortality, and assess the cumulative impacts of climate change and coastal degradation. Addressing these research needs is essential to transition from a reactive approach toward a precautionary, science-based, and adaptive conservation strategy for tarpon, aligned with

the socio-ecological complexity of the region. A detailed stepwise framework outlining proposed research, fisheries assessment, and conservation priorities for tarpon in Costa Rica is provided in Supplementary Material 2.

Author contribution statement: Aaron J. Adams conceived the study and led manuscript preparation. Thomas Enderlin designed and implemented the survey, conducted data analyses, and prepared the figures. Johel Chaves-Campos and Damián Martínez-Fernández contributed to the interpretation of fisheries information and provided regional expertise. Lucas P. Griffin contributed to the synthesis of ecological information and manuscript revision. All authors reviewed, edited, and approved the final version of the manuscript.

Ethics statement: The authors declare that they all agree with this publication and that they have made contributions that justify their authorship. They further declare that they have complied with all applicable ethical and legal requirements, both during the study and in the preparation of the manuscript; that there are no conflicts of interest of any kind; that all financial sources are fully and clearly stated in the acknowledgements section; and that they fully agree with the final edited version of the article. The respective signed legal document has been filed in the journal's archives.

See supplementary material
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