UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE BIOLOGIA ANIMAL

Fish assemblages at Praia Salgada mangrove, Príncipe Island (Gulf of Guinea)

Mariana Martins Cravo

Mestrado em Ecologia Marinha

Dissertação orientada por:
Professor Doutor José Paula

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Dedication

I dedicate this work to Príncipe Island, where I inevitably left part of my heart after five months of work, adventure, happiness, and a splash of tropical despair.

Resumo

Os mangais são comunidades florestais tropicais, compostas por árvores, arbustos e outras plantas, adaptadas à interface entre o meio salgado e doce. Podem ser encontrados em regiões tropicais e subtropicais, onde as plantas crescem sob a influência das marés e em que geralmente a água salgada é misturada com águas de rios, subterrâneas e chuvas fortes e regulares. Tipicamente ocorrem em zonas da linha de costa resguardadas, dentro de estuários, ao longo de margens de rios e lagoas, ou até mesmo em zonas abertas, onde a energia das ondas é baixa e a sedimentação favorável.

Esta interface entre o meio salgado e doce, sujeita a flutuações cíclicas das marés, requer adaptações específicas por parte das plantas que a colonizam. Os mangais "verdadeiros" possuem pneumatóforos (raízes aéreas capazes de trocar gases) e frutos vivíparos. Este ecossistema tem também vegetação acessória, que ocorre principalmente em zonas de transição ou perturbadas. Os mangais são capazes de armazenar carbono em grande quantidade e são zonas de elevada produtividade, favorecendo os ecossistemas vizinhos. No entanto, a cobertura deste ecossistema a nível mundial tem vindo a decrescer. Durante os últimos 25 anos perdeu-se cerca de 20% da área de mangal existente em 1980. As causas principais são atividades humanas, tais como aquacultura, agricultura, construção e turismo.

Estas florestas aquáticas reúnem requisitos para servir variados grupos animais, quer visitantes esporádicos, periódicos ou residentes. A comunidade de peixes beneficia deste ecossistema através do provisionamento de alimento, funções de viveiro, manutenção dos stocks, habitat, entre outros. A função de viveiro tem por base o suporte de uma fase do ciclo de vida de um determinado organismo, até que este migre permanentemente para o habitat favorável à sua vida adulta. Um viveiro providencia alimento, abrigo e risco de predação reduzido para as fases juvenis que o utilizam.

O presente estudo desenvolveu-se na ilha do Príncipe (São Tomé e Príncipe). Situa-se no Golfo da Guiné perto do equador, a 350km de distância da costa Africana. A sua formação vulcânica justifica o declive acentuado na maioria do território, assim como as elevadas taxas de endemismo e reduzida biodiversidade terrestre. O clima é tropical húmido e tem quatro estações climáticas, alternando entre fases mais ou menos chuvosas. No total existem sete florestas de mangal no país, quatro em São Tomé e três no Príncipe. *Rizhophora harrisonii* é a única espécie de árvore de mangal na Ilha do Príncipe.

A ilha do Príncipe tem uma área de apenas 142 km^2 com 8 000 habitantes e possui três pequenos mangais, Praia Caixão, Praia Grande e Praia Salgada. Nesta tese está integrada a descrição qualitativa destes, assim como os seus usos antropogénicos e os serviços ecossisténicos principais, resultados de testemunhos locais e descrição no terreno. A Praia Salgada é o mangal de melhores acessos da ilha e situa-se na baía Abade. Sendo o foco deste trabalho, foi neste em que se concentrou o esforço amostral na caracterização da massa de água e comunidade de peixes. O mangal da Praia Salgada é provavelmente o que tem maior pressão antropogénica, estando rodeado de terrenos de cultivo e perto da maior comunidade piscatória da ilha, que extrai tanino das árvores para tingir as redes de pesca.

O presente trabalho encontra-se dividido em três capítulos. O primeiro compreende a introdução teórica ao tema e complementos do segundo capítulo, tais como a descrição qualitativa dos três mangais da ilha e a estrutura das comunidades de *R. harrisonii*. Neste primeiro capítulo é também incluída a interpretação dos parâmetros da massa de água face às variações diárias, comparação das espécies de peixes registadas face aos trabalhos existentes para o país e a apresentação do contexto do trabalho relativamente ao estado de arte. Por sua vez, o artigo científico apresentado no segundo capítulo da tese, compreende os resultados principais deste trabalho, no formato conciso de publicação científica. O último capítulo consiste nas considerações finais da tese.

A descrição quantitativa da estrutura arbórea das comunidades de *R. harrisonii* dos três mangais da ilha revelou que o mangal da Praia Salgada é um local promissor e jovem, no qual existe uma proporção de 0,63 juvenis para cada árvore adulta. No entanto, foi também na Praia Salgada que foi registado o maior número de indivíduos com cortes devido à extração de tanino. O mangal da Praia Caixão apresentou a comunidade mais alta, envelhecida e com poucas árvores jovens. Por último, a Praia Grande teve a menor densidade e altura média e não apresentou danos antropogénicos nas árvores.

A maioria dos mangais de S. Tomé e Príncipe tem construções antropogénicas na interseção entre o mangal e o mar. Pontes e estradas costeiras restringem a dinâmica do mangal devido à facilidade de acumulação de sedimentos e obstrução das trocas de água e organismos. Estes constrangimentos podem ser ameaças graves à dinâmica do ecossistema porque alteram a circulação de sedimentos, características da água e geram ambientes mais propícios a anoxia. Durante o presente trabalho, o banco de areia que surgiu entre as duas épocas de amostragem no mangal da Praia Salgada causou alterações na dinâmica do mangal.

Os mangais de São Tomé e Príncipe permanecem relativamente desconhecidos e os estudos existentes são bastante escassos. Tendo em consideração a importância mundial dos mangais para o recrutamento de peixes costeiros, o presente trabalho teve como objetivos principais descrever o mangal da Praia Salgada, incluindo a dinâmica das massas de água; descrever a sua comunidade piscícola, nomeadamente em abundância e diversidade; e correlacionar a abundância e estrutura da população de peixes com as variáveis ambientais e avaliar a função de viveiro deste ecossistema para a comunidade de peixes. Para a obtenção de dados, o trabalho de campo envolveu duas componentes principais, a caracterização da massa de água com recurso a uma sonda multi-paramétrica, e a pesca de peixes com uma rede mosquiteira. Estas tarefas foram realizadas em duas estações do ano, chuvosa e seca, entre outubro 2019 e fevereiro 2020, com diferenciação do ciclo de maré.

O estudo dos parâmetros físico-químicos teve resultados concordantes com o expectável, onde os gradientes variam em função da proximidade ao mar e com a profundidade da coluna de água. A radiação solar, precipitação e interação entre água doce e salgada foram os fatores principais a condicionar as características da massa de água. A altura da coluna de água atingiu os seus mínimos em maré baixa de maré viva na época chuvosa. Inicialmente, esperaríamos que este mínimo fosse atingido em época seca, quando o caudal o rio fosse consideravelmente menor, no entanto, a presença do banco de areia impediu a entrada e saída das massas de água, atenuando a variação dos parâmetros físico-químicos em época seca. Relativamente à salinidade e temperatura, estes parâmetros aumentaram como expectável com a proximidade ao mar e com a profundidade na coluna de água, visto a água salgada ser um líquido mais denso devido aos sais dissolvidos, tendendo a diferenciar-se da água doce que provém de montante e é menos densa, que se diferencia para o topo da coluna de água.

As atividades de pesca resultaram na captura total de 772 indivíduos, pertencentes a pelo menos 14 espécies. A maioria destas espécies estava já registada nos mangais do país, no entanto, *Ethmalosa fimbriata*, *Mugil curema*, *Gobioides* cf. *Africanus*, *Citharus* cf. *linguatula* e *Caranx latus* são novas ocorrências para estes ecossistemas de São Tomé e Príncipe. A captura média de peixes foi diferente entre estações, sendo que em época chuvosa foram capturados 80,0 peixes por dia e em época seca 26,5. Os comprimentos dos indivíduos revelaram ser maiores na estação seca para alguns taxa, tendo os resultados sido estatisticamente significativos para Mugilidae, *Aplocheilichthys spilauchen* e Gobiidae. *Ethmalosa fimbriata* e *Eucinostomus melanopterus* apresentaram comprimentos semelhantes entre estações. A ocorrência das espécies consoante a salinidade registada foi também abordada, tendo como resultados a tolerância a salinidade zero por mais de 50% das espécies. Os indivíduos das espécies *Parachelon grandisquamis*, *A. spilauchen*, *C. latus* e *Porobogius schlegelii* ocorreram nos valores

mínimos e máximos de salinidade registados durante o trabalho de campo. A maioria das espécies observadas no mangal da Praia Salgada tem interesses comerciais, nomeadamente *E. fimbriata*, *P. grandisquamis*, *Mugil curema*, *C. latus*, *Lutjanus agennes*, *Lutjanus goreensis* e *E. melanopterus*. Todas estas foram registadas com comprimentos correspondentes ao estado juvenil, sugerindo a importância deste mangal para o recrutamento das espécies de stocks costeiros por desempenhar funções de viveiro.

Assim sendo, o presente trabalho sugere a possível contribuição de um pequeno mangal para o recrutamento de peixes, devido à sua função de viveiro. Este estudo é também o primeiro no país a comparar a comunidade de peixes e parâmetros da coluna de água entre marés e estações do ano. O mapa traçado durante este estudo, do mangal da Praia Salgada, irá permitir comparações futuras da cobertura e distribuição da floresta, sendo possível avaliar a evolução desta comunidade arbórea. Este estudo providencia assim informações que justificam a proteção deste e dos outros mangais da ilha.

Palavras-chave: lista de peixes, sistema salobro, estações, São Tomé e Príncipe, África Ocidental.

Abstract

Mangroves are remarkable ecosystems adapted to thrive in the interface between land and sea. The term refers to both the ecosystem itself and the plants' community that grows in brackish to saline tidal waters of tropical and subtropical coastlines. These highly productive ecosystems host an important diversity of associated species and provide several ecosystem services, both local and global. Not only do mangroves contain high carbon biomass, but they sequester carbon into sediments at higher rates than most ecosystems. Mangroves also act as nursery grounds for juvenile fish and shrimps. The nursery role of a mangrove consists in the provision of food, shelter, and reduced predation pressure to juvenile stages of fish species. The present work was developed in Príncipe Island, São Tomé and Príncipe. Príncipe is a volcanic island, with tropical humid climate and four seasons, alternating between heavy and moderate rains. The present work is organized into three chapters. Chapter 1 provides a theoretical framework, presents the results for the mangrove structure assessment of the three mangroves on the island, and gives the complementary results not included in the scientific article. Chapter 2 consists of the main results of the work, presented in scientific article format. Finally, chapter 3 has the final remarks. The mangrove forests in Príncipe Island are composed of monostands of *Rhizophora harrisonii* individuals and are all relatively small. The mangrove structure results revealed that Praia Salgada had the youngest community, with 0.63 juveniles for each adult tree and the highest density of trees, despite being the mangrove with the highest anthropogenic pressure. Praia Caixão had the oldest and tallest community, with little young trees. Praia Grande had the lower density and heights and no cuttings occurrences. This work focused on Praia Salgada mangrove, and the main goal was to perform a fish community assessment. The water mass parameters were measured with a multi-parameter probe, and the fish community assessed by fishing with mosquito nets. The fieldwork was divided between rainy and dry season, spring and neap tide. The water mass characteristics were affected by a sandbank that developed between seasons and conditioned the mangrove water exchange and organisms' movements between the mangrove and adjacent marine environment. The study identified 14 fish species occurring in Praia Salgada mangrove from a total of 772 catches. Five species were registered for the first time for the country's mangroves, namely *Caranx latus*, *Ethmalosa fimbriata*, *Mugil curema*, *Gobioides* cf. *africanus* and *Citharus* cf. *linguatula*. Some species revealed preferences of either the upper or lower part of the mangrove, being these patterns transient to season. The individuals' length tended to be higher during dry season. The average quantity of fish caught per day in the rainy season was three times higher than in dry season. More than 50% of the taxa showed tolerance to zero salinity conditions, and *Parachelon grandisquamis*, *Aplocheilichthys spilauchen*, *C. latus*, and *Porogobius schlegelii* occurred in the minimum and maximum range of the recorded salinities. The species with commercial interest were all registered in juvenile phases, suggesting the mangrove importance as a nursery for the young fish stages. The present study allows future comparisons of the mangrove coverage in Praia Salgada mangrove, reveals the importance of this small mangrove for the adjacent fish stocks and provides information for future sustained conservation measures.

Keywords: fish checklist, brackish system, season, São Tomé and Príncipe, West Africa.

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CHAPTER 1

General Introduction

Mangroves

Mangrove ecosystem

There is no fixed definition for the term mangrove, but several similar interpretations. "Mangrove" has been used to refer to both the ecosystem itself and the plants of tropical intertidal forest communities (Tomlinson 2016). It can be defined as an association of halophytic (salt-tolerant) trees, shrubs, and other plants colonizing brackish to saline tidal waters of subtropical and tropical coastlines (Mitsch and Gosselink 2007). Another accepted mangrove definition is "tropical trees restricted to intertidal and adjacent communities, or subject to the indirect influence of tides" (Tomlinson 2016). They thrive in areas where pure seawater is diluted by high and regular rainfall, groundwater flows and rivers (Spalding *et al.*, 2010).

Mangroves are commonly found in sheltered coastlines in tropical and sub-tropical regions (FAO 2007, Spalding *et al.,* 1997), inside estuaries, along riverbanks, lagoons and even in open coastlines, where the energy from waves is sufficiently low and suitable sediments occur (Spalding *et al.*, 2010). The mangrove vegetation grows between the low and high tide marks and the rivers' tidal margins, occupying the intertidal zone between land and sea (Paula *et al.*, 2014, Tomlinson 2016). These ecosystems occupy two separate hemispheric regions and are more abundant in the Indo-West Pacific complex than in the Atlantic Eastern Pacific complex.

These aquatic forests are the only woody halophytes that live in saltwater along the world's subtropical and tropical coastlines (Alongi 2012). These transition ecosystems balance between the terrestrial and marine habitats, receiving saltwater inputs from the ocean tides and, from the upland rivers, freshwater, sediments, nutrients, and silt deposits. In order to thrive in this habitat of cyclic changes, the plants adjusted to the environment developing specific adaptations.

Mangrove flora is composed of "true" and associated plant species. "True" or "strict" mangrove species are defined by having either or both breathing roots (pneumatophores) and a viviparous fruit (Beentje and Bandeira 2007, Hogarth 1999). The aerial roots are prepared for the salinity fluctuations, immersion and submersion in water and the cyclic changes through the tides. Furthermore, they partly stabilise the substrate and provide sediment retention. The roots exchange gases, anchorage the tree in the muddy soil and absorb nutrients. However, only "true" mangroves have developed this root system, and this can be translated through different adapting structures according to the species. The other characteristic of "true" mangroves is vivipary, which is the condition where the embryo that results from normal sexual reproduction has no dormancy but grows out of the seed coat and then out of the fruit while still attached to the parent plant (Tomlinson 2016). This organ is thus a seedling and neither fruit nor seed. Viviparous propagules lack the longevity of seeds, but most species can float and remain viable for some time, dispersing out of the mangroves with the tidal movements (Spalding *et al.*, 2010). Viviparity among seed plants is well developed only in mangroves (Tomlinson 2016).

Besides the presence of pneumatophores and a viviparous fruit, "true" mangrove species are also characterised by: (1) the exclusivity to the mangrove environment, being rarely, if ever, found elsewhere (Spalding *et al.*, 2010, Tomlinson 2016); (2) have a significant role in this community and can form pure stands (Tomlinson 2016); and (3) physiological mechanism for salt excretion or storage by ultrafiltration at the endodermis of the roots (Spalding *et al.*, 2010, Tomlinson 2016).

Mangrove associates are the plants not inhabiting strict mangrove communities and may occur only in transitional or disturbed vegetation (Tomlinson 2016). The much greater diversity of leaf's form, size, and texture is a form of distinction of mangrove associates from "true" mangroves (Tomlinson 2016).

These ecosystems often present tree species zonation, with variation in spatial patterns and dominant species. The most widely reported patterns of zonation in mangroves are profile diagrams of the vegetation parallel to the coastline (Spalding *et al.*, 2010, Tomlinson 2016). These zonation patterns are most affected by the variation in elevation, with certain species preferring locations higher in the tidal gradient, while others thrive in more prolonged inundation (Spalding *et al.*, 2010). Profile diagrams are often presented in certain mangroves studies because they constitute a particularly helpful comparison between these aquatic forests.

Due to the diversity of mangroves environments, it is challenging to establish species' succession by their relative positions regarding ecological requirements (Tomlinson 2016). Two equally precise descriptions of two mangroves can be contradictory, even in adjacent regions. This heterogeneity in mangrove zonation patterns is affected by several factors that influence species' survival and growth. These factors can be divided into abiotic and biotic. The abiotic factors are geomorphology, inundation type, salinity, and physiological responses to environmental gradients (Spalding *et al.*, 2010, Tomlinson 2016). Biotic factors are propagule sorting and competition (Tomlinson 2016). Although these patterns can rarely be extrapolated to broader areas, many authors continue to describe "typical" zonation patterns because they can be useful descriptors (Spalding *et al.*, 2010). The species' biological preferences tend to show off, even though mangroves in contrasting regions have demonstrated no constant sequence (Tomlinson 2016).

Mangrove trees are characteristic by the aerial roots that allow oxygen circulation and, together with tidal circulation, promote sedimentation and porewater oxygenation (Alongi 2012). In addition, this ecosystem is as well known by carbon sequestration. Their standing biomass can be very high due to below-ground biomass storage, even in low-stature forests (Spalding *et al.*, 2010). Mangrove forests are highly productive, with carbon production rates equivalent to tropical humid forests (Alongi 2012, Spalding *et al.*, 2010). Most carbon is stored as large pools in soils and dead roots, and these reserves favour the neighbouring ecosystems. Mangroves account for only approximately 1% of carbon sequestration by the world's forests, but as coastal habitats, they account for 14% of carbon sequestration by the global ocean (Alongi 2012). This ability to store carbon by mangroves suggests some relevance in buffering the impact of climate change and global carbon budgets, despite their small global extent.

Due to topography changes along coastlines, mangroves are not necessarily continuous over long distances, which can have significant implications for genetic exchange within mangrove species (Tomlinson 2016). If there are changes in the mangrove community even along a coastline due to isolation, the isolation factor is even more significant in islands. This study is focused on a small volcanic island, where the insular isolation is well noticed by the low diversity of terrestrial species (Kreft *et al.*, 2008).

The decrease in mangrove coverage worldwide is evident. According to UNEP (2010), mangroves cover 137 760 km^2 worldwide. However, in 2005, 152 000 km^2 of mangroves were estimated to exist worldwide, down from 188 000 km^2 in 1980 (FAO 2007). The majority of coverage is in Asia (42%), followed by Africa (20%), North America (15%), Oceania (12%), and South America (11%). Forty eight percent of the total global area of mangroves is within only five countries: Indonesia, Australia, Brazil, Nigeria, and Mexico (FAO 2007, Spalding *et al.*, 2010).

According to FAO (2007), the rate loss of mangrove area was about 1 850 km^2 every year in the 1980s. This scenario dropped to some 1 185 km^2 per year in the 1990s, and 1 020 km^2 per year during the 2000–2005 period, possibly reflecting an increased awareness of mangrove ecosystems' value (FAO 2007). These estimations suggest that during the past 25 years, about 36 000 km^2 have been lost, corresponding to 20% of the mangrove area in 1980 (FAO 2007). The leading causes of decreasing mangrove areas are human pressure on coastal regions and high competition for land from several human activities, such as aquaculture, agriculture, infrastructure, and tourism (Tomlinson 2016, UNEP 2010).

Over the last few years, however, awareness of mangrove ecosystems' importance and value has been growing, leading to the preparation and implementation of new legislation and better protection and management of mangrove resources (FAO 2007). In some countries, restoration or re-expansion of mangrove areas through natural regeneration or active planting has also been observed (FAO 2007). Many governments are also increasingly recognising the importance of mangroves to fisheries, forestry, coastal protection, and wildlife (FAO 2007). Despite these positive changes, there is still much to be done to preserve the existing mangrove forests and recover those already degraded over time.

Mangrove ecology

A wide variety of animal species inhabit mangroves worldwide. The trees' canopy is home to birds, insects, mammals and reptiles. In the water, the mangrove roots, substrate and water column host various organisms, from epibionts (tunicates, sponges, algae and bivalves) and annelids, to fishes, crabs and prawns. Some are characteristic of mangroves, like mudskippers, fiddler crabs, oysters and mud whelks. Animals using mangroves can be visitors when seen sporadically in the mangrove; associated, when utilising the community but not restricted to it; and resident, when the whole life is spent in the environment (Tomlinson 2016). Visitors can be of high frequency, for example with every flooding tide. Crustaceans and fish graze and hunt in spaces that hours before were populated with birds and insects. Ontogenetic migrations to or for mangroves also occur throughout the life cycle.

The fish community benefits from mangroves through provisioning of food, nursery functions, maintenance of stocks, complex life cycles, and other relations. Mangroves are known for being essential nursery grounds for juvenile fish and shrimps. They benefit coastal stocks by hosting the early stages of commercial and non-commercial fauna, like crustaceans, shellfish and fishes (Nagelkerken *et al.*, 2008, Spalding *et al.*, 2010, Tomlinson 2016).

Early designations of nursery habitats basically referred to habitats with high densities of juvenile animals (Nagelkerken *et al.*, 2013). Dahlgren *et al.* (2006) defined marine nursery as a "juvenile habitat for a particular species that contributes a greater than average number of individuals to the adult population on a per-unit-area basis, as compared to other habitats used by juveniles". Nagelkerken *et al.* (2013) stated that ultimately, the value of nurseries is related to their contribution to the support of populations. For an ecosystem to be considered nursery, the animal must migrate permanently from their nursery habitat to the adjacent habitat at a certain life-stage.

Nursery areas provide food, shelter and reduced predation pressure to juvenile stages. Shelter in a mangrove is provided by structural complexity, with tangling roots and water turbidity (Nagelkerken *et al.*, 2000). The predation pressure is reduced in part by providing shelter, but also due to the displacement of these biotopes from the places most frequented by predators as coral reefs and offshore waters (Nagelkerken *et al.*, 2000) and even by the exclusion of larger fishes by the shallow waters. The early stages of fish take advantages of these conditions to have a favourable and safe development.

When fishes become too large for optimal protection by the mangrove prop-roots, they often migrate to the coral reef (Nagelkerken *et al.*, 2000, 2001).

Studies have suggested this vital function of mangroves (e.g., Nagelkerken *et al.*, 2000, 2001, 2002, 2008, Naylor *et al.*, 2000, Rönnbäck *et al.*, 2002). Several fish species' densities on coral reefs appear to be related to nearby bays containing these habitats as nurseries (Nagelkerken *et al.*, 2002). About one-third of all commercial fish species worldwide are mangrove-dependent (Naylor *et al.*, 2000). Furthermore, when mangrove forests are destroyed, it often results in declines in local fish catches (FAO 2007).

Mangroves are rich in organic matter and have a food web based on detritus (Tomlinson 2016). The high rates of primary production ensure a rich source of nutrients that support the community (Spalding *et al.*, 2010), with plankton, epiphytic algae and microphytobenthos complementing this chain (Nagelkerken *et al.*, 2008). Classic older works have suggested the output of food to the adjacent aquatic environments from mangroves' high productivity, providing an important food source for secondary consumers, thereby supporting adjacent fisheries (e.g. Odum and Heald 1972). However, this hypothesis needs to be revised, since studies using natural tracer techniques have not found supportive evidence of this direct export of organic matter and litter (Nagelkerken *et al.*, 2008). The relationship of fisheries with nearby mangroves is more likely to result from provision of suitable nursery habitat, refuge from predators and provision of other food sources besides mangrove litter (Nagelkerken *et al.*, 2008).

Mangroves can be considered essential links in the chain of habitats, being the main habitat for part of the life cycle of some fish species. Complex life cycles can begin with spawning offshore by producing eggs that disperse in the water column for a certain time. Then, the eggs develop into planktonic larvae, with or without own movement, and influenced by currents are carried out into inshore and estuarine waters (Nagelkerken *et al.*, 2008). Lastly, the sub-adults or adults migrate out of the estuary or lagoon and back to the offshore areas or adjacent coral reefs (Nagelkerken *et al.*, 2008).

Environments subjected to tidal rhythms depend on factors such as duration and amplitude of the tidal inundations and connectivity among microhabitats along with diel cycles (Reis-Filho *et al.*, 2016). The fish community and its movements within the mangroves are in part related to these fluctuations (Reis-Filho *et al.*, 2016). Tidal cycles cause sequential microhabitats mainly with the raising and lowering the water level and salinity fluctuations. These periodical fluctuations make the changing ecosystem available to aquatic and terrestrial animals in alternating times. The tides have been proved to influence the migratory and fish behavioural patterns inside mangroves (Reis-Filho *et al.*, 2016).

With the cyclical expansion that the water body has in certain microhabitats in the mangroves, many species may benefit from undertaking tidal migrations among different microhabitats. These temporary migrations aim to exploit resources that may become sequentially available, for instance, along the different intertidal zones (Hollingsworth and Connolly 2006, Reis-Filho *et al.*, 2016). On the other hand, the amplitude of the tides can also be used to enter and exit mangroves.

To quantify the contribution of a mangrove to the coastal and offshore stocks, effective areas of all biotopes should be measured and the turnover rate of fishes from the mangrove to the outer environments be quantified (Nagelkerken *et al.*, 2000). The help that mangroves provide in maintaining the fish stocks is crucial to determine their value and ecological services, even if the recruitment is not quantified to the specific area. This should be considered when defining management policies, being particularly important in exploited mangroves with fishing activities and a community that depends on them, as it is the case of Príncipe Island.

Ecosystem services and anthropogenic pressures

The mangrove forests have major ecological importance, providing coastal protection and conservation of biological diversity. Moreover, humans use mangroves as direct provision sources. In a simple way, ecosystem services are defined by the benefits of nature to households, communities, and economies (Boyd and Banzhaf 2007). These services can be divided into four categories: provision, regulation, cultural, and support (categoric system according to Reid *et al.* (2005)). The main services that can be provided by a mangrove are (Reid *et al.*, 2005):

> Provisioning: wood (timber for construction, pulpwood for paper, bark extraction for pigments, and fuelwood) and non-wood products (food, e.g., crabs and shrimps), alcohol, sugar, medicine, and honey, and freshwater;
>
> Regulating: coastal protection (from frequent elements, like coastal erosion, wind, salt spray, waves, water currents, and possible extreme events, such as storms and tsunamis), climate regulation, flood regulation, and water purification (Reid *et al.*, 2005);
>
> Cultural: aesthetic, spiritual, educational, and recreational (Reid *et al.*, 2005);
>
> Supporting: nutrient cycling, soil formation, and primary production (Reid *et al.*, 2005). Many animal groups use this habitat, such as endangered species ranging from reptiles, amphibians, mammals, and birds. A wide variety of commercial and non-commercial fish and shellfish also depends on these coastal forests.

Accessing the ecosystem services provided by a habitat contributes to improving its management. To be effective, the conservation of an ecosystem must include the awareness of the people who use it or live nearby. This perception is intensely fed by the interaction man-ecosystem, as the higher the value that the people perceive in the mangrove, the higher the chance of its effective management.

In the surveys of Afonso (2019), on the peripheral communities of São Tomé's mangroves, only half of the population assumed to benefit from the ecosystem services provided by the mangroves. Even though they were able to identify seven of these services, it is still less than other peripheral mangrove communities (Afonso 2019). The study also revealed little awareness by the population to the benefits of mangroves in São Tomé Island, and the majority of the participants considered that there are no threats to this ecosystem (Afonso 2019).

No data is available regarding the Príncipe Island population awareness for the mangroves. However, during the present study, it was concluded that the direct exploration of the mangroves was just tannin extraction, fishing and shrimp farming, and all in small scales. Furthermore, within some casual conversations, it was realised that the term mangrove (in Portuguese, "mangal") was even unknown for some locals.

That being, the lack of awareness translated in the surveys from Afonso (2019) in São Tomé, combined with this unfamiliarity of the locals from Príncipe Island and its mangroves, demonstrates the importance of possible future surveys, educational and dissemination actions. The increasing popularity of ecotourism may also represent a new way of profit for local communities. Conducting the locals' earnings to conserving instead of destroying may also be an effective way of mangrove conservation. The population only takes care of what they perceive, so understanding mangroves is crucial for the conservation.

The benefits and ecosystem services provided by mangroves enhance its conservation importance. With the wrong exploitation methods and habitat destruction being the leading causes of damaging mangroves, implementing protection strategies is increasingly crucial. The destruction of this habitat has consequences for productivity, affecting the communities that rely on it. This dependency happens mostly in developing countries, whose coastal communities tend to be isolated and rely on subsistence provision of marine and coastal resources, and who are sometimes unaware of the indirect benefits that this ecosystem provides.

Study area

São Tomé and Príncipe

São Tomé and Príncipe is an insular African country composed of two main islands and several islets, and it is one of the youngest and smallest African countries. Its located in the Gulf of Guinea near the equator line and 350 km of the west coast of Africa. Its formation is volcanic and is part of the volcanoes chain known as the Cameroon line, with 1,600 km of extension, starting in the ocean in the Gulf of Guinea and extending into the African continent. This volcanic line also includes the islands of Annobón, Bioko and the Cameron Mount. This type of formation allows elevated levels of endemism of terrestrial biodiversity (Whittaker and Fernández-Palacios 2007). Due to the relatively young formation of the islands, the geomorphology is very steep. The country is covered predominantly with lush tropical forests.

São Tomé and Príncipe has a tropical humid climate, with four climatic seasons, alternating between rainier and dryer phases with different intensities. The main dry season is called "gravana" and it occurs between July and September (Chou *et al.*, 2020, Pisoni *et al.*, 2015). The second is less pronounced and occurs between January until March (Chou *et al.*, 2020). That being, the two rainy seasons are between October-December and April-June, being the first the most intense (Chou *et al.*, 2020).

Average annual rainfall ranges from 2000-3000 mm, reaching 7000 mm in the cloud forests (NBSAP II 2015, Chou *et al.*, 2020). Temperatures range from 18-21 ºC minimums to 30-35 ºC maximums (Abreu *et al.*, 2017) and with an annual average of 26 ºC (NBSAP II 2015). Rainfall varies along a northeast-southwest oriented gradient, following the distribution of the mountains (NBSAP II 2015). The air relative humidity is very high, reaching more than 90% at higher altitudes (NBSAP II 2015).

São Tomé's Natural Park Obô (PNOST), and Príncipe's Natural Park Obô were created in 2006. Some of the mangroves in São Tomé are located inside the Natural Park, which allows some degree of protection. However, none of the three mangroves in Príncipe is covered by the Natural Park. In 2012, the country inaugurated the World Biosphere Reserve of UNESCO, including the two national parks, with the main goal of enhancing sustainable development actions and promoting the well-being of its people under an ecosystem approach (Abreu *et al.*, 2017). Despite the recognised importance of the biodiversity and these parks' existence, the effective protection capacity is still very deficient, both on land and sea (Pisoni *et al.*, 2015).

The country has in total seven mangroves, four in São Tomé Island (Malanza, Praia das Conchas, Angolares, and Diogo Nunes) and three in Príncipe Island (Praia Salgada, Praia Grande, and Praia Caixão). However, in Afonso's (2019) work, a map from 1961 is referred with 12 identified mangroves in São Tomé Island, thus making the number of mangroves on the island uncertain. These aquatic forests in São Tomé can have two genera of trees, black mangroves of *Avicennia germinans* (Linnaeus, 1764) species, and the red mangroves from the genus *Rhizophora* (Afonso, 2019). On the other hand, the mangroves in Príncipe Island are composed of monostands of *Rhizophora harrisonii* individuals when it comes to "true" mangrove individuals. Although with just two families represented, these "true" mangrove species give national value for the conservation of the ecosystem.

The low diversity of the vegetation in this São Tomé and Príncipe mangroves it is explained for being in insular isolation. The islands were never connected to the mainland, resulting in significant differentiation of fauna and flora and a high degree of endemism (Bonfim and Carvalho 2009).

The Democratic Republic of São Tomé and Príncipe published in 11th September 2001 the Law nº 09/2001, referring the terms of fishing. Fishing activities are vital in the country since it represents a source of income for a large fraction of the population and a determining factor for the country's food security. In this law, artisanal and industrial fishing are subject to obtaining licenses and covered by regulations. However, in terms of the article nº 20, fishing from the margins or subsistence fishing is exempt from this licensing and regulations. That being, fishing inside mangroves is allowed in São Tomé and Príncipe if from the margins or for subsistence purposes.

Príncipe Island

Príncipe Island has a surface area of 142 km^2 and the highest mountain is Pico do Príncipe, with an altitude of 948 m (Abreu *et al.*, 2017). Being a small island with high forest cover, the population consists of only about 8,000 people, mostly inhabiting along the coast. The population earns their living mainly extracting natural resources and a small but responsible ecotourism sector (Abreu *et al.*, 2017). The inhabitants of Príncipe are spread over the northern zone, concentrating mainly on the only city, Santo António. The southern part of the island is entirely a natural reserve.

The island has three small mangroves: Praia Grande, Praia Caixão and Praia Salgada. They occupy in total approximately 1.6 ha, distributed in major watercourses (Herrero-Barrencua *et al.,* 2017, Vaz and Oliveira 2007). None of the three mangroves areas are exposed directly to the sea, being all located behind a beach that provides protection from sea erosion. The water exchanges, mainly due to the effect of the tide and river flow, take place through small singular mouths. Príncipe Island's population uses the mangroves for two main purposes: tannin extraction and fishing. The uses of these resources are referred to in detail within each mangrove's section presented below.

Praia Caixão mangrove

The Banzú river flows to the west of the island and opens to the sea in Praia Caixão, where a well-developed mangrove forest is present (see Fig. 1.1). The São Joaquim and Praia da Lapa are the nearest communities, extracting resources from the area. At its mouth, the estuary has the remains of a bridge, where its old wide cement posts constrain the water exchanges and promote moderate sediment accumulation.

The primary resources exploited are wood, fish, shrimp aquaculture and tannin extraction. Fishing activities within the estuary are mainly carried out by children in the shallow areas, capturing during low tide small Gobiidae by revolving the rocks. The fish caught are primarily *Eleotris annobonensis*, a brackish and demersal fish also reported in São Tomé mangroves by Félix *et al.* (2017) and Pisoni *et al.*

(2015), and is used by locals for deep frying. Regarding aquaculture, there is a small activity on the upper part of the mangrove. The technique is very artisanal, consisting of catching small shrimps, storing them in traps and then wait for them to grow in the natural habitat.

The mangrove is dense, with higher epiphytic vegetation comparing with the mangroves of Praia Salgada and Praia Grande. However, the mangrove trees are larger and older, with fewer propagules and young trees, and more stumps and cut logs showing some human pressure.

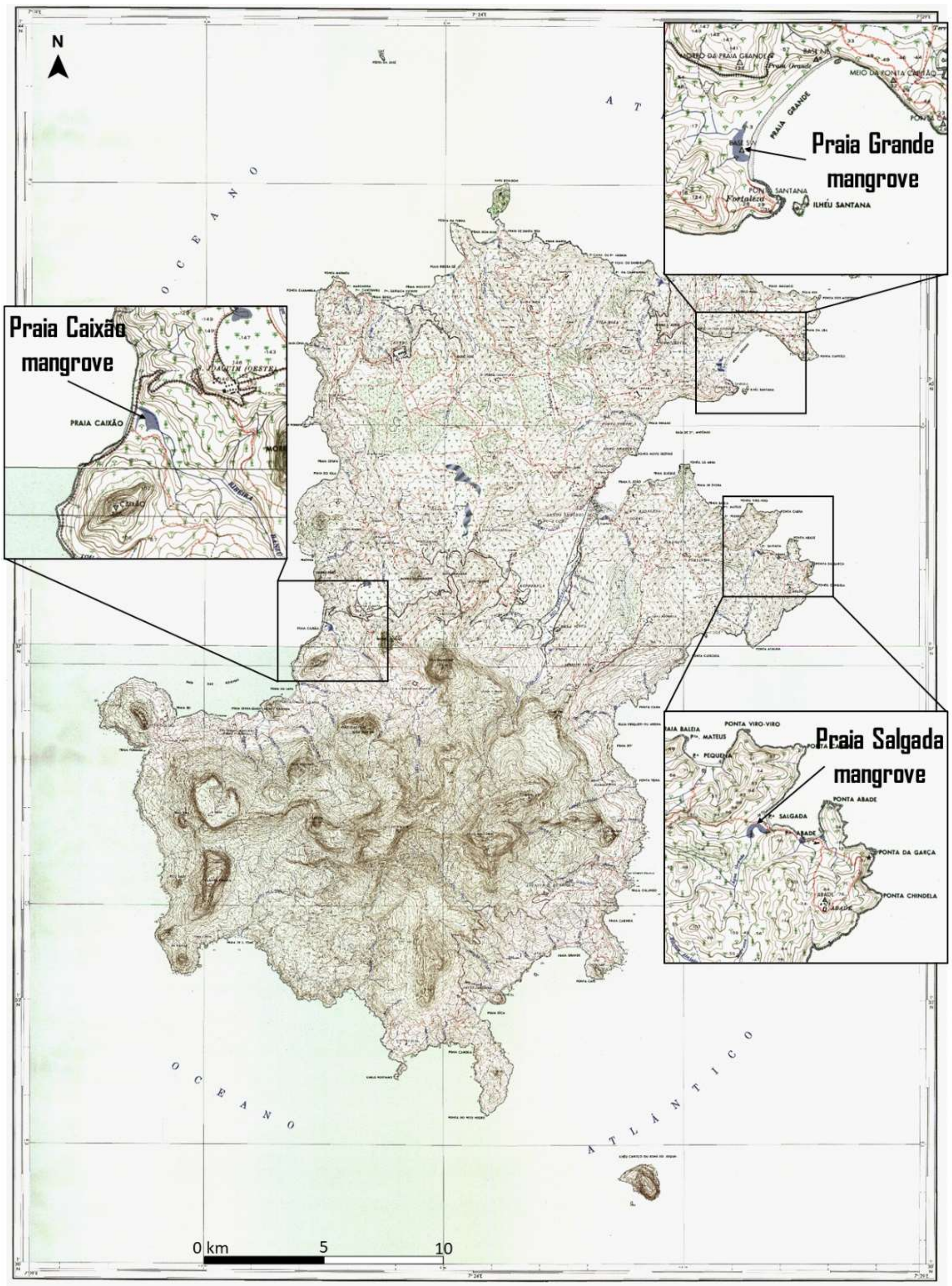

Figure 1.1. Location of the three mangroves in Príncipe Island, São Tomé and Príncipe. Image constructed from a 1961 map.

Praia Grande mangrove

In Praia Grande Bay, northeast of the island, a mangrove patch is constrained inside the lagoon protected by the beach (see Fig. 1.1). It is a very small forest with just a few trees of *R. harrisonii* in a cluster and a few others distributed on the marginal vegetation throughout the lagoon. The lagoon flows are in part controlled by the local fishermen. When children start to catch grown-up fish, they consider it is time to open the lagoon to the sea, filtering the water flow with nets and catching everything passing through it. Therefore, the lagoon can be open and closed either due to natural processes (such as heavy rains) or because fishers open it to harvest the fish. Praia Grande mangrove is the one with the most challenging access on the island. Consequently, there are no reports of tree bark extraction for tannin in this forest.

Praia Salgada mangrove

The most accessible mangrove on the island is Praia Salgada, located in Abade Bay, east of the island (see Fig. 1.1). The bay is relatively shallow with a maximum depth of 17 meters (Herrero-Barrencua *et al.*, 2017), low in hydrodynamics, and moderately polluted with trash accumulated in the bay. Inside the bay, the water is not crystal-clear comparing with the rest of the island. The turbidity is mainly due to siltation and sediments brought from the river Água Grande, adding up with the low water renewal due to the closed configuration of the bay. The local community from Praia Abade village resort to this river to wash clothes and dishes, an activity that they prefer to do in streams closer to the village when these are not dry. In the rainy season, the flow increases considerably, bringing large quantities of organic matter to the sea.

Coastal erosion is evident in Praia Salgada. Sand extraction for construction purposes accelerated the process, causing the fall and disturbance of most palm trees on the beach and on the mangrove forest's inner margins. The sand extraction exposes once covered areas and changes the geomorphology of the mouth of the estuary.

Despite the pressures subjected to the mangrove, some evidence suggest that Praia Salgada mangrove is expanding. The lack of data and records about the mangrove limits this assessment, but the local's testimonials confirm the positive changes in the aquatic forest. Adding to this, the health of the mangrove's vegetation is well noted, with young trees isolated and in the peripheries of the clusters, with new areas being colonised with *R. harrisonii* individuals.

Praia Salgada is probably the most used mangrove on the island. It is easily accessible from the city due to the existence of a road that connects them, and the Abade community is only at 400 meters distance, with the surrounding areas with several small farms for local livelihoods. Abade also represents the largest fishermen community of Príncipe Island, justifying the several cuts and peels in *R. harrisonii* trunks for extracting the pigment to tan fishing nets. This mangrove's primary uses are tanning of fishing nets, firewood for charcoal, and fishing. Like Praia Caixão, children are the only anglers in Praia Salgada's mangrove creeks, fishing with line and hook.

The tannin is extracted by peeling the outer part of the tree trunk, boiling the peels in water, and pouring the solution into the nets, letting it sit for a day (Fig. 1.2). The nets end up dark red, making them apparently seamless for the fish. According to the locals, each net needs peels from 2-3 trees and is submitted to this treatment once a year. In perspective, it is a better and cheapest alternative comparing to import and use chemical tanning. When bark extraction is very invasive, extensive and profound, the tree's survival is jeopardized. However, with the right method, the mangrove as a whole is not apparently significantly harmed. Therefore, the knowledge and technique sharing in the community are crucial to guarantee the correct extract of the peels, that as shown on site, it is possible to perform without killing the tree.

In the past, the extraction of these pigments was more intense worldwide. However, the emergence of industrial development of synthetic or more accessible alternatives led to the disuse of this resource (Tomlinson 2016). The production of artificially dyed nets and paints is relatively recent, and in a small and isolated island like Príncipe are not relevant due to the difficulty in accessing them.

Figure 1.2. The use of tannin pigment to paint fishing nets in the Abade community. **A –** *R. harrisonii* tree after intense bark extraction; **B –** fishing nets freshly painted.

Most of the mangroves in São Tomé and Príncipe have bridges near the mouth for coastal roads (Félix *et al.*, 2017, Haroun *et al.*, 2018, Pisoni *et al.*, 2015). These constructions restrict the water flows between the mangrove and the adjacent marine environment. The obstruction of water exchanges can be severe compared to other threats like fishing, extraction of bark from trees, and soil use. It consequently alters the circulation of sediments and thus erosion and deposition patterns, and ultimately the movement of organisms between the mangrove and the ocean (Pisoni *et al.*, 2015). Pisoni *et al.* (2015) considered these obstructions the most significant anthropogenic factor degrading mangroves in São Tomé. The lack of water flow limits the mangrove's natural dynamics by promoting stratification and hypoxia, retaining organic matter, nutrients and phytoplanktonic biomass, and ultimately facilitating fishing catches in the narrow connection (Félix *et al.*, 2017, Pisoni *et al.*, 2015).

A restriction in the circulation of a freshwater flow can lead to the accumulation of sediments (Nowicki and Nixon 1985). During the present work field campaigns, it was observed sediment accumulation in Praia Salgada mangrove during dry season, enhanced by the bridge and giving a different topography in the estuarine mouth area. The sandbank developed between December and January and increased until February, severing obstructing the exchange of water and organisms by sediment accumulation (Fig. 1.3). In addition, the sandbank caused the water level rise in the mangrove creek sampling points (Fig. 2.4), which may be related with the decrease in the number of fish captures during the fieldwork during the dry season (see Chapter 2).

Praia Salgada's mangrove has associated biodiversity with some characteristic species of West African mangroves, such as the Atlantic mudskipper *Periophthalmus barbarus*, the fiddler crab *Afruca tangeri*, the mud creeper *Tympanotonos fuscatus*, and the hooded oyster *Saccostrea cucullata*. This mangrove also has a high diversity of birds, being visited by terrestrial and sea birds due to its transitional environment. Apart from the most evident organisms to the human eye, the muddy water hides this work's focal point - the ichthyofauna.

Figure 1.3. Comparison of the estuarine mouth aspect between seasons. **A –** rainy season, low tide, with little sand on the area and bottom rock visible, channel width about 3 meters, November 2019; **B –** dry season, low tide, with the presence of the sandbank, channel width about one meter and very shallow, January 2020.

Mangrove community and structure at Príncipe Island

As referred earlier, the mangrove forests in Príncipe Island are composed of monostands of *R. harrisonii* individuals when it comes to "true" mangrove individuals. The genus *Rhizophora* is known to have several hybridisation cases, as for example *R. harrisonii* Leechman 1918 (Beentje and Bandeira 2007, Spalding *et al.*, 1997, Tomlinson 2016). This species is considered a hybrid between *R. mangle* and *R. racemose*, presenting intermediate morphology, a high degree of sterility, and overlapping geographic range (Tomlinson 2016). It is morphological distinct by its many-flowered inflorescences with blunt or rounded flower buds (Tomlinson 2016).

Its distribution comprehends the West coast of Africa, between Senegal and Angola and it is also present in America, on some countries of the Caribbean Sea and in Peru (Tomlinson 2016). This genus is non-native in Indo-West Pacific, and its presence is due to introductions during the last century (Duke and Allen 2005).

The Family Rhizophoraceae is commonly referred to as red mangroves. They are considered the most important and dominant mangrove species in the Atlantic Ocean's tropical coastal areas (Duke and Allen 2005). The genus is considered medium to tall and can reach 30-50 m of height, although they are commonly much shorter (Duke and Allen 2005). Red mangroves are often multi-stemmed and their roots sturdy, even when relatively thin. The flowers are located within or below leaf axils, and the leaves are opposite, simple and obovate and with a generally curved surface (Duke and Allen 2005). The similar appearance of leaf's form, size, and texture is an indication of a "true" mangrove species (Tomlinson 2016). Being a viviparous tree, the dispersal unit is the already germinated seed while the fruit is still attached to the parent plant. One viviparous seedling is produced from each fruit, although twins may be observed on rare occasions (Duke and Allen 2005).

The annual reproductive cycle of *R. harrisonii* has its flowers starting to develop from late September and October, and the viviparous fruit starts to come out in late November, becoming ripe in February-March (Hauron *et al.*, 2018). The propagules detach from the mother tree mainly in April (Hauron *et al.*, 2018). The species' dispersion mechanism can be in the long-range, but the most common is short-range, where the propagules settle close to their parent plants (Spalding *et al.*, 2010). A propagule can travel miles offshore floating with the currents, but at the opposite situation, it can stick in the soil when it falls from the tree. Although most viviparous propagules lack the seeds' longevity, *R. harrisonii* propagules proved to remain viable for over a year while in saltwater (Spalding *et al.*, 2010). This dispersion ability was probably crucial for the colonization of Príncipe Island, as only taxa with the ability to undertake long-distance dispersal can access remote islands (Gillespie *et al.*, 2012).

Figure 1.4. *R. harrisonii* community in Praia Salgada's mangrove.

Mangrove structure

The tree structure of the three mangrove forests in Príncipe Island is described in this section and complements the qualitative description already presented in sub-chapter "*Príncipe Island*". The data was collected during October 2019 and is being processed for publication, including the historical use of mangrove goods and services in Maputo Bay and Príncipe Island (Machava-António *et al.*, unpublished).

The forest structure was sampled using 10 x 10 m square plots randomly deployed, following standard field protocols (Bandeira *et al.*, 2009, Kauffman and Donato 2012, Macamo *et al.*, 2018). Tree height was estimated by eye and diameter at breast height (DBH) measured with a tape. All individuals with DBH superior to 2.5 cm were considered as adults. The adult trees were distributed in 4 categories: (1) intact, if the tree has no sign of cut; (2) partially cut, when some branches are cut (less than 50% of the canopy); (3) severely cut, when most of the branches have been cut (more than 50% of the canopy); and (4) stump, when the main tree has been cut.

In Príncipe Island, the mangrove trees are not used as sources of wood for construction. That being, the morphology of the tree was not approached. To assess if the trees are straight and can be used for construction without modification is more important in countries that use the resource for this purpose, such as in Mozambique.

The characterisation of the study areas revealed no variation on the soil characteristics, being always classified as mud and intermediate. The flood class sums up to all neap tides for Praia Salgada and Caixão, and spring tides/big spring tides for Praia Grande. The coverage percentage was estimated by eye for each sampling plot. The results were 81-100% in all plots for Praia Salgada and Caixão, and in Praia Grande 81-100% for plot 1 and 0-20% for plots 2 and 3. As mentioned before, all trees in Príncipe Island mangroves belong to the same species, *R. harrisonii*.

Praia Salgada revealed to be a site in possible expansion that presented a proportion of 0.63 juveniles for each adult tree and the higher density of the three mangroves studied (Table 1.1.), despite the tannin extraction pressure. Here, the forest margins were dominated by juveniles, and local testimonies confirm the mangrove recent expansion. However, this mangrove had the highest proportion of damaged trees and was the only with severely cut occurrences (Fig. 1.3). Praia Salgada is close to the Abade community, the largest fishing community on the island, consequently having the greatest pressure for tannin extraction.

The mangrove with the highest mean heights and DBH was Praia Caixão (Table 1.1). This is concordant with size-structure because this mangrove had the most aged *R. harrisonii* population, with the proportion of only 0.01 juvenile individuals for each adult tree. The intensity of cut trees in this mangrove is smaller but present (Fig. 1.5).

Praia Grande was the smallest mangrove, presenting the lowest density values (Fig. 1.5), lower DBH and height (Table 1.1.). Results of few juveniles and low height adults suggest few expectations to this mangrove's future, showing no signs of growth. However, the lack of records of the history of the forest makes these predictions uncertain. Praia Grande did not present any cutting occurrences, probably for being far from communities, with few trees and difficult access.

Table 1.1. Structural parameters of the mangrove tree *R. harrisonii* according to the location. N = number of adults + juveniles sampled; Q = number of sampled quadrats. Basal area = π.DBH^2. Means ± Std Error. Mean DBH and adult density had in consideration the stumps, whereas the mean height did not.

	Praia Salgada	**Praia Caixão**	**Praia Grande**
	N = 168 + 106 Q = 5	N = 103 + 11 Q = 4	N = 20 + 4 Q = 3
DBH (cm)	10.2 ± 0.9	13.8 ± 0.9	4.7 ± 0.5
Height (m)	8.9 ± 0.3	11.8 ± 0.5	8.7 ± 0.8
Adult stem density (ind/ha)	3360.0 ± 603.8	2625.0 ± 839.0	666.7 ± 517.5
Juvenile stem density (ind/ha)	2120.0 ± 869.7	275.0 ± 242.8	133.3 ± 133.3

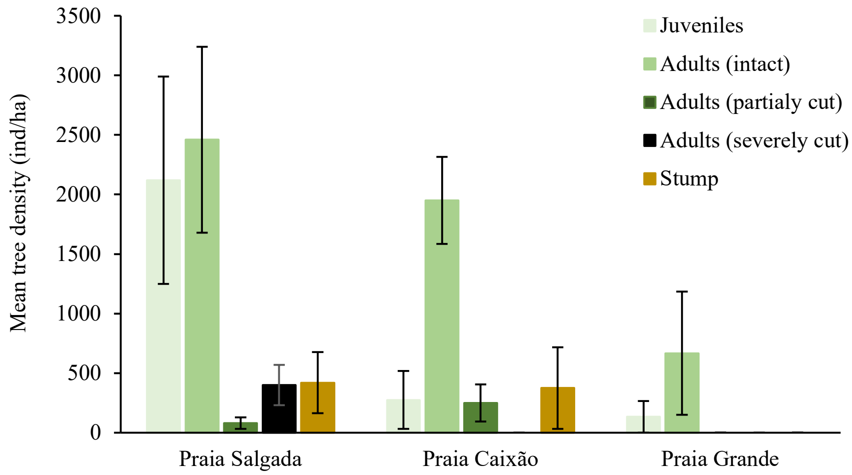

Figure 1.5. Mean density of *R. harrisonii* individuals of each condition per site. Error bars: ± SE.

Water mass and fish communities at Praia Salgada

Water mass parameters

Regarding the water mass parameters, the results presented in Chapter 2 are the mean of triplicate days for each of the four season-tide situations (Figs. 2.4, 2.5 and 2.6). This approach dissolves some important evidence due to the individuality of each day. The mangrove water conditions vary depending on the rains, solar radiation, and other daily stochastic factors. Each day's temperature and salinity graphs are presented in Fig. 1.6, allowing the interpretation of daily variances inside each season and tide situations for Praia Salgada mangrove.

A saline wedge was detected in the data presented in Chapter 2 during rainy season and neap tide situation (Fig. 2.5). However, it varies daily (Fig. 1.6). The first day of the rainy season neap tide (day 1, Fig. 1.6) was the single occasion with no salinity at all. In the other two days of rainy season neap tide (days 5 and 6, Fig. 1.6), the saline wedge is evident between the middle and lower sampling points for low and high tide. The other day that recorded the saline wedge between the same points, was day 12 (Fig. 1.6), in dry season neap tide for low and high tide. For the rest of the sampling days, the saline wedge is upper relatively to the sampling points, so it is not recorded in the results.

The pattern of increasing temperature and salinity with proximity to the sea is noticeable in the results. However, when each day's particularity is taken into consideration (Fig. 1.6), the days 1 and 11 do not show this pattern, looking like a homogeneous water column along these four points in the mangrove creek.

The other two existing works with water mass measurements in mangroves are Pisoni *et al.* (2015) and Herrerero-Barrencua *et al.* (2017) for São Tomé and Príncipe, respectively. These two works were developed in September-December of different years, including only the rainy season also approached in the present work. The top and bottom of the water column were differentiated. However, little comparison is possible since those studies did not distinguish tidal situations, such as high and low or neap and spring tide. Despite these differences, the water mass measurements reported on those two studies are within the same range of the results reported in this study and with similar variation patterns.

Pisoni *et al.* (2015) has also recorded salinities of 0 PSU and temperatures of 28 ºC in Praia das Conchas, a small mangrove comparable to the ones in Príncipe. However, the tides are not distinguished for the data. Throughout Malanza mangrove, Pisoni *et al.* (2015) also stated the same gradients as the present work. Lower salinities are associated with superficial waters and upper mangrove zones. Higher salinities are related with deeper waters and closer to the sea interception. In Herrero-Barrencua *et al.* (2017) report, the results also show higher salinities and temperatures in the lower sampling points of the three mangroves in Príncipe.

Therefore, the present thesis is the first field assessment for the country's mangroves that differentiates high tide from low tide; neap tide from spring tide; and rainy season from dry season. This approach revealed interesting patterns that characterise this ecosystem's variance in daily, monthly and seasonal factors. Besides, even within the same conditions of tides and season, it was observed different water mass conditions (showed in Fig. 1.6), where each line of graphs has three days in the same situation, revealing similar but different patterns.

Fish species richness

The main assumptions on the recorded fish species were already integrated within the article presented in Chapter 2. However, a more comparable an extended approach is possible with the data presented in Table 1.2, which resumes the species reported until today in the country mangroves, differentiating the studies. Despite the fish species richness obtained in this study being similar with the other studies in the mangrove's country (Table 2.4), they do not correspond precisely to the same species, as seen in Table 1.2.

This study reported at least 14 species to 772 individuals. The number of captures is high comparing to the low species diversity. This may mean that the accumulation curve of species reported in function of the sampling effort reached the limit. These results also reveal the expected low diversity of fish species in this insular and small mangrove.

The species *Elops senegalensis*, *Plectorhinchus macrolepis*, *Galeoides decadactylus, Monodactylus sebae*, and *Bostrychus africanus* were all reported in the other works species lists and considered expected in this work (Table 1.2). However, the present study did not register them on Praia Salgada mangrove. The extended fieldwork and inclusion of two seasons can indicate that maybe these species do not use Praia Salgada mangrove, are very rare to find or the technique used is not the adequate for their capture. When comparing the techniques by Félix *et al.* (2017), these specific species were all captured with gill nets, cast nets and seine nets, revealing that the technique is similar to this study and may not be a justification for not recording the species.

The present thesis is the first to record the species *Mugil curema* in the country. However, other works have reported *Liza dumerili* instead (Table 1.2). This situation may require confirmation since the present work had an extent field assessment, were out of 772 individuals captured, *Liza* sp. individuals were never recorded. *Parachelon grandisquamis* is common to all publications.

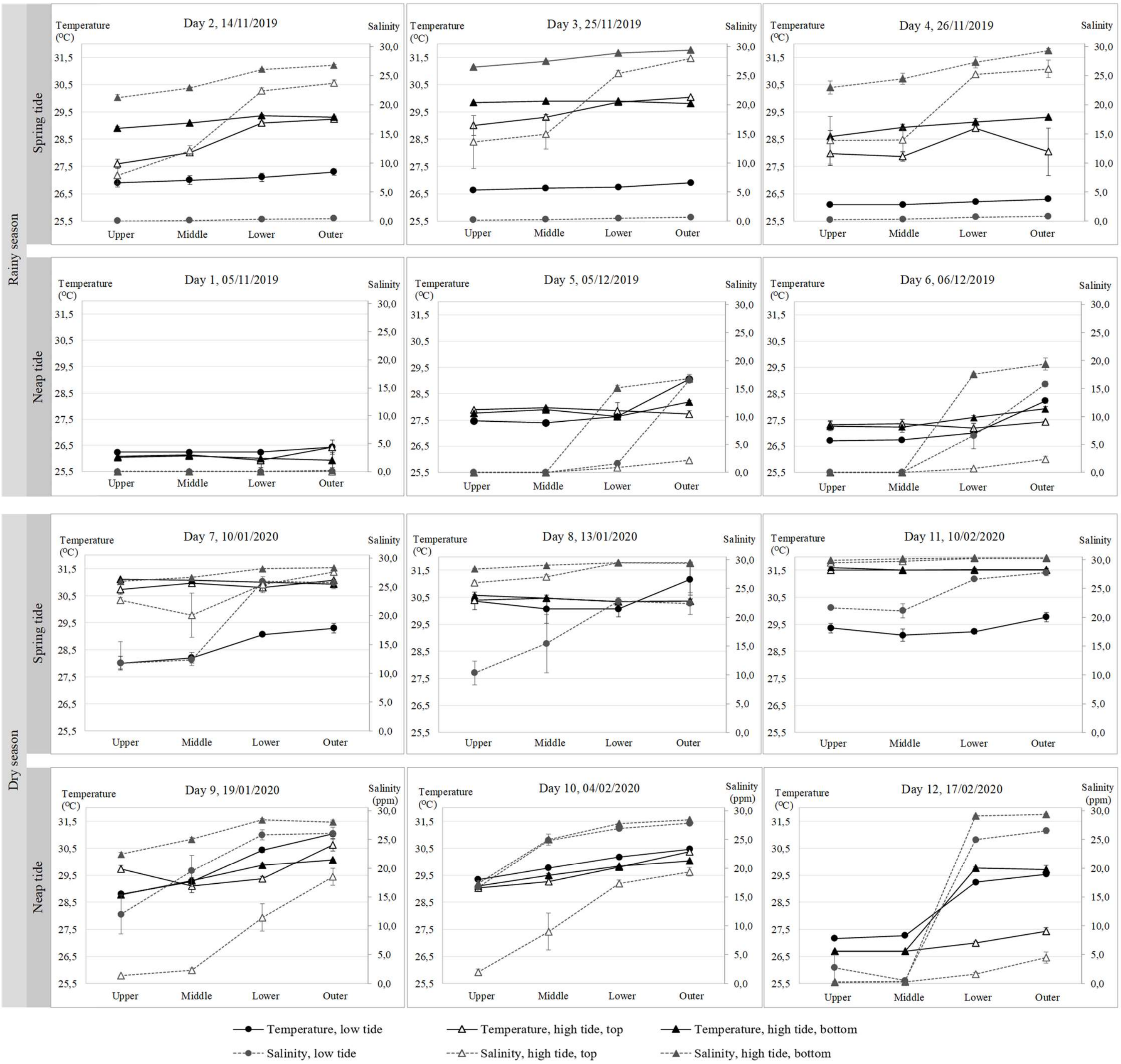

Figure 1.6. Temperature and salinity at the four study sites of the mangrove (upper, middle, lower, and outer) during rainy and dry seasons and spring or neap tides. Each graph corresponds to one day. The points represent the average temperature (black) or salinity (grey) of the triplicates measurements at each site for each tidal situation and respective standard error.

Table 1.2. Comparable table for the fish species reported in the different works published for the mangroves of São Tomé and Príncipe. Taxa ordered according to Nelson (2006). NA – non available data. ✓ - species reported in the correspondent publication. ✓* - not considered for species richness count.

			São Tomé	São Tomé	Príncipe	São Tomé and Príncipe	Príncipe (Praia Salgada)
Scientific name	**Common name**	**Family**	Pisoni et al, 2015	Félix et al, 2017	Herrero-Barrencua *et al.* 2017	Haroun *et al.*, 2018	**Present work**
Elops senegalensis	Colepinha balabo	Elopidae	✓	✓	✓	✓	
Megalops atlanticus	Taínha congo	Megalopidae	✓	✓		✓	
Megalops cf. *atlanticus* (larva)	-						✓
Dalophis cephalopeltis	-	Ophichthidae	✓	✓		✓	
Ethmalosa fimbriata	Sardinha	Clupeidae					✓
Clupeiforme (larva)	-						✓*
Liza dumerili	Taínha	Mugilidae			✓	✓	
Parachelon grandisquamis	Taínha		✓	✓	✓	✓	✓
Mugil curema	Taínha						✓
Mugilidae	Taínha		✓	✓			✓*
Platybelone sp.	Agulha	Belonidae			✓		
Aplocheilichthys spilauchen	Tose-tose	Poeciliidae			✓	✓	✓
Microphis aculeatus	Agulha	Syngnathidae	✓	✓			✓
Caranx latus	Corcovado	Carangidae					✓
Caranx sp.	Corcovado		✓	✓			
Lutjanus agennes	Corvina preta	Lutjanidae	✓	✓	✓	✓	✓
Lutjanus cf. *griseus*	Corvina		✓	✓			
Lutjanus endecacanthus	Corvina preta		✓	✓		✓	
Lutjanus goreensis	Corvina-vermelha		✓	✓		✓	✓
Lutjanus spp.	Corvina			✓*	✓*		
Eucinostomus melanopterus	Parente	Gerreidae	✓	✓	✓	✓	✓
Plectorhinchus macrolepis	Peixe-porco	Haemulidae	✓	✓	✓	✓	
Pomadasys jubelini	Roncador		✓	✓		✓	
Pomadasys sp.	-				✓		
Galeoides decadactylus	Barbudo	Polynemidae	✓	✓	✓	✓	
Monodactylus sebae	Cozinheiro	Monodactylidae	✓	✓	✓	✓	
Kyphosus incisor	Sopa	Kyphosidae	✓	✓		✓	
Oreochromis mossambicus	Papê	Cichlidae	✓	✓		✓	
Arnoglossus imperialis	Peixe chato	Bothidae			✓		
Bostrychus africanus	Xarroco-cherne	Eleotridae	✓	✓	✓	✓	
Eleotris annobonensis	Xarroco-cherne		✓	✓			
Awaous bustamantei	Xarroco	Gobiidae		✓		✓	
Awaous lateristriga	Xarroco		✓	✓		✓	
Bathygobius burtoni	Xarroco		✓	✓		✓	
Porogobius schlegelii	Xarroco-blabo		✓	✓		✓	✓
Periophthalmus barbarus	Cocumba		✓	✓	✓	✓	✓
Gobioides cf. *africanus*	-						✓
Gobiidae	-						✓*
Citharus cf. *linguatula*	-	Citharidae					✓
		Species Richness	24	25	14	22	14
		Nº individuals captured	NA	229	NA	NA	772

Work context

The work developed during this thesis is part of the project COBIONET - *Coastal biodiversity and food security in peri-urban Sub-Saharan Africa: assessment, capacity building, and regional networking in contrasting Indian and Atlantic Oceans*. The project main objectives are the assessment of biodiversity and ecosystem condition and their relation to stability of resources, optimized processes for ecosystem rehabilitation, establishment of biodiversity online repositories, and direct impacts on scientific and coastal communities derived from networking, capacity building and dissemination actions.

Apart from the fieldwork developed to the study of Praia Salgada mangrove, other studies were performed within the project activities, such as assessment of the structure of the three mangroves in Príncipe (results presented above), development of the first biodiversity marine collection in Príncipe Island, and a nursery of *R. harrisonii* in Praia Salgada mangrove.

The mangroves of São Tomé and Príncipe are poorly described. Until today, only five works have been published regarding these ecosystems, of which two addressed the fish community with fieldwork assessments. In São Tomé Island, the report by Pisoni *et al.* (2015) had the primary goal of providing preliminary information for the definition of the management plans for Malanza and Praia das Conchas mangroves. In this study, the main outputs were mapping, biodiversity characterisation, ecosystem services assessment, and significant threats identification. Sharing the same data of Pisoni *et al.* (2015), Félix *et al.* (2017) focused on the ichthyofauna of those two mangroves in São Tomé, being the first study to record fish species in the insular tropical mangroves of the country.

The only existing work for mangroves in Príncipe Island is the report by Herrero-Barrencua *et al.* (2017), where they defined and characterised the three mangrove ecosystems on the island. Although the authors presented faunal lists and the mangrove flora associated with the mangroves, there was little emphasis on the ichthyofauna. The referred works (Félix *et al.*, 2017, Herrero-Barrencua *et al.*, 2017, Pisoni *et al.*, 2015) characterized the water column, namely depth, salinity, dissolved oxygen, temperature, nutrients and metals concentration, as well as sediment granulometry and phytoplankton. The only studies with fieldwork on fish published, Pisoni *et al.* (2015) and Herrero-Barrencua *et al.* (2017), have the season in common. In both situations, the fieldwork was in the rainy season from September until December. Haroun *et al.* (2018) has a more holistic approach, including the mangroves of both islands and compiling the existing information. They listed the major botanical and faunal species and described some ecosystem services for all mangroves as a whole. Afonso (2019) further studied the ecosystem services of three mangroves in São Tomé island.

The existing works have all in common a limited period of sampling, and in fact were performed during the same months, unable to detect possible mangrove seasonality. The continuity of studies regarding fish community assessment is crucial to the country. The lack of knowledge regarding fishing resources makes very difficult to implement grounded sustainability measures, as Vaz and Oliveira (2007) also stated.

Objectives

This work aimed to study the Praia Salgada mangrove and assess its potential role as a nursery for the fish community.

The specific objectives are:

a) To describe the mangrove environment, including water mass dynamics and mangrove tree cover;
b) to describe the fish fauna, namely abundance and species richness;
c) to correlate the fish abundance and size-structure with environmental variables and assess the mangrove's nursery role for fish populations.

Methodologic approach

The present dissertation comprises a general introduction (Chapter 1), presenting the framework to the theme and the complementary results obtained during the research and not included in Chapter 2. Chapter 2 consists of the article "Fish assemblages at Praia Salgada mangrove, Príncipe Island (Gulf of Guinea)", which will be submitted soon to the peer-review in the scientific journal *Marine and Freshwater Research*.

The main focus of this thesis is the Praia Salgada mangrove. This site was chosen from the three existing mangroves in Príncipe due to the easy access and presence of a nearby fishing community. The forest structure was assessed for all three mangroves. However, the fish community and water mass assessment, being the central part of the work, was performed only in this specific mangrove.

The present work had field assessments from October until February, including two seasons. The rainy season was studied between 22nd October and 6th December 2019 and the dry season between 10th January and 17th February 2020. In each season, water mass parameters were measured during high and low tide during both neap and spring tidal periods. Sampling for fish assessments was made in the same periods. The organisms collected for conservation purposes were stored in museums: some were deposited on the first natural history collections of Príncipe Biosphere Reserve; and others were deposited on the National Museum of Natural History and Science (MUHNAC).

CHAPTER 2

Fish assemblages at Praia Salgada mangrove, Príncipe Island (Gulf of Guinea)

Fish assemblages at Praia Salgada mangrove, Príncipe Island (Gulf of Guinea)

Cravo, M[1,*], A. J. Almeida[1], H. Lima[3], J. A. Silva[1], S. Bandeira[4], V. Machava[4] and J. Paula[1,2]

[1] Department of Animal Biology, Faculty of Sciences, University of Lisbon, Campo Grande, 1749-016 Lisboa, Portugal
[2] MARE (Marine and Environmental Sciences Centre), Faculty of Sciences, University of Lisbon, Campo Grande, 1749-016 Lisboa, Portugal
[3] Príncipe Island UNESCO Biosphere Reserve, Autonomous Region of Príncipe, Santo António City, São Tomé and Príncipe
[4] Department of Biological Sciences, Eduardo Mondlane University, Maputo, Mozambique
[*]Corresponding author: marianamartinscravo@gmail.com

Abstract

Mangroves are highly productive ecosystems with complex adaptations to the transition between freshwater and sea. Mangroves function as nursery habitats for many organisms, providing protection and food sources for early developmental stages of crustaceans and fish, helping to maintain adjacent marine stocks. Mangroves in São Tomé and Príncipe remain poorly studied. This study approaches the importance of a small mangrove to the ichthyofauna. The main goal was to describe the fish assemblages of Praia Salgada mangrove on Príncipe Island and assess its nursery role. Fish assemblages were sampled during rainy and dry seasons, and neap and spring tides with mosquito nets. Water mass parameters were also described with water column depth, temperature, and salinity measurements. The water column mass characteristics were affected by a sandbank that developed between sampling seasons, which affects the dynamics of the water and biological exchanges between the mangrove and the adjacent marine environment. The study identified 14 fish species occurring in Praia Salgada mangrove from a total of 772 catches. Five species were registered for the first time for the country's mangroves, namely *Caranx latus*, *Ethmalosa fimbriata*, *Mugil curema*, *Gobioides* cf. *africanus* and *Citharus* cf. *linguatula*. Most of the reported species have commercial interest, and their fish life stages were predominantly juveniles, suggesting that the mangrove ecosystem provides a nursery function for several species. Some species revealed preferences of either the upper or lower part of the mangrove, being these patterns transient to season. The individuals' length tended to be higher during dry season, being significant to Mugilidae, *Aplocheilichthys spilauchen* and Gobiidae groups. The species *Ethmalosa fimbriata* and *Eucinostomus melanopterus* had similar sizes between seasons. The average quantity of fish caught per day in the rainy season was three times higher than in dry season. More than 50% of the taxa showed tolerance to zero salinity situations, and *Parachelon grandisquamis*, *A. spilauchen*, *C. latus*, and *Porogobius schlegelii* ocurred in the minimum and maximum range of the recorded salinities.

Keywords: fish checklist, brackish system, season, São Tomé and Príncipe, West Africa.

Introduction

Mangroves are defined as tropical trees restricted to intertidal and adjacent biological communities or subjected to indirect tidal influence (Tomlinson 2016). According to Alongi (2012), these ecosystems are true ecotones, having some marine and terrestrial biomes' components. Mangrove environments have unique characteristics, both environmental and biological, attracting high biodiversity and providing important ecological services.

These aquatic forests benefit coastal stocks by supporting early stages of commercial and non-commercial fauna, like crustaceans, molluscs, and fishes (Tomlinson 2016). Mangroves supply food sources mainly via the detritus chain (Tomlinson 2016) and provide shelter by the complex tangling of roots and water turbidity. Young stages of fish take advantage of these conditions to have favourable and safe development. Several fish species' densities on coral reefs appear to be related to nearby bays containing mangroves functioning as nurseries (Nagelkerken *et al.*, 2002). In addition, when mangrove forests are destroyed, it often results in declines in local fish catches (FAO 2007).

Besides the nursery function of mangroves, breeding, and feeding areas for juvenile fishes, other ecosystem services are provided. These transition ecosystems provide shoreline protection, wood and non-wood provisioning products, climate regulation, water purification, cultural services, and several ecosystem supporting benefits such as nutrient cycling, soil formation, and primary production (MEA 2005).

São Tomé and Príncipe is an insular African country composed of two main islands and several islets. Its formation is volcanic and is part of the volcanoes chain known as the Cameroon line, with 1,600 km of extension, starting in the ocean in the Gulf of Guinea and extending into the African continent. The islands were never connected to the mainland, resulting in significant differentiation of fauna and flora and a high degree of endemism (Bonfim and Carvalho 2009).

São Tomé has at least four mangrove forests and Príncipe three small ones (Praia Salgada, Praia Grande, and Praia Caixão). These aquatic forests in São Tomé can have two families of mangrove trees, black mangroves of *Avicennia germinans* (Linnaeus, 1764) species, and the red mangroves from the genus *Rhizophora* (Afonso, 2019). On the other hand, the "true" mangroves in Príncipe Island are composed of monostands of *Rhizophora harrisonii* individuals.

In the past 25 years, 20% of the mangrove area worldwide has been lost (FAO 2007). Even though mangrove forests have been proved to be essential to human populations' well-being and coastal fish stocks (FAO 2007, UNEP 2010), there is still much to describe and monitor so that sustainable management of these environments is achieved, particularly for insular tropical systems. São Tomé and Príncipe has almost no records about its mangroves. Relatively to Príncipe Island, the only published work is the report by Herrero-Barrencua *et al.* (2017), describing the tree mangroves' ecosystem with faunal lists and flora characterization, but with little emphasis on the ichthyofauna.

The study aimed to describe the mangrove environment of Praia Salgada in Príncipe Island, including water dynamics and mangrove tree coverage. The specific objectives were to describe the abundance and species richness of the fish fauna, correlate the fish abundance and size-structure with environmental variables and assess the potential nursery role of the mangrove for the fish community.

The present work is the first in the country to compare the mangrove fish abundance between the seasons. It has also determined the exact tree coverage of *R. harrisonii*, allowing future comparisons of the mangrove trees distribution and detect possible regressions or growth. This study along two seasons, between October 2019 and February 2020, approached the influences of seasonality on the water mass and the species richness and abundance of fish. Variability between tides was also addressed to the water mass parameters. The water mass was characterised on temperature, salinity, and depth in four points to low and high tide and, when possible, these parameters were associated with the fish catches.

Materials and methods

Study area

This study is focused on a small mangrove system in Príncipe Island, São Tomé and Príncipe (Gulf of Guinea). The Praia Salgada mangrove (Fig. 2.1), located in Abade Bay on the east coast of the island, is a small brackish water system receiving freshwater from the Água Grande River and salt water from the Atlantic Ocean. Four sampling sites were established, being the first three inside the mangrove main creek (upper, middle, and lower mangrove) surrounded by *R. harrisonii* trees, and the fourth between the end of the mangrove vegetation and the mouth of the estuary.

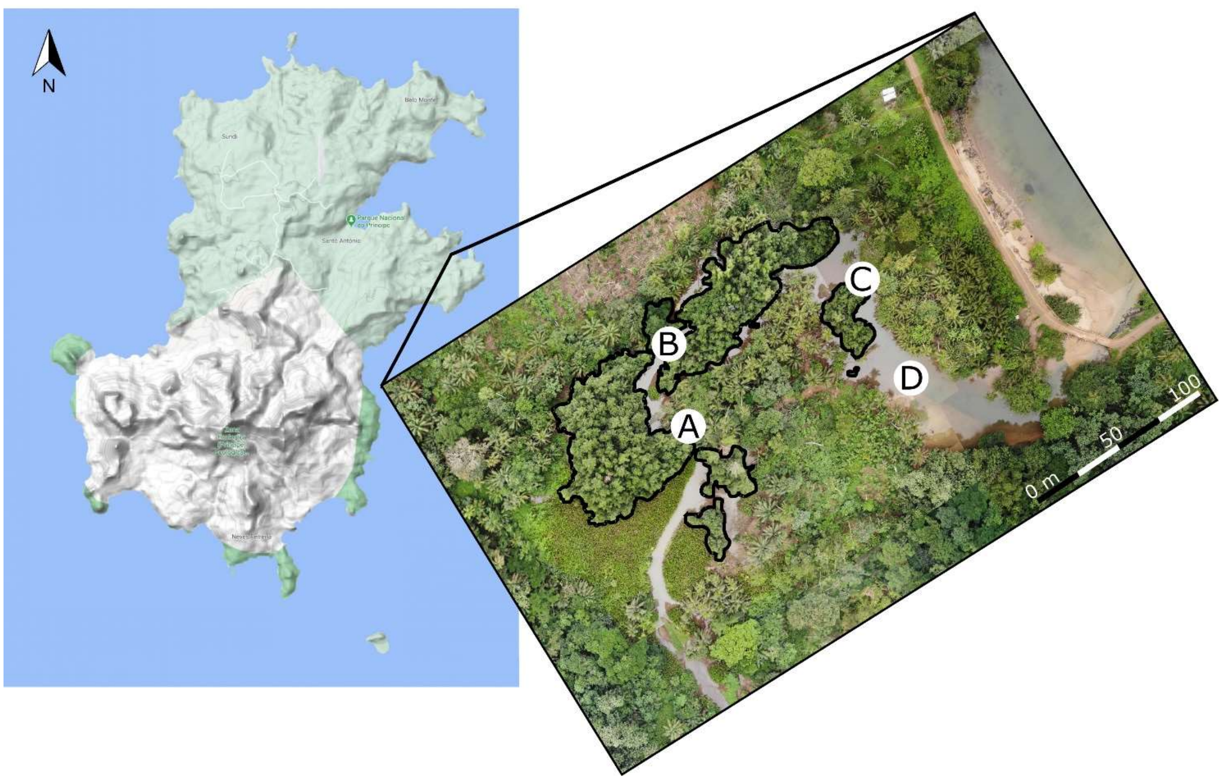

Figure 2.1. Location of sampling sites (A-D) at Praia Salgada mangrove. A - upper; B - middle; C - lower; D - outer. Points A-D represent the sampling points for the water column characterisation, and points A and C correspond as well to the fishing points. The mangrove map results from the combination of the Príncipe Island map, from Google maps website, with aerial photography obtained with a drone.

The country has tropical humid climate, with four climatic seasons, alternating between rainier and dryer phases with different intensities. The main dry season is called "gravana" which occurs between July and September (Chou *et al.*, 2020, Pisoni *et al.*, 2015). The second is less pronounced and occurs between January until March (Chou *et al.*, 2020). That being, the two rainy seasons are between October-December and April-June, being the first the most intense (Chou *et al.*, 2020). The average annual rainfall ranges from 2000-3000 mm, reaching 7000 mm in the cloud forests (Chou *et al.*, 2020, NBSAP II 2015). Temperatures range from 18-21 ºC minimums to 30-35 ºC maximums (Herrero-Barrencua *et al.*, 2017) and with an annual average of 26 ºC (NBSAP II 2015). The air relative humidity is very high, reaching more than 90% at higher altitudes (NBSAP II 2015).

Water column characterisation

To characterise the water mass, sampling was performed with a multimeter probe (Ysi Multiparameter 350i) measuring temperature and salinity. The water column depth was measured with a measuring tape or a depth probe, depending on the sampling method (by foot or by boat, respectively). During high tide, the measurements were taken twice, at the top and bottom of the water column, and during low tide only once at mid-depth due to the reduced water column height.

The sampling took place in two seasons: rainy (October, November, and December) and dry (January and February), with six days of sampling in each. These six days were evenly distributed between neap and spring tides, with fieldwork during low and high tide situations in each day (Fig. 2.2).

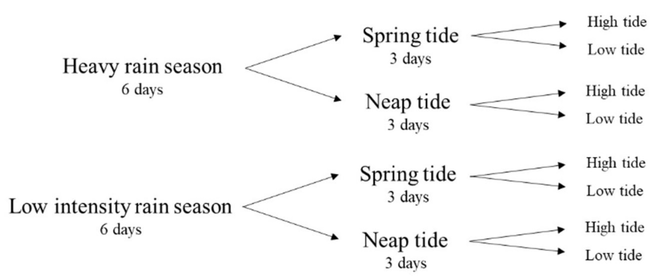

Figure 2.2. Scheme of the fieldwork for water mass sampling.

Along the mangrove were established four working stations (see Fig. 2.1 A-D). Each day, the water column was characterised (temperature, salinity, and depth) in non-successive triplicates for each of the four points.

A sandbank at the river mouth has developed between December and January and increased until February, obstructing water circulation and organisms' mobility across the estuarine boundary. This different topography was due to the transport and deposition of sediments originating upstream, together with the transport of sand by sea waves. This culmination of sediments that were retained at the mouth originated the sandbank that significantly reduced the river channel width to about one meter and very shallow in the narrowest part. During the rainy season, the strength of the estuarine discharge precludes the formation of these deposits.

Fish assemblages assessment

To assess the fish community's species richness and abundance, the sampling took place on the same months of the water mass characterisation (Fig. 2.3), with 11 of the total 15 days of fishing coincident with the water mass characterisation. Sampling was performed at low tide (only then possible to fish due to the width and height of the water column) in two of the mangrove sites: upper and lower (Fig. 2.1, A and C), with two attempts at each site per day.

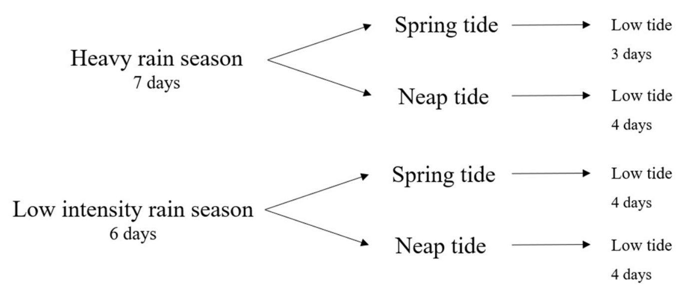

Figure 2.3. Scheme of fishing sampling.

The sampling resorted to mosquito nets (2.0 m wide and 1.2 m high with a sac shape) and operations involved at least four people. Two of them holding the net open, and the other two roughly shaking the water from a starting point thereabout 10 m upstream, converging into the net, in order to direct the organisms to the net and collect them. The procedure was taken as fast as possible to return most of the fish to the environment without jeopardizing their survival. Fish sub-samples for identification purposes were transported to the Biosphere Reserve and fixed in a 6% formaldehyde solution and after approximately 24h in a new solution of 80% alcohol.

The fish were photographed on-site with a reference scale to later determine each individual's total length (TL), using the software ImageJ^{TM}. The individuals were identified to the species level when possible, except when the lack of adequate descriptions prevented an accurate identification, such as in some cases of late larval and juveniles stages. For identification purposes were used the fish guides by FAO (2016a, 2016b), Lévêque *et al.* (1990a), Oren (1981), Guatier and Hussenot (2005), and complemented with the consultation of FishBase (Froese and Pauly 2019). The lists of fish taxa are presented in taxonomic order according to Nelson (2006).

Data treatment

Two-way ANOVA was applied to the captures per day data, after a logarithmic transformation to homogenise variances (Levene test). Non-parametric Mann-Whitney test was used to assess the differences in the size of the taxa between seasons, as some of the data groups were not homoscedastic (even with logarithmic transformation).

Results

Water mass parameters

The water column depth along the mangrove is shown in Fig. 2.4. During spring tides, the depth observed was similar in the two seasons, and a similar pattern was seen for the neap tides. As expected, the amplitude between low and high tide for spring tides is larger than that of neap tides. The sandbank presence is evident during the dry season, justifying that the low tide during the spring tidal period is never as low as in rainy season, and that during neap tides the values have less amplitude throughout the day when comparing to the neap tide of the rainy season.

The spring tides during the rainy season were distinctly lower in height comparing to the neap tides. The water column reached the lowest values due to the spring tide event with no obstruction of water flow to the sea (sandbank), resulting in a very low string with a few centimeters of height in the lower part of the mangrove. During spring tides in the dry season, the low tide does not show the same pattern, contrary to expectation, again due to the sandbank. In the dry season, the water column is higher. Comparing the neap tides, in the dry season the water column was higher inside the mangrove by roughly 15 cm for both low and high tide situations.

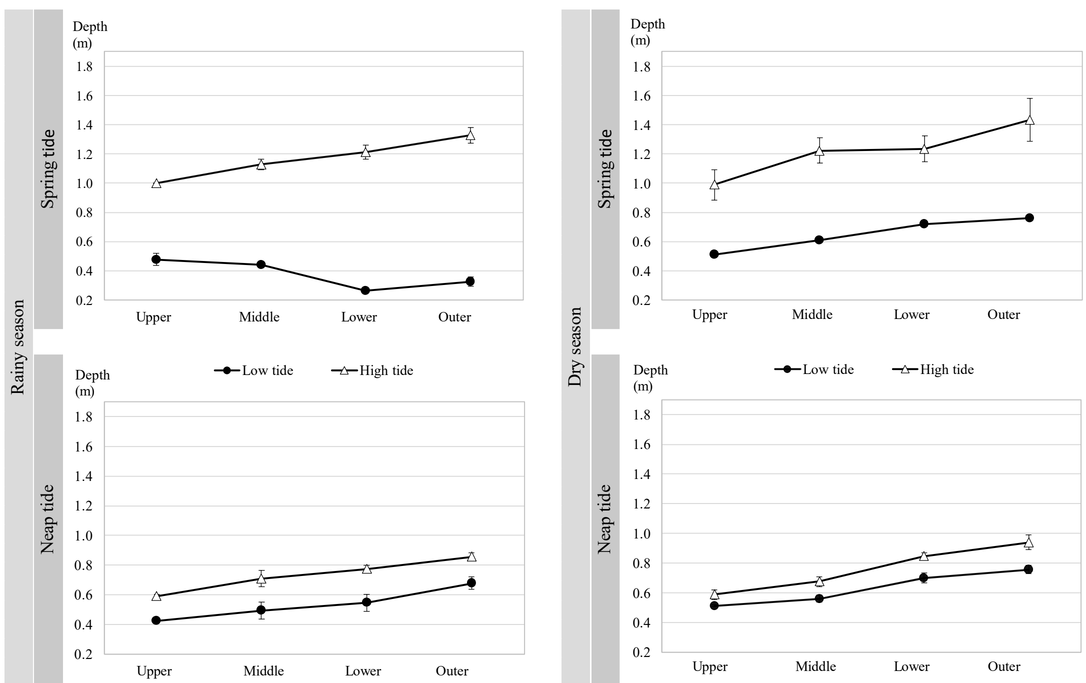

Figure 2.4. Average water column depth at the four sampling sites of the mangrove (upper, middle, lower, and outer) during rainy and dry seasons and spring or neap tides. The points represent the average depth of the three days measured for each tidal situation and respective standard error.

The salinity variation on the mangrove creek (Fig. 2.5) increases with proximity to the sea, as expected. The stratification of the water column, revealed by the difference between the high tide top and bottom values, confirms the expectation of salinity being higher at the bottom.

The saline wedge is the lack of mixing between saltwater from the ocean and fresh water from the river that creates a line between the two and represents the limit of saltwater intrusion. This happens due to the differences in density and temperature of the waters that do not mix due to low tidal motion. This situation was detected in the rainy season neap tide, where the salinity wedge is between the mangrove's middle and lower points. In all other situations, the salinity wedge was upper to the sampling points. The entry of saltwater is more intense in spring tides, explaining the higher temperatures registered in this situation at the upper and middle sites.

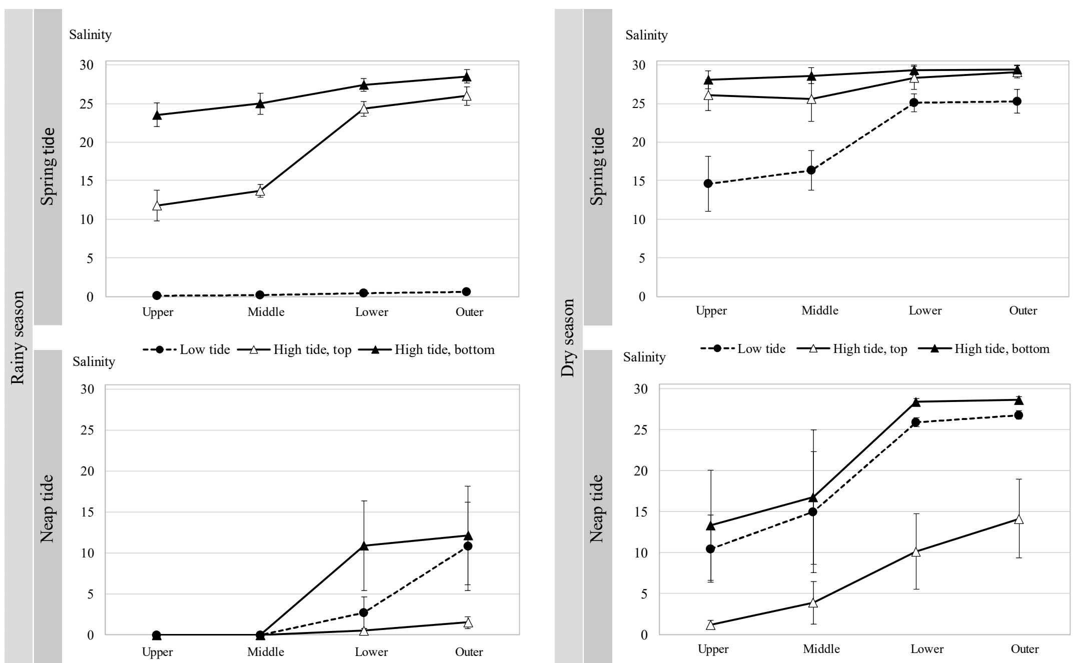

Figure 2.5. Salinity at the four study sites of the mangrove (upper, middle, lower, and outer) during rainy and dry seasons and spring or neap tides. The points represent the average salinity of the three days measured for each tidal situation and respective standard error.

Temperature (Fig. 2.6) generally increases with proximity to the sea. The patterns obtained are similar to those of salinity (Fig. 2.5), mainly because lower salinities are associated with lower temperatures from water masses descending from upstream. For both of these parameters (temperature and salinity), the rainy season presents low tide values lower than high tide. Still, the dry season shows the low tide values very close to high tide, indicating a more homogeneous water column.

Regarding the water column stratification, there is the expected tendency of lower temperature and salinity on top, and higher temperature and salinity on the bottom. Temperature is higher during dry season. This can be mainly explained by the increase of radiation due to less cloudy skies, less precipitation, more stagnation of water due to the sandbank, and less flow from the river upstream.

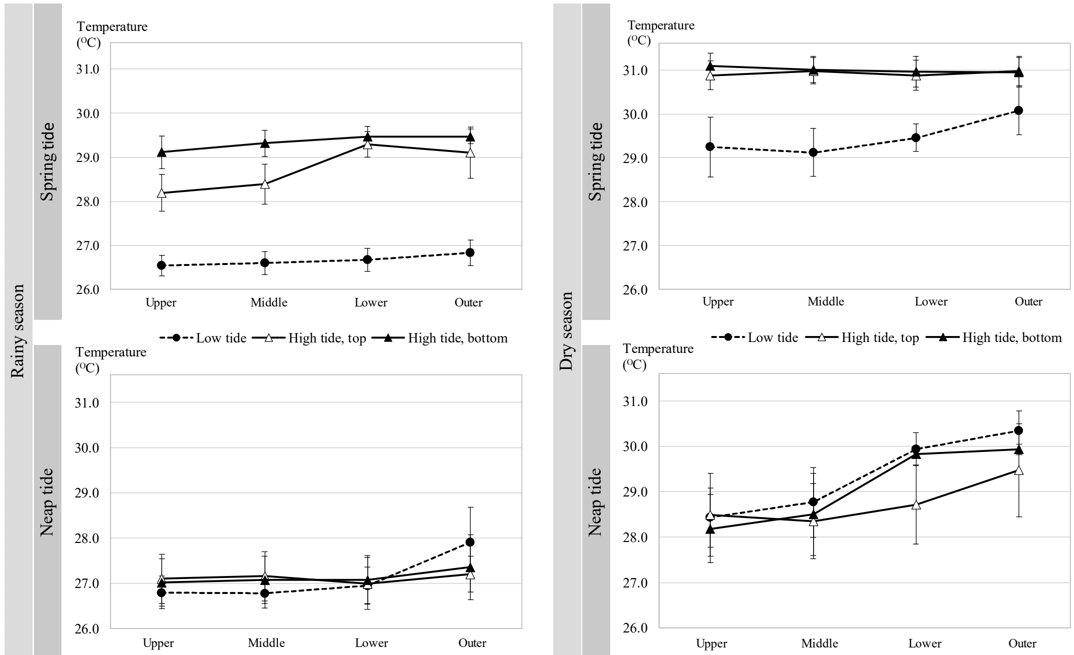

Figure 2.6. Water temperature on the four study points of the mangrove (upper, middle, lower, and outer) during rainy and dry seasons and spring or neap tides. The points represent the average temperature of the three days measured for each tidal situation and respective standard error.

Fish communities

A total of 772 individuals of at least 14 species were caught in Praia Salgada's mangrove (Table 2.1). The majority of these species have already been reported for the country's mangrove systems (Félix *et al*., 2017, Hauron *et al*., 2018, Herrero-Barrencua *et al*., 2017, Pisoni *et al*., 2015), except for *Ethmalosa fimbriata*, *Mugil curema*, *Gobioides* cf. *africanus* and *Citharus* cf. *linguatula*. The genus *Caranx* had already been reported for São Tomé Island (Félix *et al.*, 2017, Pisoni *et al.*, 2015), however, the present study is the first to identify a species of this genus in a mangrove system. If confirmed, *Gobioides* cf. *africanus* presence on Praia Salgada mangrove, will be the first record of the species in the country.

The Atlantic Mudskipper *Periophthalmus barbarus* was very abundant on banks and margins of the mangrove, however it was never caught during the sampling due to his ability in avoiding the nets.

During this field survey, two species of mullets were caught in Praia Salgada's mangrove: *Mugil curema* and *Parachelon grandisquamis*. The designation "Mugilidae n.d." was used when the individual's size was too small to determine the species. This happened in one sampling event (in 26th November 2019), when 113 individuals of this family were caught simultaneously with an average length of only 1.484 cm.

Relatively to Gobiidae family, two species were identified (*Porogobius* cf. *schlegelii* and *Gobioides* cf. *africanus*). When "Gobiidae n.d." designation occurs, these individuals may be one of these two species or another different. The diversity of this family and the lack of adequate descriptions for the area made it difficult to accurately identify some individuals. The probability of these individuals counted in "Mugilidae n.d." and "Gobiidae n.d." belonging to the recorded species led to disregard them for species richness analysis.

Table 2.1. Fish taxa, respective number of catches, and species richness (number of species) according to the season. NA - fish recorded in that season but with no catches in the nets. * - not considered for species richness.

Taxa	Rainy season	Dry season	Total
Ethmalosa fimbriata (Bowdich, 1825)	42	42	84
Clupeiform (larval stage)	1*	-	1*
Megalops cf. *atlanticus* Valenciennes, 1847 (larval stage)	-	1	1
Mugilidae n.d.	113*	-	113*
Parachelon grandisquamis (Valenciennes, 1836)	187	16	203
Mugil curema Valenciennes, 1836	18	25	43
Aplocheilichthys spilauchen (Duméril, 1861)	122	64	186
Microphis aculeatus (Kaup, 1856)	6	-	6
Caranx latus Agassiz, 1831	12	9	21
Lutjanus agennes Bleeker, 1863	10	4	14
Lutjanus goreensis (Valenciennes, 1830)	1	3	4
Eucinostomus melanopterus (Bleeker, 1863)	6	12	18
Gobiidae n.d.	27*	5*	32*
Porogobius cf. *schlegelii* (Günther, 1861)	13	31	44
Gobioides cf. *africanus* (Giltay, 1935)	1	-	1
Periophthalmus barbarus	NA	NA	NA
Citharus cf. *linguatula* (Linnaeus, 1758)	1	-	1
TOTAL catches	**560**	**212**	**772**
Species richness	**13**	**11**	**14**

The total fishing days were seven in the rainy season and eight in the dry season. The average quantity of fish caught per day was 80.0 for rainy season and 26.5 for dry season. The dry season had two of the fishing attempts with no catches. The average quantity of fish caught per day was higher in the rainy season and lower but more stable in the dry season (Fig. 2.7).

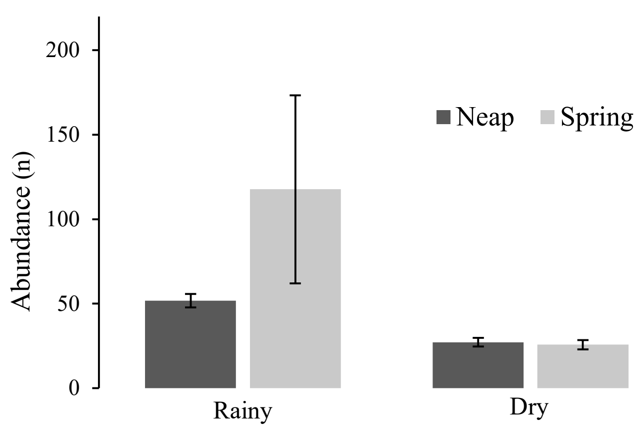

Figure 2.7. Average abundance of fish caught per day according to the season and tide. Error bars: ± SE.

To test the significance of differences between the seasons and tides, a 2-way factorial ANOVA was performed. After testing the homogeneity of variances (result of *p*-value < 0.001), a logarithmic transformation was applied to the data to homogenize variances, resulting in a *p*-value of 0.066 thus homoscedastic data. The results (Table 2.2.) show a significant difference between the seasons and non-significant between the tides. The interaction of the factors was not significant at 0.05 probability.

Table 2.2. Results from the 2-way ANOVA of the daily captures of fish according to seasons and tides. SS - sum of squares; MS - mean square; F – F-value.

	SS	Degree of freedom	MS	F	p-value
Intercept	39.63906	1	39.63906	1501.130	0.000000
Season	0.67816	1	0.67816	25.682	**0.000362**
Tide	0.04679	1	0.04679	1.772	0.210069
Season*Tide	0.08971	1	0.08971	3.397	0.092388
Error	0.29047	11	0.02641		

The individuals' sizes tended to be higher during dry season (Fig. 2.8). In order to assess the significance of the differences, Mann-Whitney U tests (at 95% confidence) were performed. For the Mugilidae, the test indicates significant differences (U = 761.000, *p* < 0.001), as well as for *A. spilauchen* (U = 2612.000, *p* < 0.001) and Gobiidae (U = 337.000, *p* < 0.001).

Even though the results for *C. latus* (Fig. 2.8) show a tendency for higher individuals during dry season, the Mann-Whitney U results did not reveal significant differences (U = 36.000, *p* = 0.219), due to the variable distribution of the data from the rainy season.

The species *E. fimbriata* and *E. melanopterus* did not reveal the tendency for bigger individuals in the dry season and the Mann-Whitney U results indicates non-significant differences between the seasons (*E. fimbriata*: U = 955.000, *p* = 0.514; *E. melanopterus*: U = 47.000, *p* = 0.335).

The other fish species (*L. agennes*, *L. goreensis*, *M. aculeatus*, *C. linguatula*, Clupeiforme larva and *M. atlanticus*) were not analysed for length according to season because their abundance was considered too low (≤14). Regarding the Mugilidae family, the average length of individuals considering the separate groups of *P. grandisquamis* (rainy = 2.966 cm; dry = 12.515 cm), *M. curema* (rainy = 3.406 cm; dry = 6.603 cm) and Mugilidae n.d. (rainy = 1.484 cm; dry = NA) does show the same pattern of higher lengths in rainy season. That being, the Mugilidae's boxplot is presented with the lengths considered together, in order to synthesize the results.

The same situation happened for Gobiidae family, where the pattern of higher average length for dry season was present (Gobiidae n.d.: rainy = 2.196 cm, dry = 2.239 cm; *Porogobius* cf. *schlegelii*: rainy = 3.706 cm, dry = 5.064 cm; *Gobioides* cf. *africanus*: rainy = 5.692 cm, dry = NA). However, when looking to the average length of Gobiidae n.d., there are similar lengths due to the difficulty in determine the species in these smaller individuals (until approximately 2.2 cm), a situation that with this family occurred in rainy and dry season.

The Lutjanidae family occurred 14 times with specimens of *L. agennes* and 4 with *L. goreensis*. *L. agennes* presented an average length of 14.5 cm and minimum and maximum values of 2.01 and 43.7

cm, respectively. *Lutjanus goreensis* showed less variable values with an average of 13.3 and minimum and maximum values of 11.3 and 16.5 cm, respectively.

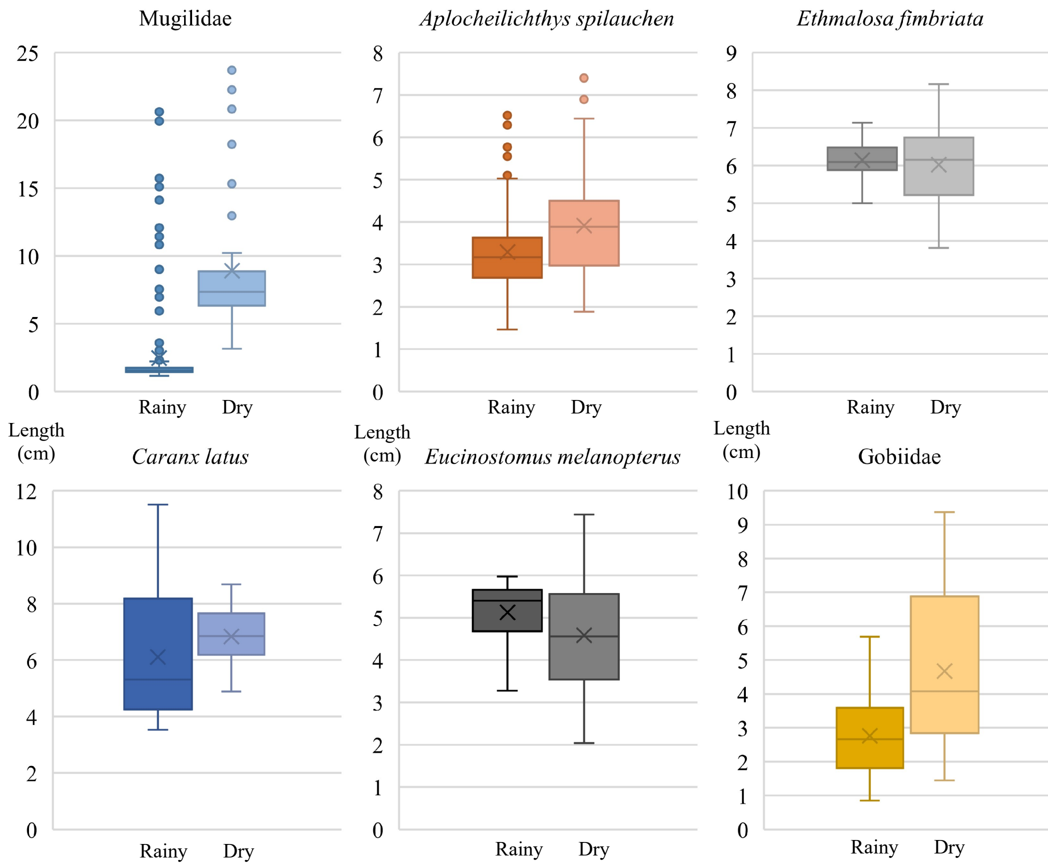

Figure 2.8. Results of the fish lengths (TL), during the rainy and dry seasons. The boxplots represent the four quartiles of the data and the "X" the mean. The outliers represent a data point that exceeds 1.5 times the interquartile range (IQR) from the top or bottom of the box.

The salinity at which the various taxa occurred is presented in Table 2.3. The salinity registration was taken with the probe on the correspondent points, however, it does not correspond to the species' saline tolerance range. Especially for species with fewer occurrences, the ranges of values presented can be a limiting interpretation of the salt tolerance of that species. The species *P. grandisquamis*, *A. spilauchen*, *C. latus*, and *P. schlegelii* ocurred in the minimum and maximum range of the recorded salinities. *E. fimbriata* showed less preference for low salinity situations, occurring in this study only from 1.6 PSU. Nine of the sixteen taxa listed in Table 2.3 showed tolerance to zero salinity situations.

Microphis aculeatus was recorded six times and only in rainy season and low salinity conditions, with the average length and standard error of 9.55 cm and 1.67 cm, respectively. To the maximum size of approximately 20 cm, this genus is better represented in freshwater or low salinity habitats (Dawson 1984).

Table 2.3. Saline occurrence of the fish species for Praia Salgada's mangrove, represented by the minimum and maximum value of salinity in which each species was registered for both sampling seasons. NA - no water mass parameters measured in this occurrence.

Taxa	**Rainy season**		**Dry season**	
	Min.	Max.	Min.	Max.
Ethmalosa fimbriata (Bowdich, 1825)	1.6	6.5	11.7	26.9
Clupeiform (larval stage)	0.3	0.3	-	-
Megalops cf. *atlanticus* Valenciennes, 1847 (larval stage)	-	-	24.9	24.9
Mugilidae n.d.	0.7	0.7	-	-
Parachelon grandisquamis (Valenciennes, 1836)	0.0	1.6	2.7	26.9
Mugil curema Valenciennes, 1836	0.0	0.2	2.7	24.9
Aplocheilichthys spilauchen (Duméril, 1861)	0.0	0.2	2.7	26.9
Microphis aculeatus (Kaup, 1856)	0.0	0.7	-	-
Caranx latus Agassiz, 1831	0.0	6.5	16.7	26.9
Lutjanus agennes Bleeker, 1863	0.0	6.5	12.0	25.9
Lutjanus goreensis (Valenciennes, 1830)	NA	NA	26.9	26.9
Eucinostomus melanopterus (Bleeker, 1863)	0.2	0.2	11.7	25.9
Gobiidae n.d.	0.0	0.2	24.9	24.9
Porogobius cf. *schlegelii* (Günther, 1861)	0.0	0.2	2.7	26.9
Gobioides cf. *africanus* (Giltay, 1935)	0.7	0.7	-	-
Citharus cf. *linguatula* (Linnaeus, 1758)	0.0	0.0	-	-
Limit values registered for the season	**0.0**	**6.5**	**2.7**	**26.9**

The distribution of the fish community in relation to the mangrove location (Fig. 2.9) revealed that each species' preference is transient to season. The Mugilidae family species, *C. latus,* and *E. melanopterus,* showed no significant preference between upper and lower locations in the mangrove creek. However, the Gobiidae and *E. spilauchen* populations seemed to prefer the upper part and *E. fimbriata* the lower mangrove creek.

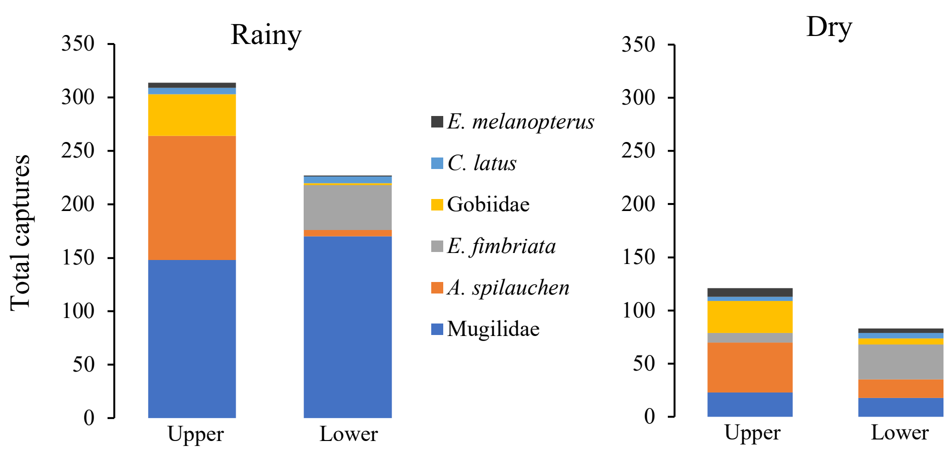

Figure 2.9. Distribution of fish taxa caught according to mangrove location (upper or lower) in rainy and dry season.

Discussion

Water mass parameters

The water mass parameter results were concordant with the expected. It was observed the expected patterns of the gradients with proximity to the sea, the irradiation influence, rains, and interaction between fresh and saltwater. There are two published works with water mass parameter measurements, Pisoni *et al.* (2015) and Herrero-Barrencua *et al.* (2017) for São Tomé and Príncipe, respectively. They were developed in September-December of different years, including only the rainy season of the present work. The top and bottom of the water column were differentiated. However, limited comparison is possible since the water mass characteristics of a given estuary are mainly related to its specific geomorphological and basin setup. Moreover, these studies did not distinguish high and low or neap and spring tide. Despite these differences, the values reported on those two studies are within the same range as the ones reported in this study and with similar variation patterns.

The water column depth results show the tide's expected influence on the mangrove's water dynamics, raising and lowering the level with the tide movements. However, during the dry season, the presence of the sand bank affected these water exchanges and, consequently, the mangrove system's biological communities. This obstruction raised the water level inside the mangrove during the dry season, decreased the water exchange, and enlarged the mangrove creek. The differences are negligible during the neap tide, when the low tide in the dry season tends to be higher by approximately 15 cm at the lower mangrove study site, but similar at the outer site. However, regarding the low tides during spring tide, the height is always higher for the three lowest sampling points (middle, lower, and outer) during the dry season, with differences of approximately more 19 cm in the middle site and 43 cm in lower and outer sites. These differences may suggest that fishing was more difficult due to the technique used and fish more likely to escape, thus justifying why the average quantity of fish caught per day was 80 for rainy season and 26.5 for dry season.

The water column depth seems to influence fish catches, as the lowest water column height is associated with the greatest abundance of fish (spring tide during the rainy season). In the dry season, when the low tides were identical between spring and neap tides, the abundance of fish caught was the same. The abundance of fish during neap tides in the rainy season had the intermediate abundance values, and in fact the height of the water column also presented intermediate values. However, the data obtained are not strong enough to assess with certainty the factors that most contribute to the variation in fish abundance, especially in view of the effects of the variable environmental conditions on the sampling rates.

Fish composition and abundance

The total 772 individuals of fish caught in Praia Salgada mangrove correspond to at least 14 different species. When comparing with the other two works with fieldwork assessment for the fish community in the mangroves of São Tomé and Príncipe (Table 2.4.), the reported fish species richness in this study is similar to the other small mangroves of the country (Praia das Conchas, Praia Salgada, Praia Caixão, and Praia Grande) and below the most extensive mangrove of the country in São Tomé Island (Malanza).

Table 2.4. Comparison of fish species richness with other works in São Tomé and Príncipe.

		São Tomé		Príncipe			Total number of fish caught
		Malanza	Praia das Conchas	Praia Salgada	Praia Caixão	Praia Grande	
References	Félix *et al.*, 2017	21	13	-	-	-	229
	Herrero-Barrencua *et al.*, 2017	-	-	13	11	10	NA
	Present paper	**-**	**-**	**14**	**-**	**-**	**772**

The species richness was slightly lower in dry season than rainy season, which may be related to the abundance of fish caught being lower and the sandbank preventing exchanges with the sea. From the 14 different species reported, four are new to the country's mangrove: *E. fimbriata*, *M. curema*, *G. africanus* and *C. linguatula*. The abundance of *E. fimbriata* and *M. curema* was significant, with total captures of 84 and 43 in total, respectively, revealing the mangrove's frequent use by this species. *C. linguatula*, caught only once, is reported for the country (Krakstad *et al.*, 2010) and can occur in tropical estuaries (Munroe, 2016b). However, *G. africanus* is recorded for the first time in São Tomé and Príncipe.

Despite the species richness having similar numbers within the other studies (Table 2.4.), they do not correspond precisely to the same species. For example, *Elops senegalensis*, *Plectorhinchus macrolepis*, *Galeoides decadactylus, Monodactylus sebae*, and *Bostrychus africanus* were all reported in the other two works (Félix *et al.*, 2017, Herrero-Barrencua *et al.*, 2017) but not registered in this survey.

The feeding behaviours of the reported species are mainly detritivores and carnivores. The mullets *P. grandisquamis* and *M. curema* are detritivores, feeding on particulate organic matter (Diouf 1996, Harrison 2016). The Gobiidae individuals, *C. latus, E. melanopterus, L. agennes, L. goreensis, C. linguatula* and *M. atlanticus* are all carnivore, feeding on fish and invertebrates. Some can even resort to detritus and phytoplankton, like the Gobiidae (Carpenter 2016, Diouf 1996, Ferraris Jr and Smith 2016, Iwatsuki 2016, Miller and Murdy 2016, Munroe 2016b, Smith-Vaniz 2016). *A. spilauchen* is also a carnivore, feeding mainly on insects (Okyere 2012). *E. fimbriata* feeds on phytoplankton and zooplankton (Munroe 2016a) by filtering the water with the very fine gill raker sieve, and *M. aculeatus* relies on zooplankton (Fritzsche 2016).

All the reported species can be found in brackish systems, some characterized by living in these environments and others come to feed or seek refuge in their juvenile stages. Although some of the species registered in zero salinity situations are marine, the majority are juveniles, as already stated before. Young stages of fish species tend to be more tolerant to low salinity waters.

The most important factor affecting the fish population in a mangrove swamp can be the salinity (Wright 1986). Salinity affects the distribution patterns and survival of fishes in estuaries, but may even affect metabolic processes (Nagelkerken *et al.*, 2008). The species most ascribed to freshwater, like *A. spilauchen* and Gobiidae preferred the upper part of the mangrove creek and *E. fimbriata* the lower location, being near to the sea and more salty waters. The referred species more common on the upper part of the mangrove creek can be classified as residents (Félix *et al.*, 2017, Wright 1986).

The majority of the fish caught in Praia Salgada mangrove has commercial interest. *E. fimbriata*, *P. grandisquamis*, *M. curema*, *C. latus*, *L. agennes*, *L. goreensis* and *E. melanopterus* all have been reported as fish resources to the country (Afonso *et al.*, 1999, Direção das Pescas 2015, Horemans *et al.*, 1994, Krakstad *et al.*, 2010, OMALI 2019, Wirtz *et al.*, 2007), leaving behind only freshwater fish and too small species to be interesting for consumption: *A. spilauchen*, *M. aculeatus*, *P. schelegelii* and *G. africanus*. Regarding *C. linguatula* and *M. atlanticus*, these are reported has fish resources for the Eastern Central Atlantic (Ferraris Jr and Smith 2016, Munroe 2016b), but not explicitly found in references for São Tomé and Príncipe.

A *Megalops atlanticus* leptocephalus larva was captured once in the Praia Salgada mangrove. This amphi-Atlantic species is classified as vulnerable in the IUCN Red List (Adams *et al.*, 2019) and the existing records for mangroves are only adults in Malanza, São Tomé (Félix *et al.*, 2017, Pisoni *et al.*, 2015). This species spawns offshore and the leptocephalus larva, when ready, goes to shallow coastal waters and lagoons to undergo metamorphosis (Taylor *et al.*, 2011). These turbid anoxic waters in mangrove marshes offers protection to the young. The occurrence of this larval phase inside the mangroves has been reported by others (e.g. Harrington 1966), although the most common are juveniles, leading to the conclusion that this occurrence was a sporadic individual on the edge of initiating metamorphosis. Nevertheless, is an important record because the species has not yet been identified on the mangroves in Príncipe Island.

Fish size and life stage

The maturity length of the Bonga shad *E. fimbriata* varies depending on the bibliography consulted. According to Blay Jr and Eyeson (1982), the species matures at 22.0 cm in Ghana waters and other two works referred sizes between 12.0 and 17.5 cm, with higher lengths for females (Facade and Olaniyan 1972, Faye *et al.*, 2014). Although the values in the literature vary, the individuals caught in this study belong all to the juvenile phase because the range of recorded lengths was between 3.8 and 8.2 cm.

Regarding mugilids, the maturity length of *P. grandisquamis* is 15.0 cm, and of *M. curema* 19.7 cm, according to FishBase (Froese and Pauly 2019), and 18-20.8 cm according to Aguirre and Gallardo-Cabello (2004). The recorded lengths of the captured individuals from this family presented averages of 2.5 cm and 8.9 cm, with standard deviations of 8.9 cm and 4.9 cm for rainy and dry season, respectively. That being, all individuals captured from Mugilidae are also juveniles, with the exception of a few outliers.

Caranx latus was registered in Praia Salgada mangrove with a maximum length of 11.5 cm. The species has a maturity length of 37.0 cm (Froese and Pauly 2019), underlining that all registered individuals were juveniles. The same applies to *E. melanopterus*, with a maximum length recorded of 7.4 cm and a maturity length of 7.5 cm (Ramos *et al.*, 2012) and for *C. linguatuta*, which the only specimen captured was a small individual with 6.5 cm and the maturity of this species is reported to be a length of 14.5 cm (Cengiz *et al.*, 2014).

Lutjanus agennes was registered 14 times in this study. The size at first maturity reference is uncertain, however, the variability of the length recorded ranging from 2.01 to 43.7 cm with the average of 14.5 cm indicates that the specimens caught were mainly juveniles but some sporadic adults. *L. goreensis* was registered in Praia Salgada four times, all juveniles, with an average length of 13.3 cm. This species is recorded with mean sizes at first sexual maturity around 34.4 cm (Fakoya and Anetekha 2019).

Aplocheilichthys spilauchen is a non-migratory brackish water species, occurring in swamps, river mouths, lagoons, and mangrove swamps (Lévêque *et al.*, 1990b, Wildekamp *et al.*, 1986). The length distribution of the species presented is similar to the reported by Okyere (2012), revealing that the sampling encompassed juveniles and adults of that population. In the study by Okyere (2012), immature individuals corresponded to 9.2% of the total population.

After analysing the length at first maturity of the species with commercial interest, it was determined that they were all recorded exclusively as juvenile stages inside the mangrove, except for some adults of *L. agennes* and the larva of *M. atlanticus*. This strongly suggests a nursery role from Praia Salgada mangrove, where early stages of marine species can find shelter from predators and food sources.

Conclusion

The present study for Praia Salgada mangrove fish species provides a fish list species for this brackish system, a description of the water mass parameters, and patterns of distribution of the fish community along the mangrove creek, all assessed for the seasonal variation between October and February.

Although Praia Salgada is a small mangrove, its importance to fish recruitment is clearly suggested by the results of this study. After analysing the length at first maturity of the species with commercial interest, it was observed a majority of juvenile fish stages within the mangrove. This suggests a nursery role by Praia Salgada mangrove, where early stages of marine species can find shelter from predators and food sources. The accumulation of sediments forming a sandbank between sampling seasons constrained the water exchanges of the creek with the sea, consequently affecting fish movements. With this constraint, a decrease in fish catches was observed. The preservation of this habitat is vital to maintain its benefits to local fisheries, together with other environmental services it provides.

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FINAL REMARKS

This study was performed in Príncipe Island, and contributes with new information regarding its poorly studied mangroves. The forest structure was described for all tree mangroves existing on the island, and the water mass dynamic, mangrove cover mapping and assemblages of fish were particularly assessed for Praia Salgada. The fish fauna was described, namely species occurrence, abundance and size, during contrasting conditions of season, tidal period and tidal phase.

The main conclusions of this work were:

- Praia Salgada mangrove appears to be a promising location with mangrove vegetation in expansion;
- The fish community in Praia Salgada mangrove had 14 reported species, which varied in abundance, diversity and length between the two seasons;
- Praia Salgada mangrove suggested to have a role as nursery habitat for the fish community.

The mangrove structure results revealed that Praia Salgada might be an expanding mangrove. The abundance of young trees and propagules in new zones of the brackish system, along with the locals' testimonials, indicates the growth of *R. harrisonii* monostands in the last years. However, the lack of formal previous records of the cover of these trees makes this conclusion of limited value. During this work, a map with the cover of *R. harrisonii* with GPS coordinates was built, which will allow for future comparisons. It would also be relevant to obtain this information for the other two mangrove forests in Príncipe, not possible during the present work.

Although small, Praia Salgada mangrove seems to play a role in maintaining adjacent coastal fish stocks. The fish assemblages on this mangrove were studied to assess the possible contribution of the forest to the recruitment of the fish species and the maintenance of stocks. The fish assessments and their correlation with environmental variables suggested a role of the mangrove as nursery habitat for a number of fish species. Summing up, the results revealed this possibility due to the presence of species with commercial interest on the mangrove creek which were all represented as juvenile stages.

São Tomé and Príncipe is long known for the fishing communities and the importance of this activity in maintaining households, mainly for coastal villages. The awareness of mangroves' contribution to the stability of the stocks is crucial to protect the environment. Although the people of Príncipe do not exploit the mangroves to extract timber for construction, they use extractable ecosystem services such as tannin and small subsistence fishing. During this study, the exploitation of mangroves has not proved to be exhaustive or very invasive. However, some exploitation is made and assessing its impacts may be essential, mainly for such small mangroves with little resilience capacity. More importantly, it is considered that awareness on the effects of these practices and sharing the best technique in tannin extraction to guarantee the survival of the trees may be the best strategies for reducing the negative impact in the mangroves of the island.

As future considerations, it would be interesting to study the mangrove over the year, since the seasons included correspond for half of the year and do not represent the annual variability. For example, the annual driest season may come to reveal interesting results, such as if the sandbank ends up closing the mangrove in a lagoon, or if this was a unique event and non-recurring of the dry seasons. Another interesting approach to future works would be to apply a fishing method that does not vary in effectiveness with the water level's height. The possible decrease in efficiency of this method between seasons can bring some uncertainty about the fish abundance results. Furthermore, the applications of more diverse fishing methods would also possibly enable higher fish species richness.

The unexpected appearance of the sandbank highlights the possible anoxia at the bottom of the water column. In future work, the measurement of oxygen levels would enable us to better evaluate the creek environment. Limited resources have led to a concentration of efforts on Praia Salgada mangrove forest. However, it will be important in the future to study more closely the other two mangroves of Príncipe.

All things considered, it is important to continue researching and describing the mangrove ecosystems in this small country, in order to enable sustained conservation implementation and a better understanding of the exchanges with adjacent ecosystems. Ecotourism is an attractive way to change the people uses of mangroves from destructive methods for conservative methods instead. If the value derived from ecotourism outweighs the benefits derived from invasive extractions on the ecosystem, we can expect a redirection of the mangrove use. As already referred, the primary provisioning ecosystem services obtained from mangroves in Príncipe Island are tannin extraction, small amounts of fishing, and low-scale shrimp farming. That being, the population does not depend strictly on these direct uses and resorts to them in a complementary way. If a better service with higher profit may arise, we can expect a change in the people awareness.

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