Subsistence fisheries in Small Island Developing States: the case study of the goby-fry fishery in Guinea Gulf

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ABSTRACT

1. Artisanal and subsistence fisheries are crucial for the livelihood and food security of local communities of Small Island Developing States (SIDS), yet they remain largely excluded from formal catch statistics and management frameworks. Using Ostrom's Social-Ecological Systems (SES) diagnostic framework, this study characterizes the previously unreported goby-fry ("peixinho") fishery across 14 riparian communities in São Tomé and Príncipe (Gulf of Guinea). Data were collected through semi-structured interviews and validated via synthesized member checking.
2. The fishery is strongly dominated by women (74%), with fishing tactics structured by regional geomorphology and age. Traditional traps ("tchanga") dominate on the western coast (52%), where they are primarily used by older fishers. On the eastern coast, nylon nets (40%) and mosquito nets (17%) dominate, whereas mosquito nets are used exclusively on Príncipe Island. The shift from traditional to synthetic fishing gear affects ecological performance: nylon nets and multi-gear tactics capture significantly more accidental bycatch (21 non-target species identified) than traditional "tchanga" traps.
3. Fishers possess detailed Local Ecological Knowledge (LEK) regarding lunar and seasonal recruitment cycles, aligned with the amphidromous life history of Sicydiinae gobies; however, results show that LEK alone cannot replace systematic monitoring.
4. Although 63% view the fishery as commercial, one-third retain catches for household protein, and 72% reinvest revenues directly into essential basic needs

(mostly food and education). Most fishers (90%) are aware of resource decline, yet they hesitate to support top-down gear prohibitions due to subsistence dependence, preferring instead community-based rules (46%).

5. Sustainable government will require establishing co-management arrangements that integrate LEK with scientific monitoring, address gendered participation, and build multilevel institutional linkages, infrastructure currently lacking in São Tomé and Príncipe.

KEYWORDS: Gobiidae, food security, fish early life stages, fishing communities, Local Ecological Knowledge (LEK)

1. INTRODUCTION

Despite globalization, most populations in Small Island Developing States (SIDS) reside in rural areas, where fishing and agriculture are essential to their livelihoods, food security, and nutritional well-being. Artisanal fisheries are particularly relevant, as aquatic foods serve as a primary source of protein, accounting for more than 50% of the total animal protein supply in some SIDS (Connell et al., 2020; FAO, 2022). Fishing communities across SIDS face extreme exposure to climate change impacts alongside high vulnerability driven by marine resource dependence, limited economic development, and poverty (Petzold and Magnan, 2019). Furthermore, low spatial flexibility, few alternative livelihood options, and constrained markets restrict fishers' ability to switch target species. Consequently, assessing their exposure and adaptive capacity is essential to developing targeted interventions that strengthen the resilience of artisanal fisheries (Belhabib et al., 2016; Thomas and Diouf, 2023).

In São Tomé and Príncipe, artisanal fishing is a primary livelihood and safety net, providing over 50% of the population's dietary animal protein with an average per capita consumption of 29.3 kg per year (Costa, 2009; FAO, 2019; Serkovic and Million, 2019; Amador et al., 2023). However, artisanal catches have steadily declined due to overfishing by foreign vessels, illegal, unreported and unregulated (IUU) fishing in the Exclusive

Economic Zone, climate change, and persistent gaps in monitoring and policy enforcement (Carneiro, 2011; Caillart et al., 2017; Zacarias et al. 2022; Amador et al., 2023). Although improved road infrastructure has accelerated commercialisation, a substantial portion of catches remains dedicated to direct household consumption (Belhabib, 2015; de Labra et al., 2023). Moreover, subsistence fishing is frequently merged with commercial artisanal activities in national statistics, hindering its role in local nutrition and hindering evidence-based management of vital aquatic resources (Oceanic Développement et al., 2004; Virdin et al., 2023).

Governments often prioritise monitoring commercial, export-oriented fisheries, introducing a downward bias into national catch statistics (Pauly, 2006, 2009; Zeller and Pauly, 2007). This underreporting contributes to the neglect of artisanal and subsistence fisheries, threatening essential safety nets against poverty and malnutrition in climate-vulnerable communities (Cooley et al., 2022; Virdin et al., 2023). This is the case of the artisanal goby-fry fishery of São Tomé and Príncipe, locally known as "peixinho" ("little fish" or "small fish" in Portuguese), first documented in 1877 (Ribeiro, 1877). This traditional activity targets immature individuals (post-larvae) during their upstream migration across river mouths, estuaries, beaches, and river cascades (Jiménez-Prado, 2014; Thomas, 2017).

These post-larvae are amphidromous gobies, primarily from the subfamily Sicydiinae, which rely on oceanic larval development followed by freshwater recruitment, a strategy typically used by gobies in tropical, oligotrophic river systems with pronounced seasonal hydrology (Manacop, 1953; Bell, 1999; McDowall, 2007; Castellanos-Galindo et al., 2011; Keith and Lord, 2012). Given that spawning, larval dispersal, and upstream migration are connected to seasonal rainfall and river discharge, hydrological variations can influence the survival of amphidromous goby populations, potentially leading to local extinctions (McDowall, 2003; Keith, 2003). Therefore, this specific life strategy allows the colonization of new habitats and their recolonization following seasonal local extinctions (McDowall, 2007; Thomas, 2017).

In São Tomé and Principe, at least two species of the subfamily Sicydiinae are found in the catches, namely *Sicydium bustamantei* Greeff, 1884, and *Sicydium brevifile* Ogilvie-Grant, 1884 (Ribeiro, 1877; Pezold et al., 2006; Baptista et al., 2020). Two other goby species from the Gobionellinae subfamily, *Awaous lateristriga* (Duméril, 1861), and *Awaous bustamantei,* may also contribute to the fishery (Greff, 1882; Harrison et al., 2008). Although the recruitment of post-larval gobies to the "peixinho" fishery represents a vital resource for local livelihoods, studies describing and analysing this fishery from ecological, socioeconomic, or cultural perspectives are limited, hindering the development of effective management measures to preserve these aquatic resources (McDowall, 2007; Thomas, 2017).

Fishers' knowledge and experience can provide crucial insights into the biology and ecology of target species, establishing historical and contemporary baselines for conservation planning and fisheries management (Thornton and Scheer, 2012; Begossi et al., 2016). Fishers possess firsthand experience of aquatic ecosystems and face the direct impacts of climate change, adjusting their practices accordingly (Daw et al., 2009). This understanding, known as Local Ecological Knowledge (LEK), represents cumulative ecological insights transmitted across generations and refined through extensive personal empirical observation and interactions with local ecosystems (García-Quijano, 2007; Davis and Ruddle, 2010).

These reciprocal dynamics between human communities and biophysical environments operate within complex adaptive systems, conceptualised as social-ecological systems

(SES). While broad SES perspectives emphasize the connections between human actions and ecological processes, functioning as an interdependent, co-evolving system (Berkes and Folke, 1998), diagnosing why some systems achieve sustainability while others experience resource degradation requires a structured taxonomic lens (Ostrom, 2009). To achieve this, we adopted the multi-tiered diagnostic SES framework by Ostrom (2009) and refined by McGinnis & Ostrom (2014); by decomposing the SES into four primary first-tier subsystem, namely the Resource System, Resource Units, Governance System, and Actors, this tool allows us to examine how second-tier attributes interact within focal Action Situations to produce social and ecological Outcomes. Applying this tool is particularly relevant for data-poor, informal fisheries activities in SIDS, where formal monitoring is absent and management must instead be built upon rules-in-use and informal networks. This approach is increasingly used for small-scale fisheries, emphasizing the interdependence of sustainable livelihoods, participatory governance, and the integration of local and traditional knowledge (Berkes, 2003).

To address these challenges, this study uses the traditional, previously unreported goby-fry fishery of São Tomé and Príncipe, commonly known as the “peixinho” fishery, as a diagnostic case study. Our overarching research question is: How do the interactions between localized human subsystems (gendered actor groups, local ecological knowledge) and seasonal biophysical subsystems (lunar and precipitation cycles) shape fisheries practices and outcomes? To answer this question, we address three specific sub-questions grounded in the SES framework:

a) How do the attributes of local Actors (such as gender and age) and geographical factors determine their choice of fishing tactics (Interactions) across communities?

b) How does Knowledge of the SES held by fishers, specifically regarding lunar phases and precipitation cycles, align with actual fishery dynamics to guide harvesting effort?

c) How do these social and ecological interactions generate combined Outcomes for local livelihoods (food, security, income) and resources, and what are the implications for developing community-led Governance Systems?

To operationalise the SES framework, we systematically map the qualitative and quantitative data collected from 14 riparian fishing communities onto different diagnostic subsystems (McGinnis & Ostrom, 2014). In this study, we consider the "peixinho" as the Resource Units, characterized by their unique amphidromous life history, and the river cascades and estuaries and the Resource System. The fishers represent the central Actors, whose socio-demographic attributes and LEK are analysed in relation to their fishing practices (Interactions). Finally, we evaluate the resulting social and ecological Outcomes, such as gear-specific bycatch rate and household investment patterns, to identify pathways for co-developing community-based rules and multilevel linkages (Governance Systems), thus providing a theoretically grounded diagnosis of a vulnerable SIDS fishery.

2. METHODS

2.1 Study area

São Tomé and Príncipe is a Small Island Developing State (SIDS) located in the Gulf of Guinea, 200 km off the west coast of Africa (Figure 1). The country comprises two main volcanic islands, São Tomé and Príncipe, situated 140 km apart. The archipelago encompasses a total land area of 1,001 km² and an Exclusive Economic Zone (EEZ) of 160,000 km², roughly 160 times its landmass (World Bank, 2021; de Labra et al., 2023). Both islands are of volcanic origin and display a radial hydrographic network where rivers and streams flow from the central mountains toward the coast. The archipelago features 116 river basins and 223 rivers and streams, ranging between 5 and 27 km in length

(Lopes, 2020; Ceríaco et al., 2022; da Costa et al., 2022; Sanitation and Water for All, 2022). The river network is evenly dispersed, flowing into the sea and forming small estuarine habitats or creating little waterfalls and cascades (da Costa et al., 2022). The coastal zone experiences a microtidal regime with semidiurnal tides ranging from 0.30 m to 1.80 m (Giardino et al., 2012). The climate is oceanic equatorial characterized by alternating wet and dry seasons (Lains and Silva 1958). The dry periods comprise a primary dry season ("gravana") from June to mid-September, and a shorter dry period ("gravaninha") lasting a few weeks between mid-December and mid-March (Lains and Silva, 1958).

The archipelago's colonial past has brought together a culturally diverse population, including several ethnic groups: the "Forros" (descendants of freed enslaved Africans and Europeans), the "Angolares" (descendants of Angolean slaves), and Cape Verdean settlers (Eyzaguirre, 1989; Seibert and Clarence-Smith, 2025). In recent decades, rapid demographic growth brought the population to 231,856 inhabitants in 2023 (Muñoz-Torrent et al., 2022; World Bank, 2024).

This study focused on 14 riparian fishing communities of São Tomé and Príncipe, where the goby-fry fishery takes place (Figure 1). On the western coast of São Tomé, sampling covered Lembá, Santa Catarina, Paga-Fogo and Neves; on the eastern coast, it included Santana, Ribeira Afonso, Angra Toldo, Iô-Grande, Praia Pesqueira, Monte Mario and Malanza. On Príncipe Island, the sampled communities were Praia Lapa, Praia Campanha and Budo-Budo.

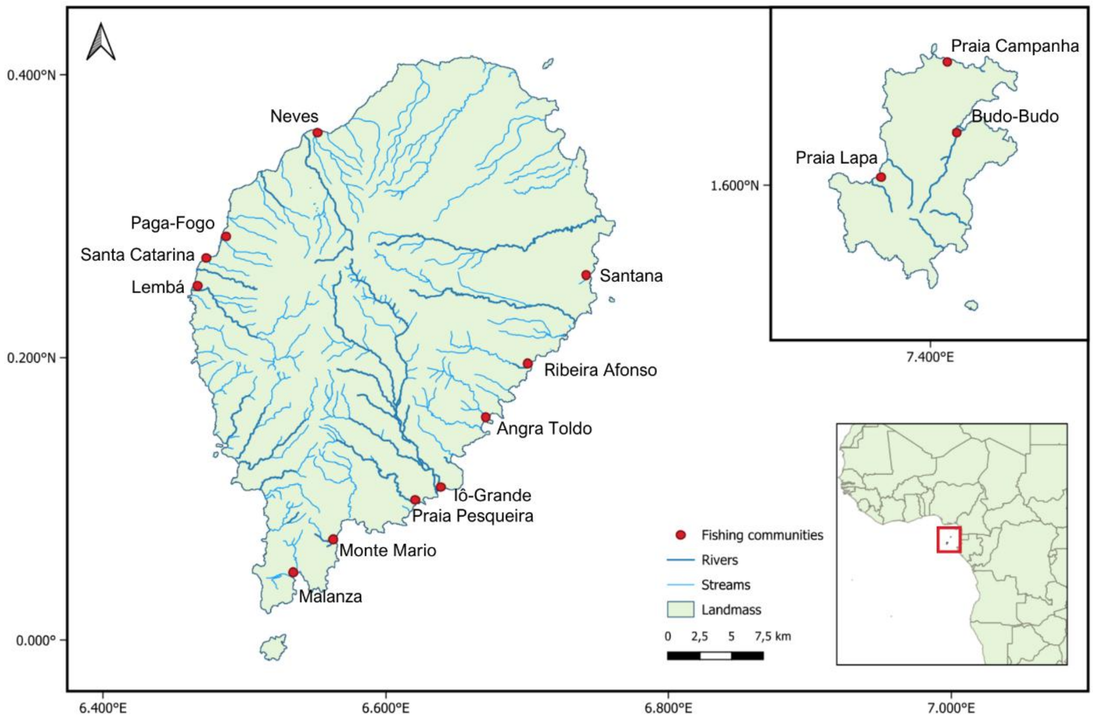

Figure 1. Geographic distribution of the 14 surveyed riparian fishing communities involved in the goby-fry ("peixinho") fishery across São Tomé and Príncipe. Red circles indicate sampled community locations on São Tomé Island (n = 11) and Príncipe Island (n = 3, top-right inset). Dark blue lines represent primary rivers, light blue lines represent secondary streams and tributaries, and light green depicts landmass area. The bottom-right inset highlights the geographic location of the archipelago within the Gulf of Guinea off the west coast of Central Africa.

2.2 Data collection

Data collection followed a two-phase, mixed methods approach, conducted between 2022 and 2024, designed to capture the social-ecological complexity of the "peixinho" fishery by integrating quantitative socioeconomic indicators with qualitative data from fishers' LEK.

All research protocols adhered to the International Society of Ethnobiology Code of Ethics (International Society of Ethnobiology, 2006). Prior to each interview, participants received a detailed explanation of the objectives and provided informed verbal consent. The research instruments and data governance procedures were approved by the Data and

Privacy Protection Policy and Ethics Commission of the University of Algarve, as well as the National Institute of Statistics (INE) of São Tomé and Príncipe.

2.2.1 Fishers interviews

In the first phase (July-November 2022), we administered a questionnaire consisting of 45 questions organized into five thematic sections (socio-demographic characteristics; fishing gear and methods; gobiid post-larval catches; fishery revenues; perceptions of management and resource state), based on previous studies conducted in other Atlantic sub-Saharan African artisanal fisheries, specifically in Luanda Bay, Angola (Faria et al., 2021). The questionnaire included both closed and open-ended questions, allowing for semi-quantitative and qualitative data collection. This approach, often employed in conservation studies, offers flexibility while maintaining data quality (Young et al., 2014; Rose et al., 2018). The survey was pilot-tested and translated, and interviews were conducted in Portuguese or local languages (Forro, Angolar, Lunguyè) by trained local students and researchers, taking approximately 20 minutes to complete. A non-probabilistic snowball sampling method was employed, identifying active and retired fishers through community chains, resulting in a sample size of 224 fishers across the 14 communities.

2.2.2 Synthesized Member Checking

A second fieldwork phase was conducted in May 2024 following Synthesized Member Checking approach (SMC; Birt et al., 2016; Harvey, 2015; Young et al., 2018). This methodology validates findings by integrating diverse perspectives (objectivism), while encouraging reflection on personal experiences and creating opportunities for complementary qualitative data collection through triangulation (constructivism; Birt et al., 2016).

Synthesized results, including demographic and fishing gear distributions, perceived catch correlations with lunar and seasonal cycles, fishery status evaluations, and proposed management options, were presented back to the fishers. Using anonymized, illustrative questions, participants were invited to discuss and comment on the preliminary management measures identified during the initial survey phase. Given that logistical constraints limited the access to the original fishing communities, some subsequent steps in the SMC methodology, namely determining participant eligibility to receive SMC and distributing the SMC report for feedback, were not feasible. Instead, we held direct, in-person feedback sessions in communities with high initial participation rates. Thus, findings were presented and discussed in two dedicated sessions with fishers from Praia Pesqueira (n = 3) and Iô-Grande (n = 4). In addition, follow-up feedback regarding the perceived state of the fishery and local selling prices of “peixinho” was collected from fishers in Lembá (n = 2).

2.2.3 Bycatch validation

Given that physical bycatch could not be collected, local common names of accidental species reported by fishers were scientifically validated. We cross-referenced regional common names with taxonomic checklists and fish databases of São Tomé and Príncipe, and showed pictures of candidate by-catch species to local fishery experts to verify species-level identifications, while more uncertain identifications were kept at genus level.

2.3 Statistical analysis

Survey data were translated and transcribed into English, and open-ended answers were coded thematically to generate a structured database in Microsoft Excel. Missing data and non-responses were excluded from subsequent statistical analyses, except for the questions concerning fishers' perceptions of fisheries management measures. Descriptive statistics and exploratory data visualizations were computed across all questionnaire modules.

Chi-square tests of independence with Yates' continuity correction, where appropriate, were performed to evaluate associations between nominal variables (such as gear choice vs. geographical area, age class, or gender). Crámer's V was calculated to evaluate the strength of these associations, with values close to 0 indicating a weak correlation and values close to 1 indicating a strong correlation (Husson et al., 2011). Because bycatch species counts did not meet assumptions of normality, we used non-parametric Kruskal-Wallis tests to assess differences in accidental species richness across different fishing gears, followed by pairwise post-hoc Wilcoxon rank-sum test with Bonferroni corrections.

All the analysis and visualization of the data were conducted using R software (R Core Team, 2024) and the packages "dplyr" (Wickham et al., 2023), "fmsb" (Nakazawa, 2024), "ggplot2" (Wickham, 2016), "networkD3" (Allaire et al., 2017), "readr" (Wickham et al., 2024), "tidyverse" (Wickham et al., 2019) and "ufs" (Peters and Gruijters, 2023). All statistical tests were conducted with a 95% confidence interval and a significance level of 0.05.

2.4 Application and operationalisation of the SES framework

To translate the taxonomical structure of the SES framework into a diagnostic research tool, we classified qualitative LEK and quantitative survey metrics into standardized diagnostic categories. Table 1 details the operationalisation of the second-tier variables within the context of the "peixinho" fishery in São Tomé and Príncipe.

Table 1. Social-ecological systems (SES) mapping for the "peixinho" fishery in São Tomé and Príncipe.

SES Subsystem & Code	Fishery Variable & Metric	Primary Data Source / Method
Resource System (RS)		
• Location (*RS9*)	14 riparian communities across São Tomé and Príncipe Island	Fishery sampling coordinates
• Predictability (*RS7*)	Larval runs highly synchronized with rainfall and lunar cycles	Local Ecological Knowledge (LEK) & workshops
Resource Units (RU)		
• Mobility (*RU1*)	Migrating Gobiidae post-larvae (*Sicydiinae*) traveling upstream	Gobiid biological literature
• Characteristics (*RU6*)	"Peixinho branco" (early larvae) vs. "peixinho preto" (pigmented)	Fishery Survey (Section 3)
Actors (A)		
• Attributes (*A2*)	Predominantly middle-aged women fishers (74% of fishers)	Demographic Survey (Section 1)
• Importance (*A8*)	Critical safety net for household food security and informal cash	Economic Survey (Section 4)
• Technologies (*A9*)	Traditional traps (*tchanga*) vs. modern nylon/mosquito nets	Gear Survey (Section 2)
Governance System (GS)		
• Organizations (*GS1*)	National monitoring vacuum (exclusion from official statistics)	Policy and institutional review
• Collective Rules (*GS6*)	Strong stakeholder preference for community co-management (46%)	Fishery Survey (Section 5)
Action Situations		
• Interactions (*I1*)	Fishing effort (averaging 12 days/month) and gear choice	Survey (Sections 2 & 3)
• Social Outcomes (*O1*)	Livelihood support (72% of income spent on basic household needs)	Household Revenue Survey (Section 4)
• Ecological Outcomes (*O2*)	Selective catch impact (nylon nets capture highest bycatch)	Kruskal-Wallis tests on bycatch

Our statistical analyses were structured to test the linkages within the SES framework. Specifically, we evaluated how the geographic location of the Resource System (RS9) and the socio-demographic attributes (age, gender) of the Actors (A2) influence the choice of available harvesting technology (A9). We also examined how these technological choices (Interactions, I1) directly determine ecological performance outcomes (O2), measured as the diversity of accidental bycatch species. Finally, we evaluated the relationship between fisher investment choices (Social Outcomes O1) and socioeconomic variables (sex, commercial/subsistence category). These analyses allowed us to empirically test the interactions between the social and ecological subsystems rather than treating them as isolated variables.

3. RESULTS

3.1 Characterization of the social subsystems: Actors (A) and Technologies used (A9)

The socio-demographic baseline of the fishers (Actors) is highly gendered (Figure 2). Out of 224 surveyed fishers, 74% are women (n = 166), and 26% are men (n = 58). Fishers are predominantly middle-aged, with 61% of respondents between 23 and 54 years old. Formal education levels are relatively low, with 53% of fishers having completed primary education. Some gender and generational patterns were identified, with 52% of the unschooled fishers being older women (aged 55 and above), whereas the majority of fishers with secondary school education are women aged between 15 and 24 (59%).

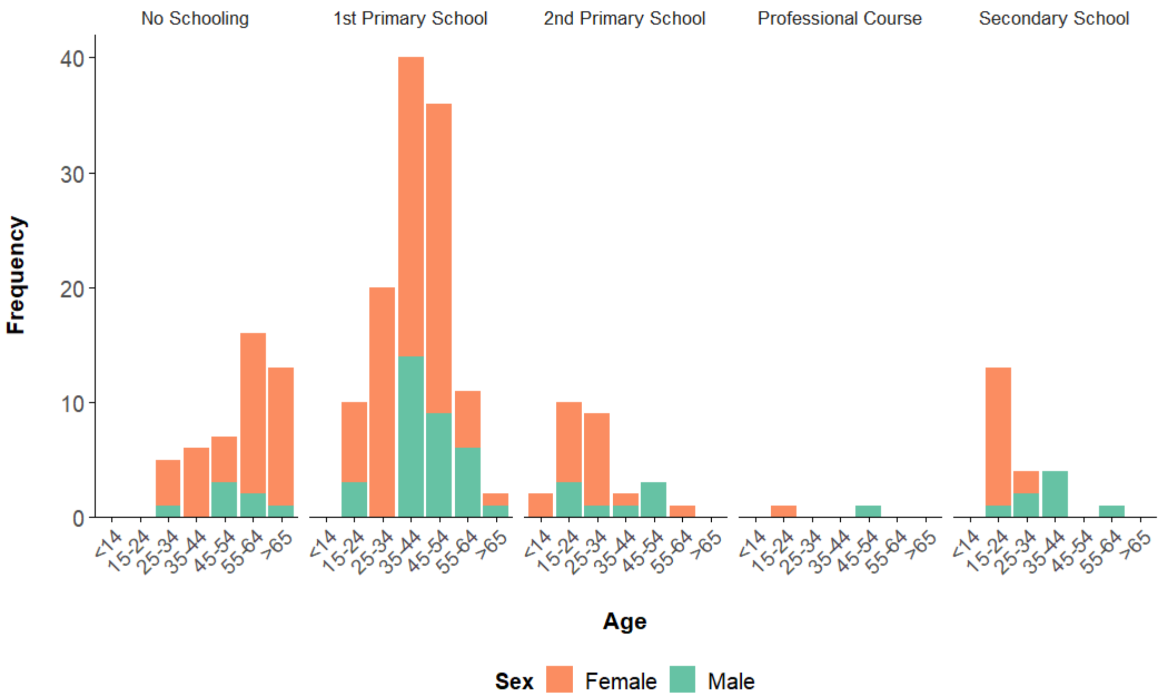

Figure 2. Age and education-level distribution of fishers targeting gobiid post-larvae in São Tomé and Príncipe, by sex. Age groups: under 14 years old, 15-24 years old, 25-34 years old, 35-44 years old, 45-54 years old, 55-64 years old, and 65 years old and above. Education level: no schooling, 1st primary school (grades 1-6), 2nd primary school (grades 7-9), professional course and secondary school (grades 10-12). Female fishers are represented in orange, and male fishers in green.

Fishers use four primary technologies to harvest "peixinho": the nylon net (used by 35% of respondents), the traditional basket made of vegetal fibres called "tchanga" (31% of respondents), the mosquito net (22%), and cloth nets (improvised from clothing; 12%) (Figure 3). While 73% of "peixinho" fishers frequently employ a single type of fishing gear, 27% adopt a multi-gear tactic, preferring to use multiple types of fishing gear. Operating techniques differ between technologies: netting is highly collaborative, with fishers working in groups of two to three (85%), whereas the traditional "tchanga" is used individually (92%; Table 2).

Figure 3. Fishing gears and tactics used to capture gobiid post-larvae ("peixinho") in São Tomé and Príncipe. A) Fishers using a nylon net, with post-larvae displayed in a plastic basin; B) Women using a mosquito net to catch a schooling of post-larval gobies in the mouth of the river; C) Fisherwoman setting up the traditional trap or “tchanga” at the end of the funnel built from rocks and vegetal material; D) Fisherwomen using a nylon net and a “cafuca” (oil lamp) to attract the post-larvae towards the nets. Source: LittleFish-STP project.

Table 2. Equipment, operating techniques, and characteristics of each fishing gear, and number of fishers involved in the goby-fry fishery from São Tomé and Príncipe.

Fishing gear	Gear description	Method of operation	Nº of people involved
Cloth net	Piece of fabric or clothing used as improvised net to catch the post-larval schooling.	Fishers recognize the schooling of post-larval individuals; the nets are submerged in the water and lifted once they have their catches. During the night, they use oil lamps (“cafucas”) to locate the schoolings and attract them to the nets.	2-3
Mosquito net	Net made from fine mesh fabric designed to prevent mosquitoes from passing through, which it is used to catch the post-larval schooling.	Two people hold opposite ends of the mosquito net and sweep it through the water. Or using an “scooping” technique, as the net moves through the water, it catches the schooling. During the night they use torches to detect and attract the post-larvae.	2-3
Nylon net	Nets made by synthetic fibres of nylon. The size can be of 3 meters of length and 1,5 meters of width.	A group of people hold the extreme of the net, once they locate the schooling, they move the net through the water capturing the schooling. During the night, they attract the fish with oil lamps or flashlights, and then, they capture them.	2-3
Basket (“tchanga”)	Trap made by vegetal fibres united by a plastic band creating a cylindrical basket with a wider entrance. The end of the trap is closed by a thin rope locally known as “bongo”.	With pebbles and vegetal material, they create channels to guide the post-larval gobies towards the baskets, where they are captured. The “tchanga” has a funnel opening which avoid that the post-larvae turn around.	1

The “peixinho” fishery can occur during daylight (30%), at night (18%), or both (52%; Figure 4). During daylight, the most common fishing strategies are the “tchanga” (48%) and mosquito nets (34%). At night, fishers mainly use nylon nets (43%) or mosquito nets (22%). They also use lighting tools such as traditional oil lamp made from a bottle, locally known as “cafuca”, or flashlights to identify post-larvae schooling and to attract them toward the nets. When fishers operate both during the day and at night, they mainly use nylon nets (44%), or the multi-gear technique mentioned above (39%). Among those operating during both day and night, 80% prefer night fishing, due to the high effectiveness of artificial light in identifying and attracting post-larvae schools.

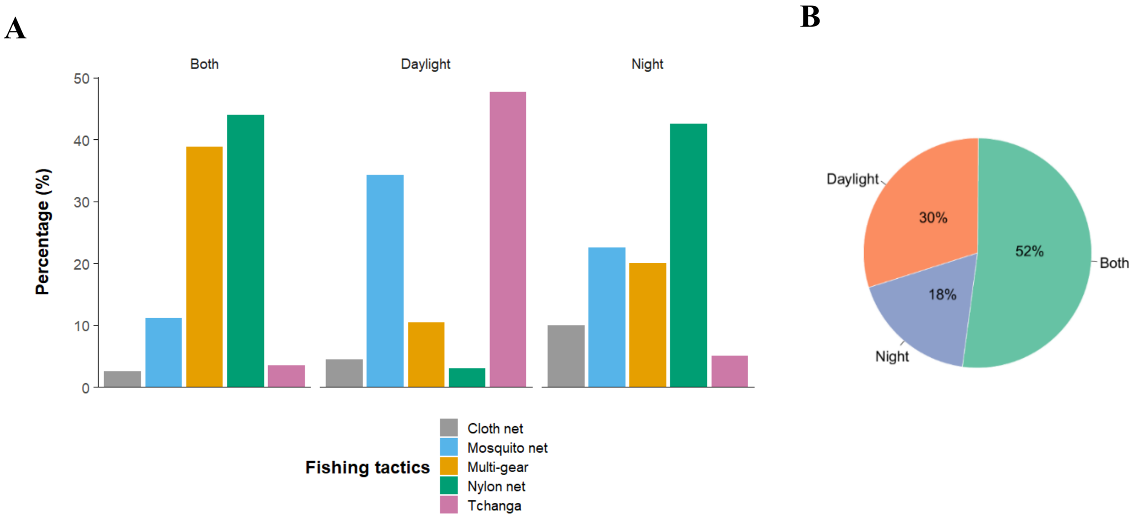

Figure 4. Fishing tactics by time of the day in the goby-fry fishery of São Tomé and Príncipe. A) Percentage of each fishing technique (cloth net, multi-gear, mosquito net, nylon net, and “tchanga”) used during daylight, night, and both periods combined; B) Proportion of fishing activity conducted during daylight, night and both periods.

We found statistically significant spatial and demographic divisions in the use of fishing technologies (Figure 5). On the western coast of São Tomé, characterized by steep volcanic profiles and rocky riverbeds, fishers predominantly use the traditional *tchanga* trap (52%), followed by multi-gear tactics (22%), and nylon nets

(22%), with mosquito nets rarely deployed (3%). In contrast, on the sandy, lower-gradient eastern coast of São Tomé, fishers use nylon nets (40%), multi-gear tactics (32%), mosquito nets (17%), cloth nets (7%), and rarely use traditional traps (4%). On Príncipe Island, the mosquito net is used exclusively (100%). This geographic split in technology choice is highly significant (Chi-square = 69.37, df = 4, $p < 0.001$, Cramer's V = 0.57).

Figure 5. "Peixinho" fishing tactics by sex and region in São Tomé and Príncipe. A) Fishing techniques (cloth nets, mosquito nets, multi-gear, nylon nets and “tchanga”) used in Western São Tomé Island, Eastern São Tomé Island, and Príncipe Island. For each region, the number of fishers and the sex related to the fishing tactics are displayed; B) Percentage of fishers using each fishing technique by age class (under 14 years old, 15-24 years old, 25-34 years old, 35-44 years old, 45-54 years old, 55-64 years old, and 65 years old and above) in Eastern and Western São Tomé.

Within communities, technology choice is associated with age. On the western coast, there is a significant, moderate correlation between age and gear selection (Chi-square = 21.49, df = 3, $p < 0.001$, Cramer's V = 0.56), with younger fishers (14–34 years) using primarily nylon nets (67%), while older fishers (35+ years) prefer the traditional *tchanga* (63%). On the eastern coast, age-based gear deployment is more diverse but is also statistically significant (Chi-square = 32.78, df = 8, $p < 0.001$, Cramer's V = 0.35): mosquito nets are dominant among the youngest fishers (15–24 years at 55%), nylon nets are chosen mostly by fishers aged 25–34 (47%), and multi-gear tactics are most common among fishers aged 35–44 (57%). No significant associations were found between gender and gear selection within either the eastern ($p = 0.84$) or western ($p = 1.00$) basins.

3.2 Characterization of the biophysical subsystems: Resource System (RS), Resource Units (RU) and LEK Mental Models (A7)

The boundaries of the Resource System (RS) are defined by the volcanic geomorphology of the archipelago. The Resource Units (RU) comprise Gobiidae post-larvae of the subfamily Sicydiinae. These post-larvae undergo different development stages during their upstream migration, recognized by fishers as “peixinho branco” (early, unpigmented post-larvae) and “peixinho preto” (older, pigmented post-larvae). While 87% of fishers report targeting “peixinho branco” due to its higher market value, 83% continue to catch the fish when they become “peixinho preto”, due to household economic necessity (50%; “it gives money back too”). Other reasons include no perceived difference between different post-larval stages (12%) or simply because the post-larvae swim up the river (7%).

The fishers' LEK (A7 – Knowledge of SES/Mental Models) is highly associated with the biophysical cycles of the resource system. Approximately 88% of fishers report that "peixinho" fishery is connected to lunar phases, with higher catches of post-larvae during the new moon phase (37%) and last quarter (40%). In addition, 88% of fishers report that higher catches of "peixinho" occur during the wet season.

This high seasonality is reflected in the harvesting effort, as 70% of fishers do not fish every month, and 95% do not fish throughout the entire month, resulting in an average fishing frequency of 12 ± 6 days per fisher per month. Approximately 56% of fishers attribute this fishing frequency to the amphidromous life cycle of the resource (e.g., "it stops swimming up the rivers"), while 34% cited socioeconomic reasons and a lack of other livelihood options.

3.3 Focal Action Situations: Interactions (I) and Outcomes (O)

The focal Action Situation in this Socio-Ecological System involves the catches of "peixinho" and the resulting social and ecological feedback loops.

3.3.1 Ecological Performance Outcomes (O2): gear-specific bycatch

The primary Ecological Performance Outcome (O2) evaluated was the accidental capture of non-target species during the "peixinho" harvesting. Fishers reported a total of 21 additional species, with the most frequent being the crevalle jack ("concovado", *Caranx hippos;* 15.71%), followed by decapod river shrimps of the genera *Macrobrachium* and *Atya* (locally "camarão" or "klacá" post-larvae: 15.52%), and sleeper gobies (*Eleotris* and *Bostrychus*, locally "charroco": 11.49%) (Table 3).

Table 3. Frequency of occurrence of additional species caught in the goby-fry fishery of São Tomé and Príncipe, with their local name and scientific name.

Common name	**Scientific name**	**Frequency of occurrence (%)**
Concovado, concom do rio ou cococcó	*Caranx hippos*	15.71
Camarão (adult) or klaclá (post-larvae)	*Macrobrachium* sp. *Atya* sp.	15.52
Charroco	*Eleotris* sp. *Bostrychus* sp.	11.49
Tainha congo	*Mugil curema*	10.73
Parente	*Parakuhlia macrophthalmus*	10.35
Barbudo	*Galeoides decadactylus*	9.58
Corvina	*Lutjanus goreensis*	9.20
Roncador	*Pomadasys jubelini*	6.13
Sardinha	*Sardinella* sp.	2.49
Caranguejo	*Potamonautes* spp.	2.30
Papê or tilapia	*Oreochromis mossambicus*	1.53
Moreia	*Muraena robusta*	0.96
Pata-pata	*Alectis alexandrina*	0.96
Zamvé	*Sardinella* sp.	0.77
Bonito	*Caranx crysos*	0.57
Sopa or maiâ	*Kyphosus* sp.	0.57
Cozinheiro or San Cluso	*Drepane Africana*	0,38
Azno	*Acantharus monroviae*	0.19
Linguado	*Bothus* sp.	0.19
Colombeta	*Coryphaena equiselis*	0.19
Tchintchin	*Holocanthus africanus*	0.19

The number of accidental bycatch species per fishing trip differed across fishing technologies (Kruskal-Wallis chi-squared = 9.83, df = 4, p-value = 0.04). Fishers using nylon nets reported the highest number of additional species (3.79 ± 1.76), followed by multi-gear users (3.48 ± 0.91), cloth nets (3.12 ± 0.84), mosquito nets (2.97 ± 1.18), and the traditional basket, "tchanga" (2.82 ± 1.01). Pairwise post-hoc Wilcoxon tests confirmed that nylon nets capture significantly more non-target species than traditional "tchanga" traps ($p = 0.04$) and mosquito nets ($p = 0.02$). Similarly, multi-gear tactics show significantly more bycatch that traditional traps ($p = 0.03$) and mosquito nets ($p = 0.03$).

3.3.2 Social Performance Outcomes (O1): Livelihoods and Investment Choices

The Social Performance Outcome (O1) reflects the contribution of the fishery to household economics and food security. The "peixinho" is sold in 300 g cans, with a morning starting price of 25 Dobras (DB) for two cans (equivalent to 1.01 EUR or 1.68 USD per kg), but as the day progresses and catches saturate local markets, the price decrease to 17 DB for two cans by evening.

The revenue is critical for local households: 72% of fisher invest their earning directly in household basic needs, while 28% invest in small-scale animal husbandry, mainly pigs (Figure 6). Whitin household expenditures, fisher prioritise education (32% for school uniforms, fees, and books), followed by direct food purchases (18%), clothing (18%), building materials (6%), and domestic electronics (6%). We found a significant relationship between the destination of the catch (whether sold or kept for consumption) and the specific investment choice (X-squared = 5.46, df = 1, p-value = 0.02, Cramer-V = 0.16).

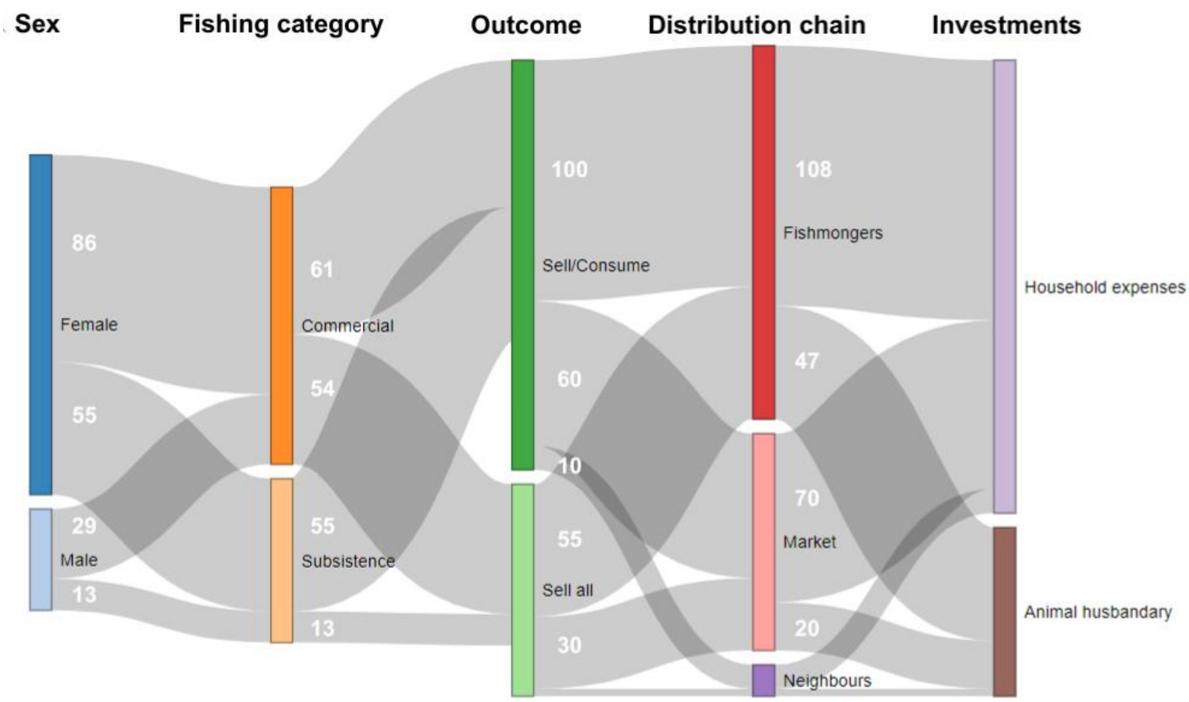

Figure 6. Sankey diagram of the "peixinho" fishery value chain in São Tomé and Príncipe by sex, fishing category, outcome, distribution chain, and investment choices. The width of the flows corresponds to the number of individuals in each category, with the counts (n) represented.

The "peixinho" fishery represents a commercial-subsistence system; while 63% of fishers consider the goby-fry fishery a commercial activity, 33% do not sell their entire catch, retaining a portion for household consumption to secure animal protein. This duality is highly significant (X-squared with Yates' continuity correction= 13.09, df = 1, p-value < 0.001, V-Cramer = 0.27). In terms of distribution channels, 58% of fishers sell their catch directly to local fishmongers (locally known as "palaiês"), 37% transport catches to formal fish markets, and 5% sell informally to neighbours.

3.3.3 Institutional Perceptions and Resource State Perceptions

Fishers' perceptions of the Resource System State (RS5) are overwhelmingly negative: 90% of respondents state that the fishery is in a worse condition today than when they began, while only 6% report no changes in the fishery; 4% consider that it has improved.

Despite this awareness of resource depletion, 66% of fishers believe “peixinho” will never entirely disappear, while 25% believe local extinction is possible (Figure 7a).

Regarding management measures, 53% of fishers agree that they are necessary, but 46% believe that regulations are not needed (Figure 7b). Therefore, 55% of fisher did not propose any specific regulatory measures. Among those who did, the most common were focused on environmental cleanliness rather than catch quotas: 20% proposed banning the use of toxic products in the rivers, and 17% proposed cleaning riverbanks and beaches (Figure 7d). Regarding responsibility for the development of measures, 46% of fishers stated that rules should be created by the riparian communities themselves, while 41% provided no response (Figure 7c).

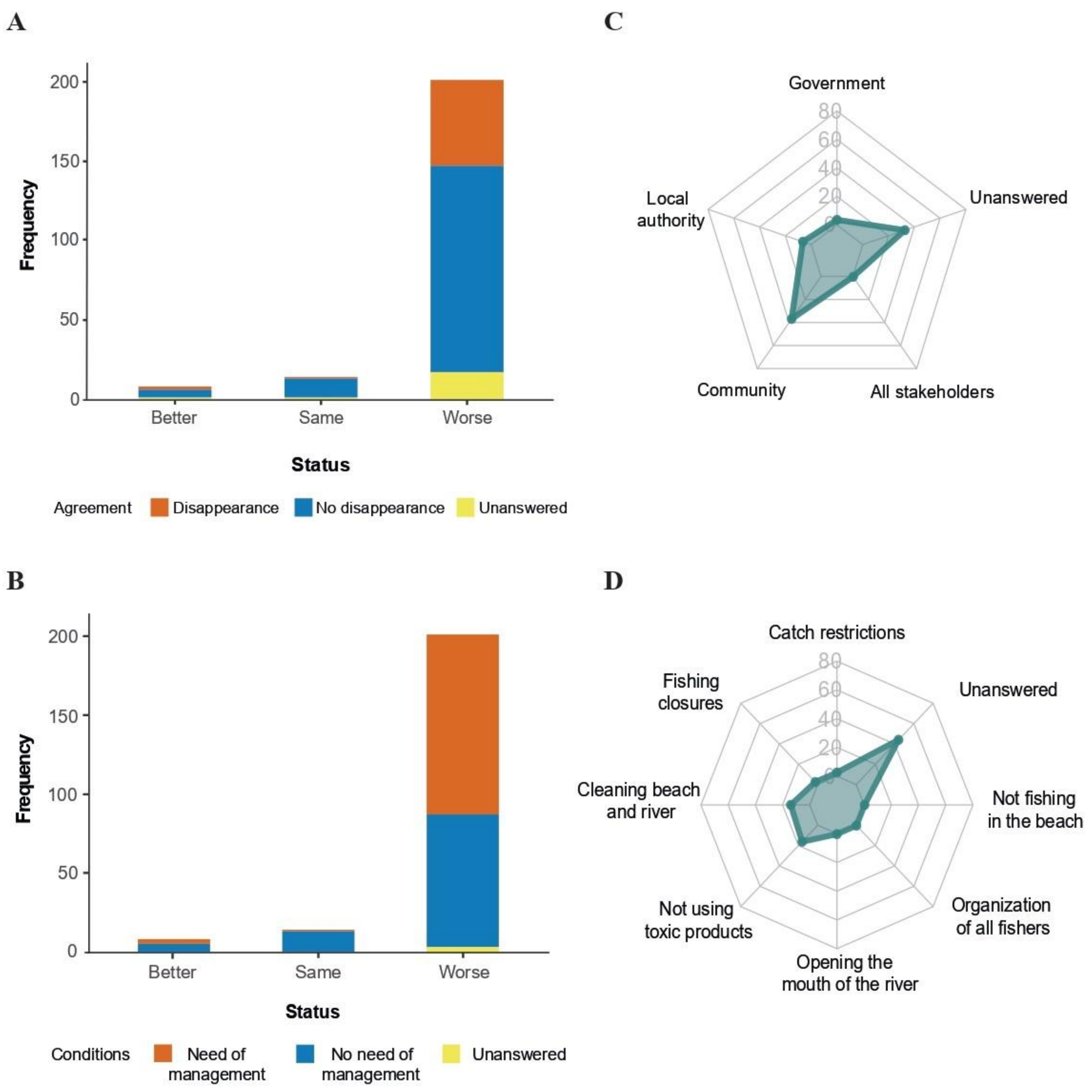

Figure 7. Fishers' perceptions of gobiid post-larvae status and management in the "peixinho" fishery of São Tomé and Príncipe. A) Perceived status (better, same, worse) and future post-larvae presence; B) Perceived status (better, same, worse) and need for management measures; C) Contribution to the creation of management measures; D) Preferences for possible management measure. Non-responses were considered in analyses.

4. DISCUSSION

Our application of Ostrom's (2009) Social-Ecological Systems (SES) framework reveals that the traditional "peixinho" fishery of São Tomé and Príncipe is a highly interconnected system where biological, social and informal institutional variables are closely linked.

A central question in the SES framework is how biophysical variables affect the likelihood of fishers to self-organize to manage a common resource (Ostrom, 2009). Theoretically, a high Resource Unit Mobility (RU1) hinders self-organization because it is very costly to define spatial boundaries and monitoring stock dynamics (Schlager et al. 1994). In the “peixinho” fishery, the post-larvae of amphidromous gobies are highly mobile units that drift offshore before migrating upstream. However, this mobility is compensated by a high Predictability of System Dynamics (RS7), as larval recruitment occurs in predictable locations, primarily during the wet season and specific lunar phases (new moon and last quarter).

Our findings show that fishers’ Local Ecological Knowledge (A7) functions as a highly accurate “mental model” of these biophysical dynamics. The 12-day monthly fishing pattern and the focus on the rainy season reported by fishers align with the recruitment biology of amphidromous gobies observed globally, such as in La Réunion Island for *Sicyopterus lagocephalus* (Delacroix, 1987), and in Puerto Rico for sirajo goby (*Sicydium* spp.) and river goby, *Awaous banana* (Valenciennes, 1837; Keith et al., 1999; Hoareau, 2005; Keith et al., 2008; Engman et al., 2017).

However, we observed high variability in catch reporting, making it difficult to quantitatively validate lunar-seasonal correlations from survey data. This suggests that LEK may provide a valuable qualitative baseline, but it is not precise enough for active catch controls, highlighting the need to integrate local mental models with systematic, community-led monitoring.

The transition in the fishery’s Available Technologies (A9) represents a major shift in the system’s interactions and outcomes. For over a century, the “peixinho” fishery relied on highly selective, labour-intensive technologies. Ribeiro (1877) described fishers using simple stretched cloths to capture post-larvae. Today, while the traditional basket traps, known as “tchanga”, persist on the volcanic western coast, modern, synthetic nylon and mosquito bed nets dominate in the eastern coast and Príncipe Island. This technological transition reflects a classic SES trade-off: modern gears simplify harvesting and reduce labour, but they severely degrade Ecological Performance Outcomes (O2). Our statistical analyses confirmed that modern nylon nets and multi-gear tactics yield significantly higher non-target bycatch rates. The traditional “tchanga” relies on the construction of stone and vegetal funnels that utilise river geomorphology, capturing post-larvae with high selectivity and lower bycatch (Shester and Micheli, 2011; Lively and McKenzie, 2023).

The geographic distribution of these technologies is further constrained by the physical Location (RS9) and substrate of the resource system. The steep, rocky riverbeds of the western coast provide the pebbles necessary to anchor traditional traps, whereas the sandy estuaries of the eastern coast force the use of active fishing nets. Similar variations in fishing tactics associated with river basin substrates have also been reported in Colombia and Dominica (Bell, 2009; Sánchez-Garcés, 2017).

Originally distributed by public health campaigns for malaria prevention, the widespread adoption of mosquito nets for fishing, due to their durability, lightweight and easy accessibility (Short et al., 2018; Jones and Unsworth, 2020), highlights a critical institutional externality. While these fine-mesh nets are highly efficient at capturing small post-larvae, their use poses ecological concerns, namely potential leaching of insecticide into riverine ecosystems and the high capture of juvenile commercial fish. The long-term effects of the use of mosquito nets on fish populations and ecosystems are still unknown (McLean et al., 2014; Short et al., 2018).

Ostrom’s (2009) SES framework underscores that understanding the socio-demographic attributes of Actors (A2) is essential for diagnosing governance capacity. Globally, small-scale fisheries research has focused on direct, formal, and paid harvesting activities, which are predominantly male dominated, while overlooking informal, unpaid, or subsistence activities led by women (Harper et al., 2017). This gap leads to an underestimation of total human catch and the diversity of animals and habitats targeted by fishers, while hindering a broader social-ecological understanding of fisheries (Chambon et al., 2024; Kleiber et al., 2015).

The São Tomé and Príncipe goby-fry fishery is predominantly a women’s activity, with women constituting 74% of active fishers. This female dominance is particularly pronounced on the western coast, where older women maintain the traditional “tchanga” heritage. In contrast, in Dominica, men are mainly in charge of the beach seiners and women operate with traps, whereas in Colombia, the post-larval fishery has been considered a women's activity until recently (Bell, 2009; Blanco-Libreros et al., 2015). Women account for nearly 40% of the worldwide small-scale fishing workforce, with approximately 24 million women engaged in unpaid and informal activities, which benefit directly their families, yet their contribution tends to be overlooked (Ogden, 2017; FAO, Duke University and WorldFish, 2023; Basurto et al., 2025).

A main challenge in socio-ecological systems is the disconnect between fishers’ awareness of resource decline (90%) and their hesitancy to accept fishing regulations (46% believing no measures are needed). Under the SES framework, this can be diagnosed through the Importance of the Resource to Users (A8). For these riparian communities, “peixinho” is not just a commercial product, but a vital subsistence safety net. While 63% view it commercially, 33% retain a portion for household consumption, and 72% of revenues are invested in immediate basic needs. Because households are highly dependent on this activity, any top-down, restrictive regulations (such as a total gear ban) impose survival costs that fishers cannot afford.

Currently, the fishery operates with a complete governance vacuum (GS1), excluded from national catch statistics and formal monitoring. However, we found that 46% of fishers express a preference for community-based rulemaking (GS6 – Collective-choice rules). Indeed, community-based collaborative approaches are often presented as a universal solution, but it is essential to address the multilevel linkages between partners from institutions that connect the local level to higher level of social and political organization to create sound management measures (Conley and Moote, 2003; Berkes, 2007; Ostrom et al., 2007).

5. RECOMMENDATIONS

From a diagnostic social-ecological system perspective, the "peixinho" fishery of São Tomé and Príncipe depicts how deeply intertwined human harvesting practices and ecological impacts are. Unmonitored increases in fishing effort through the use of synthetic mosquito or nylon nets risk aggravating non-target bycatch and localised gear conflicts. Although most fishers perceive a temporal decline in the resource, they remain hesitant regarding top-down gear bans due to short-term subsistence dependence, while many express a clear preference for community-based rulemaking. Therefore, a participatory co-management approach involving all local stakeholders is the most viable way forward, supported by continuous fishery monitoring.

This collaborative co-creation provides a structured platform to agree in adaptive management options guided by scientific advice, while ensuring the equitable participation and voting representation of women, who constitute most of the active harvesters and manage household safety nets. To successfully implement this social-ecological approach, key knowledge gaps regarding gear selectivity and environmental context must be addressed. Further research is required to detail fine-mesh gear selectivity and ecotoxicological risks, alongside river basin geomorphology, to understand the regional differences between western trap-based (tchanga) and eastern net-based communities. Finally, while the Local Ecological Knowledge documented in this study provides a crucial qualitative baseline, it must be integrated with systematic, community-led biological monitoring to validate lunar-seasonal recruitment patterns, evaluate bycatch impacts, and establish early warning indicators for sustainable resource governance.

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