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# Assessment and management of sea cucumber resources in the coastal waters of Sri Lanka

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# Abstract

Sea cucumbers (class Holothuroidea) are a group of marine invertebrates which provide an important source of livelihood for many artisanal fishers throughout the world, particularly for the developing countries in the tropical and subtropical regions. Over the past few decades declining of sea cucumber populations was witnessed in many regions due to overexploitation and lack of proper management measures.

This thesis addresses the stock status of commercial sea cucumber species in the coastal waters of Sri Lanka and possible management measures to ensure their sustainable utilization. The stock status of commercial sea cucumbers was evaluated using data collected from an Underwater Visual Census (UVC) and fishery dependent surveys carried out off the east and northwest coasts of Sri Lanka in 2008 and 2009. Of the 25 sea cucumber species identified, 21 species are commercially important and 11 species were predominant in the commercial catches. The total abundance of sea cucumbers was higher off the northwest coast (62.3 x $10^6$ nos) than the east coast (11.9 x $10^6$ nos) and low-value species were predominant in both survey areas. *Holothuria edulis* was the most abundant species in numbers while *Holothuria atra* had the highest stock biomass. In both regions, commercial fishery predominantly relies on two nocturnal species; *Holothuria spinifera* and *Thelenota anax*. *H. spinifera* had the highest contribution (70%) to the total landings off the northwest coast while this was provided by from *T. anax* (90%) off the east coast. Density estimates indicate that all the sea cucumber stocks in the coastal waters of Sri Lanka are at critical level ($<$30 ind ha$^{-1}$) except for 3 stocks (*H. atra*, *H. edulis* and *H. spinifera*) off the northwest coast and one stock (*H. edulis*) off the east coast.

Biological and ecological aspects of *H. atra* and *H. edulis*, which were found to have potential to contribute to future fisheries, were further investigated. The habitat association of these species was mainly influenced by bottom sediment conditions, depth and bottom habitat types. High densities of *H. atra* were found in the shallow ($<$10 m) seagrass beds and *H. edulis* was commonly reported in shallow reef flats and rocky habitat. Although these two species favoured similar bottom sediment conditions, they have different preferences towards the sediment organic contents making it possible for them to have separate niches. When the reproductive biology of *H. atra* was evaluated using gonadosomatic indices and histology of gonads, a synchronous seasonal gametogenesis with some asynchrony among individuals was revealed. Further, this population was sexually active throughout the year having peak spawning in April and October. The main spawning event coincided with the highest temperatures and the size at first sexual maturity of *H. atra* was 16 cm.

Estimates of average natural mortality (M) for sea cucumbers are important findings of this study. Two approaches; simple linear regression and random effects models were used in this analysis and the estimated values were $0.5 \text{yr}^{-1}$ and $0.45 \text{ yr}^{-1}$, respectively. The random effects model predicted lower natural mortality (M) for nocturnal species than for the diurnal species.

A number of possible management measures were identified, including limiting the exploitation of some commercial species, setting of total allowable catch (TAC) limit and minimum landing size (particularly for highly abundant species), implementation of routine monitoring, reporting of commercial landings and implementation of marine protected areas (MPAs). A Multi-area bulk biomass model was used to design MPAs off the east coast of Sri Lanka and spatial management through marine reserves is seen to have potential to rebuild the highly depleted sea cucumber populations.

Apart from the management of local sea cucumber resources, the information gained through this study is important to update the regional and global sea cucumber statistics. Further, this information contributes for launching regional management programmes as trends in managing sea cucumber fisheries are towards regional rather than national management.

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# 1

# Introduction

This thesis evaluates the stock status of commercial sea cucumber species in the coastal waters of Sri Lanka and possible management measures for their sustainable utilization.

Sri Lanka is a small tropical island in the Indian Ocean, southeast of the Indian sub-continent between $5^0 55'$ - $9^0 55'$N latitudes and $79^0 42'$ -$81^0 52'$E longitudes. The coastline of Sri Lanka is about 1340 km long and characterized by several bays, lagoons and shallow inlets. Though Sri Lanka has sovereign rights to some 500,000 $km^2$ of the sea, the major fishing activities are restricted to the relatively narrow continental shelf of 30,000 $km^2$ with an average width of 25 km (Joseph, 1999).

The sea cucumber fishery was introduced to Sri Lanka by the Chinese and beche-de-mer appears to have been one of the major commodities taken to China for centuries (Hornell, 1917). Fishing activities were initially concentrated off the north (around Jaffna peninsula), east (Trincomalee, Pothuwil and Kalmunei) and north-west (from Kalpitiya to the Gulf of Mannar) coasts of Sri Lanka (Adithiya, 1969; Joseph and Moiyadeen, 1990). In mid 1990's, sea cucumber fishing was started along the southern coastal belt but it did not sustain for a long period due to overharvesting of the resources (Kumara et al., 2005).

As in many other coastal fisheries off Sri Lanka, the sea cucumber fishery is primarily artisanal but provides significant contribution to the livelihoods of coastal fishing communities off the north, east and northwest coasts (Dissanayake et al., 2010). Sea cucumbers were initially harvested by hand walking along the coastal areas during the low tide periods and since early 1980's fishers moved further offshore using snorkeling and SCUBA (Self Contained Underwater Breathing Apparatus) diving as shallow water stocks became depleted (Kumara et al., 2005). The decline of high-value species and entry of new sea cucumber species to the fishery were reported, particularly in the vicinity of Kalpitiya off the northwest coast, where the number of targeted species has increased from 8 to 16 during 1990 to 2002 (Dissanayake and Wijayarathne, 2007; Joseph and Moiyadeen, 1990).

Although the fishery has been practiced for several centuries, there is no tradition of consuming sea cucumbers in Sri Lanka. The entire production is processed as beche-de-mer and exported to Singapore, Taiwan and China. Sea cucumber exports peaked between 1995 and 1997 at nearly 300 metric tons, worth about US$ 3 million, followed by a drastic drop to almost half of this volume during the period 2000 to 2003 (Dissanayake et al., 2010; Kumara et al., 2005). According to statistics from the customs office, import of sea cucumbers commenced in 1996 but accurate information on import quantities and the source of imports have not been established so far (Kumara et al., 2005). Information on the annual exports was poorly documented and there were no records on catch and effort statistics at all. Hence, it is difficult to quantify the historical and current production trends of sea cucumbers in the coastal waters of Sri Lanka.

The sea cucumber fishery has continued to be an open access resource and to date no regulations or precautionary approaches have been adopted except for issuing diving and transportation licenses. Except for taxonomic work by Herdman (1903), no information is available on the distribution, abundance, biology and ecology of sea cucumbers along the coastal waters of Sri Lanka. As there was no large-scale assessment, the resource status and fishery potential is unknown to-date though it generates considerable export earnings to Sri Lanka. However, spatial expansion of fishery from shallow to deep waters, declining of exports and entering of new species to the fishery provides some evidence for resource depletion. Hence, if the same fishing intensity is maintained, the sea cucumber stocks will be even more seriously depleted over the next few years.

Given the importance of this resource to the coastal fishing community and the national economy, there was an urgent need to carry out a detailed stock assessment, biological and ecological studies on sea cucumbers in order to evaluate the stock status and propose possible management measures to ensure their sustainable utilization. This thesis presents work towards this overall objective through five different tasks. A detailed description of each task is given in the thesis as listed below. The scientific background to these tasks is compiled in chapter 2.

**1.** The first task was designed to assess the abundance and distribution of sea cucumbers in the coastal waters of Sri Lanka. To achieve this task an Underwater Visual Census (UVC) was carried out off the northwest and the east coasts of Sri Lanka in 2008. The detailed study is compiled in Chapter 3 which is based on **Dissanayake and Stefansson (2010a)**.

**2.** The second task was designed to understand the present status of the commercial sea cucumber fishery in the coastal waters of Sri Lanka. The underwater visual census was repeated at the same sampling sites off the northwest and east coasts in 2009 and catch and effort data were also collected at the major landing sites of these two areas in the season following each survey in 2008 and 2009. An open source database system, MySQL, was used to construct a database to store all these data. Total production, CPUE trends, exploitation rates, mortality parameters and fluctuations of adults and juveniles abundance of major commercial species were assessed. An attempt was made to estimate the overall natural mortality (M) of sea cucumbers using linear regression and models with random effects as reported in Chapter 4.

**3.** As *Holothuria atra* and *Holothuria edulis* were found to have potential to contribute to future fisheries, specially off the northwest coast of Sri Lanka, preferable habitat conditions of these two species were evaluated using generalized additive models (GAMs). Research methodology and results of this study are compiled in Chapter 5 which is based on **Dissanayake and Stefansson (2011)**.

**4.** The reproductive biology of *Holothuria atra* was also studied in order to understand the reproductive pattern, reproductive seasonality and the size at first sexual maturity as this information is useful to ensure the sustainable utilization of this resource. Chapter 6 is a synthesis of **Dissanayake and Stefansson (2010b)**.

**5.** The analyses presented above imply that most of the sea cucumber stocks have been over exploited off the east coast of Sri Lanka and are currently depleted. Hence, a step was taken to design Marine Protected Areas (MPAs) specifically to protect the high-value species and Chapter 7 describes this study.

The last chapter concludes the important findings of this study and possible future directions.

The outcome of this study provides first detailed information on stock status of commercial sea cucumber species in the coastal waters of Sri Lanka and the necessary basis for resource management. Hence, the information gained through this study is therefore not only of academic interest but can provide a basis for the management of the sea cucumber resources in Sri Lanka.

# 2

# Background

Herein a general overview of sea cucumbers including their biology, ecology, distribution, importance, global fishery and management measures is put into perspective by formulating the scientific background related to the PhD study.

## 2.1 General characteristics of sea cucumbers

The sea cucumbers, class Holothuroidea, form one of the five classes of exclusively marine phylum Echinodermata. The approximately 1400 sea cucumber species belonging to Holothuroidea are partitioned into six orders, Aspidochirotida, Apodida, Dactylochirotida, Dendrochirotida, Elasipodida and Molpadiida (Conand, 1990; James, 2001; Pawson, 2007). Aspidochirotida is considered as the most conspicuous group in the world's ocean and they are important in fisheries and nutrient recycling process in marine ecosystems (Byrne et al., 2010; Conand, 2001, 2004a; Conand and Byrne, 1993; Mangion et al., 2004; Uthicke, 1999, 2001a,b; Uthicke and Benzie, 2001). Almost 50% of the Aspidochirote holothurians are within the family Holothuriidae (Sewell et al., 1997) which comprises of 5 genera; *Actinopyga*, *Bohadschia*, *Holothuria*, *Labidodemas* and *Pearsonothuria*. *Holothuria* forms the largest genus with about 150 species (Samyn et al., 2005).

Amongst the many body shapes of sea cucumbers, which vary from almost spherical to worm like, the elongated tubular or flattened soft bodies with leathery skin is the most common (Lawrence, 1987). Body length also shows wide variation ranging from a few millimeters to a meter and 10 to 30 cm being the typical (Bakus, 1968;

Bell, 1892; Lawrence, 1987). As in all echinoderms, sea cucumbers possess a reduced endoskeleton formed by microscopic spicules embedded in the body wall which consists of powerful longitudinal muscles running along the radii and transverse muscles in the inter-radii (Conand, 1990; Kerr et al., 2005). There are five rows of tube feet along the body and the mouth is surrounded by a varying number of oral tentacles. Alimentary canal, respiratory trees, and reproductive organ are the main internal structures of sea cucumbers and some species, in addition to these basic structures possess a cuvierian oragan (Bakus, 1968; Bell, 1892).

## 2.2 Distribution of sea cucumbers

Sea cucumbers can be found in every marine environment at all latitudes and in all depths. They are usually benthic except for some pelagic Elasipodida (Conand, 1990; Hickman et al., 2004). Although some species live on hard substrates (near rocks, corals and seaweeds), in epibiosis on plants or invertebrates, they are more regularly found on soft bottoms. Some species live freely on the sea bottoms while others are temporarily or permanently burying themselves in the sediments (Rowe, 1969).

The abundance and distribution of sea cucumbers vary greatly with species as well as with bottom habitat conditions. It has been found that Aspidochirotida are more predominant in tropical waters while Dendrochirotida are common in temperate waters at higher latitudes (Choo, 2008b; Conand, 1990; Hamel and Mercier, 2008). The greatest degree of diversity exists in tropical shallow waters (Rowe, 1969) where seagrass beds, soft and hard substrates of coral reefs are often reported as the favourable habitat (Conand and Muthiga, 2007; Kinch et al., 2008). Temperate species mainly colonize in rocky or pebbly bottoms (Hamel and Mercier, 1996, 2008) and are also common in gravel and muddy bottoms (Hamel and Mercier, 2008; Levin and Gudimova, 1997). However, even within the same species spatial distribution pattern can vary with their life history stages. Juveniles generally inhabit shallower waters than the adults, often in association with sediments with higher organic matter and smaller grain sizes (Bulteel et al., 1992; Choe, 1963; Mercier et al., 2000b). An association of juvenile sea cucumbers with macroalgae is also common as this substrate provides an initial settlement surface, food and refuge from predation (Mercier et al., 2000a; Slater and Jeffs, 2010). Moreover, the habitat choice and spatial distribution of sea cucumbers are attributed to variety of factors including hydrographic processes, substrate types, food availability, depth and predatory pressure (Cameron and Fankboner, 1986; Eckert, 2007; Entrambasaguas et al., 2008; Mercier et al., 2000b; Slater and Jeffs, 2010;

Sloan and Von Bodungen, 1980; Young and Chia, 1982).

## 2.3 Biology of sea cucumbers

### 2.3.1 Feeding

Sea cucumbers are either deposit or suspension feeders and they use their tentacles for feeding. They mainly feed on decaying organic material which is either on the sea floor or floating around them (Dar and Ahmad, 2006; Jumars and Self, 1986). Exceptions include pelagic sea cucumbers and the species *Rynkatropa pawsoni* which has a commensal relationship with deep-sea anglerfish (Figueras, 2001).

Many sea cucumber species are deposit feeders and observations of gut contents indicate that guts are predominantly filled with the top layer of surrounding substrate. For example the gut contents of *Holothuria atra* collected from sandy patches in the reef lagoon were composed mainly of sand (Samyn, 2003) and feeding tracks of *Holothuria arenacava* appeared to be filled with sand next to the individuals (Muthiga, 2006). Feeding mainly occurs during the day, although some species such as *Holothuria fuscocinerea* are nocturnal (Samyn, 2003). Sea cucumbers exhibit a wide range of deposit feeding strategies (Billett, 1991; Hudson et al., 2003; Massin, 1982) and some can alter their feeding strategies with environmental variables such as pressure, salinity and physiological effects (Roberts et al., 2000).

Deposit feeding sea cucumbers can either ingest materials on the surface of the substrate or swallow the nutrient-laden sediments (Roberts et al., 2000, 2001b). The ingested sediments are mainly rich with inorganic compounds (coral debris, shell remains, coralline algae, foraminiferal tests, inorganic benthos remains and silicates), organic detritus (seagrass, algae, dead and decaying animals), micro-organisms (bacteria, diatoms and protozoans) and the faecal pellets of other animals or their own faecal pellets (Massin, 1982; Moriarty, 1982). The quantity and quality of organic matter taken by sea cucumbers may vary spatially and temporarily due to the underlying sediments and possibly pollution levels (Dar and Ahmad, 2006). Normally a large amount of sediment passes through the digestive tract of sea cucumbers in order to assimilate the required amount of food (Moriarty, 1982; Uthicke, 1999; Yingst, 1976).

The feeding of shallow water sea cucumbers (Hammond, 1983; Hauksson, 1979; Sloan and Von Bodungen, 1980; Uthicke, 1999) and deep-sea sea cucumbers (Billett et al., 1988; Uthicke and Karez, 1999) have been found to be highly selective.

According to Uthicke and Karez (1999), sea cucumbers have the ability to select certain grain sizes or particles with higher organic content within a sediment patch or microhabitat. Previous studies have revealed that *Stichopus chloronotus* has a selection towards the sediments rich with microalgae (Uthicke and Karez, 1999) and *Stichopus japonicus* prefers to feed sediments with their feaces as it contains higher organic matter than the surrounding substrates (Michio et al., 2003). According to Yingst (1976), sea cucumbers are generally less selective towards certain grain sizes and Powell (1977) confirmed that sea cucumbers feed on everything surrounding them regardless of the grain size. However, Miller et al. (2000) reported that sea cucumbers are very selective about particles settled in the sea floor and according to his observations, *Stichopus tremolus* mainly feeds on coarse particles and *Holothuria scabra* tends to assimilate the coarsest particles more than the finest fractions. Dar and Ahmad (2006) found that *Holothuria atra*, *Bohadschia marmorata* and *Holothuria leucospilota* scavenge through coarse sediments much more than through medium or fine ones. Some studies have shown the marked differences among the type of sediments ingested by younger and older individuals. Smaller individuals of *Parastichopus parvhnensis* feed on fine particulate materials while larger individuals prefer to feed on granular sediments (Dar and Ahmad, 2006; Yingst, 1982).

Although, it was hypothesized that feeding selectivity of sea cucumbers is mainly related to their tentacle structure and mode of feeding, studies on deep sea holothurians have shown that there is no correlation between tentacle structure and gut contents (Wigham et al., 2003). Hence, the factors influencing the feeding selectivity of sea cucumbers still remain unclear. However, the selective feeding mechanism of sea cucumbers provides obvious advantages of obtaining food with higher nutritional value and this may function as a means of niche partitioning between species dwelling in the same habitat (Massin and Doumen, 1986; Roberts, 1979; Sloan and Von Bodungen, 1980).

### 2.3.2 Reproduction

The majority of sea cucumbers are dioecious (having male and female reproductive organs in separate animals) but there is no sexual dimorphism. However, the sex can be readily determined by the appearance of gonad at a late stage of development (Uehara, 1991) or in immature individuals, from histological preparations (Conand, 1990; Costelloe, 1985). Sea cucumbers have single gonad located in the anterior part of the coelom and it consists of numerous germinal tubules that can vary in size, colour and state in accordance with gametogenic development (Kille, 1942; Smiley, 1988; Smiley and Cloney, 1985; Smiley et al., 1991; Theel, 1901).

Sea cucumbers have the ability to reproduce both sexually and asexually. Sexual reproduction is the most common mode and generally displays a seasonal reproductive cycle (Bakus, 1973; Conand, 1990; Conand and Muthiga, 2007; Smiley et al., 1991). Temperate species generally have discrete spawning periods in spring and summer (Cameron and Fankboner, 1986; Hamel, 1993; McEuen and Chia, 1991) while tropical species reproduce for longer periods throughout the year (Che and Gomez, 1985; Conand, 1993; Pearse, 1968). Both annual and semiannual reproductive cycles are also common among some tropical species (Cameron and Fankboner, 1986; Chao, 1993; Chao et al., 1994; Che, 1990; Harriott, 1985; Smiley et al., 1991; Tuwo and Conand, 1992). In general, gametogenesis is correlated with environmental factors such as photoperiod and water temperature (Morgan, 2000; Ramofafia et al., 2000). Spawning is believed to be triggered by changes in water temperature (Battaglene et al., 2002; Ramofafia et al., 2000), food availability (Cameron and Fankboner, 1986; Hamel, 1993), light intensity (Cameron and Fankboner, 1986; Muthiga, 2006), water turbulence (Engstrom, 1980), salinity (Krishnaswamy and Krishnan, 1967), phytoplankton blooms (Himmelman, 1980) and lunar periodicity (Muthiga, 2006).

Most species, probably Aspidochirotids, spawn in late afternoon, evening or during the night (Hyman, 1955; McEuen and Chia, 1991). Both sperm and eggs are released into the water and fertilization takes place externally. Current speeds and tidal patterns have effect on fertilization success (McEuen and Chia, 1991; Sewell, 1994). Larvae are housed in the brood pouch in viviparous species such as *Afrocucumis africana* and *Scoliodotella lindbergi* (Smiley et al., 1991; Uehara, 1991). Some species, such as *Synaptula hydriformis*, release their larvae either by rupturing the body wall or through a perforation in the intestine wall (Bakus, 1973).

Thermal stimulation is the widely practiced induced spawning technique for sea cucumbers (Morgan, 2000; Smiley et al., 1991; Tanaka, 1958; Yanagisawa, 1998), although, the variety of physical, chemical and biological cues have been invented (Engstrom, 1980; James, 1994; Yanagisawa, 1998).

Asexual reproduction of sea cucumbers mainly occurs through transverse fission and this has been observed in a few species of Aspidochirotida. In transverse fission, the body splits into two parts and each part regenerates the missing part within five to six months (Conand et al., 1997b, 1998; Ebert, 1978; Lee et al., 2008; Uthicke, 1997b, 2001c). Thus far, six *Holothuria* and two *Stichopus* species are known to be fissiparous (Harriott, 1985; Uthicke, 1997b; Uthicke and Conand, 2005a). Asexual reproduction of *Holothuria edulis* by transverse fission has been observed in the Great barrier reef, Heron Island and Sri Lanka (Dissanayake and Athukorala, 2011; Harriott, 1985; Uthicke, 1997b). There were some records on the asexual reproduction of *Holothuria atra*, *Stichopus chloronotus* and *Stichopus horrens* in Heron Island (Harriott, 1985; Uthicke, 1997a, 2001c; Uthicke et al., 1998), some areas of Southern Taiwan (Chao et al., 1994), La Reunion and the east Australia (Conand et al., 2002).

Fission is more prevalent in intertidal and shallow water populations and it is a seasonal event with a higher fission rate during the cold months (Chao et al., 1995; Lee et al., 2008; Uthicke, 2001c). A conceptual model (Uthicke, 2001c) based on several studies and literature data has predicted five factors; high mortality, low habitat stability, small optimum individual size, high food availability and low larval supply promote the asexual reproduction of sea cucumbers. Fission is considered to play an important role in maintaining populations of several Indo- Pacific holothurians by compensating high level of mortality and low rate of migration (Chao et al., 1994; Conand et al., 1997b; Ebert, 1978; Harriott, 1982; Lee et al., 2008; Uthicke, 2001c).

## 2.4 Importance of sea cucumbers

Sea cucumbers play an important ecological role in marine ecosystem as suspension feeders, detritivores and prey (Anderson et al., 2010; Uthicke, 2001a,b; Uthicke and Karez, 1999). Suspension feeders are important to regulate water quality by affecting carbonate content and pH (Massin, 1982). Deposit feeding sea cucumbers contribute to changing the sea floor sediment composition via bioturbation (Dar and Ahmad, 2006; Rhoads and Young, 1971; Uthicke, 1999, 2001a,b) and according to Powell (1977), high densities of *Holothuria arenicola* have ability to rework 3 cm thick sediment layer less than a month. Sea cucumbers also play a substantial role of nutrients recycling in oligotrophic environments (Uthicke, 2001b; Uthicke and Karez, 1999) and they are important prey to a vast array of predators particularly fish, sea stars and crustaceans (Birkeland, 1989; Birkeland et al., 1982; Francour, 1997).

In addition to the ecological importance, sea cucumber fisheries are of great importance for many rural coastal communities as it forms the main source of income (Anderson et al., 2010; Conand and Byrne, 1993; Friedman et al., 2010a; Nash et al., 2006; Toral-Granda, 2008a).

Sea cucumbers are served as a good source of food especially to the Chinese. Processed body wall of sea cucumbers known as beche-de-mer or trepang is considered as an ideal tonic food in most cultures in the east and the Southeast Asia (Chen, 2003; Choo, 2008b; James and James, 1994a). An extract of boiled skin is also very popular among the Malaysians as a tonic (Choo, 2004, 2008b). The fermented sea cucumber viscera, known as "konowata", is a delicacy in Japan and eaten mainly when drinking Japanese whisky or distilled Japanese sake. As it is believed that the intestines are particularly good for pregnant women and new mothers, there is a good demand for raw and processed intestines of sea cucumbers specially for *Stichopus variegatus* in the Pacific island countries (Durairaj, 1982; Kinch et al., 2008). The other organs of sea cucumbers such as dry form of ovaries and salted, fermented respiratory trees are also considered as delicacies (Conand, 1990).

A wealth of potential medicinal compounds have been isolated from sea cucumbers and some compounds exhibit antiviral, anti-tumoral, anti-fertility, anticoagulant and antimicrobial properties (Abraham et al., 2002; James, 2001; Kelly, 2005). For example, Haug et al. (2002) has identified high levels of antibacterial activity in the eggs of *Cucumaria frondosa* and Abraham et al. (2002) reported antimicrobial substances in a range of holothurian species in the coastal waters of India. From the western medical view point, sea cucumbers serve as a rich source of polysaccharide chondroitin sulfate, which is well-known for its ability to reduce arthritis pain. It has been found that the use of a small amount ($\sim$ 3g) of dried sea cucumbers per day has significant impact of reducing arthralgia. Sulfated polysaccharides also have the ability to inhibit viruses and there is a Japanese patent for sea cucumber chondroitin sulfate for HIV therapy (Chen, 2003; Choo, 2008b). Furthermore, the sticky cuvierian tubules are placed over bleeding wounds as a bandage. Sea cucumbers are also credited with curative powers for ailments like high blood pressure and some muscular disorders (James and James, 1994b).

The muscle bands of some sea cucumber species are used as clam substitutes in Asia and the United States (Bruce, 1983) and some sea cucumber species like *Pseudocnus echinatus* are used to feed ducks in China (James, 2001).

## 2.5 Fishery for sea cucumbers: past and present status

The exploitation history of sea cucumbers was dated back to several centuries and sea cucumbers first became commoditized in China and India more than 1000 years ago (Chen, 2003; Friedman et al., 2010b; James and James, 1994a). However, resource depletion was evident in those traditional fishing grounds during early 1800's (Choo, 2008;). As there was a lucrative market for sea cucumber products throughout the world, fishing activities were expanded into new fishing grounds and current activities are mainly confined to five geographical regions; east and southeast Asia, Pacific region, countries in western Indian Ocean and Africa, Latin America including Caribbean region and temperate areas of the northern hemisphere (Toral-Granda et al., 2008). A multitude of sea cucumber species are being exploited in these areas with new species being entered into the fishery while valuable species become scarcer. The fisheries in the tropical and sub-tropical waters are multi-specific whilst temperate fisheries are more or less monospecific having many critically overfished stocks (Bruckner, 2006; Conand, 2004b, 2005; Lovatelli and Conand, 2004; Uthicke and Conand, 2005b).

### 2.5.1 East and Southeast Asia

Asia has the longest history of sea cucumber exploitation, probably more than 1000 years and fishing activities are presently confined to Indonesia, Malaysia, Thailand, Myanmar, Viet Nam, Philippines, Singapore, the Spratly Islands, Japan, Korea, Far East Russian Federation, China, Taiwan, India and Sri Lanka (Choo, 2008b; Friedman et al., 2010b; James and James, 1994a,b; Trinidad-Roa, 1987). However, not all these countries have a long history of sea cucumber exploitation. For example, the sea cucumber fishery in Viet Nam, was only dated back to early 1980's but it lasted for a short period of ten years (Del Mar Otero-Villanueva and Ut, 2007). A total of 52 sea cucumber species are commercially exploited in the Asian region mainly to produce beche-de-mer. Species belonging to families Holothuriidae and Stichopodidae are mainly targeted in tropical and sub-tropical waters while *Apostichopus japonicus* is dominant in the temperate waters. Indonesia is the world's top producer of sea cucumbers from the capture fishery and the Philippines is second in line. Indonesia, together with the Philippines is responsible for around half of the world sea cucumber landings (Choo, 2004, 2008b). Some sea cucumber species belonging to family Cucumariidae (*Colochirus quadrangularis, Colochirus robustus* and *Pseudocolochirus violaceaus*) and genus *Euapta*, *Synapta* and *Opheodesoma* are commonly exploited in the aquarium trade (Toonen, 2002). Gleaning, hand picking, bottom trawl nets, spears, hooks, scoop nets, SCUBA and hookah are widely practiced fishing methods in the sea cucumber fishery. Although, severe depletion of sea cucumber resources has been reported in many countries, management and regulation measures are still lacking in this region except in Japan (Choo, 2008b; Conand, 2004a; Lovatelli and Conand, 2004; Purcell, 2010b).

### 2.5.2 Pacific region

Rapid development of sea cucumber fishery began in the Pacific region in the late eighteenth century, then peaked in the early nineteenth century and then declined rapidly (Conand, 1990; Moore, 2003; Ward, 1972). Sea cucumber fishing activities were re-developed in this region during the 1980's due to elevated export prices and an enhanced demand from the Chinese communities around the world (Preston, 1993). Although there were records on the presence of around 300 shallow water sea cucumber species in this region (Clark, 1946; Conand, 1990; Dalzell et al., 1996; Preston, 1993), 35 species belonging to families Holothuriidae and Stichopodidae are currently exploited (Kinch et al., 2008). Exploitation often involves a high number of artisanal fishers and the most common fishing methods are gleaning and hand picking. Australia and Pacific island countries are the largest exporters of beche-de-mer in the Pacific region (Conand, 1990; Kinch, 2002; Kinch et al., 2008). Depletion of sea cucumber stocks has been reported in many places and previously unfished, low-value species are becoming dominant in the commercial catches (Kinch et al., 2008; Purcell et al., 2009). Several species including *Thelenota ananas, Holothuria leucospilota, Bohadschia argus* and *Holothuria hilla* are fished for the aquarium industry in the Solomon Islands, the Cook Islands, Fiji, French Polynesia, Tonga and Kiribati (Kinch, 2004a). Resource management seems to be quite difficult due to the multispecies nature of the fishery and lack of necessary funds and technical capacity for adequate surveillance and enforcement (Adams, 1992, 1998; Jimmy, 1996; Kinch, 2002; Kinch et al., 2008; Lokani et al., 1996; Purcell et al., 2009; Trianni, 2002).

### 2.5.3 Western Indian Ocean and Africa

Around 30 countries in this region are involved in the sea cucumber fishery and they are responsible for approximately 1/3 of the world sea cucumber production. Kenya, Madagascar, Tanzania and the Seychelles are the major sea cucumber producers in this region (Aumeeruddy and Conand, 2007; Conand, 2008; Conand and Muthiga, 2007; Rasolofonirina et al., 2005). It was difficult to state the commencement of sea cucumber fishery in this region but export records were dated back to early 1900's (Conand, 2008; Hampus Eriksson et al., 2010). Nearly 30 sea cucumber species belonging to two families; Holothuriidae (23) and Stichopodidae (6) are presently exploited. The commercial values vary from species to species and there are differences in harvesting and processing methodologies. The sea cucumber resources appeared to be over exploited or fully exploited in 12 countries out of the 30 countries involved in sea cucumber fishery (Conand, 2008; Conand and Muthiga, 2007). Although several sea cucumber management programmes have been implemented in national and regional levels, these seem to be insufficient for sustainable use of this resource in this region (Aumeeruddy et al., 2005; Conand, 2008; Conand et al., 1997a, 2006).

### 2.5.4 Latin America and the Caribbean region

Sea cucumber fishing activities are currently preactised in 25 countries belonging to Latin America and the Caribbean regions. Eleven species are currently harvested in commercial state but limited or no information is available on their biology, ecology and population status (Toral-Granda et al., 2008). *Isostichopus fuscus* is the major commercial species in the Pacific coast of Mexico, south and central America (Castro, 1998; Conand et al., 1992; Toral-Granda and Martinez, 2007) while three species; *Isostichopus badionotus*, *Astichopus multifidus* and *Holothuria mexicana* are dominant in the Caribbean region (Guzman and Guevara, 2002). No or limited sea cucumber management measures are in placed in most of these countries (Castro, 1995; Toral-Granda et al., 2008).

### 2.5.5 Temperate areas of the northern hemisphere

Canada, the United States of America, the Russian Federation and Iceland are mainly involved in the sea cucumber fishery in higher latitudes on northern hemisphere and catches are being sustained by four species; *Cucumaria frondosa*, *Cucumaria japonica*, *Parastichopus californicus* and *Parastichopus parvimensis*. According to the available information, *C. frondosa* is the most abundant commercial sea cucumber species in the globe and it can be harvested around 15 tons per day in some areas (Bradbury, 1999; Bruckner, 2001; Hamel and Mercier, 1999). *Parastichopus* species are mainly exploited through diving and hand picking while trawling is used to harvest *Cucumaria* species and this involves a more industrialized process. The sea cucumber fishing activities are fairly new to this region and only dates back to early 1970's (Hamel and Mercier, 2008).

On an average, global sea cucumber production has increased from 2300 tons (wet weight) to 30500 tons (wet weight) over the past six decades (Anderson et al., 2010), although, severe declining of many local and regional sea cucumber populations were witnessed throughout the world (Anderson et al., 2010; Conand, 2001, 2004a; Friedman et al., 2010a; Sloan et al., 1985). In most of the occasions, individual sea cucumber fisheries have followed a typical trajectory with a rapid increase, short peak and a substantial downward trend suggesting a boom-and-bust pattern (Anderson et al., 2010; Friedman et al., 2010a). Increasing demand together with some features of sea cucumbers such as sedentary behaviour, easiness of harvesting, late age at maturity, slow growth and low rates of recruitment were found to be the major reasons for their vulnerability to overfishing (Bruckner, 2006; Lovatelli and Conand, 2004; Uthicke, 2004; Uthicke et al., 2004).

However, the evaluation of global status of sea cucumbers is highly challenging at present due to a lack of abundance data and incomplete catch, export and import statistics (Anderson et al., 2010; Baine and Sze, 1999; Toral-Granda et al., 2008).

## 2.6 Processing and marketing of sea cucumbers

### 2.6.1 Processing

Sea cucumbers are mainly marketed as beche-de-mer or trepang (dried product) but salted, cooked and frozen products are also available (Conand, 1990; Ferdouse, 2004; James, 1989; Therkildsen and Petersen, 2006; Toral-Granda et al., 2008).

Beche-de-mer is produced mainly by a process of cleaning, boiling, salting, and drying. At the first stage, animals are cleaned in sea water to remove dried slime, sand and other extraneous particles. Then, the internal organs are removed by making a small slit either in the posterior end or mid ventral surface. Eviscerated sea cucumbers are boiled and stored in salt or buried in moist sand to activate bacterial decomposition. The boiling time and the storage time in salt or sand vary with the species. The salted or buried products are boiled once again and placed on drying platforms or mats for sun drying and /or smoking (Connad, 1990). However, there may be slight differences in the major processing steps depending on the species and the regions or areas (Chen, 2003; Conand, 1990; Dissanayake et al., 2010; Lavitra et al., 2008; Poh-Sze, 2004).

### 2.6.2 Marketing

Approximately 90% of the world sea cucumber production is destinated in China, Hong Kong SAR, Singapore and Taiwan Province of China and global sea cucumber trade is mainly controlled by these four countries (Anderson et al., 2010; Baine, 2004; Choo, 2008b; Jaquemet and Conand, 1999). The market demand particularly for beche-de-mer mainly fluctuates with species and factors such as size, shape, appearance, colour, odour, packing and moisture content have influence on the market price.

Consumer prefers certain varieties of beche-de-mer than the others and these species fetch the highest price in the international market. Considering this market demand, commercial sea cucumber species have been categorized into high-value, medium-value and low-value categories. However, market demand is subject to change rapidly with the resource availability and value category of each species may fluctuate accordingly (Conand, 2008; Kinch et al., 2008; Purcell, 2010b).

In many countries, sea cucumbers are mainly exploited to provide beche-de-mer for the Chinese market (Baine, 2004; Conand, 2001; Toral-Granda et al., 2008). However, there are no accurate sea cucumber trade statistics in most of these countries and available information is often incomplete. For example, although Indonesia is the world's largest sea cucumber producer, export statistics have not been reported since 1989 and also in addition there were a lot of gaps in the export statistics of Indo-Pacific countries (Choo, 2008b). In some countries, including China and Canada, sea cucumber exports have been reported under combined categories such as invertebrates or echinoderms (Choo, 2008b; Hamel and Mercier, 2008). Further, there is often great pressure to under -report the exports for tax evasion purposes and this has created huge discrepancies between catch and export figures in many countries including Indonesia, Papua New Guinea, Mozambique and the Solomon Islands (Choo, 2004, 2008b; Clarke, 2004). Apart from the food trade, a large number of sea cucumbers are traded in the aquarium industry, but little data on species, quantities and source countries are available (Bruckner et al., 2003). The volume of sea cucumbers used in the medicinal and cosmetic industries is also unknown (Anderson et al., 2010; Choo, 2008b). Although trade statistics are considered as a good source of information to evaluate the exploitation trends and resource status, it is difficult to use existing trade statistics to quantify the trends and volume of world sea cucumber fishery due to its poor quality (Anderson et al., 2010; Baine, 2004).

## 2.7 Assessment and Management of sea cucumber resources

### 2.7.1 Resource Assessment

Proper understanding of stock status is a prerequisite to ensure the long term sustainability of marine resources and stock surveys are commonly used to collect such information (Gulland, 1983; Hilborn and Walters, 1992). Stock surveys can be broadly categorized into two main groups; fishery dependent and fishery independent surveys and both these surveys are often used to estimate the abundance and biomass of sea cucumbers in a given region or a fishery (Aumeeruddy et al., 2005; Friedman et al., 2008; Skewes et al., 2002a,b).

**(a) Fishery dependent surveys**

The fishery dependent surveys involve a process of collecting and analyzing of catch, effort and other fishery related information. In most of the cases, fishery dependent data on sea cucumbers are collected by fishery officers on a regular field visits or data submitted by fishers via log books (Purcell, 2010b). Time series data on commercial landings are used to illustrate catch structure (mainly refers to species composition and size of individuals), level of exploitation and to calculate the catch per unit effort (CPUE) which provides useful information on the resource abundance (Hilborn and Walters, 1992). Changes in catch structure and CPUE estimates provide strong signals of stock status and future potentials. However, fishery-dependent data often provide biased indications on the species composition, sizes and abundance of wild sea cucumber stocks as fishers or fishing gears are probably selective towards certain species and particular sizes. Further, the environmental conditions, experience of fishers, morphology of species, harvesting methods and gear improvement may have great influence on CPUE trends and catch structure (Purcell, 2010b; Purcell et al., 2009; Toral-Granda, 2008b).

Although the monitoring of catch and effort data is the easiest and cheapest way of understanding the stock status of sea cucumbers, most countries have given less attention to report such information as sea cucumbers form very low contribution to their total marine fishery production. For example, Malaysia stopped recording of catch and effort information after the fishery started to decline in 1993 and therefore catches were severely underestimated in some Southeast Asian countries (Choo, 2008b; Conand et al., 1992; Purcell, 2010b).

**(b) Fishery independent surveys**

Underwater Visual Census (UVC) is the widely practiced fishery independent survey technique in sea cucumber resource assessment as it provides rapid estimates of relative abundance, biomass and length frequency distributions of sea cucumbers (Kalaeb et al., 2008; Mulochau and Conand, 2008; Skewes et al., 2006, 2002a,b). Different sampling methods such as simple dive transect, manta-tow, quadrets and remote video equipments are used when practicing UVC for sea cucumber assessments (Aumeeruddy et al., 2005; Leeworthy and Skewes, 2007; Purcell et al., 2009; Shiell and Knott, 2010; Skewes et al., 1999; Uthicke and Benzie, 2001). Censuses are mainly done through snorkeling or scuba diving but use of submersible gears are reported in some instances. As sea cucumbers have a patchy distribution, large number of survey sites need to be surveyed to get reliable stock estimates. Hence, population surveys by underwater visual census are relatively costly and time-consuming. Well experienced and trained divers are required for underwater sampling and species identification. Further, several sources of bias can be associated in visual surveys such as failure of an observer to notice individuals, observer experience and observer speed (Purcell, 2010b; Sale and Sharp, 1983; Smith, 1988; Thresher and Gunn, 1986).

### 2.7.2 Resource Management

Inadequate management has resulted in severe declining of global sea cucumber stocks specially during the last two decades (Anderson et al., 2010; Conand, 1990, 1997; Richards et al., 1994; Sloan et al., 1985; Toral-Granda et al., 2008). According to the recent reviews, management of sea cucumbers is highly challenging due to several reasons. More often the sea cucumber fishery is continued as an open access resource in many countries hence the controlling of fishing efforts is difficult (Purcell, 2010b). Sea cucumber fisheries are within the class of "S-Fisheries" where small-scale, spatially-structured and sedentary stocks are targeted. As these fisheries are different from usual finfish fishery, the established classical theories and models are not readily applicable to predict the productivity and potentials of sea cucumber populations. Further, the abundance estimates of sea cucumbers are difficult due to underlying cost and also fishery-dependent indicators such as CPUE are often useless (Orensanz et al., 2005; Perry et al., 1999; Purcell, 2010b). All these reasons together with inadequate knowledge on biology and ecology of sea cucumbers have made it impossible to design and implement proper management measures to safeguard global sea cucumber resources (Conand, 1990, 2001; Purcell, 2010b; Shepherd et al., 2004; Toral-Granda et al., 2008). Poor recording of catch and trade statistics, difficulties in tracing the species origin from processed products and Illegal, Unregulated and Unreported (IUU) fishing activities are other challenges in management and conservation of sea cucumbers (Lovatelli and Conand, 2004; Purcell, 2010b; Toral-Granda et al., 2008; Uthicke et al., 2010).

However, limited management measures have been adopted in some countries and regions to regulate fishing pressure on sea cucumber resources. These management measures mainly include;

**(a) Minimum landing size**

Minimum landing size (MLS) is one technical measure used to manage fisheries with the aim of allowing enough juveniles to survive and spawn (Jennings et al., 2001;

Stewart, 2008). The minimum landing size is often based on the size at first sexual maturity ($L_{50}$ or $W_{50}$) (Bruckner, 2006; Kearney, 1990; Stewart, 2008). However, several studies have shown that some sea cucumbers have not actively participated in spawning though; they have attained the size at first maturity. Hence, by considering more conservative aspects, scientists have suggested to use $L_{90}$ (estimated body length at which 90 percent of the population is mature) plus few centimeters instead of $L_{50}$ when setting minimum landing size for sea cucumbers (Conand, 1990, 1993; Gaudron et al., 2008; Purcell et al., 2009). Minimum landing size is mainly species specific and it varies from country to country and sometimes even between regions within a country (Kinch et al., 2008; Purcell, 2010b; Toral-Granda et al., 2008). MLS is the commonly used management measure in sea cucumber fishery and this has been successfully implemented in Cuba, Fiji, New Caledonia, Ecuador, the Torres Strait and Yap Federal States of Micronesia. MLS is often set for both live animals and processed products (Conand, 2008; Friedman et al., 2008; Kinch et al., 2008; Toral-Granda, 2008a).

**(b) Catch quota (setting TAC)**

Catch quota aims to control the quantity of animals removed by fishing within a year or fishing season. Quotas are also referred to as total allowable catch (TAC) limitations, usually expressed in tons of live weight, and assigned to the entire fishery ("global quota"), or an individual basis to fishers (ITQs) or fishing vessels (IVQs). Maximum sustainable yield (MSY) is used as the basis when assigning quotas (Akamine, 2004; Hilborn and Walters, 1992; Hilborn et al., 2005; Parma et al., 2006). However, application of MSY theory has been found to be problematic in some sea cucumber fisheries due to underlying model assumptions and lack of input model parameters such as natural mortality, intrinsic rate of population growth and virgin biomass (Uthicke, 2004; Uthicke et al., 2004). It is believed that sustainable harvest rate of sea cucumbers is a small fraction of virgin biomass as most species have low productivity, high longevity and low growth rate. Practically, TAC have been proposed for sea cucumber species with sufficient information on abundance estimated through population surveys (Kinch et al., 2008; Purcell, 2010b). Catch quotas have been successfully implemented for the sea cucumber fishery in the Great Barrier reef, British Colombia and attempts were made in the Seychelles and Galapagos Islands too (Aumeeruddy and Conand, 2007; Purcell, 2010b; Shepherd et al., 2004; Uthicke and Benzie, 2001). However, implementation and compliance of catch quotas is quite difficult in tropical sea cucumber fisheries due to the large number of fishers, difficulties of monitoring catch statistics and the multispecies nature of fishery (Purcell, 2010b; Toral-Granda et al., 2008).

**(c) Gear restrictions**

Gear restriction is important to limit or prohibit the use of certain amount and type of fishing gears or equipments in sea cucumber fishery. More often, efficient and industrialized fishing gears such as SCUBA or hookah equipments, "bombs", spears and trawlers are found to be prohibited in sea cucumber fishery (Choo, 2008b; Conand, 2008; Kinch et al., 2008; Purcell, 2010b). This management measure has been imposed in many western central Pacific (Kinch et al., 2008) and temperate countries (Hamel and Mercier, 2008). Prohibition of compressed-air diving (SCUBA and hookah gear) seems to be widely practiced in many places (Bruckner, 2006; Purcell, 2010b).

**(d) Temporal closures**

Temporarily closed areas are used to protect target stocks from mortality at a specific stage of life history, such as when a species aggregates to spawn (Halliday, 1988; Horwood et al., 1998). According to Purcell (2010b), this concept is not valid for a majority of sea cucumber species as they do not form spawning aggregations and even they are not vulnerable for higher fishing pressure during the spawning season. However, seasonal closures are widely used in sea cucumber fishery to reduce annual fishing efforts. For example, in some parts of Japan and Galapagos Islands sea cucumber fishing is allowed for two months in each year (Choo, 2008b; Toral-Granda, 2008b) and in British Colombia *Parastichopus californicus* is allowed to be harvested only for three weeks during October (Hamel and Mercier, 2008).

A long term prohibition of fishing activities (ban or moratorium) is generally set in place where the resource is overexploited to the extent that other management measures are not adequate to rebuild the populations within a satisfactory time frame. Collection, processing and trade of sea cucumbers have been banned in India since 2001(Conand, 2008), Egypt in 2004 (Lawrence et al., 2004) and fishing for surf redfish (*Actinopyga mauritiana*) and black teatfish (*Holothuria whitmaei*) was banned in the Torres Strait in 2003 (Skewes et al., 2006)

**(e) Effort control**

Effort control is mainly implemented through limiting number of fishing licenses, number of fishers onboard and fishing time. These were used as the basic management measures in some sea cucumber producing countries and recently the Seychelles fishing authority has limited the sea cucumber fishing effort (fishing licenses) up to 25 boats and each boat was permitted to have 4 divers onboard (Aumeeruddy and Conand, 2007). In some instances fishing capacity has been controlled by prohibiting the use of vessels above a certain length (eg: maximum beam length of mother boats is restricted to 18 m in Galapagos) or engine capacity. Both effort and capacity control measures are useful to control the exploitation rate (Friedman et al., 2008; Purcell, 2010b; Toral-Granda, 2008b).

**(f) Marine protected areas**

Marine protected areas (MPAs) seem to be an effective management tool for sea cucumbers as it provides insurance for larval recruitment by promoting dense breeding populations (Bell et al., 2008). In Philippines, more than 500 MPAs have been declared to protect the breeding populations of sea cucumbers as it is difficult to regulate the fishing through quotas and rotational harvest strategies (Choo, 2008a). Further, MPAs in New Caledonia are reported to be working effectively as spawning refuge for sea cucumbers (Purcell, 2010b). However, planning of MPAs is difficult for sea cucumbers due to their irregular reproduction, differences in habitat preference, poor information on larval dispersion and connectivity among the local populations (Purcell, 2010b; Sale et al., 2005).

Rotational harvest closures and regularization of catch and effort data collection are other possible management measures in the sea cucumber fishery. Although sea ranching and restocking have been identified as possible solutions to enhance the wild sea cucumber populations, it is an expensive remedy. However, inadequate and poor enforcement capacity has posed considerable constraints on the effectiveness of these management measures (Anderson et al., 2010; Purcell, 2010b; Toral-Granda et al., 2008).

# 3

# Abundance and distribution of sea cucumbers

## 3.1 Background

The sea cucumber fisheries throughout the world have been characterized by boom and bust cycles where biological overexploitation often occurs before an economic overexploitation (Conand, 1997; Preston, 1993). Overharvesting of sea cucumber species can now be considered as a worldwide phenomenon (Conand, 2008) and the recovery of depleted populations seem to be slow and sporadic. Therefore, information on stock status is essential for the efficient and durable management of sea cucumber resources throughout the world (Choo, 2008b; Kinch, 2002).

The sea cucumber fishery was introduced to Sri Lanka by the Chinese and this has provided significant contribution to the livelihoods of coastal fishing communities for centuries (Hornell, 1917). The fishing activities are greatly influenced by the monsoon winds, hence harvesting off the northwest coast occurs intensively during the northeast monsoon (from October to April) and in the north and east fishing is undertaken during the southwest monsoon period (from May to September). No special gear or net is devised exclusively to catch sea cucumbers and they are mainly harvested by hand picking either through scuba or skin diving (Dissanayake and Wijayarathne, 2007). Relatively little information is available on the biology and ecology of sea cucumbers around the island.

As the fishery has developed without baseline biological data or routine monitoring, the resource status is unknown and un-quantified. Despite the observations by fishers of local depletion of sea cucumbers, particularly, the high-value species, no systematic study has been conducted in Sri Lanka to assess the status of sea cucumber populations or to evaluate the sustainability of the fishery. Therefore, it is timely to assess these populations in order to provide a foundation for management of the local fishing activities.

In the absence of reliable long term fishery dependant data, a stock survey is the only viable method for determining the status of fished populations. An Underwater Visual Census (UVC), a non-destructive, fishery independent method (Curtis et al., 2004), was carried out to assess the status of sea cucumber stocks in the two geographical regions; northwest and east coast of Sri Lanka. This approach has been successful for estimating the abundance of reef-associated fishes (Sale et al. 1984), spiny lobster (Pitcher et al., 1992) and sea cucumbers in the Great Barrier Reef and New Caledonia (Purcell et al., 2009; Skewes et al., 2006; Uthicke et al., 2004).

## 3.2 Methodology

### 3.2.1 Survey area

An underwater visual census was carried out off the east and northwest coasts of Sri Lanka in 2008. The east coast survey area was between $08^0 17'$ - $06^0$ $50'$ N and $81^0$ $25'$ - $82^0$ E where the distance of the study area along the shore was 190 km. The northwest coast study area was between $07^0$ $55'$N - $08^0$ $55'$ N latitudes and $79^0$ $35'$ E - $79^0$ $57'$ E longitudes and the study area extended 112 km along the shore (Figure 3.1). Due to logistical and practical constraints, the study was confined to 1 - 30 m depth resulting in survey area of 1307 $km^2$ off the east coast and 1779 $km^2$ off the northwest coast. Two surveys were carried out at the beginning of each fishing season by temporarily closing the commercial fishing activities. Thus, the east coast survey started in early June and the northwest coast survey was in early October with the survey period extending up to 4 weeks on each occasion.

An initial description of the survey area was formulated from interviews with fishers, researchers, collectors and exporters. Nautical charts were used as the basis for the surveys by importing scanned, digitized, geo-referenced charts into a Geographic Information System (GIS) to set up a geo-database and demarcate the survey areas.

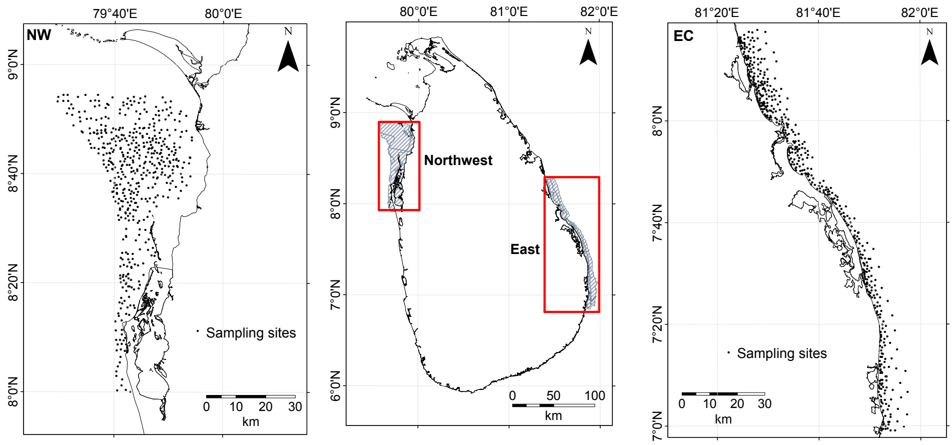


**Figure 3.1:** Sea cucumber sampling sites off the northwest (NW) and the east (EC) coasts of Sri Lanka

### 3.2.2 Pilot study

A pilot study was carried out off the east coast to select the best transect dimension with two goals;

1) To gather maximum information on the abundance and distribution of sea cucumbers as well as bottom habitat characteristics

2) To select practically convenient transects for the divers.

Fifty sampling sites were surveyed by using eight transect dimensions belonging to four transect categories (Table 3.1). An area of 600 $m^2$ was surveyed by each transect dimension using different transect numbers (n). The number of transects in each transect dimension were equally allocated among the three survey boats except for the 150 $m^2$ transect category where the allocation was done in a 3:3:2 ratio. The time required for surveying each transect was calculated by taking the difference between total dive time (time between the departure and return to the boat including survey time) and dive time (time between the departure and return to the boat without doing transect). Dive time was measured from random dives in sampling sites and time measurements were recorded by the onboard staff.

The variance was considered as the main determinant when selecting a feasible transect dimension as all the other factors affecting the survey (survey time, survey divers, survey boats and financial allocations) were fixed. By considering the safety of the divers, maximum number of transects which could be covered per boat (2 divers onboard) per day were decided to be 8. The mean abundance and variance were

**Table 3.1:** Different transect categories ($m^2$), transect dimensions (length × width combinations) and number of transects (n) used to cover 600 $m^2$ in each transect dimension during the pilot survey carried out off the east coast of Sri Lanka

| Transect category ($m^2$) | Transect dimension ($m^2$) | Transect nos (n) |
|---|---|---|
| 50 | 25 × 2 | 12 |
| | 50 × 1 | 12 |
| 100 | 50 × 2 | 6 |
| | 100 × 1 | 6 |
| 150 | 75 × 2 | 4 |
| | 150 × 1 | 4 |
| 200 | 100 × 2 | 3 |
| | 200 × 1 | 3 |

calculated with respect to each transect dimension.

### 3.2.3 Survey proper

Due to lack of information on bottom habitat characteristics and bathymetry of the survey areas, sampling sites were allocated randomly throughout each survey area to cover all the possible sea cucumber habitat and to increase the precision of the surveys. Five hundred sampling sites were allocated into each survey area using Hawth's tool (http://www.hawthstools.com) integrated into a Geographic Information System. Both day (400 sites) and night (100 sites) diving activities were carried out in the northwest while only day diving was carried out in the east due to security constraints during the study period.

The survey employed rapid marine assessment technique that has been used for sea cucumber surveys in the Torres Strait (Long et al., 1996). Field work was undertaken by a team of divers operating from small boats and locating sampling sites using a portable Global Positioning System (GPS) device. On each sampling occasion one or two divers swam along a 100 m transect, collecting sea cucumbers on a 1 m strip to each side of the transect line (Figure 3.2).

At the same time, bottom substrate within each transect was visually estimated in terms of the percent cover of sand, rubble, limestone platform, coral, terrestrial rock, mud, seagrass and macroalgae. Based on this information, eleven habitat types; sandy, seagrass, macroalgae, sandy habitat with rocks/corals, sandy habitat with macroalgae, sandy habitat with seagrass, rocky habitat with macroalgae/seagrass, muddy habitat, sandy and muddy habitat with corals, muddy and sandy habitat and

**Figure 3.2:** Some steps carried out during the underwater visual census: locating a sampling site using portable GPS (left) and a survey diver is covering a transect (right)

muddy habitat with macroalgae were described. Each sampling site was categorized into one of these habitat by considering the estimated percent cover of each component (Figure 3.3). When defining a habitat type for the sampling site, the percent cover of each component was added together and the dominant component or components were taken into account.

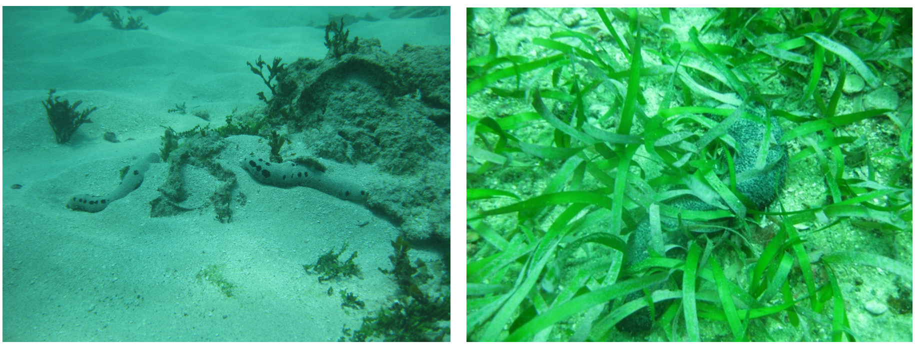

**Figure 3.3:** Two different habitat types; sandy habitat with rocks/corals (left) and seagrass habitat (right) encountered during the underwater visual census in 2008

### 3.2.4 Size and weight measurements

All sea cucumbers collected during the surveys were brought to the base camp where they were individually weighed and measured for total length. The body length was measured to the nearest 1 cm and weighed to the nearest 1 g using an electronic balance. The animals were allowed approximately 2 minutes to drain before being weighed. Both the whole body weight and gutted body weight were taken.

### 3.2.5 Data analysis

Average density (ind $ha^{-1}$) of each sea cucumber species was calculated from site counts (per unit area) and the total study area. The standing stock estimates were based on the product of mean density, survey area and the average weight from size frequency data collected during the surveys. The density distribution of different sea cucumber species was mapped using Arcinfo integrated with Geographical Information System (GIS). The Kruskal Wallis test was performed to investigate the density of sea cucumber species in relation to different habitat types and depth categories. The statistical analyses were performed using R version 2.10.1 (R Development Core Team, 2008).

Two approaches were used to estimate the indicative maximum sustainable yield (MSY) in this study.

1. According to Gulland (1983); $MSY = x \times MB_0$ where $B_0$ is virgin (unfished) biomass, $M$ is natural mortality and $x$ scaling factor, is based on the logistic function which assumes that population growth is highest at intermediate population size where $x = 0.5$. But various authors have suggested that the $MSY$ calculated using this formula is an overestimate as it is highly unlikely that the observed or estimated biomass ($B$) to be virgin. Hence, as a conservative measure, Garcia et al. (1989) and Woodby et al. (1993) suggested to use $x = 0.2$ and this approach was used in the present analysis.

2. The second approach is to determine optimal catch rates (to use an estimate of the optimal fishery mortality rate - $F_{opt}$) based on natural mortality, such that $F_{opt}$ = 0.6 M (Perry et al., 1999). The exploitation rate $E$, being the proportion of the population fished for a given $F$ can be calculated as; $E = \frac{F}{Z}(1 - e^{-Z})$ where $Z$ is the total mortality rate ($Z = M + F$). Here $MSY = E \times B$, where $B$ is the biomass

Though the use of $F_{opt} = 0.6M$ for calculating exploitation rate for invertebrates is arguable, these two approaches have been used to produce indicative $MSY$ estimates for sea cucumber fisheries in Alaska (Woodby et al., 1993), Moreton Bay (Skewes et al., 2002a), the Torres Strait (Skewes et al., 2006) and the Seychelles (Aumeeruddy et al., 2005).

As the mortality rates of sea cucumbers are difficult to estimate, the published estimates of natural mortality (Conand, 1990; Uthicke et al., 2004) for tropical sea cucumber species were used when estimating $MSY$.

## 3.3 Results

### 3.3.1 Pilot study

Transects of 150 m and 200 m length were not feasible as divers were not able to cover 8 transects when the transect lengths were greater than 100 m. There was a little pattern in variance among the remaining transect dimensions (Table 3.2). However the lowest variance and CV were observed in 100 × 2 m transect dimension. In addition to the lowest CV and variance, the 100 × 2 m transect covered the greatest area per transect hence 100 × 2 m was chosen as the transect dimension for subsequent use.

**Table 3.2:** Mean density (ind transect$^{-1}$), variance, CV and time ± SD (minutes) required to cover each transect dimension during the pilot survey off the east coast of Sri Lanka in June 2008

| Transect category | Transect Dimension | Mean Density | Variance | CV | Time ± SD |
|---|---|---|---|---|---|
| 50 | 50 × 1 | 0.33 | 0.67 | 2.48 | 6.4 ± 0.7 |
| | 25 × 2 | 0.37 | 1.11 | 2.85 | 6.2 ± 0.7 |
| 100 | 100 × 1 | 1.00 | 1.09 | 1.04 | 9.2 ± 1.2 |
| | 50 × 2 | 0.66 | 0.97 | 1.49 | 8.0 ±1.4 |
| 150 | 150 × 1 | 0.75 | 0.78 | 1.18 | 11.2 ± 1.7 |
| | 75 × 2 | 0.63 | 1.12 | 1.68 | 10.2 ± 1.5 |
| 200 | 200 × 1 | 1.00 | 1.33 | 1.15 | 12.3 ± 1.5 |
| | 100 × 2 | 1.30 | 0.66 | 0.62 | 11.3 ± 1.6 |

### 3.3.2 Observed species

A total of 25 sea cucumber species belonging to seven genera (*Actinopyga*, *Bohadschia*, *Holothuria*, *Pearsonothuria*, *Stichopus*, *Thelenota* and *Acaudina*) were identified during the surveys (Table 3.3). Of these 18 species were common to both east and northwest areas, three species were unique to the east and four species were found only in the northwest. Except for *H. fuscocinerea*, *H. hilla*, *H. leucospilota* and *P. graeffei*, all the other species are commercially exploited in Sri Lanka and categorized as "high-value" (species with a commercial value greater than US$ 40/kg dry weight), "medium-value" (species with a commercial value in between US$ 15-40/kg dry weight) and "low-value" (species with a commercial value less than US$ 15/kg dry weight) based on the export market value (Table 3.3).

**Table 3.3:** Scientific name, commercial value, temporal (day/night) distribution of sea cucumber species observed off the east (EC) and northwest (NW) coasts of Sri Lanka during two surveys in June and October 2008 & 2009

| No | Scientific name | Value | Time | Area |
|---|---|---|---|---|
| 1 | *Actinopyga echinites* | Medium | D,N | NW, EC |
| 2 | *Actinopyga mauritiana* | Medium | D | EC |
| 3 | *Actinopyga miliaris* | Medium | D,N | NW, EC |
| 4 | *Bohadschia atra* | Low | D,N | NW, EC |
| 5 | *Bohadschia maculisparsa* | Low | N | NW |
| 6 | *Bohadschia marmorata* | Low | N | NW, EC* |
| 7 | *Bohadschia* species "lines" | Low | D,N | NW, EC |
| 8 | *Bohadschia vitiensis* | Low | D,N | NW, EC |
| 9 | *Holothuria atra* | Low | D,N | NW, EC |
| 10 | *Holothuria edulis* | Low | D,N | NW, EC |
| 11 | *Holothuria fuscocinerea* | No | D | EC |
| 12 | *Holothuria fuscogilva* | High | D | NW, EC |
| 13 | *Holothuria hilla* | No | D | NW |
| 14 | *Holothuria isuga* | Low | D | NW, EC |
| 15 | *Holothuria leucospilota* | No | D | NW, EC |
| 16 | *Holothuria nobilis* | High | D | NW, EC |
| 17 | *Holothuria scabra* | High | D,N | NW |
| 18 | *Holothuria spinifera* | Medium | N | NW |
| 19 | *Holothuria* "pentard" | High | D | NW, EC |
| 20 | *Pearsonothuria graeffei* | No | D | NW, EC |
| 21 | *Stichopus chloronotus* | Medium | D,N | NW, EC |
| 22 | *Stichopus herrmanni* | Medium | D,N | NW, EC |
| 23 | *Thelenota ananas* | Medium | D | NW, EC |
| 24 | *Thelenota anax* | Medium | N | NW, EC* |
| 25 | *Acaudina molpadioides* | Low | D,N | EC |

(*updated based on 2009 survey results)

The high-value species include *H. scabra*, *H. fuscogilva*, *H. nobilis* and *Holothuria* "pentard". Species belonging to the genus *Actinopyga*, *Stichopus*, *Thelenota* and *H. spinifera* are considered as medium-value and the rest belong to the low-value category. Temporal and spatial variations of sea cucumber diversity were revealed. *H. spinifera*, *T. anax* and two *Bohadschia* species (*B. maculisparsa* and *B. marmorata*) were recorded only at night whilst others were found either in the day or both day and night. The species diversity comparison between two survey areas indicated more or less equal species diversity in both northwest (22 species) and east (21 species).

### 3.3.3 Abundance and spatial distribution

A total of 2640 sea cucumbers were counted from the northwest survey and 872 from the east. The overall average density (± SD) of sea cucumbers was higher in the northwest (350 ± 648 ind ha$^{-1}$) than in the east (90 ± 130 ind ha$^{-1}$, Table 3.4). Low-value species were predominant in both survey areas (79 ± 125 ind ha$^{-1}$ in the east and 244 ± 488 ha$^{-1}$ in the northwest) and species of medium value were relatively abundant (10 ± 34 ind ha$^{-1}$ in the east and 105 ± 175 ha$^{-1}$ in the northwest) when compared with high-value species ($<$ 2 ind ha$^{-1}$). The result illustrates that the abundance of sea cucumbers varied markedly among the survey sites within the survey area as well as between the survey areas (Figure 3.4). Sea cucumbers were highly abundant in some survey sites while others were less abundant giving patchiness of spatial distribution and this was common in the northwest. However, it was hard to see any systematic pattern of the distribution within the survey areas.

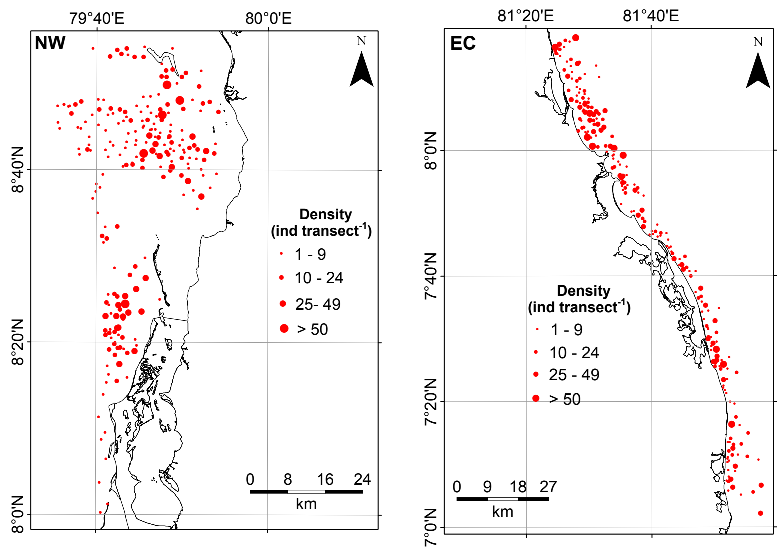


**Figure 3.4:** Average density (ind transect$^{-1}$) and spatial distribution of all sea cucumber species off the northwest (NW) and the east (EC) coasts of Sri Lanka in 2008

The abundance of low-value species was heavily weighted by the presence of large numbers of *H. edulis* which was the most dominant species both in east (40 ± 87 ind ha$^{-1}$) and northwest (138 ± 346 ind ha$^{-1}$). *H. edulis* was reported at 29% of sampling sites in the northwest and 22% in the east. The distribution of this species

**Table 3.4:** Average density (D) ± SD (ind $ha^{-1}$) and total abundance (Ab, Nos $10^6$) of individual sea cucumber species and major commercial groups in the east (EC) and the northwest (NW) coasts of Sri Lanka in 2008

| **Species** | **EC** | | **NW** | |
|---|---|---|---|---|
| | **D** | **Ab** | **D** | **Ab** |
| *A. echinites* | 2 ± 13 | 0.28 | 2 ± 15 | 0.27 |
| *A. miliaris* | 3 ± 16 | 0.41 | 2 ± 14 | 0.35 |
| All *Actinopyga* spp. | 5 ± 22 | 0.70 | 4 ± 29 | 0.65 |
| *B. marmorata* | 0 | 0.00 | 5 ± 38 | 0.91 |
| *B.* species "lines" | 7 ± 30 | 0.85 | 4 ± 26 | 0.72 |
| *B. vitiensis* | 6 ± 27 | 0.74 | 3 ± 20 | 0.55 |
| All *Bohadschia* spp. | 13 ± 44 | 1.70 | 13 ± 56 | 2.30 |
| *H. atra* | 24 ± 54 | 3.15 | 90 ± 252 | 15.99 |
| *H. edulis* | 40 ± 87 | 5.21 | 138 ± 346 | 24.57 |
| *H. fuscogilva* | 1 ± 6 | 0.08 | 0 ± 5 | 0.06 |
| *H. nobilis* | 0 ± 4 | 0.04 | 0 ± 2 | 0.02 |
| *H. scabra* | 0 | 0.00 | 1 ±16 | 0.24 |
| *H. spinifera* | 0 | 0.00 | 70 ± 34 | 12.45 |
| Other *Holothuria* spp. | 2 ± 15 | 0.30 | 3 ± 21 | 0.60 |
| All *Holothuria* spp. | 67 ± 109 | 8.78 | 302 ± 491 | 53.93 |
| *S. chloronotus* | 5 ± 26 | 0.70 | 5 ± 25 | 0.89 |
| *S. herrmanni* | 0 | 0.00 | 0 ± 0 | 0.01 |
| All *Stichopus* spp | 5 ± 26 | 0.70 | 5 ± 25 | 0.90 |
| *T. anax* | 0 | 0.00 | 26 ±47 | 4.54 |
| All Thelenota spp. | 0 | 0.00 | 26 ±47 | 4.54 |
| All Sea cucumber species | 90 ± 130 | 11.88 | 350 ± 648 | 62.32 |
| High-value species | 1 ± 7 | 0.12 | 1 ± 17 | 0.32 |
| Medium-value species | 10 ± 34 | 1.40 | 105 ± 175 | 18.54 |
| Low-value species | 79 ± 125 | 10.36 | 244 ± 488 | 43.46 |

within the northwest survey sites was highly heterogeneous and the highest densities were concentrated close to the lagoon mouth and the northern part of the survey area. The distribution of *H. edulis* seemed to be more even in the east (Figure 3.5).

*H. atra* was the second highest species with an average density of 90 ± 252 ind $ha^{-1}$ in the northwest and 24 ± 54 $ha^{-1}$ in the east. This species was observed around 22% of sampling sites in both areas and distribution pattern was much similar to *H. edulis* (Figure 3.6)

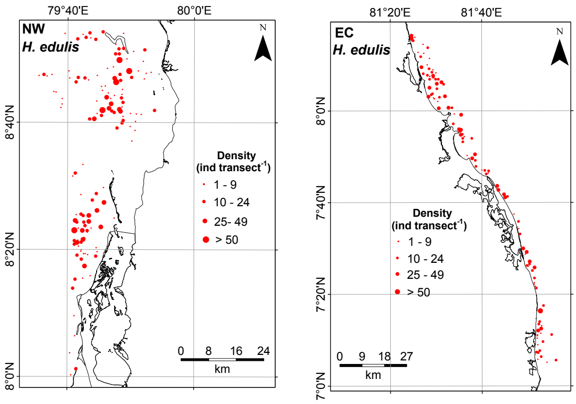


**Figure 3.5:** Average density (ind transect$^{-1}$) and spatial distribution of *H. edulis* off the northwest(NW) and the east (EC) coasts of Sri Lanka in 2008

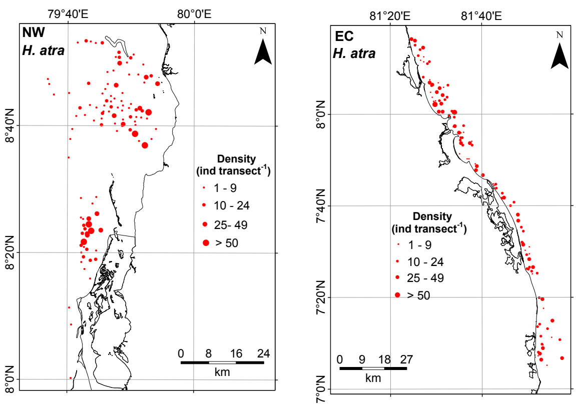


**Figure 3.6:** Average density (ind transect$^{-1}$) and spatial distribution of *H. atra* off the northwest (NW) and the east (EC) coasts of Sri Lanka in 2008

*H. spinifera* which is a nocturnal species restricted only to the northwest survey area, was the next most dominant species (70 ± 34 ind ha$^{-1}$). The mean densities of *Bohadschia* species ranged between 3 to 5 ind ha$^{-1}$ in the northwest whilst it was 6 to 7 ind ha$^{-1}$ in the east. Species belonging to the genus *Actinopyga* were less abundant when compared with the other genera ($<$ 5 ind ha$^{-1}$ in both east and northwest). The density of teatfish (*H. fuscogilva* and *H. nobilis*) was found to be less than 1 ind ha$^{-1}$ in both areas while it was 1 ± 16 ind ha$^{-1}$ for *H. scabra* in the northwest.

*H. edulis* was the most abundant species in numbers followed by *H. atra* in both areas (Table 3.4). The total abundance of sea cucumbers was 62.3 x $10^6$ (in numbers) in the northwest and 11.9 x $10^6$ (in numbers) in the east.

### 3.3.4 Distribution in relation to depth and habitat types

Sea cucumbers were found in most of the habitat defined under the methodology. The densities (ind transect$^{-1}$) were reported to be changed significantly among the habitat (P$<$ 0.001, Figure 3.7). The highest densities were recorded in rocky habitat with macroalgae/seagrass while the lowest were reported in muddy and sandy habitat and this was common in both survey areas.

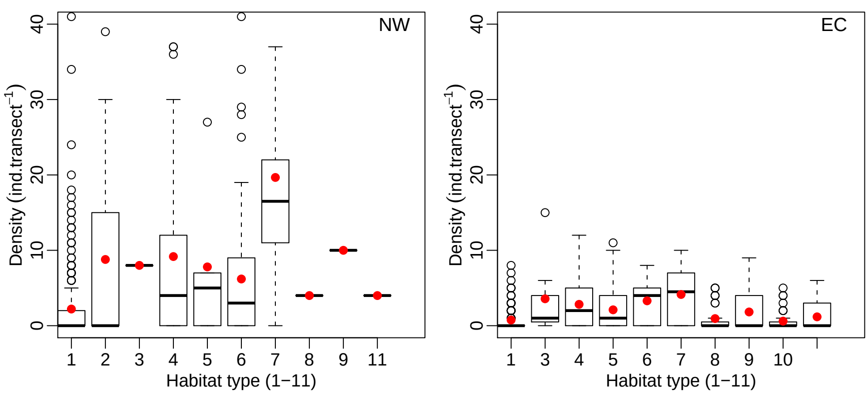


**Figure 3.7:** Box and Whisker plot to show the density (ind transect$^{-1}$) of all sea cucumbers species in the different habitat types (1-sandy; 2-seagrass; 3-macroalgae; 4-sandy habitat with rocks/corals; 5-sandy habitat with macroalgae; 6-sandy habitat with seagrass; 7-rocky habitat with macroalgae/seagrass; 8-muddy habitat; 9-sandy and muddy habitat with corals; 10-muddy and sandy ; 11-muddy habitat with macroalgae) off the northwest (NW) and the east (EC) coasts of Sri Lanka in 2008. Filled circle represents the mean density in each habitat

*H. atra*, *H. edulis* and *S. chloronotus* were mostly found in shallow depth range of 1-10 m in the northwest while in the east *H. atra* and *H. edulis* were found in 10-20 m depth class and *S. chloronotus* was in 20-30 m (Table 3.5). Two species belonging to genus *Bohadschia* were common in 20-30 m depth range. High-value and medium-value species were mainly confined to the deeper depth category (20-30) in both areas while low-value species were predominant in shallow (1-10 m ) and medium (10-20 m) depth category in the northwest and the east, respectively.

**Table 3.5:** Average density (ind transect$^{-1}$) of numerically dominant sea cucumber species and major commercial groups in different depth categories (1-10 m, 10-20 m and 20-30 m) off the northwest (NW) and the east (EC) coasts of Sri Lanka in 2008. Kruskal Wallis test was used to compare the average density of each species in different depth categories and respective P value is given

| Species | Area | (1-10 m) | (10-20 m) | (20-30 m) | P value |
|---|---|---|---|---|---|
| *B.* sp. "lines" | NW | 0.02 | 0.12 | 0.12 | 0.0380 |
| *B.* sp. "lines" | EC | 0.00 | 0.25 | 0.4 | 0.0000 |
| *B. vitiensis* | NW | 0.00 | 0.11 | 0.27 | 0.0029 |
| *B. vitiensis* | EC | 0.03 | 0.15 | 0.44 | 0.0000 |
| *H. atra* | NW | 3.41 | 0.83 | 0.15 | 0.0000 |
| *H. atra* | EC | 0.34 | 0.67 | 0.56 | 0.0016 |
| *H. edulis* | NW | 3.62 | 2.09 | 3.09 | 0.0095 |
| *H. edulis* | EC | 0.70 | 1.02 | 0.46 | 0.0200 |
| *S. chloronotus* | NW | 0.16 | 0.06 | 0.00 | 0.0144 |
| *S. chloronotus* | EC | 0.04 | 0.11 | 0.42 | 0.0027 |
| High-value spp. | NW | 0.00 | 0.07 | 0.12 | 0.0001 |
| High-value spp. | EC | 0.00 | 0.01 | 0.17 | 0.0000 |
| Medium-value spp. | NW | 0.30 | 0.54 | 0.63 | 0.7198 |
| Medium-value spp. | EC | 0.04 | 0.28 | 0.83 | 0.0000 |
| Low-value spp. | NW | 7.11 | 3.28 | 3.63 | 0.0016 |
| Low-value spp. | EC | 1.07 | 2.09 | 1.85 | 0.0000 |

(To use a Bonferroni correction for multiplicity, each P -value can be compared with $0.05/16 = 0.0031$ to maintain a family wise error rate of 0.05 for the entire table)

### 3.3.5 Total Biomass and Maximum Sustainable Yield (MSY)

In the northwest, the highest total biomass was reported by *H. atra* (4798 tons) subsequently followed by *H. spinifera*, *T. anax* and *H. edulis* (Table 3.6). Even in the east, *H. atra* had the highest total biomass and two species belonging to the genus *Bohadschia* (*B. vitiensis* and *Bohadschia* species "lines") seemed to be the next dominant (558 and 529 tons, respectively). Standing stock estimates of high-value species rarely exceeded 200 tons in both areas. The total biomass in the northwest survey area (13,024 tons) was roughly 4 times higher than the east survey area (3,027 tons). MSY fluctuation trends were much similar to the described standing stock fluctuation trends above. But MSY estimate from method 1 always had the lower value than the method 2.

**Table 3.6:** Total Biomass (TB in tons) and MSY (tons $yr^{-1}$) for different sea cucumber species off the east (EC) and the northwest (NW) coasts of Sri Lanka in 2008. MSY estimate on first approach is indicated in $MSY_1$ column and the second approach is in $MSY_2$ column.

| Species | EC | | | NW | | |
|---|---|---|---|---|---|---|
| | TB | $MSY_1$ | $MSY_2$ | TB | $MSY_1$ | $MSY_2$ |
| *A. echinites* | 152 | 18 | 36 | 149 | 18 | 35 |
| *A. miliaris* | 192 | 23 | 45 | 166 | 20 | 39 |
| *B. marmorata* | 0 | 0 | 0 | 294 | 35 | 70 |
| *B.* sp. "lines" | 529 | 63 | 125 | 448 | 54 | 106 |
| *B. vitiensis* | 558 | 67 | 132 | 416 | 50 | 99 |
| *H. atra* | 945 | 151 | 258 | 4798 | 768 | 1309 |
| *H. edulis* | 413 | 66 | 113 | 1951 | 312 | 532 |
| *H. fuscogilva* | 153 | 15 | 32 | 105 | 10 | 22 |
| *H. scabra* | 0 | 0 | 0 | 204 | 25 | 48 |
| *H. spinifera* | 0 | 0 | 0 | 2241 | 269 | 531 |
| *S. chloronotus* | 85 | 14 | 23 | 111 | 18 | 30 |
| *T. anax* | 0 | 0 | 0 | 2141 | 214 | 442 |
| Total | 3027 | 417 | 764 | 13024 | 1793 | 3263 |

## 3.4 Discussion

The sea cucumber diversity in the present study (25) was lower than the observation made by Clark (1971) where 75 sea cucumber species have been recorded in inter-tidal areas of Sri Lanka. The relatively few holothurian taxa in this study might be due to many reasons and most likely reasons are; rare abundance due to overexploitation, restriction of sampling to particular areas as well as to depths and the problems associated with visibility due to their behaviour.

At present 21 sea cucumber species are commercially exploited in Sri Lanka and this is within a relatively high range of some other sea cucumber exploiting countries; China (27), Indonesia (35), Philippines (26), Solomon Islands (29) and Madagascar (27) (Choo, 2008b; Conand, 2001; Kinch et al., 2008). It seems that the ranking of sea cucumbers based on commercial value is highly subjective (Conand, 1990; James and James, 1994a; Toral-Granda, 2007). Though four species (*H. hilla*, *H. fuscocinerea*, *H. leucospilota* and *P. graeffei*) which are not commercially exploited in Sri Lanka were categorized as no-value species, these species were exploited by other sea cucumber producing nations and grouped under low-value category (Conand, 2008; Purcell, 2010b).

Sea cucumber densities were known to be highly variable in the northwest (350 ind $ha^{-1}$) and the east (90 ind $ha^{-1}$). Comparison of these densities with other studies indicated that the populations were not as depleted as in the Milne Bay (21 ind $ha^{-1}$), Timor MOU Box (27 ind $ha^{-1}$) and the Torres Strait (Skewes et al., 2006, 1999, 2002b). However, the overall density in each area was much lower than the densities of marine protected areas or better managed fishing grounds in; Heron Island (8460 ind $ha^{-1}$), Moreton Bay (1035 ind $ha^{-1}$) and Solomon Islands (1115 ind $ha^{-1}$) (Buckius et al., 2010; Klinger and Johnson, 1994; Skewes et al., 2004).

The low-value species were more abundant than the medium and high-value species in both areas. Similar observations were made by population surveys in other countries including Solomon Islands, Philippines, Indonesia, Papua New Guinea and New Caledonia (Purcell et al., 2009). The density of low-value species in Sri Lanka was quite low when compared with the Heron Island (6420 ind $ha^{-1}$) and Solomon Islands (677 ind $ha^{-1}$). The comparison made for high-value category with the above mentioned localities (2040 ind $ha^{-1}$, 438 ind $ha^{-1}$ respectively) confirmed the greater reduction of this resource in both northwest and east.

Lower densities of Sri Lankan sea cucumbers compared to the marine protected areas of other localities are probably indicative of heavy fishing pressure applied both historically and in recent times and such reduction in stocks due to severe fishing pressure was common in several parts of the Indo-Pacific region (Lovatelli and Conand, 2004; Uthicke and Conand, 2005b). Differences in ecological conditions and habitat suitability may have potential influence on the reported lower holothurian densities when compared to other localities. Further, sheltering or burying behaviour of some species (Purcell et al., 2009) may have affected the visibility during the surveys, resulting in underestimated stock densities. Similarly, low population densities in the east were due to lack of estimates for nocturnal species, over exploitation and differences in ecological and habitat conditions in those areas. However, due to lack of past records on sea cucumber densities or even catch data it was hard to do any local comparison with survey results but the reduction of high and medium-value species was in accordance with anecdotal evidences from fishers in two areas.

*H. atra* was in fact the most common and abundant sea cucumber species in most parts of the Indo-Pacific region (Conand and Muthiga, 2007) including Fringing reef (Pouget, 2005), Reunion Island (Conand and Mangion, 2002) and Solomon Islands (Buckius et al., 2010). *H. edulis* was reported as the highest abundant species off the coastal waters of Sri Lanka followed by *H. atra*. The highest abundance of *H. edulis* could be due to high level of recruitment, habitat suitability and lower level of exploitation compared to the other species.

The patchiness of distribution is quite common in sea cucumbers and this phenomenon has been previously observed in; LaGrande Terre in New Caledonia (Purcell et al., 2009), the Torres Strait (Skewes et al., 2006), Milne Bay Province (Skewes et al., 2002b) and most parts of the western Indian Ocean (Conand, 2008). The patchy distribution of sea cucumbers could be linked with their feeding and bottom habitat characteristics (Hammond, 1983; Uthicke and Karez, 1999).

The observed pattern of distribution in different depth categories could be due to differences in habitat selection by species. The higher abundance of low-value species in shallow waters has been previously reported by Conand (1990), Purcell et al. (2009) and Kinch et al. (2008). According to Mercier et al. (2000b) high-value species were common in deeper areas and the results of the present study is consistent with their findings. Further, the lower abundance of high and medium-value species in shallow waters likely to be caused by increased harvesting pressure from the commercial divers who commonly descend to 20 m depth to harvest sea cucumbers.

The habitat preference of sea cucumbers varied greatly; e.g. some species (*T. ananas*, *H. nobilis* and *B. argus*) live among coral reefs while others seek shelter in sandy bottoms and seagrass (Conand, 1990, 2008; Purcell et al., 2009). However, high densities of sea cucumbers in coastal seagrass beds, soft and hard substrates of coral reefs and rocks have been previously reported by Kinch et al. (2008) and present results are also supported for their findings. Burial in sediments and living under the rocks, corals and inside the crevices are the most common self-protecting behaviours of sea cucumbers (Purcell, 2010a). So the high densities of sea cucumbers in rocky and coral areas could be an adaptation for the protection specially from predators, waves and currents. The main food sources of sea cucumbers are bacteria, microalgae and dead organic matter (Massin, 1982; Moriarty, 1982; Yingst, 1982). Hence, high abundance of sea cucumbers in seagrass beds and macroalgae habitat could be due to the richness of detritus and nutrients in those areas. Very few animals were present on open sand and this finding is consistent with the observations made by Moriarty (1982) and Massin and Doumen (1986).

Purcell et al. (2009) postulated that, as a rough guide, population densities below 100 ind $ha^{-1}$ could be classified as "low" and densities below 30 ind $ha^{-1}$ to be at a "critical level" at which populations may fail to repopulate effectively. According to this, all the sea cucumber species except for *H. edulis* in the northwest coast belong to one of the above categories. Therefore, it would appear timely to implement a management plan to avoid further depletion and even a collapse of the Sri Lankan sea cucumber fishery.

As the stock density of all the sea cucumber species except for *H. atra* and *H.*

*spinifera* off the northwest and *H. edulis* in both areas is below the critical level, temporal banning of the fishery for these species would be a better management option.

Further, limiting the total allowable catch (TAC) could be considered as implemented in Northern Territory, Queensland and the Torres Strait (Kinch et al., 2008). Though simple fisheries models have been used to estimate indicative MSYs for sea cucumber fishery (Aumeeruddy et al., 2005), the estimates can only be used as an indicator of the potential annual yield that could be gained from this fishery under stable recruitment. But recruitment of sea cucumbers seems to be very irregular. Due to underline model assumptions and the other application problems of these models such as availability of fewer data (Conand, 1990) and unawareness of potential for an "Allee-effect" (Uthicke et al., 2004), the optimal catch rate was found to be much lower than the MSY estimates. Hence, MSY based management plans could have adverse effect on the stock structure (Uthicke, 2004; Uthicke et al., 2004). Further, previous studies have shown that setting of TAC limit around to 5% of the standing stock biomass could lead to depletion of stocks (Uthicke et al. 2004a). Hence, the lower exploitation rate (e.g. 1-3%) can be considered when implementing TAC limit for sea cucumber species off the coastal waters of Sri Lanka. However, to implement a system of TAC for the sea cucumber fishery in Sri Lanka more work is required including regularization of reporting and monitoring of commercial landings.

# 4

# Present status of the commercial sea cucumber fishery

## 4.1 Background

Sea cucumbers are a poorly understood coastal resource, despite of their long history of exploitation (Bruckner, 2006; Conand, 2004a; Lovatelli and Conand, 2004). Overharvesting of sea cucumber stocks has been reported in many countries over the last few decades (Friedman et al., 2010a). Hence, the management of sea cucumbers has become a worldwide concern and much attention is now being paid to study the stock status, level of exploitation and population parameters (recruitment, growth and mortality) to allow for more effective management (Choo, 2008b; Conand et al., 2006; Mercier et al., 1999; Wiedemeyer, 1994).

Fishery independent surveys provide one form of data for understanding stock status and catch statistics are useful to characterize the species composition. In combination, these provide estimates of the level exploitation, fishing mortality, catch per unit of effort (CPUE) and historical trends in fisheries (Purcell, 2010b; Purcell et al., 2009; Skewes et al., 2006; Uthicke et al., 2004). Recruitment has not been extensively studied in sea cucumbers, particularly for tropical species, although, it is an important parameter for fisheries management. The level of recruitment of sea cucumbers is difficult to quantify due to the lack of basic biological information for this multispecies group, scarcity of data on juveniles and various reproductive strategies adopted (Conand, 1990; Shiell, 2004). Few attempts have been made to estimate the natural mortality rates of sea cucumbers (Conand, 1990; Ebert, 1983; Reyes-Bonilla and Herrero-Pérezrul, 2003) and most of these estimates have only been derived for the species with low commercial value (Uthicke et al., 2004).

Although sea cucumbers have been widely exploited in the Indo-Pacific region (Conand, 1990; Hornell, 1917; Shelley, 1985), it is difficult to make a thorough assessment of sea cucumber resources in this region due to lack of information on the abundance and distribution as well as poor records of catch statistics (Conand and Muthiga, 2007). Even in Sri Lanka, there were no historical data on the sea cucumber fishery therefore, resource status and the level of exploitation is yet to be unknown. However, of the 25 sea cucumber species identified, 21 species are considered as commercially important (Dissanayake and Stefansson, 2010a).

The aim of this study is twofold. Firstly to provide information on commercial fishing activities, stock status and the level of exploitation of widely exploited commercial sea cucumber species off the northwest and east coasts of Sri Lanka. Secondly to estimate the mortality parameters particularly natural mortality (M) and total mortality (Z) of these species.

## 4.2 Methodology

### 4.2.1 Data collection

In addition to the 2008 survey described in chapter 3, an underwater visual census was repeated at the same sampling sites off the northwest and east coasts of Sri Lanka in 2009. Additional 210 sampling sites were also surveyed at night off the east coast during 2009. The surveys were carried out at the beginning of each fishing season by temporarily closing the commercial fishing activities and the survey time was much similar to 2008.

Catch and effort data were also collected at the major landing sites of those two areas in the season following each survey. In each year, catch data were collected by making regular weekly field visits to the landing sites. On each sampling day, more than 50% of the total number of fishing crafts operated were sampled randomly. Information on fishing gears, details on fishing operations, the total catch and its species composition (in Nos.) was collected from each sampling boat. The total number of boats operated from all the landing sites from that area were recorded at the end of each sampling day. At the end of each month, fishers and collectors were interviewed to obtain the information on number of fishing days on that particular month. The body length of selected sea cucumber species was measured to the nearest 1 cm from the samples taken from commercial landings.

### 4.2.2 Data analysis

The total abundance of each commercial species was calculated using the average density (ind $ha^{-1}$) estimate and total survey area. The sea cucumbers collected during the surveys were grouped into adults ($\geq L_{50}$) and juveniles ($< L_{50}$) based on the length at first sexual maturity information summarized in Table 4.1. Adults to juveniles ratio was calculated from the samples collected during the underwater visual census and this ratio was used to calculate the adults and juveniles abundance seperately.

**Table 4.1:** Length at first sexual maturity ($L_{50}$ in cm) of sea cucumbers used to estimate the total abundance of adults and juviniles in the coastal waters of Sri Lanka in 2008 and 2009. The source of information is also summarized

| **Species** | **$L_{50}$** | **Source** |
|---|---|---|
| *Holothuria atra* | 16 | Dissanayake and Stefansson (2010b) |
| *Holoturia spinifera* | 14 | Local study (unpublished) |
| *Holothuria fuscogilva* | 32 | Conand (1993) |
| *Holothuria scabra* | 21 | James (1994) |
| *Bohadschia vitiensis* | 20 | Local study (unpublished) |
| *Bohadschia marmorata* | 20 | Same value as other *Bohadschia* |
| *Bohadschia* species "‘lines" | 20 | Local study (unpublished) |
| *Stichopus chloronotus* | 13 | Local study (unpublished) |
| *Thelenota anax* | 21 | Local study (unpublished) |
| *Actinopyga echinites* | 12 | Conand (1993) |
| *Actinopyga miliaris* | 15 | Kinch et al. (2008) |

The fishing effort is expressed as the mean number of fishing operations per day and the mean catch in numbers per operation was used as a measure of catch per unit effort ($CPUE$). The monthly total production ($MTP$) of each sea cucumber species was estimated as the product of mean catch per boat ($CPUE$), mean number of fishing operations per day ($NFO$) and total number of fishing days for that particular month ($MRD$).

$$MTP = CPUE \times NFO \times MRD \tag{4.1}$$

The statistical significance of $CPUE$ and the total catch between the species and areas was compared using one-way analysis of variance (ANOVA). The mean length of selected commercial species was computed for both years and statistically compared using Student's t-test.

The exploitation rate (E) of each sea cucumber species was calculated as

$$E = \frac{C}{N}, \tag{4.2}$$

where $C$ is the total annual catch in numbers and $N$ is the number of individuals available to the fishery.

The total mortality ($Z$) of each species can be calcualted

$$Z = ln(N_1 + R_1) - ln(N_2), \tag{4.3}$$

where $N_2$ - Number of adults in year 2 (2009); $N_1$ - Number of adults in year 1 (2008); $R_1$ - Number of recruits. Here it is assumed that juveniles in year 1( 2008) will enter to the fishery in the following year (2009).

It is obvious that some sea cucumber species fetch higher price than the others and fishers always tend to search for such species. As a result the fishing mortality for each species must in some manner be linked to the price. The simplest model would be to assume that fishing mortality ($F$) is proportional to the price ($P$) offered for each species. Based on this assumption, the following regression models were constructed to estimate the average natural mortality ($M$) of sea cucumbers.

(A) $Z_{ij} = M_i + \beta_i P_{ij}$

(B) $Z_{ij} = M_i + \beta P_{ij}$

(C) $Z_{ij} = M + \beta_i P_{ij}$

(D) $Z_{ij} = M + \beta P_{ij}$

Here $j = 1 \ldots J_i; i = 1, 2$

Most of these models can be compared in pairs using appropriate t-tests or F-tests (A-B, A-C, A-D, B-D, C-D) and this was used to select the best model to estimate the overall natural mortality ($M$) of sea cucumbers.

As an alternative to simple linear regression, following random effects model was constructed.

$$y_{ij} = \mu + \alpha_i + \beta_j + \gamma p_j + \epsilon_{ij} \tag{4.4}$$

where $\mu$ denotes the natural mortality of sea cucumbers, $\alpha_i$ - random effect due to area, $\beta_j$ - random effect due to species, $p_j$ - price of each species , $\epsilon_{ij}$ - within sample error, $y_{ij}$ - total mortality of j$^{th}$ species in i$^{th}area.$

In this model, area and species are treated as random effects and the price is considered as a linear term. Three reduced models were constructed from this model by dropping one variable at a time and all four models were compared using Akaike Information Criterion (AIC) to select the best model to estimate the natural mortality of sea cucumbers. The contribution of species and area to the total variance was estimated using variance component analysis (Helle and Pennington, 2004). The random effects $\alpha_i$ , $\beta_j$ and $\epsilon_{ij}$ will be assumed independent and thus

$$V[y_{ij}] = \sigma_A^2 + \sigma_S^2 + \sigma_\epsilon^2. \tag{4.5}$$

Here, $\sigma_A^2$ is the variance between areas, $\sigma_S^2$ is variance between species and $\sigma_\epsilon^2$ is the residual variance. The variance component analysis was performed using lmer in R-software package (R Development Core Team, 2008).

## 4.3 Results

### 4.3.1 Fishery

The Fiberglass Reinforced Plastic (FRP) boats powered with 9, 15 or 25 HP outboard motors were the major fishing crafts used for the sea cucumber fishery in Sri Lanka. Sea cucumbers were mainly harvested through diving and hand picking. SCUBA diving was carried out by almost all the divers and skin diving was rarely practiced. Normally two divers and a boat operator were onboard during a fishing trip but sometimes there were three divers onboard. On average, four Oxygen tanks were used by each diver during a fishing trip and true fishing time varied from 30 to 45 minutes per tank.

Both day and night fishing activities were dominant in the northwest but only night diving activities were carried out in the east as day diving activities were not profitable due to low catch rates. The fishing crafts left around 0700 - 0800 hours and returned around 1500 - 1600 hours when day diving activities were carried out while they left around 1800 hours and came back next day early morning around 0200 hours during the night fishing. There were considerable variations in fishing depths according to the fishing time. Day diving was carried out down to a depth of 20 m while the night diving was restricted to 10 -15 m. However, the effective fishing time ranged from 2 to 2.5 hours per boat per day in both day and night diving activities. Around 280 boats were engaged in sea cucumber fishing activities off the northwest coast while there were 200 boats off the east coast. Local migration of fishers took place specially from the northwest to east during the respective fishing season.

In each area, around 2000 - 2500 fishing families were directly or indirectly dependent on the sea cucumber fishery for their livelihoods. Almost all the fishers were either Muslims or Catholics and they did not go for fishing on Friday and Sunday, respectively due to their religious activities. Hence, the fishing operations were mostly conducted six days per week and the active number of fishing days varied with climatic conditions as it required clear and calm seas for successful fishing.

### 4.3.2 Total abundance

Eleven species were predominant in the commercial landings off the northwest coast and nine species were in the east. Two species; *H. scabra* and *H. spinifera* were not reported in the east and three species; *B. marmorata*, *H. spinifera* and *T. anax* were found only at night. In both areas, the highest total abundance was reported by *H. atra* (Table 4.2).

**Table 4.2:** Adults (Ad) and juveniles (Ju) abundance (Nos in $10^3$) of commercial sea cucumbers off the northwest(NW) and east (EC) coasts of Sri Lanka in 2008 and 2009

| **Species** | **NW 08** | | **NW 09** | | **EC 08** | | **EC 09** | |
|---|---|---|---|---|---|---|---|---|
| | Ad | Ju | Ad | Ju | Ad | Ju | Ad | Ju |
| *A. echinites* | 243 | 35 | 93 | 0 | 243 | 41 | 87 | 0 |
| *A. miliaris* | 312 | 39 | 198 | 25 | 345 | 61 | 164 | 0 |
| *B. marmorata** | 604 | 302 | 798 | 114 | ni | ni | 68 | 87 |
| *B.* sp. "lines" | 492 | 229 | 149 | 37 | 828 | 24 | 278 | 147 |
| *B. vitiensis* | 416 | 139 | 248 | 31 | 680 | 64 | 289 | 39 |
| *H. atra* | 12,447 | 3,545 | 11,584 | 3,266 | 2,525 | 625 | 1,927 | 243 |
| *H. fuscogilva* | 55 | 0 | 19 | 0 | 81 | 0 | 19 | 0 |
| *H. scabra* | 200 | 40 | 130 | 0 | na | na | na | na |
| *H. spinifera** | 10,406 | 2,044 | 10,096 | 1,553 | na | na | na | na |
| *S. chloronotus* | 730 | 159 | 684 | 190 | 512 | 164 | 482 | 58 |
| *T. anax** | 3,024 | 1,512 | 3,611 | 212 | ni | ni | 1,471 | 448 |

*nocturnal species, ni - data are not available, na - species is not available

*H. spinifera* was the second most abundant species off the northwest coast and

*T. anax* was in the east. For all the commercial species, total abundance of adults and juveniles has declined in 2009 when compared with 2008. The lowest abundance was reported for *H. fuscogilva* in the coastal waters of Sri Lanka and there were no records on the presence of juveniles of this species during the study period. The total abundance of commercial sea cucumber species was significantly higher off the northwest coast than the east coast (P<0.01).

### 4.3.3 Fishing effort, CPUE and total catch

In both 2008 and 2009, the total fishing effort (boat days) was higher off the northwest coast (20,238 and 19,792, respectively) than the east coast (14,183 and 13,265, respectively). In the northwest, the diurnal fishing effort in 2008 has declined by 38% in 2009 while the nocturnal activities have increased by 68% (Figure 4.1). Only night fishing was operated off the east coast and there was a slight reduction of total fishing effort in 2009 compared to 2008.

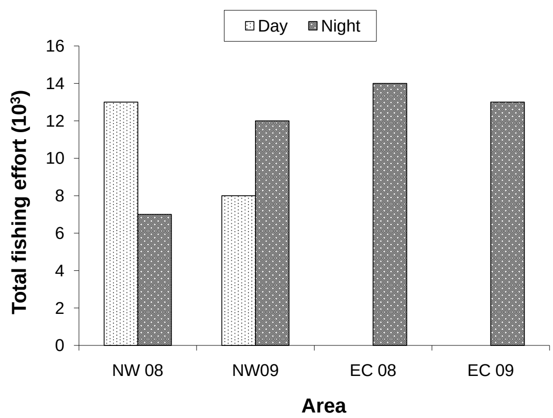


**Figure 4.1:** Fluctuations of day and night fishing efforts off the northwest and east coasts of Sri Lanka in 2008 and 2009

Among these species, *H. spinifera* had the highest CPUE (P<0.01) in the northwest while it was reported by *T. anax* (P<0.001) in the east (Table 4.3). Off the northwest coast, the average CPUE in night fishing was significantly higher than the day fishing (P<0.01) (Figure 4.5). However, the CPUE of commercial sea cucumbers has declined towards 2009 in both areas having three exceptions (*H. spinifera*, *H. atra* and *S. chloronotus*) off the northwest coast.

**Table 4.3:** CPUE fluctuations of major commercial sea cucumber species in day (D) and night (N) fishing activities off the northwest and east coasts of Sri Lanka in 2008 and 2009

| Species | NW 08 | | NW 09 | | EC 08 | EC 09 |
|---|---|---|---|---|---|---|
| | D | N | D | N | N | N |
| *A. echinites* | 1 ± 1 | 0 | 0 ± 1 | 0 | 1 ± 2 | 1 ± 1 |
| *A. miliaris* | 2 ± 3 | 0 | 1 ± 1 | 0 | 2 ± 4 | 1 ± 1 |
| *B. marmorata* | 0 | 11 ± 15 | 0 | 9 ± 13 | 1 ± 2 | 1 ± 2 |
| *B.* sp. "lines" | 7 ± 7 | 1 ± 1 | 6 ± 9 | 1± 3 | 2 ± 6 | 1 ± 2 |
| *B. vitiensis* | 5 ± 5 | 1 ± 2 | 5 ±7 | 1 ± 4 | 0 ± 1 | 0 ± 1 |
| *H. atra* | 23 ± 12 | 2 ± 4 | 22 ±20 | 6 ± 13 | 3 ± 4 | 2 ± 4 |
| *H. fuscogilva* | 0 ± 0 | 0 | 0 ± 0 | 0 | 0 | 0 ± 0 |
| *H. scabra* | 0 ± 1 | 2 ± 1 | 0 ± 1 | 1 ± 1 | 0 | 0 |
| *H. spinifera* | 0 | 170 ± 80 | 0 | 180 ± 124 | 0 | 0 |
| *S. chloronotus* | 8 ± 13 | 4 ± 5 | 17 ± 25 | 5 ± 8 | 1 ± 3 | 1 ± 3 |
| *T. anax* | 0 | 31 ± 43 | 0 | 19 ± 34 | 92 ± 64 | 75 ± 48 |

**Table 4.4:** The total production (Nos in $10^3$ ) of major commercial sea cucumber species and their percentage contribution (%C) to the total production (TP) off the northwest and east coats of Sri Lanka in 2008 and 2009

| Species | NW 08 | | NW 09 | | EC 08 | | EC 09 | |
|---|---|---|---|---|---|---|---|---|
| | TP | % C | TP | % C | TP | % C | TP | % C |
| *A. echinites* | 7.1 | 0.3 | 2.8 | 0.1 | 12.8 | 0.8 | 7.8 | 0.7 |
| *A. miliaris* | 26.7 | 1.2 | 8.3 | 0.3 | 34.1 | 2.2 | 7.2 | 0.7 |
| *B. marmorata* | 72.5 | 3.2 | 97.4 | 3.1 | 13.7 | 0.9 | 8.6 | 0.8 |
| *B.* sp. "lines" | 92.3 | 4.1 | 54.1 | 1.7 | 33.2 | 2.2 | 16.1 | 1.5 |
| *B. vitiensis* | 81.3 | 3.6 | 53.0 | 1.7 | 3.9 | 0.3 | 2.8 | 0.3 |
| *H. atra* | 329.2 | 14.5 | 262.4 | 8.2 | 36.8 | 2.4 | 22.3 | 2.0 |
| *H. fuscogilva* | 0.8 | 0.0 | 0.7 | 0.0 | 0.0 | 0.0 | 0.1 | 0.0 |
| *H. scabra* | 9.5 | 0.4 | 8.3 | 0.3 | 0.0 | 0.0 | 0.0 | 0.0 |
| *H. spinifera* | 1319.6 | 58.2 | 2338.1 | 73.2 | 0.0 | 0.0 | 0.0 | 0.0 |
| *S. chloronotus* | 134.8 | 6.0 | 197.6 | 6.2 | 16.3 | 1.1 | 11.3 | 1.0 |
| *T. anax* | 190.1 | 8.4 | 168.2 | 5.3 | 1375.6 | 90.0 | 1017.1 | 93.0 |
| Others | 1.6 | 0.1 | 1.1 | 0.0 | 1.3 | 0.1 | 0.1 | 0.0 |
| **Total** | **2265.5** | | **3192.0** | | **1527.8** | | **1093.4** | |

The commercial landings of all the species except for three (*A. echinites*, *A. miliaris* and T. anax) were higher in the northwest than the east (Table 4.4). In 2008, the highest percentage contribution to the total production in the northwest was given by *H. spinifera* (58%) and its contribution has increased up to 73% in the following year. But in the east, the highest contribution was from *T. anax* and its average contribution was more than 90% in both years. The contribution of high-value species (*H. fuscogilva*, *H. scabra*) to the total production was negligible in both areas. Due to increased landings of nocturnal species, the total sea cucumber production has increased off the northwest coast in 2009 than 2008. However, the total production has declined in the east from 2008 to 2009.

### 4.3.4 Length distribution and mean lengths in the commercial catch

The smaller length classes which were totally absent in 2008 fishing season found to be appeared in 2009 length distributions specially off the northwest coast (Figure 4.2 & 4.3).

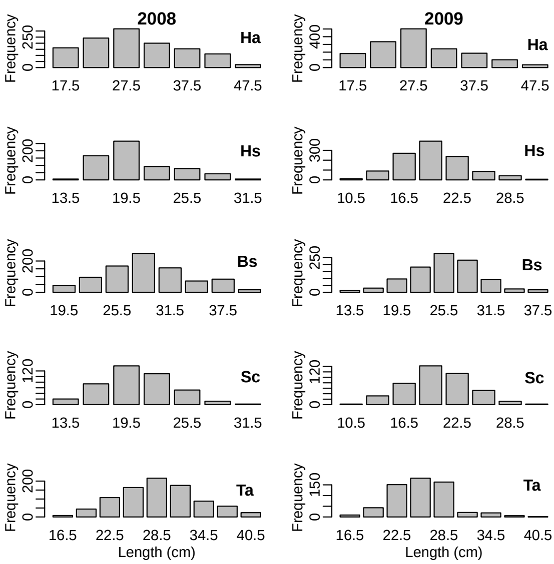


**Figure 4.2:** Length distribution of major commercial species: *H. atra* (Ha), *H. spinifera* (Hs), *Bohadschia* species "lines" (Bs), *S. chloronotus* (Sc) and *T. anax* (Ta) landed by the commercial catches off the northwest coast of Sri Lanka in 2008 and 2009

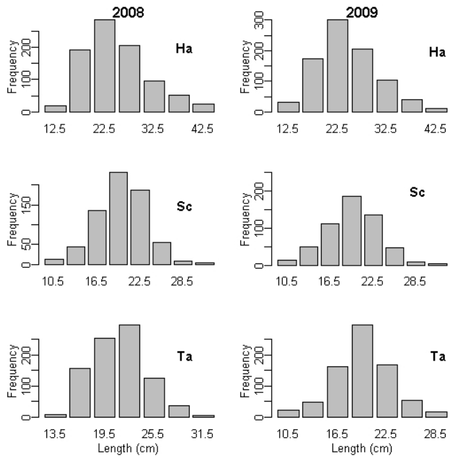


**Figure 4.3:** Length distribution of major commercial species: *H. atra* (Ha), *S. chloronotus* (Sc) and *T. anax* (Ta) landed by the commercial catches off the east coast of Sri Lanka in 2008 and 2009

Further, in most of the commercial species, harvesting of juveniles (sexually immature individuals) has increased in 2009 than 2008. The highest % of immature individuals was reported in *T. anax* catches off the east coast (Table 4.5). The mean length of *H. spinifera*, *Bohadschia* species "lines" and *T. anax* has declined significantly (P<0.000) in 2009 compared to 2008.

**Table 4.5:** Percentage landings of juveniles (%I) and the mean length (ML in cm) of major commercial species off the northwest and the east coasts of Sri Lanka in 2008 and 2009. The mean length of each species in 2008 and 2009 was statistically compared using Student's t-test and P value is given

| **Species** | **Area** | **%I (08)** | **%I (09)** | **ML(08)** | **ML(09)** | **P value** |
|---|---|---|---|---|---|---|
| *H.atra* | NW | 1 | 1 | 28.6 | 28.2 | 0.2 |
| *H. spinifera* | NW | 0 | 5 | 20.1 | 19.2 | < 0.000 |
| *B.* sp. "lines" | NW | 3 | 11 | 28.5 | 25.1 | < 0.000 |
| *S. chloronotus* | NW | 1 | 2 | 20.1 | 19.8 | 0.3 |
| *T.anax* | NW | 6 | 9 | 28.3 | 25.1 | <0.000 |
| *H. atra* | EC | 5 | 6 | 24.3 | 24.0 | 0.3 |
| *S.chloronotus* | EC | 3 | 4 | 20.1 | 19.8 | 0.3 |
| *T.anax* | EC | 47 | 69 | 20.8 | 19.1 | < 0.000 |

### 4.3.5 Mortality and price information

The exploitation rate has varied from species to species off the northwest and the east coasts of Sri Lanka during the study period (Table 4.6). In 2009, *Bohadschia* species "‘lines"’ had the highest exploitation rate off the northwest coast and it was for *T. anax* off the east coast. Except for *H. atra, T. anax, B. marmorata* and two *Actinopyga* species, the exploitation rate of all the commercial species has increased off the northwest coast in 2009 than 2008. However, it is difficult to make any comparison on exploitation rate of commercial sea cucumbers off the east coast due to absence of abundance estimates for nocturnal species in 2008. Although the market price ($P$) of sea cucumbers varied from species to species, it did not change between areas. *H. fuscogilva* and *H. scabra* always had the highest market price while the lowest price was for *B. marmorata*.

**Table 4.6:** Exploitation rate ($E$), total mortality ($Z$), individual price ($P$ in US$) and predicted natural mortality ($M$) of commercial sea cucumbers off the northwest and the east coasts of Sri Lanka. Exploitation rate (E) of each species is given for 2008 and 2009 seperately

| **Species** | **NW** | | | **EC** | | | $P$ | **M** |
|---|---|---|---|---|---|---|---|---|
| | $E(08)$ | $E(09)$ | $Z$ | $E(08)$ | $E(09)$ | $Z$ | US$ | |
| *A. echinites* | 0.03 | 0.03 | 1.09 | 0.05 | 0.09 | 1.18 | 4.45 | 0.8 |
| *A. miliaris* | 0.09 | 0.04 | 0.57 | 0.1 | 0.04 | 0.91 | 4.45 | 0.5 |
| *B. marmorata* | 0.12 | 0.12 | 0.13 | ni | 0.13 | ni | 0.45 | 0.18 |
| *B.* sp. "lines" | 0.19 | 0.36 | 1.58 | 0.04 | 0.06 | 1.12 | 2.14 | 1.12 |
| *B. vitiensis* | 0.2 | 0.21 | 0.8 | 0.01 | 0.01 | 0.95 | 2.14 | 0.70 |
| *H. atra* | 0.03 | 0.02 | 0.32 | 0.01 | 0.01 | 0.49 | 0.54 | 0.38 |
| *H. fuscogilva* | 0.01 | 0.04 | 1.09 | 0 | 0.01 | 1.44 | 11.2 | 0.54 |
| *H. scabra* | 0.05 | 0.06 | 0.61 | na | na | na | 9.8 | 0.47 |
| *H. spinifera* | 0.13 | 0.23 | 0.21 | na | na | na | 0.98 | 0.21 |
| *S. chloronotus* | 0.18 | 0.29 | 0.26 | 0.03 | 0.02 | 0.34 | 0.54 | 0.30 |
| *T. anax* | 0.06 | 0.05 | 0.23 | ni | 0.69 | ni | 2.14 | 0.17 |

na - Species is not available, ni - data is not available, 110 LKR = 1 US$

As the regression models were not significantly different from each other, model D (one regression line through entire dataset) was selected to estimate the average natural mortality ($M$) of commercial sea cucumbers and the estimated M was 0.5 $yr^{-1}$ (Figure 4.4)

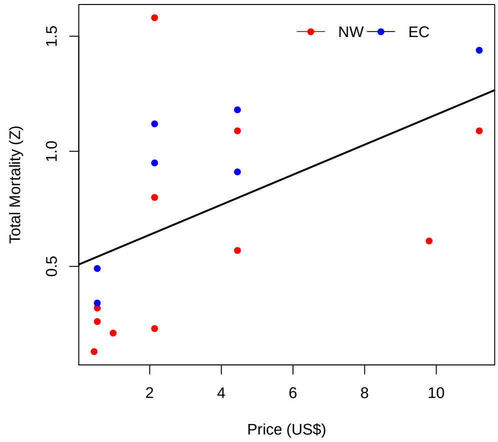


**Figure 4.4:** Simple linear regression on price vs total moratality of commercial sea cucumbers off the northwest and the east coasts of Sri Lanka

The random effects model given by 4.4 is considered as the full model and this model contains price as a linear term and both species and area as random effects. In the full model, species variance was much higher than the area variance and the variance due to species was significant (P<0.05). Comparision of AIC (Akaike Information Criterion) values indicated that the species and price model ($S + P$) has a better fit than the other models and this model was selected to estimate the average natural mortality ($M$) of sea cucumbers (Table 4.7). The estimated average natural mortality of sea cucumbers ($M$) was 0.45 yr$^{-1}$ and this can be fluctuated between 0 and 1.18 yr$^{-1}$. The predicted natural mortality values suggest that nocturnal species have lower natural mortality than most of the diurnal species (Table 4.6). *Bohadschia* species "lines" and *A. echinites* had the highest natural mortality.

### 4.3.6 Economics of fisheries

Most of the fishing vessels and diving equipments were owned by entrepreneurs who rent them out to the fishers at a fee. At the same time, fuel for the boats was also supplied by entrepreneurs and they were the first level of buyers. All the sea cucumbers were landed in fresh form and sold as pieces at the landing sites. The market price of sea cucumbers varied from species to species (Table 6) and there were fluctuations from time to time. Even within the same species, the price was

**Table 4.7:** Full and reduced versions of random effects models used to estimate the overall natural mortality ($M$) of commercial sea cucumbers in the coastal waters of Sri Lanka. Variance (Var) and standard deviation (SD) of each random effect and standard deviation and error of linear terms are given

| **Effect** | **Full Model** | | $S+P$ | | $S+A$ | | $P+A$ | |
|---|---|---|---|---|---|---|---|---|
| Random | Var | SD | Var | SD | Var | SD | Var | SD |
| Species (S) | 0.13 | 0.36 | 0.13 | 0.37 | 0.17 | 0.41 | | |
| Area (A) | 0.01 | 0.07 | | | 0.00 | 0.07 | 0.02 | 0.16 |
| Residual | 0.03 | 0.19 | 0.04 | 0.19 | 0.03 | 0.19 | 0.14 | 0.38 |
| **AIC (ML)** | **20.2** | | **18.5** | | **21.9** | | **23.8** | |
| Fixed | SD | Error | SD | Error | SD | Error | SD | Error |
| Intercept | 0.46 | 0.17 | 0.45 | 0.17 | 0.68 | 0.14 | 0.53 | 0.17 |
| Price (P) | 0.06 | 0.03 | 0.06 | 0.03 | | | 0.07 | 0.03 |

quite variable depending on the individual size where larger individuals fetch higher price than the smaller individuals. Sixteen small scale entrepreneurs involved in the sea cucumber fishery off the northwest coast and there were two major processing plants. As the buyers sell their catches directly to the processing plants, the small scale domestic level of processing was rare in the northwest. There were 11 buyers in the east and they carried out domestic processing as there was no any large scale processing plant in this region. Processing steps found to be much similar in both areas and the major processing steps involved evisceration, boiling, salting, cleaning and sun drying though there were some modifications from species to species (Figure 4.5).

At the end of each fishing operation, entrepreneurs deduct the cost for lending boats and usage of fuel and diving equipments out of the total income. Depending on the fishing time there were differences in the net income per operation. IAlways night fishing generated higher profit than the day fishing. Although net income per day fishing operation has declined from 2008 (1071 LKR) to 2009 (995 LKR) off the northwest, it has increased from 7997 LKR to 8769 LKR per night operation. However, in the east, the net income per night operation has declined from 2008 (3257 LKR) to 2009 (2349 LKR).

(a) *Sea cucumber landing site*

(b) *Catch per boat - Day diving*

(c) *Catch per boat - Night diving*

(d) *Sea cucumber processing - Boiling*

(e) *Cleaning of sea cucumbers*

(f) *Sun drying of sea cucumbers*

**Figure 4.5:** Sea cucumber landing site, commercial landings from day and night diving activities and some processing steps of sea cucumbers off the northwest coast of Sri Lanka

## 4.4 Discussion

Harvesting and processing of sea cucumbers have been provided an important means of livelihood to the coastal fishing communities in many parts of the world (Choo, 2008b; Clarke, 2002). According to the present study, around 5000 families are also dependent on sea cucumber fishery in the coastal waters of Sri Lanka. Different fishing methods are used to exploit sea cucumbers and these include collecting by hand, bottom trawl nets, scallop-drag gear, spears, hooks, scoop nets, SCUBA and hookah (Bruckner et al., 2003; Purcell, 2010b). In Sri Lanka, sea cucumbers are mainly exploited by SCUBA diving and divers access the fishing grounds using small boats.

Sea cucumber populations are highly vulnerable to overfishing particularly, due to easiness of harvesting, late age at maturity, slow growth and low rates of recruitment (Choo, 2008b; Conand, 1990, 2004a; Lovatelli and Conand, 2004). Overexploitation of sea cucumbers has been frequently reported in many parts of the Indo-Pacific region during the last few years (Choo, 2008b; Conand, 2008; Woodby et al., 1993). This study indicates the declining of adults and juveniles abundance off the northwest and east coasts of Sri Lanka and this could be due to overharvesting of sea cucumber resources in these areas. Recent study revealed that population densities of most of the commercial sea cucumbers were less than 30 ind $ha^{-1}$ in the coastal waters of Sri Lanka (Dissanayake and Stefansson, 2010a). Declining of abundance particulary, juveniles may be due to existing low population densities because sea cucumbers are broadcast spawners and high population densities are required for successful fertilization and subsequent recruitments (Uthicke et al., 2004). Use of SCUBA diving with motor boats could have some effect on depletion of sea cucumber resources in the coastal waters of Sri Lanka as this method implies an exhaustive search of specimens, including younger ones.

The degree of confidence in CPUE as an index of abundance varies with the type of behavioural interactions between fish and fishers (Purcell, 2010b). Specially in the sea cucumber fishery, divers are more selective towards certain species (high-value species) and sizes of individuals (larger individuals). Further, fishing conditions may have a major impact on the productivity of divers. Hence, the CPUE estimates of this study need to be interpreted with much caution as we have limited information. Time series data on abundance and CPUE will improve the understanding of this relationship further.

Absence of day diving activities off the east coast might be due to overharvesting of diurnal species and this was in accordance with the anecdotal evidences of fishers in the area. Though there were day fishing operations in the northwest, the diurnal fishing operations declined from 2008 to 2009. The reason for this observation is not quite clear but this may be a signal of resource depletion.

Collection of juveniles (immature individuals) and temporal shifting of fishing activities were observed in both areas. Further, in both regions, the contribution of high-value species to the total production is negligible and the commercial fishery mainly relies on nocturnal species belonging to the medium-value category. According to Dissanayake and Stefansson (2010a), the population density of high-value species is very low ($<2$ ind ha$^{-1}$) off the northwest and east coasts Sri Lanka and this may be a possible reason for them to have very low contribution to the commercial landings. Immature individuals and observed small size classes in the commercial catches may be a result of excessive fishing pressure on these stocks over the time. Spatial and temporal shifting of fishing activities, declining of high-value species and harvesting of sexually immature individuals have been identified as some signs of resource depletion and these were experienced in several nations in the Indo-Pacific region within the last few years (Choo, 2008b; Conand and Muthiga, 2007; Friedman et al., 2010a; Purcell, 2010b).

The exploitation rate of commercial sea cucumbers was less than 0.5 except for *T. anax* in the east. The observed exploitation rates could be due to several reasons. The estimated total sea cucumber production may not be accurate due to complexity of fishery, ghost landings and sampling error. On the other hand, the total abundance may be overestimated for some species because specific habitat preference of each species as well as the volume of different habitat within the survey areas were not taken into account. However, according to Uthicke et al. (2004), it is difficult to use exploitation rate as a reliable indicator to assess the stock status of sea cucumbers because previous studies have shown that harvesting of small percentage ($<5\%$) of standing stock biomass can lead to stock depletion. As sea cucumbers have very low contribution to the total marine fishery production in Sri Lanka, no attention has been paid to report the catch statistics so far. Hence, it is difficult to make any inference on the trends of total landings, exploitation rates and changes in stock structure.

Despite the information of value of sea cucumbers, the level and potential contribution of sea cucumbers to the national economy as well as to the livelihoods of coastal communities is not yet known in Sri Lanka. However, it seems that fishers tend to collect sea cucumbers continuously even some commercial species were severely diminished in numbers. Friedman et al. (2010a) also made the same observation in many remote islands where fishers have searched for new species or expanded the fishing activities into deeper waters when some commercial species were depleted or "economically extinct". As it is difficult to find alternative job opportunities for these fishers in Sri Lanka, they may have continued fishing activities even though there were scant catches.

Estimation of natural mortality of sea cucumbers is often difficult and subjected to considerable errors (Uthicke et al., 2004). In this study, two methods simple linear regression and random effects models were used to estimate the natural mortality of sea cucumbers and the estimated values were close to each other. Further, the estimated values are consistent with the results from other studies (Conand, 1990; Ebert, 1983). Though the predicted $M$ value has high variance due to limited data, this is a useful finding specially in the field of sea cucumber stock assessment. Random effects model predicted lower natural mortality for nocturnal species than for the diurnal species and this could be due to low level of predation on former species or differences in biological and genetic characteristics of larval life stages of these two groups. However, further studies need to confirm this hypothesis and use of time series data will validate the prediction further.

In this study an attempt was made to understand the stock status and mortality parameters of commercial sea cucumbers using data collected from both fishery dependent and fishery independent surveys. To the author's knowledge, this is the first detailed study of sea cucumber fishery in Sri Lanka. Hence, these findings are useful for fishery managers to prepare proper management plans to avoid further depletion of this resource off the northwest and east coasts of Sri Lanka. Further, this information is also useful to update the regional sea cucumber statistics as well as for regional management programmes.

# 5

# Habitat preference of two sea cucumbers; *Holothuria atra* and *Holothuria edulis*

## 5.1 Background

*Holothuria atra* and *Holothuria edulis* are the most abundant and widely distributed sea cucumber species in the Indo-Pacific region (Choo, 2008b; Conand, 2008; Conand and Mangion, 2002; Harriott, 1985; Uthicke, 2001c) including the coastal waters of Sri Lanka (Dissanayake et al., 2010). They inhabit a wide range of depths and a broad variety of habitat ranging from rocky reefs to mudflats (Conand, 2008; Conand and Mangion, 2002; Purcell et al., 2009). As a result of increasing demand most of the high-value sea cucumber stocks have been overexploited, thus fisheries seem to be shifted towards these low-value species (Choo, 2008b; Conand and Muthiga, 2007; Lovatelli and Conand, 2004). Therefore, appropriate management measures need to be implemented to ensure the sustainable utilization of these low-value species. Preliminary biological and ecological information about sea cucumbers are important in developing combined management approaches (Conand and Muthiga, 2007; Mercier et al., 1999; Purcell, 2004; Wiedemeyer, 1994). Though some studies have been undertaken to study the biology of these two sea cucumber species, the knowledge of the spatial distribution patterns, habitat and ecological preference are scant, except for the work of Conand and Mangion (2002), Uthicke and Karez (1999). According to Sloan and Von Bodungen (1980) and Slater and Jeffs (2010), bottom sediment characteristics are one of the crucial components affecting the habitat preference of sea cucumbers but the relationships between the bottom sediment characteristics and the spatial distribution pattern of these species still remain unclear.

Hence, the present study was designed to determine the influence of bottom sediment characteristics and some environmental variables on the habitat preference of *Holothuria atra* and *Holothuria edulis* off the northwest coast of Sri Lanka.

## 5.2 Methodology

### 5.2.1 Data collection

Apart from the information on sea cucumber densities and bottom habitat characteristics, sediment samples were collected at 151 sampling sites (Figure 5.1) off the northwest coast of Sri Lanka during the underwater visual census (UVC) carried out in 2008. Collection and analysis of sediment samples from all the survey sites were not possible due to practical difficulties and monetary constrains.

A Ponar grab sampler (400 $cm^2$) was used to collect sediment samples from each sampling site. In all the cases, penetration of the grab was 12 to 15 cm and three replicate samples were collected. These samples were first stored in ice and then frozen (-$4^0$C) until the subsequent analysis. In the laboratory, sediments were analyzed by standard sieve fractionation method (Folk, 1966). The sediment samples were washed through a 0.062 mm mesh sieve to separate the silt-mud and sand fractions. The sand fraction was dried and fractionated on a mechanical shaker with sieves spanning from 40 to 0.062 mm. The mean grain size was calculated using the method described by Mcbride (1971). Total organic matter (TOM) was determined using a variation on the combustion method as recommended by Luczak et al. (1997). Sub-samples of surface sediment (approximately 1g) were dried in a $50^0$C oven to constant weight. Preweighed dry samples were burned in a muffle furnace at $500^0$C for 6 hours and then reweighed. Total organic matter was calculated as percentage weight loss following combustion.

### 5.2.2 Data analysis

The generalized additive model (GAM) was used to examine the relationships between the habitat variables and the density of each sea cucumber species. A GAM is a non-

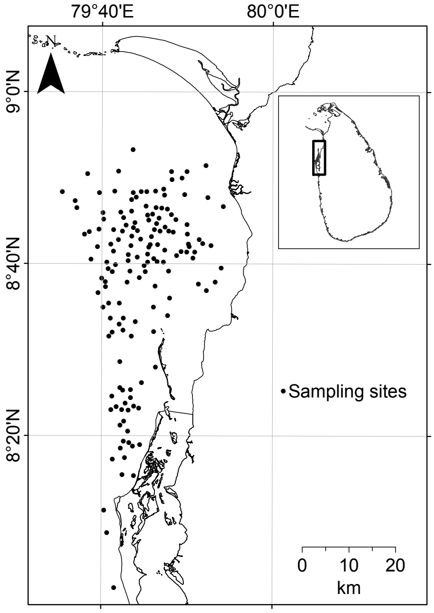


**Figure 5.1:** Distribution of sampling sites (n = 151) used to collect sediment samples off the northwest coast of Sri Lanka in 2008

parametric generalization of multiple linear regression (Hastie and Tibshirani, 1986) and this has been widely used in describing the complex relationships between animals and their environment (Maravelias, 1999; Stoner et al., 2001).

The density of sea cucumbers in each transect (Nos 200 $m^{-2}$) was used as the dependent variable and the variables summarized in Table 5.1 served as the independent variables.

**Table 5.1:** Parameters serve as the independent variables when constructing the generalized additive models for the two sea cucumber species (*Holothuria atra* and *Holothuria edulis*) off the northwest coast of Sri Lanka.

| Variable | Source | Description | Values |
|---|---|---|---|
| Depth (m) | Depth gages | Recorded by divers | 1 − 30 |
| Grain size (mm) | Grab samples | Method, Mcbride (1971) | 0.07−1.45 |
| Silt - mud (% ) | Grab samples | Particle size < 0.062 mm | 0.01−39.86 |
| Gravel (%) | Grab samples | Particle size > 2 mm | 0.01−45.05 |
| Organic (%) | Grab samples | % of total organic | 0.13−5.55 |

As the response variable follows a Poisson distribution, the Poisson response with the log link function (scale = -1) was used to construct the GAMs. In the first step, a GAM model was constructed using a single predictor to identify the relationship between individual habitat predictor and the density of each sea cucumber species. Each predictor was prioritized according to the percentage deviance explained (0-100%, the highest deviance was taken as the best) and the generalized cross validation (GCV) score (the lowest was considered as the best). The best predictors for the final model were selected based on the above prioritization.

As GAMs allow for fitting single response variable to multiple predictors, a series of GAMs were constructed with multiple predictors to model the density of *H. atra* and *H. edulis*. The 'best' model for each species was again selected on the basis of GCV score and the level of deviance explained. The GAMs smoothing predictors were selected following the method proposed by Wood and Augustin (2002), using the 'mgcv' library in the R statistical software (R Development Core Team, 2008). The density of each species in different habitat types was also compared using the Kruskal Wallis test.

## 5.3 Results

### 5.3.1 Distribution in different habitat

Seven out of 11 habitat categories defined in chapter 3 were encountered at 151 sampling sites and both *H. atra* and *H. edulis* were found in all these habitat categories (Figure 5.2).

The density of each sea cucumber species varied significantly among the habitat ($P < 0.0001$). The highest density of *H. atra* was reported in the seagrass habitat followed by the sandy habitat with rocks/corals, rocky habitat with algae/seagrass. *Holothuria edulis* was also commonly found in the latter two habitat categories. For both these species, sandy bottom yielded the lowest densities.

### 5.3.2 Generalized additive model

**Single predictor fits**

Organic content (% of dry weight) had the highest influence on the density of *H. atra* followed by gravel (%), mean grain size, depth and the amount of silt-mud (%). Mean grain size was the best predictor that can be used to explain the differences in spatial distribution of *H. edulis*. Furthermore, gravel (%), organic content (% of dry

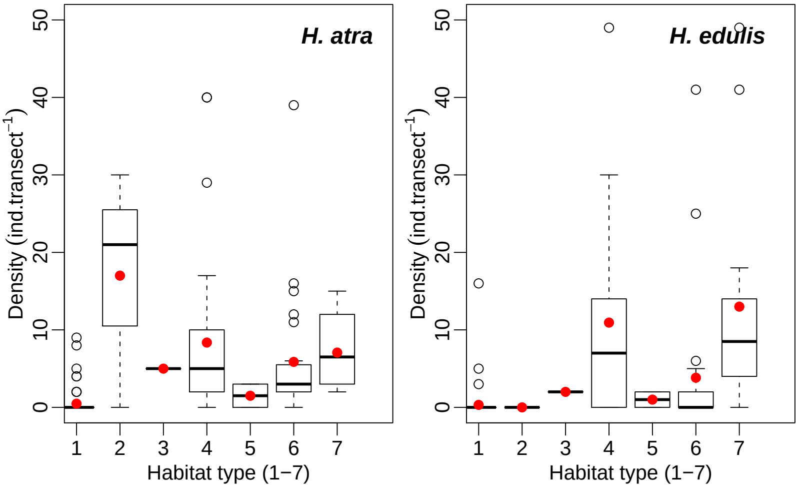


**Figure 5.2:** Box and Whisker plot to show the density (ind transect$^{-1}$) of *H. atra* and *H. edulis* in the different micro habitat categories (1-sandy; 2-seagrass; 3-macroalgae; 4-sandy habitat with rocks/corals; 5-sandy habitat with macroalgae; 6-sandy habitat with seagrass and 7-rocky habitat with algae/seagrass) off the northwest coast of Sri Lanka. The filled circle represents the mean density in each habitat

weight), depth and silt-mud (%) were the other variables that affect the density of *H. edulis* (Table 5.2).

**Table 5.2:** Percentage deviance explained and the generalized cross validation (GCV) score for each predictor of the GAM model constructed for *H.atra* and *H.edulis*

| Parameter | ***H.atra*** | | ***H. edulis*** | |
|---|---|---|---|---|
| | % Deviance | GCV Score | % Deviance | GCV Score |
| Depth (D) | 18.8% | 7.93 | 22.6% | 12.07 |
| Mean grain (G) | 24.6% | 7.79 | 35.8% | 9.81 |
| Organic (O) | 53.8% | 4.88 | 23.8% | 11.23 |
| Gravel (GR) | 29.5% | 7.03 | 26.9% | 10.77 |
| Silt-mud (SM) | 17.2% | 8.72 | 18.5% | 12.21 |

### Multiple predictor fits

(**a**) *Holothuria atra*

For *H. atra* GAMs were constructed by combining 1 to 5 predictors and the best combination in each step was selected by considering the deviance explained (%) and the GCV score. Though the quality of the model increased up to five predictors, the latter combination resulted in little gain to the final model (Table 5.3). The combination of four predictors; depth, mean grain size, percentage organic contents (% of dry weight) and percentage gravel contents have a significant effect on the density of *H. atra* ($P < 0.05$). These four predictors explained 74.4% of the deviance in the final model (Table 5.4).

**Table 5.3:** Multiple predictors GAM fits for *H.atra*. For each predictor, percentage deviance explained and the generalized cross validation (GCV) score is given

| Parameter | % Deviance | GCV Score |
|---|---|---|
| O | 53.8% | 4.88 |
| O + G | 65.3% | 4.12 |
| O + G + D | 71.5% | 3.65 |
| **O + G + D+ GR** | **74.4%** | **3.33** |
| O + G + D + GR + SM | 75.2% | 3.12 |

**Table 5.4:** Results of the final GAM model constructed for *H. atra* off the northwest coast of Sri Lanka

| **Parametric coefficients** | **Std error** | **t value** | **P** |
|---|---|---|---|
| Intercept | 0.266 | 0.221 | 0.826 |
| **Non- parametric terms** | **edf** | **F** | **P** |
| Depth | 4.401 | 2.277 | < 0.05 |
| Gravel | 1.000 | 14.327 | < 0.001 |
| Mean grain | 7.935 | 5.481 | < 0.0001 |
| Organics | 8.422 | 11.052 | < 0.0001 |
| n | 151 | | |

The density of *H. atra* greatly varied with individual variables. According to the GAM outputs, the highest densities of *H. atra* were concentrated in shallow depths (< 10 m) and the deeper areas were carrying very low sea cucumber densities. *H. atra* densities were highest in association with the mean grain size of about 0.7 -1.2 (mm) and the organic contents between 2 - 3.5 % of dry weight. The density of *H. atra* increased with an increase in gravel percentage and the highest densities were observed in the areas where there was 15 - 25 % of gravel (Figure 5.3).

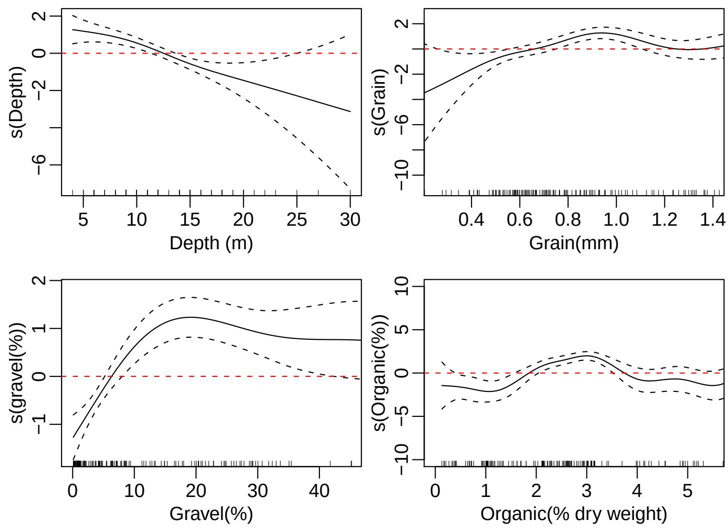


**Figure 5.3:** Generalized additive models (GAMs) obtained for *H. atra* off the northwest coast of Sri Lanka. Plots show the additive effect of each variable; depth (m), grain size (mm), gravel (%) and organic (% dry weight) on the density of *H. atra*. Confidence intervals represent two standard error ranges around the main effect and the horizontal line indicates the zero level. Vertical dashes at the bottom of the plots show the distribution of points entering into the model

(**b**) *Holothuria edulis*

The quality of the model increased with increasing number of predictors (Table 5.5). The four variables; depth, mean grain size, gravel (%) and silt-mud (%) have significant influence on the density of *H. edulis* ($P < 0.05$) while the organic content (% dry weight) has marginal effect (Table 5.6). The final model explained 72.8% deviance and 4.62 GCV score.

The relationship between the density of *H. edulis* and the water depth was not clear. The high densities were concentrated in shallow depths (<10 m), declined at depths of 12-15 m, and again increased towards the deeper depths (> 25 m). Moreover, the highest densities of *H. edulis* occurred in the sediments with coarse sand (0.8 - 1.1 mm mean grain sizes) and relatively lower gravel percentage (15 - 25%). There was no distinct organic preference by *H. edulis* and the relationship between % organic contents and the density of *H. edulis* was almost flat beyond the 2% organic content (Figure 5.4).

**Table 5.5:** Multiple predictors GAM fits for *H.edulis*. For each predictor, percentage deviance explained and the generalized cross validation (GCV) score is given

| Parameter | % Deviance | GCV Score |
|---|---|---|
| G | 35.8% | 9.81 |
| G + D | 56.3% | 7.44 |
| G + D + SM | 63.6% | 6.56 |
| G + D + SM+O | 67.7% | 6.16 |
| **G+ D+ SM+ O+ GR** | **72.8%** | **4.62** |

**Table 5.6:** Results of the final GAM model constructed for *H. edulis* off the northwest coast of Sri Lanka

| Parametric coefficients | Std error | t value | P |
|---|---|---|---|
| Intercept | 0.251 | 0.33 | 0.742 |
| | | | |
| **Non- parametric terms** | **edf** | **F** | **P** |
| Depth | 7.822 | 3.451 | < 0.001 |
| Gravel | 6.16 | 2.522 | < 0.05 |
| Mean grain | 5.089 | 4.888 | < 0.0001 |
| Organics | 3.805 | 2.211 | 0.052. |
| Silt-mud | 4.331 | 3.966 | <0.001 |
| n | 151 | | |

## 5.4 Discussion

The habitat preference of sea cucumbers has been reported to vary from species to species and even within the different life stages of same species (Conand, 1990, 2008; James, 2005; Mercier et al., 2000b; Purcell, 2004; Purcell et al., 2009; Shiell, 2004; Slater and Jeffs, 2010). According to the present study, the highest density of *H. atra* was observed in the seagrass areas. Most sea cucumbers are deposit feeders and dense aggregation in seagrass associated habitat could be directly related to their feeding, as seagrass areas are rich in accumulation of particulate matter and detritus. Dense aggregation of *Holothuria* species (*H. atra, H. edulis, Holothuria leucospilota* and *Holothuria scabra*) in the shallow water seagrass habitat has been previously reported in several studies (Forbes et al., 1999; Mercier et al., 2000b; Zhou and Shirley, 1996). Though, wide occurrence of *H. edulis* in the seagrass habitat was commonly reported (Choo, 2008b; Conand, 2008), low numbers of *H. edulis* were collected at the seagrass habitat during this study. The reason for this observation was not quite clear but some possible reasons could be; existence of more favourable habitat than the seagrass, or poor visibility of this species during the survey due to their sheltering

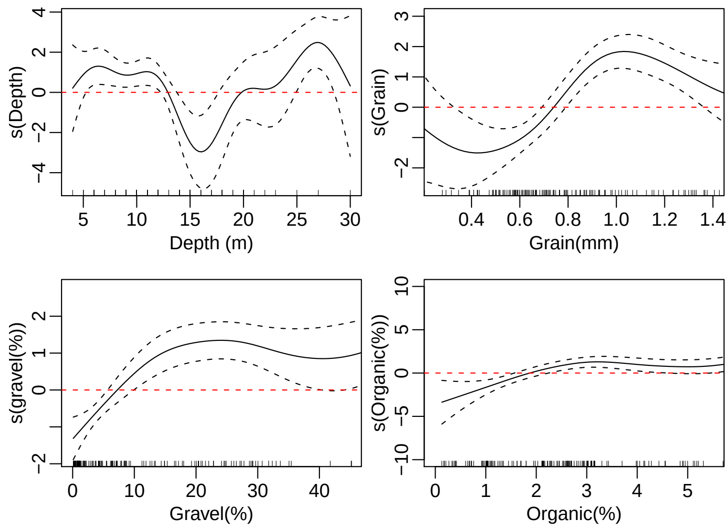


**Figure 5.4:** Generalized additive models (GAMs) obtained for *H. edulis* off the northwest coast of Sri Lanka. Plots show the additive effect of each variable; depth (m), grain size (mm), gravel (%) and organic (% dry weight) on the density of *H. edulis*. Confidence intervals represent two standard error ranges around the main effect and the horizontal line indicates the zero level. Vertical dashes at the bottom of the plots show the distribution of points entering into the model

or hiding behaviour. The higher aggregation of both *H. atra* and *H. edulis* in the reef flats and the rocky substrates was consistent with the findings of Conand (2008) and Purcell et al. (2009) and this aggregation found to be related to the protection from waves and currents (Conand and Mangion, 2002; Deroski and Drumm, 2003). Very few animals were present on open sand and this result confirmed the findings of Moriarty (1982), Massin and Doumen (1986).

Present study revealed that the highest sea cucumber densities were concentrated at the shallow stations ($< 10$ m) together with decreasing densities with depth. Several studies have shown that low-value species including *H. atra* and *H. edulis* are more abundant in shallow waters due to the presence of preferable habitat conditions for these species (Conand, 1990; Kinch et al., 2008; Purcell et al., 2009). Further, there is a relationship between bottom sediment characteristics and depth. With increasing depth, silt mud content increases and gravel content is reported to be decreased (Martin et al., 2010). Hence, the variations of sea cucumber densities with depth seem to be related with the bottom sediment characteristics. However, increasing densities of *H. edulis* in the deeper depths need to be interpreted carefully as we did not have sufficient data.

As sea cucumbers feed on bacteria, microalgae and dead organic matter (Moriarty, 1982; Yingst, 1982), sediment organic content seems to have great influence on the habitat preference of sea cucumbers. As there is a close relationship between the sediment grain size and the level of organic matter (Cammem, 1982; Dale, 1974; Hargrave, 1972; Longbottom, 1970), the sediment grain size could be considered as another important factor which governs the habitat preference of sea cucumbers. Previous investigations have shown that fine grained sediments are nutritionally rich food source in the marine environment (Mayer et al., 1985; Yamamoto and Lopez, 1985). According to the present study, *H. atra* densely associate in coarse sand (0.7 - 1.2 mm) with 2 - 3.5% organic content and they avoid the bottom substrates with high levels of silt-mud content ($>$ 1%). The highest aggregation of *H. atra* in these habitat conditions provides some evidence of their preference towards the particular level of sediment organic materials, grain size and silt-mud content. Previous studies have also shown that *H. atra* has slight selection on sediment organic and sediment patches rich with microalgae (Roberts, 1979; Uthicke, 1999; Wiedemeyer, 1994).

Favourable bottom sediment conditions of *H. edulis* seem to be mainly similar to the conditions preferred by *H. atra*, except in the level of organic contents. Uthicke and Karez (1999) have revealed that there is no any selectivity towards the sediment organic content by *H. edulis*. Though these two species favoured similar habitat conditions, they have different preferences towards the sediment organic contents and this makes possible for them to have particular niches.

Although some sea cucumber species have selection towards the certain grain size to obtain required food (Hauksson, 1979; Rhoads and Young, 1971; Roberts, 1979), such evidence was not available for *H. atra* and *H. edulis*. Hence, the effect of sediment grain size in facilitating the feeding of these species is unclear. However, the favourable grain size probably supports to maintain the preferable levels of organic materials as well as the required space in the sediments.

The habitat preference and spatial distribution of the two sea cucumber species seemed to be influenced by the depth and bottom sediment characteristics, and the optimum conditions have varied from species to species. The GAM used in this study achieves an acceptable level of accuracy by giving higher deviance.

The management implications of this study include the information of habitat preference and environmental influence on the distribution of commercial sea cucumber species; *H. atra* and *H. edulis* in the coastal waters of Sri Lanka and this will assist to identify and conserve the preferable habitat of each species. Further, the information on habitat and ecological requirements of these species is important to implement successful rehabilitation programmes and precise stock assessment surveys. Model application can be easily extended for the other sea cucumbers especially for the high-value category. Incorporation of important oceanographic variables such as turbidity, water temperature, salinity and tidal influence will further improve the model.

# 6

# Reproduction of the commercial sea cucumber *Holothuria atra*

## 6.1 Background

Increasing demand for sea cucumbers has led to unsustainable fishing of natural stocks throughout the world (Conand, 2004a; Conand and Byrne, 1993). As spawning is the basis for recruitment and stock conservation, significant interest has generated to understand the reproduction of sea cucumbers (Sloan et al., 1985). However, few studies have been carried out to study the reproductive biology of commercial sea cucumbers so far (Choo, 2008b; Conand, 1981, 2008; Conand et al., 1997b).

*Holothuria atra* is an Aspidochirote holothurian species, widely distributed in the Indo-Pacific region including Sri Lanka (Dissanayake and Stefansson, 2010a; Harriott, 1985; Uthicke, 1997b, 2001c). Some studies have shown that *H. atra* can reproduce both sexually and asexually. Further, they have ability to shift the reproductive pattern from asexual to sexual mode with their growth (Chao et al., 1994, 1995; Conand, 1990; Harriott, 1982, 1985; Smiley et al., 1991). It seems that smaller individuals ($<$ 250 g) in shallow waters prefer to reproduce asexually while larger individuals ($>$ 300 g) in deep areas ($>$ 2 m) have sexual reproduction (Lee et al., 2008). However, in general, studies on reproductive biology and population dynamics of *H. atra* are scant specially in the Indo-Pacific region and no information from the coastal waters of Sri Lanka.

Reproductive pattern of sea cucumbers has known to be controlled by changes in water temperature (Battaglene et al., 2002; Ramofafia et al., 2000), food availability (Cameron and Fankboner, 1986; Hamel, 1993), light intensity (Cameron and Fankboner, 1986), water turbulence (Engstrom, 1980), salinity (Krishnaswamy and Krishnan, 1967), phytoplankton blooms (Himmelman, 1980) and apparently spawning has also influenced by the lunar pattern (Mercier et al., 2000b; Muthiga, 2006). Further, Ramofafia et al. (2003) reported that even within the same species, there may have variations of timing and duration of spawning depending on the geographical locations. Although the marine environment of Sri Lanka is greatly influenced by the monsoon winds (southwest and northeast) causing characteristic seasonality in temperature, rainfall and phytoplankton concentration, importance of these factors for controlling the reproduction of *H. atra* in the coastal waters of Sri Lanka is not yet known.

This study describes the annual sexual reproductive cycle of *H. atra*, using the gonadosomatic index (GSI) method, confirmed by histological examination of gonads in the north western coastal waters of Sri Lanka. In addition, the population structure is assessed based on the sex ratio and minimum reproductive size. The relationship between the reproductive pattern and environmental parameters such as temperature and rainfall is examined to view the possible synchrony with gametogenesis and spawning events.

## 6.2 Methodology

### 6.2.1 Collection of specimens

Samples of *H. atra* were collected by SCUBA diving at the two sampling sites; site 1 and site 2 off the northwest coast of Sri Lanka (Figure 6.1). Twenty or more individuals were collected on a monthly basis for a period of 13 months from July 2008 to 2009. All the collected individuals were transported to the regional research station of National Aquatic Resources Research and Development Agency (NARA) for analysis. Specimens were placed in a solution of magnesium chloride (5%) until dissection in the laboratory.

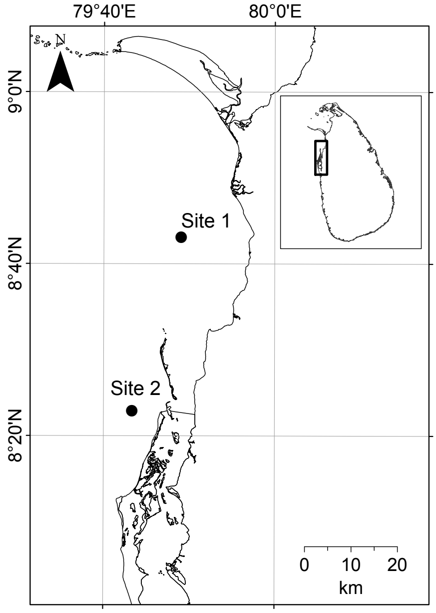


**Figure 6.1:** Two sampling sites (site 1 and site 2) used to collect *Holothuria atra* specimens off the northwest coast of Sri Lanka from July 2008 to July 2009

### 6.2.2 Biometric measurements

At the laboratory, each individual was placed on a flat surface and both total length (TL) from mouth to anus to the nearest 0.5 cm and the total weight (TW) to the nearest 1 g were recorded before the specimen was dissected. Each individual was dissected longitudinally in the dorsal position permitting coelomic fluid to drain. The whole gonad including the gonad basis and germinal tubules was removed from each animal, weighted (GW) to the nearest 1 g and fixed in 7% buffered formaldehyde as described by (Chao et al., 1995; Conand, 1981, 1993). The body wall wet weight (EW) of gutted individuals was also measured to the nearest 1 g. For each gonad, the tubule length from the gonad base to the distal tip was measured using a measuring tape and the tubule diameter was measured through a microscope.

The pattern of reproduction was investigated using the gonadosomatic index (GSI), calculated from the following equation

$$GSI = \frac{GW}{EW} \times 100. \tag{6.1}$$

The gonadosomatic index (%GSI) for males and females was calculated separately.

Differences between the biometric parameters and gonadosomatic index (%GSI) of males and females were evaluated by Student's t-test. A sex ratio, as the proportion of males to females, was calculated and significance was measured by $\chi^2$ test. Monthly mean %GSI was compared using single factor Analysis of Variance (ANOVA) to determine the temporal variability of gonadosomatic index.

### 6.2.3 Gonad morphology

Male and female gonads were classified into five stages of sexual development: Resting (I), Immature (II), Growing (III), Maturing (IV) and Spent (V) following the criteria defined by Ramofafia et al. (2003) and Gaudron et al. (2008). Firstly, sex of each individual and gonad development stage was visually assessed particularly considering the appearance and colour of the gonads. Then the gonad tissues were prepared for histological examination in order to validate the macroscopic description of the various maturity stages. For histological examinations, gonads were transferred into alcoholic Bouin's fixative for a period of four weeks and later on dehydration was performed through a series of alcohol solutions at 30%, 50%, and 70% allowing two hours between each change. Finally, samples were preserved in 70% alcohol. Five to six cross sections of 5 $\mu$m thickness were taken from the tubules of each individual and sections were stained with hematoxylin-eosin (H & E).

### 6.2.4 Size at first sexual maturity

A larger number of individuals (n = 136) were collected outside the monthly collection areas between January and March 2009. To obtain precise estimate for length at first sexual maturity ($L_{50}$), samples were collected only during peak spawning season to reduce the possibility of including large number of immature or inactive individuals. A Generalized Linear Model (GLM, family= binomial) was used to determine the length at first sexual maturity.

### 6.2.5 Effect of environmental variables

The relationship between the average monthly gonadosomatic index and two environmental variables; temperature and rainfall was analyzed. Data on monthly variation of rainfall and temperature in the study area were obtained from the Meteorology Department of Sri Lanka.

All the statistical analyses were performed using R version 2.10.1 (R Development Core Team, 2008).

# 6.3 Results

## 6.3.1 Sex ratio

*Holothuria atra* is a dioecious species and there is no evidence on sexual dimorphism. They possessed a single gonad consisting of numerous filamentous tubules united basely into one tuft, attached to the left side of the dorsal mesentery and hanging freely in the coelom. The tubules were elongated and branched. In mature gonads, the filaments of the ovary appeared in red colour with swollen distal parts and the testes consisted of long creamy white beaded filaments (Figure 6.2a & b). Of the 256 individuals examined, 126 were males and 130 were females, giving a ratio of 1:1.03 which did not depart significantly from a 1:1 ratio ($P > 0.05$).

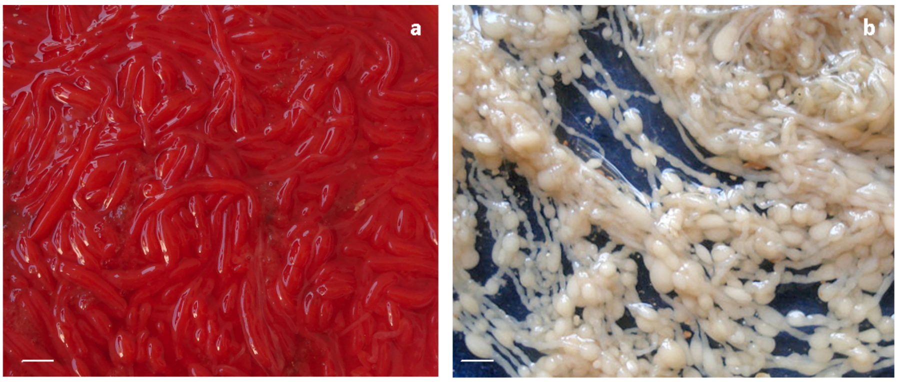


**Figure 6.2:** Macroscopic appearance of mature female gonad tubules with swollen distal parts (a) and mature male gonad with beaded filaments (b). Scale bar = 1.0 cm

## 6.3.2 Biometric measurements

The total body weight (TW) of sea cucumbers ranged from 419 to 1125 g and the gutted body weight (EW) was between 154 and 621 g. It was found that females were significantly heavier than the males ($P<0.05$: Table 6.1). Further, females gonads were significantly heavier than the males gonads ($P<0.001$) and they also had higher gonadosomatic indices ($P<0.001$). Tubule length ($P<0.01$) as well as the tubule diameter ($P<0.05$) of females was significantly greater than the males.

The gonadosomatic index (%GSI) was variable between sexes. The %GSI of males ranged from 0.6 to 14.1 with a mean (± SD) value of 7.69 ± 3.58 (n = 126) and for females it varied from 0.1 to 16.1 (9.26 ± 3.85, n = 130). There were significant

**Table 6.1:** Biometric characteristics of (mean ± SD) females (n=130), males (n=126) and both males and females of (n=256) *H. atra* collected in the north western coastal waters of Sri Lanka. Differences between biometric data of males and females were tested by Student's t-test and P value is given

| Biometric parameter | Males | Females | Both | P value |
|---|---|---|---|---|
| Gutted weight (g) | 395.2 ± 69.6 | 415.1 ± 86.5 | 405.3 ± 79.1 | $<$0.05 |
| Gonad weight (g) | 32.4 ± 18.1 | 40.5 ± 21.8 | 36.5 ± 20.4 | $<$0.001 |
| Gonadosomatic Index (%) | 7.7 ± 3.6 | 9.25 ± 3.8 | 8.5 ± 3.8 | $<$0.001 |
| Tubule length (mm) | 34.1 ± 17.2 | 39.9 ± 21.0 | 37.1 ± 19.4 | $<$0.01 |
| Tubule diameter (mm) | 1.1 ± 0.7 | 1.3 ± 0.6 | 1.2 ± 0.7 | $<$0.05 |

fluctuations in the monthly average gonadosomatic index of *H. atra* during the study period ($P < 0.001$).

The average %GSI (pooled for both males and females) increased gradually from July to September with a small peak in September 2008 (Figure 6.3). Then there was a declining trend of %GSI specially during October and November but started to increase again since December with a dominant peak in March 2009. The %GSI value declined sharply in April and since then a gradual increasing trend was observed. It was noted that GSI values varied greatly between the individuals, suggesting that patterns of spawning may be asynchronous among individuals. The mean monthly gonadosomatic index of females was often higher than males, but the pattern of monthly changes was similar in both sexes. The ripe individuals of *H. atra* were found throughout the year with a distinct period of activity during September and March.

### 6.3.3 Gonad morphology

The gonad tubules became branched and extended into the visceral cavity during the gonad developments. The gonad tubules were dominant in the cavity when the gonad was gravid. The observed morphological differences in the five different stages of gonad development are summarized below.

**I. Resting stage**

Thin and little branching transparent tubules were observed in the gonads. The walls of the tubules were thick and the lumen was devoid of content. Few disintegrated oocytes / spermatocytes were surrounded by phagocytes.

**II. Immature stage**

Immature gonads of both males and females were characterized by short, thin and branched yellow-white tubules. The tubule length of males ranged from 4 to 12 mm

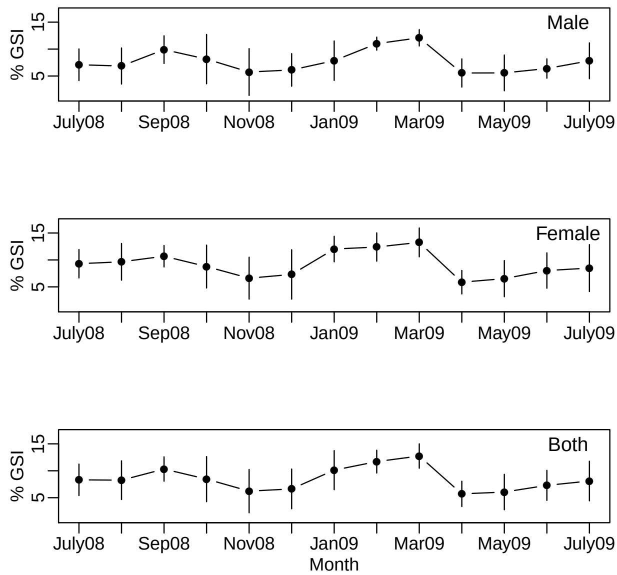


**Figure 6.3:** Fluctuations of mean monthly gonadosomatic index (± SD) of males, females and both males and females of *H. atra* in the north western coastal waters of Sri Lanka from July 2008 to July 2009

with a diameter from 0.2 to 0.9 mm and for females, it was within the range of 4 to 15 mm and 0.3 to 1.1 mm, respectively. Gonadosomatic indices (%GSI) of males and females were between 0.6-3.4 and 2.1-4.7, respectively. In histological sections, lumen found to be empty and only the primordial germ layer could be seen in both males and females. Further, there were no germinal cells inside the tubule (Figure 6.4a & b).

**III. Growing stage**

Testes consisted of long, slender, creamy-white branched tubules and ovaries were characterized by long, thick and yellow colour branched tubules. Tubule length was within the range of 15 to 49 mm in males and 22 to 53 mm in females. Tubule diameter of males varied between 0.4-1.2 mm and for females it was within 0.7 mm-2.0 mm. Gonadosomatic indices (%GSI) of females (6.7-12.7) were comparatively higher than the males (6.7-10.7).

The presence of numerous longitudinal infolds on the germinal epithelium was the most striking character of the growing testes. Infolds were lined by a dense layer of spermatocytes organized into short columns. As testes growth progressed, spermatozoa accumulated in the lumen whilst spermatocytes continued to develop along the germinal epithelium (Figure 6.4c & d).

Growing ovaries were characterized by active vitellogenesis. Oocytes at early and mid vitellogenic stages were dominant along the germinal epithelium and vitellogenic oocytes were surrounded by follicle cells. Oocytes were spherical in shape with or without nucleus. The gonad wall was thick and the lumen was not entirely filled with oocytes (Figure 6.5a).

**IV. Maturing stage**

Mature gonads have large fecund tubules (32-67 mm long in males and 28-87 mm in females) which were dominant in the coelomic cavity. When gonads became mature, the sex of the specimens was able to determine through the gonad colour.

Mature testes were beige in colour with a beaded appearance, as filaments were packed with spermatozoa. Mature ovaries were red in colour and oocytes were apparent through the thin transparent tubule wall. The tubule diameter was within the same range between 1 and 2.6 mm in both males and females. The maximum value for %GSI was reported in this stage (6.9-14.1 in males, 8.7-16.1 in females) for both sexes. In mature testes, the lumen was packed with spermatozoa and infolds of the germinal epithelium were reduced or absent. The presence of few spermatocytes was observed. The wall of the mature testes was also at its minimum thickness (Figure 6.4e & f ).

Figure 6.5b shows the cross section of mature ovary which is densely packed with late vitellogenic oocytes with distinct germinal vesicle. The germinal vesicle of these oocytes was prominent and occupied a central or eccentric position near the basal protuberance (Figure 6.5c). The protuberance is important to attach the oocyte to the germinal epithelium. Oocytes were polymodal in shape and remained within the follicles. Oocytes could be clearly visible through the thin transparent tubule wall.

**V. Spent stage**

Spent gonads possessed a combination of large fecund tubules and tubules that have released their gametes. Male tubules were ranged from 15 to 31 mm in length, 0.3 to 0.8 mm in diameter and those tubules were white in colour, transparent and shrunken in appearance. The %GSI was within the range of 3.2-7.8. Ovaries were characterized by yellow colour, empty and branched tubules. The tubules length ranged from 18 to 27 mm with a diameter of 0.3 to 1.0 mm. %GSI showed a sharp decline (3.1 to 7.4) when compared with the maturing stage. Oocytes in the unspawned tubules were clearly being broken down. The tubules of the spent testes were empty with few unspawned spermatozoa. Occasionally, the germinal epithelium of the spent testes took on a convoluted appearance without evidences of re-initiation of gametogenesis. Gradual increment of ovary wall thickness was observed in the spent females. A few relict oocytes were occasionally present and phagocytes were also seen in some specimens (Figure 6.5d, e & f).

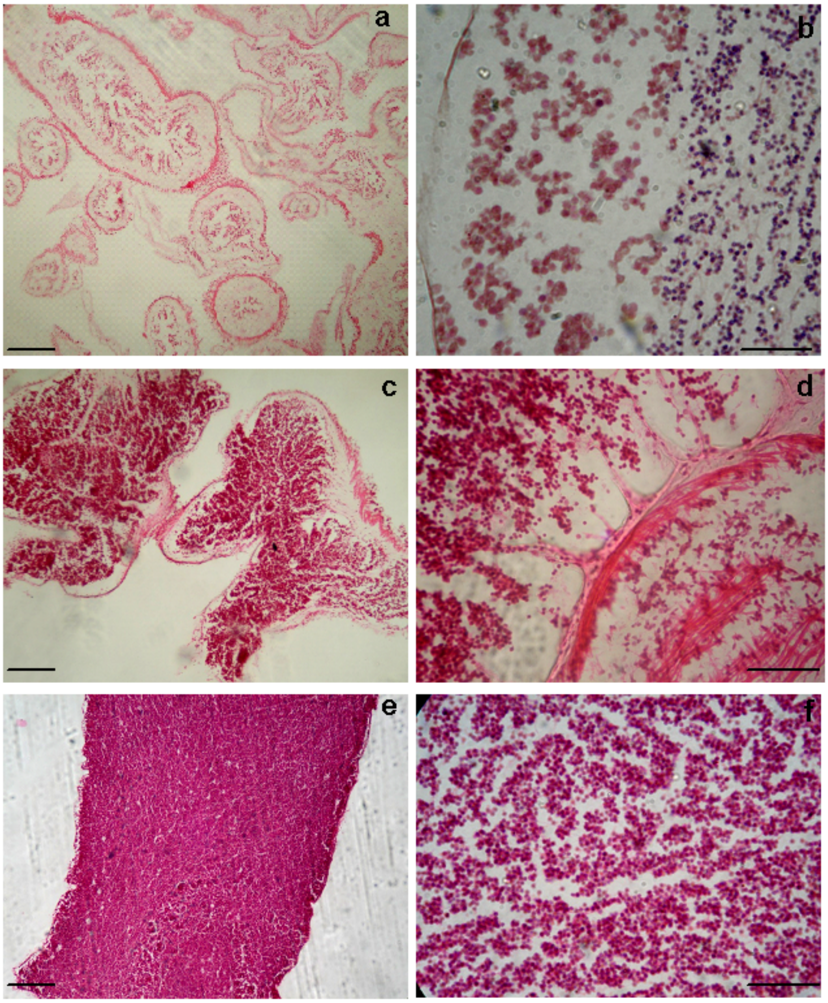


**Figure 6.4:** Testis tubules development stages of *H. atra*; a: germinal cells are along germinal epithelium and lumen is empty, b: germinal cells are along germinal epithelium and lumen is empty, c: infolds on the germinal epithelium lined with developing spermatocytes along the edge and spermatozoa within the lumen, d: infolds on the germinal epithelium lined with developing spermatocytes along the edge and spermatozoa within the lumen, e: lumen packed with spermatozoa, f: lumen packed with spermatozoa. The scale bar in the photographs a, c, e represents 100 $\mu$m whereas the scale bar in the photographs b, d, f represents 400 $\mu$m

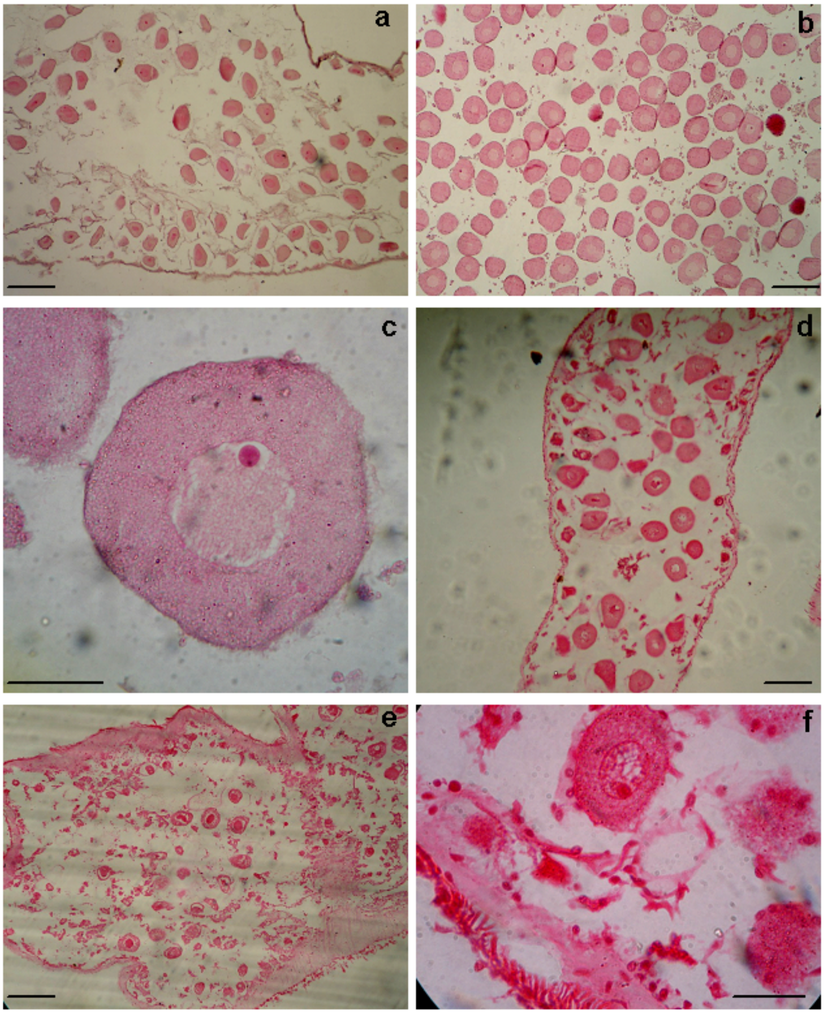


**Figure 6.5:** Oocyte tubules development stages of *H. atra*; a: tubule containing both early to mid vitellogenic oocytes, b: tubule packed with mature oocytes, c: mature oocyte with prominent germinal vesicle and nucleolus, d: partly spawned tubule (early stage) containing mature oocytes and early to mid vitellogenic oocytes, e: partly spawned tubule (latter stage) containing mature oocytes and early to mid vitellogenic oocytes, f: re-initiation of gametogenesis. previtellogenic oocytes and early to mid vitellogenic oocytes are evident. The scale bar in photographs a, b, d & e represents 100 $\mu$m whereas the scale bars in photograph c & f represent 1000 $\mu$m & 400 $\mu$m respectively

### 6.3.4 Size at first sexual maturity

The estimated length at first sexual maturity of *H. atra* (when 50% of the individuals in the population showed developing gonads) was 16 cm and the estimate was done by ignoring the sexual differences (Figure 6.6).

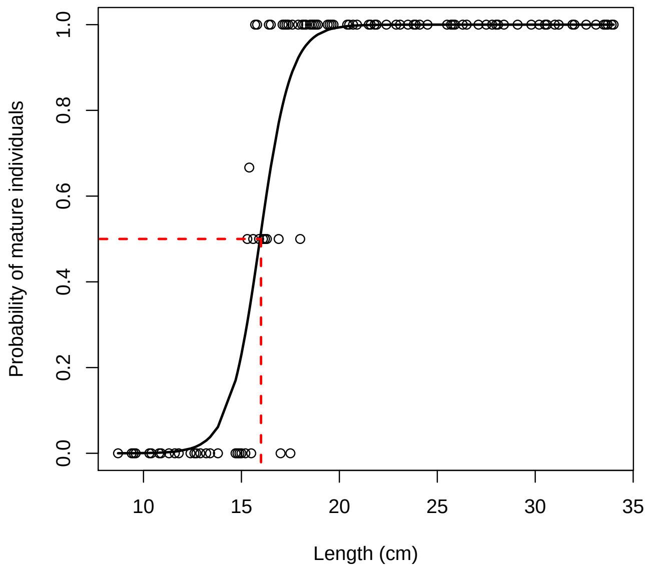


**Figure 6.6:** Length at first sexual maturity of *H. atra* in the northwestern coastal waters of Sri Lanka. Open dots indicate the observed proportions of mature individuals and the solid curve represents the GLM output

### 6.3.5 Reproductive cycle

*Holothuria atra* population was sexually active throughout the year (Figure 6.7). "Mature" individuals were reported throughout the study period having peaks in September and March, when the "‘immature"’ individuals reached the lowest percentage. Individuals with growing gonads were peak in June, July and December. Spent individuals were dominant in October and April though they were reported in the other months.

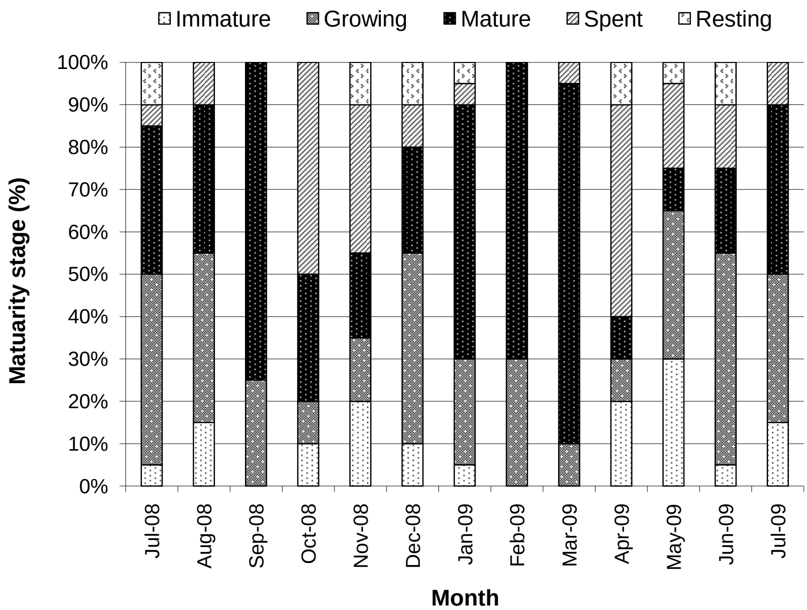


**Figure 6.7:** Gametogenic cycle of *Holothuria atra* collected off the northwest coast of Sri Lanka from July 2008 to July 2009. Histogram shows the percentage of individuals in one of the five gametogenic stages: immature, growing, mature, spent and resting

### 6.3.6 Effect of environmental variables

The mean monthly temperature exhibited a seasonal pattern peaking in April where the mean monthly temperature reached the maximum of $29.3^0$C and the minimum monthly mean temperature was found in December ($26.3^0$C). The average monthly gonadosomatic index found to be increased with increasing temperature from December to March and during these periods development of gametes was in progress. The highest %GSI value was coincided with mature gonads which were found in March. Temperature remained at high level in April but %GSI declined drastically by indicating the spawning of individuals. The same relationship was found from July to October between %GSI and temperature (Figure 6.8a). In both cases the highest temperature appeared to be initiated the spawning activity.

There was a seasonal pattern of rainfall with a peak in December. However it was difficult to find any relationship between mean monthly rainfall and the average monthly gonadosomatic index of *H. atra* (Figure 6.8b).

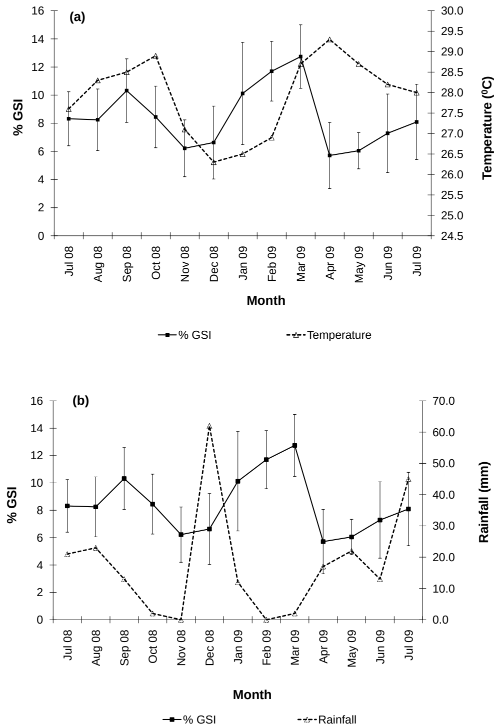


**Figure 6.8:** Fluctuations of mean monthly % GSI of *Holothuria atra* in relation to monthly mean air temperature (a) and rainfall (b) off the northwest coast of Sri Lanka from July 2008 to July 2009. Both temperature and rainfall data were obtained from the Meteorological Department of Sri Lanka.

## 6.4 Discussion

The observed sex ration of *H. atra* is consistent with previous research findings on sea cucumber sex ratio which is often close to 1:1 (Hamel, 1993; Hopper et al., 1998; Uthicke, 1997a). However, unbalanced sex ratios have been discovered for some *Holothuria* species specially including *H. atra* and *Holothuria edulis* and this was found to be associated with the asexual mode of reproduction of these species (Shiell and Uthicke, 2006; Uthicke et al., 1998).

The reproductive behaviour of *H. atra* is much similar to the other tropical Aspidochirote holothurians including separate sexes and external fertilization. Further, this study confirms that females are having significantly higher body weight (gutted body) than the males and similar phenomenon has been observed by Gaudron et al. (2008) for *Holothuria leucospilota* in the western Indian Ocean and *Holothuria arenacava* in Kenyan marine protected area (Muthiga, 2006). Sexual dimorphism was also recorded for gonad weight, gonadosomatic index, tubule length and the tubule diameter where the female measurements tend to be higher than those for the males. The similar observations were made previously by Conand (1993) for the nine tropical holothurian species in the New Caledonian lagoon. The gonadosomatic index has been recognized as a reliable indicator for studying the sexual reproductive cycle of holothurians (Chao et al., 1995). According to Conand (1993), the percentage of individuals with mature gonads and the gonadosomatic index, can be used to estimate reproductive effort or energy invested in reproduction. However, there is a possibility of affecting the gonadosomatic index by small variations in body length or body weight (Engstrom, 1980).

The pattern of gonads development in females and males was very similar, indicating the synchronous gametogenesis, with increasing and decreasing of gonadosomatic indices in both sexes simultaneously. From July to September, the gonadosomatic indices (GSI) of both males and females increased gradually and same trend was observed from December to March where the individuals were mainly in stage III and gradually attained stage IV. Mature individuals were observed most of the year with higher magnitude in March and September. Spent specimens were usually found with empty tubules towards the April and October by highlighting the spawning. This study revealed that there were numerous individuals with mature gonads throughout the year, suggesting that individuals may reproduce continuously or asynchronously several times during the year having peak in April and October off the northwest coast of Sri Lanka. However, the timing of reproduction can be varied with other factors such as the ability of adults to acquire food reserves enabling them to devote energy for reproduction and the availability of optimal conditions for settlement and development of larval stages (Ramofafia et al., 2003).

A number of studies have been carried out by different authors to study the reproductive pattern of *H. atra* in different geographical locations. Existence of different reproductive patterns such as continuous, annual and semi-annual have been reported for *H. atra* (Harriott, 1985). The annual reproductive cycle has been reported as the most common reproductive pattern in *H. atra* (Cameron and Fankboner, 1986; Chao et al., 1995; Conand and Byrne, 1993; Harriott, 1982; Smiley et al., 1991). Abdel-Razek et al. (2005) reported that *H. atra* living near the equator have mature gonads throughout the year and the present study also confirms that finding. *H. atra* in Heron

Island reef ($23^0$ $27^{'}$S, $151^0$ $55^{'}$E) were reported to have mature gonads throughout the year with distinct gonad maturity peaks in summer and early winter months. *H. atra* in New Caledonia (220 $^0$5$^{'}$S, $166^0$ $24^{'}$) and off the southern Taiwan ($21^0$N, $120^0$E) tend to have an annual reproductive cycle with spawning in warm months (Abdel-Razek et al., 2005; Chao et al., 1995; Conand, 1990; Smiley et al., 1991). So, it is clear that sea cucumbers inhabit close to the equator tend to reproduce throughout the year while distance populations would have restricted spawning periods (Abdel-Razek et al., 2005; Harriott, 1985).

Identification of maturity stages using the external appearance of the gonad was consistent with the histological findings. The observed gametogenesis pattern of *H. atra* was much similar to the gametogenesis of other *Holothuria* species (Smiley et al., 1991). Initiation of gametogenesis and subsequent maturation and gamete release were found to be occurred simultaneously in both sexes. The presence of numerous longitudinal folds in the germinal epithelium of males appears to be common in holothurians spermatogenesis (Smiley et al., 1991). These folds are mainly important to increase the surface for proliferation of spermatogonia (Cameron and Fankboner, 1986) and to provide a reservoir of nutrients in the haemal fluid to support spermatogenesis (Smiley et al., 1991).

Information on size at first sexual maturity is an important specially to determine the minimum legal size by maintaining adequate spawning stocks allowing ripe individuals to complete at least one spawning cycle. Size at first sexual maturity of sea cucumbers is reported to be varied with species and geographical locations. The size at first sexual maturity of male *H. atra* in the Red sea was reported as 16.5 cm and it was 15.5 cm for females (Abdel-Razek et al., 2005). The size at first sexual maturity of the same species collected from the New Caledonian Lagoon was 16.5 cm (Conand, 1993). The estimated size at first maturity of *H. atra* in the northwest coast of Sri Lankan was smaller (16.0 cm) than the above reported values, probably suggesting faster growth in Sri Lanka or simply earlier maturation due to the different environmental conditions.

According to the present study, the main spawning event of *H. atra* coincided with the highest temperatures. The consistent relationship between the temperature and spawning of *Holothuria leucospilota* has been observed in the western Indian Ocean (Gaudron et al., 2008). Tanaka (1958) has also suggested that temperature may have great influence on the spawning initiation of sea cucumbers and higher temperatures appear to be triggered the spawning event. However, it was hard to see any relationship between the spawning of *H. atra* with precipitation.

According to Dissanayake and Stefansson (2010a), *H. atra* is the second most abundant sea cucumber species in the coastal waters of Sri Lanka and there is a possibility of expanding the fishery for this species specially off the northwest coast. As sea cucumber fishing activities are currently practiced without any management measures, it is timely to implement at least simple management measures such as legal landing size, catch limitation through close season to ensure the sustainability of this resource off the coastal waters of Sri Lanka. The information presented here on reproductive pattern and the size at first sexual maturity can be used to implement such management strategies. However, further research and analysis of growth, recruitment and survivorship on longer time-scales is needed to understand the population ecology of this species to determine the potential yield and sustainable utilization of this resource.

# 7

# Design of marine protected areas for sea cucumbers

## 7.1 Introduction

Most of the traditional fisheries management approaches have not been successful in protecting marine environments due to inadequate control over the human activities (Crosby et al., 2000). Hence, increased attention has been given to ecosystem-based fisheries management approaches and marine protected areas (MPAs) as a fisheries management tool has gained greater attention recently (Levin and Lubchenco, 2008; Palumbi et al., 2008; Rosenberg and McLeod, 2005; Ruckelshaus et al., 2008). MPAs are spatially delimited areas designed to conserve the coastal and marine resources under restricted human activities (Edgar et al., 2007; Jamieson and Levings, 2001). In application, a variety of terms have been used to define MPAs; marine sanctuaries, no-take reserves, harvest refugia, marine reserves, ecological reserves with different combinations of motives (Hilborn et al., 2004; Kelleher, 1999; Lubchenco et al., 2003).

A wide range of roles has been suggested for MPAs in fisheries management (Sainsbury and Sumaila, 2002; Stefansson and Rosenberg, 2005). Greater densities and size of fish in MPAs may induce spillover of adults and export of eggs and larvae across their boundaries to enhance the outside production (Edgar et al., 2007; Guidetti and Claudet, 2010; Harmelin-Vivien et al., 2008; Roberts et al., 2001a; Sale et al., 2005). Substantial improvement of local catches due to spillover of adults from MPAs has been reported in many places, a good example being Sumilon Island in Philippines (Alcala and Russ, 1990). Tagging experiments have also demonstrated net movement of animals from reserves to local fishing grounds (Klima et al., 1986; Rowe, 1969). In some cases, increased fecundity and reproductive capacity were reported within MPAs, potentially giving larval export to other areas (Guidetti and Claudet, 2010; Sainsbury and Sumaila, 2002). However, larval export seems to be more effective for species with high fecundity and possibly a relatively short larval lifespan. In some cases, marine reserves have been shown to reverse the decline of species richness and genetic diversity caused by fishing. Naturally, MPAs also eliminate bycatch of non-target species and protect habitat from damage by fishing gear (Botsford et al., 2003; Palumbi, 2002; Sale et al., 2005).

Several modeling applications have shown that under certain conditions MPA's can increase the fisheries yield even at very low stock levels (Greenville and MacAulay, 2005; Pezzey et al., 2000; Polacheck, 1990; Sanchirico and Wilen, 2001; Stefansson and Rosenberg, 2005; White and Kendall, 2007). Further, new technologies have made the design, enforcement and monitoring of MPAs much easy and more practical (Sainsbury and Sumaila, 2002).

According to Hilborn et al. (2004), MPAs are expected to perform best for sedentary species rather than pelagic or migratory species. In particular, MPAs have considerable potential for sea cucumbers because they are sedentary broadcast spawners and the successful spawning and fertilization depend on the high population densities which rarely exist in most of the "open" fishing grounds (Bell et al., 2008).

According to previous studies, most of the high-value sea cucumber species such as *Holothuria fuscogilva*, *Holothuria nobilis* have been fished to the level of reproductive extinction throughout the world and the situation is much worst in Asian region (Choo, 2008b; Conand, 2004a; Purcell, 2010b; Uthicke and Benzie, 2001; Uthicke et al., 2004). Even in Sri Lanka, the population densities of these species were less than 1 ind $ha^{-1}$ (Dissanayake and Stefansson, 2010a). In this study, an attempt was made to design MPA's to avoid further depletion of high-value sea cucumber species off the east coast of Sri Lanka. Simulation model was adapted and used to understand how MPAs will help to meet the biological objectives under different biological situations.

## 7.2 Methodology

Simulation model developed by Stefansson and Rosenberg (2005) was used for this analysis.

### 7.2.1 Model components

**(a) Population biomass**

The following model was used to build up a bulk biomass population dynamics model

$$B_{t+1} = B_t + rB_t(1 - B_t/K) - Y_t, \tag{7.1}$$

where $B_t$ denotes the biomass at the beginning of time step t, $Y_t$ denotes the yield in biomass or catches during the same time-step, $r$ indicates the rate of production and $K$ indicates the carrying capacity.

As the current model is spatially disaggregated, multiple areas and migrations need to be taken into account when it expands into bulk biomass population dynamics model (7.2). The multiple areas were arranged in a grid and adult migrations (both feeding and spawning) and larval dispersal were incorporated into the model to build up the multi-area-extension

$$B_{t+1} = P_t^B(B_t - Y_t) + P_t^R R_{t-\tau}, \tag{7.2}$$

where $B_t$ is the vector biomass by area, $R_t$ is the vector of biomass production of each area, two matrices $P_t^B$ and $P_t^R$ describes the adult migration rate (both spawning and feeding) and larval dispersal rate, respectively. $\tau$ indicates the recruitment delay factor and this was used to account for recruitment delay.

In this model, production enters every month and $r$ is a monthly production rate. To link the production and biomass, the components of the production vector, $R_t$ are defined for the first month of any year (i.e. when t = 12y + 1) by

$$R_{A,t} = rB_{At}(1 - B_{At}/K_A). \tag{7.3}$$

For the other months, $R_{A,12y+i} = R_{A,12y+1}$, i= 2,....12.

**(b) Fishing mortality and harvests**

The catches are determined by removal rates; $Y_{At} = F_{At}B_{At}$. Here $F_{At}$ is removal fraction and this is also referred to as fishing mortality.

**(c) Geometry and migration**

The east coast survey area described in chapter 3 was considered as the entire habitat of sea cucumbers and this area was assumed to form a rectangular 5 x 5 grid with a total of 25 areas. It was found that population densities of two sea cucumber species (*Holothuria fuscogilva* and *Holothuria nobilis*) varied with depth. Hence, in this analysis, 5 vertical rectangles were allocated to represent 5 different depth categories; 0-5 m, 5-10 m, 10-15 m, 15-20 m and 20-25 m. In this model, 3 types of migrations; spawning, feeding and larval dispersal is considered and it is assumed that any types of migration can occur only between adjacent areas in any given month.

As described in Stefansson and Rosenberg (2005), general variations in fish migrations and uncertainties were considered when migration rates were generated. Further, the approach was taken to only allow migration of positive population growth and also to constrain all population to be non-negative.

**(d) Economic model**

Economic model described in Stefansson and Rosenberg (2005) was used in this simulation. For a given time step ($t$) and area ($A$), income ($I$) of the fishery is

$$I = pY_{At}. \tag{7.4}$$

Here $p$ is the first sale price and $Y_{At}$ denotes landings.

Cost of operation (c) is assumed to be of the form

$$c = kE_{At}. \tag{7.5}$$

Here $E_{At}$ is local monthly effort in the area. By assuming a known profit level ($\delta$) in a reference year, the base value for the multiplier $k$ was determined

$$k = pY_0(1-\delta)/E_0. \tag{7.6}$$

Monthly yield in area $A$ can be rewritten as

$$Y_{At} = F_{At}B_{At} = q_{At}E_{At}B_{At}. \tag{7.7}$$

Hence the profit function becomes

$$\Pi_t = \Sigma_A c_{At}E_{At}. \tag{7.8}$$

where $c_{At} = (pq_{At}B_{At} - k)$.

**(e) MPAs**

Area closures were modeled by forcing fishing mortality of those areas to be zero. In the base simulation 6 contiguous rectangles in between 10 - 25 m were considered as closed areas.

### 7.2.2 Input parameters to the model

Initial biomass ($B$) was calculated using data collected from the underwater visual census off the east coast of Sri Lanka in 2009 and $B$ was set at 87. As anecdotal evidences suggest that the current biomass is around 10% of virgin biomass, $K$ was set at 870. $F_{hist}$ was calculated using the regression model described in chapter 4 and $r$ was set at 0.44.

The base model was run for 50 years before the onset of management in order to get internally consistent population structure (with respect to migration assumption) to get start the simulation. It was assumed that fishing was in accordance with the target fishing mortality during the historical time and economic model was used to allocate effort to areas.

The historical fishing mortality was set at $F_{hist} = F_{crash}$ where $F_{crash} = r = 0.44$. By considering population density in different depth categories, it was assumed that areas belonging to the 15 - 20 m depth range were remained as historical MPAs for a period of 25 years and areas belonging to the 20-25 m were for 45 years. As sea cucumbers are sedentary species, only larval dispersal was considered and both feeding and spawning migrations were set at 0.

The model was simulated under different biological assumptions to understand changes in biomass for next 15 years.

## 7.3 Results

First consider the fluctuations of biomass for next 15 years under different larval dispersal rates; 90%, 50%, 25% and 0% (Figure 7.1). The observed pattern is straightforward where the high rate of biomass increase can be expected when there is high rate of larval dispersal. If there is no larval dispersal, it is difficult to expect recovery of biomass even though MPA's are existed.

Biomass changes in open and closed areas (MPAs) were computed and compared with respect to different larval dispersal rates. The results indicate that the rate of biomass recovery relates to the larval dispersal rates. Higher rates of larval dispersal

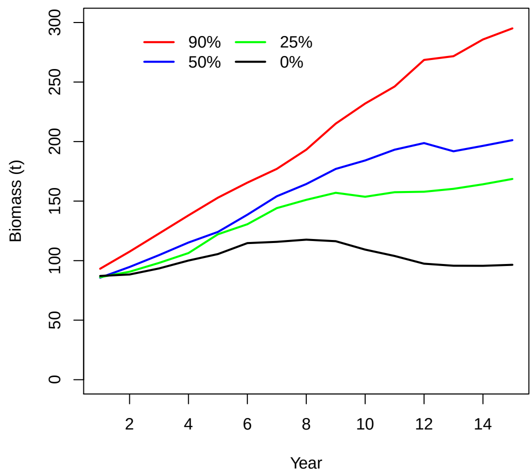


**Figure 7.1:** Fluctuations of biomass under different larval dispersal rates; 90%, 50%, 25% and 0%. Six contiguous rectangles in between 10-25 m are considered as MPA's in this simulation

(Figure 7.2a) generate high amount of biomass in open areas than the lower rates of larval dispersal (Figure 7.2b & c). When there is no larval dispersal, it is difficult to see any improvement in biomass outside the MPAs even after 15 years (Figure 7.2d).

Biomass changes in five different depth categories were simulated for next 15 years under 90% larval dispersal rate and 6 contiguous MPA's. In deeper areas, the rate of biomass increase is higher than the shallower areas. Further, areas belonging to the 0 - 5 m depth category require more than 10 years to show any gain in biomass while in the 5 - 10 m depth category, the development of biomass can be expected after 6 years (Figure 7.3)

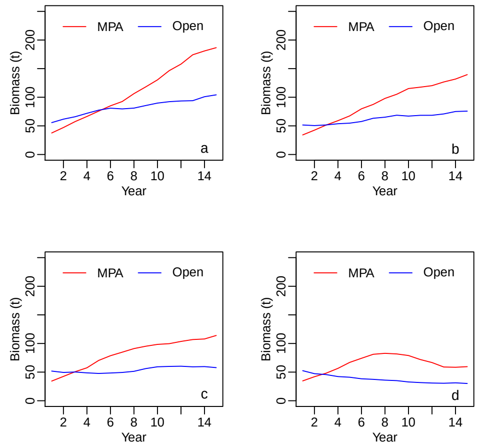


**Figure 7.2:** Fluctuations of biomass in closed (MPA's) and open areas under different larval dispersal rates; a = 90%, b = 50%, c = 25% and d = 0%. Six contiguous rectangles in between 10-25 m are considered as MPA's in this simulation

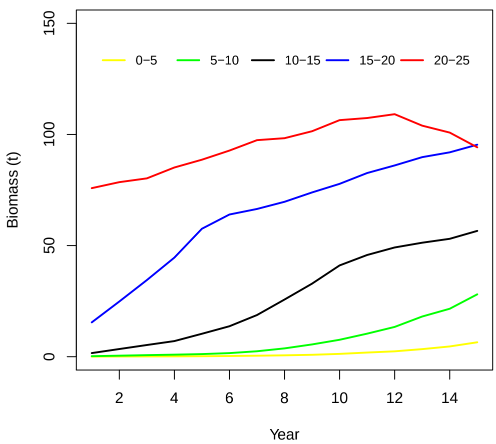


**Figure 7.3:** Fluctuations of biomass in different depth categories for the next 15 years under 90% larval dispersal rate and six contiguous MPAs in between 10-25 m depth

The fluctuations of sea cucumber yield was considered and according to the simulation results, it can be expected three times increase of current yield at the end of 15 years (Figure 7.4).

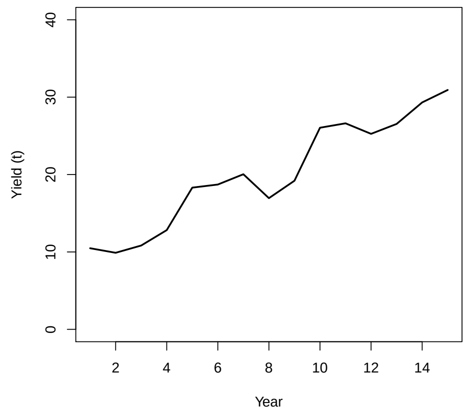


**Figure 7.4:** Fluctuations of yields for 15 years under 90% larval dispersal rate and six contiguous MPA's in between 10-25 m

The rate of biomass change in open and closed areas was analyzed under 4 different closures; 4, 6, 10 and 15. When there are 10 and 15 closures, all the rectangles belonging to two (15-2 m and 20-25 m) and three (10-15 m, 15-20 m and 20-25 m) depth categories are assumed to be closed for fishing, respectively. When implementing 4 and 6 closed areas, 4 contiguous rectangles in the 15-25 m depth category and 6 contiguous rectangles in the 10-25 depth category are assumed to be closed. According to the simulation results, the rate of biomass increase is related to the number of closed areas (Figure 7.5). When there are 15 closed areas, the highest biomass can be observed within MPAs but it is difficult to see any improvement of biomass in open areas up to 10 years. Gradual increasing of biomass within closed and open areas is seen even under 4 and 6 closures but in these situations biomass will not attain the higher levels as predicted for 10 or 15 closures (Figure 7.6).

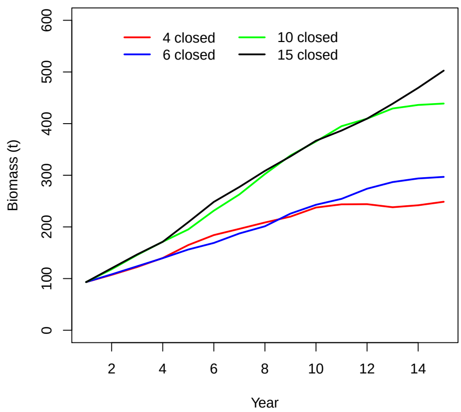


**Figure 7.5:** Fluctuations of total biomass under different closures (4, 6, 10 and 15 closed rectangles) for 15 years. 90% larval dispersal rate is considered in this simulation

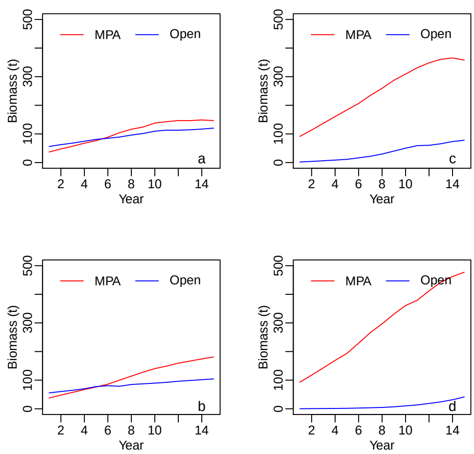


**Figure 7.6:** Fluctuations of biomass in open and closed areas under different closures; a = 4 areas, b= 6 areas, c = 10 areas, d = 15 areas for15 years. 90% larval dispersal rate is considered in this simulation

## 7.4 Discussion

Previous studies have shown that fisheries outside marine protected areas may be beneficial due to export of adult biomass and /or larvae from protected areas (Bohnsack, 1998; Russ and Alcala, 1994, 1996; Stefansson and Rosenberg, 2006). According to this study, the rate of biomass recovery is related to larval dispersal rate and a considerable biomass increase can be gained when there is high rate of larval dispersal. As sea cucumbers are sedentary organisms, movement of adults from MPA's to open areas was neglected in this analysis.

Various studies have shown that the beneficial effects of MPAs can be maximized by implementing a large number of closures (Ramos-Espla and McNeill, 1994; Stefansson and Rosenberg, 2005). The simulation results under different closures also indicate that there is a potential to gain high stock biomass when there are large number of MPAs. As high population densities and proposed closures are in the deeper depth categories, rapid increase of population biomass in deeper waters can be expected than shallower areas. Few MPA's have been implemented for sea cucumbers so far and these studies have highlighted the need of large number of reserves for long time period to rebuild the highly depleted sea cucumber populations (Purcell, 2010b; Uthicke, 2004). According to Purcell (2010b), reserves, unless very large, will rarely satisfy the conservation objectives of tropical sea cucumber fishery because it is a multispecies in nature and habitat requirement of these species is difficult to represent in one small reserve.

Spatial management through marine reserves is seen to have potential to rebuild the sea cucumber populations in the east coast of Sri Lanka. The model application used in this study provides the basis for planning MPA's. However, multi-species interaction and the habitat preference of sea cucumber species are not considered in this model. The dispersal potential of sea cucumber larvae and their behaviour in water column is still questionable (Lovatelli and Conand, 2004; Uthicke and Benzie, 2000; Uthicke and Purcell, 2004). Hydrographic studies coupled with population genetics of sea cucumbers will be useful to resolve this problem and incorporation of this information into the model will be useful in future.

# 8

# Conclusions and future perspectives

The species diversity, spatial distribution pattern and stock status of commercial sea cucumber species off the east and northwest coasts of Sri Lanka and possible management measures to ensure their sustainable utilization were revealed in this study. The presence of twenty-five sea cucumber species belonging to seven genera; *Actinopyga*, *Bohadschia*, *Holothuria*, *Pearsonothuria*, *Stichopus*, *Thelenota* and *Acaudina* was identified. The overall average density of sea cucumbers was higher on the northwest fishing grounds than the east and this may be due to differences in habitat conditions and the level of exploitation. The population densities of all the sea cucumber species in the coastal waters of Sri Lanka were less than 30 ind $ha^{-1}$ except for *H. atra*, *H. edulis* and *H. spinifera* off the northwest coast and *H. edulis* off the east coast. According to the classification in Purcell et al. (2009), population densities below 30 ind $ha^{-1}$ can be considered as at "critical level". The observed pattern of juveniles abundance may be a result of insufficient stock densities where eggs released by females may not encounter sperm by distant males to produce sufficient offspring.

The extensive surveys will be useful in future to gain a better understanding of the stock status and the species diversity of sea cucumbers in the coastal waters of Sri Lanka. As there were confusions on the taxonomic identification of some sea cucumber species (e.g. *Bohadschia* species "lines" and *Holothuria* "pentard"), more taxonomic work coupled with genetic studies will be useful in future. Further studies are needed to determine the minimum population density required to ensure the successful reproduction of each sea cucumber species and the information on fertilization kinetics, reproduction and chemical cues in holothurians will be useful to achieve this task.

The reduced densities of high and medium-value species in the shallow coastal waters seemed to be an indication of excessive fishing pressure on these resources over time. On the other hand, these density differences may be related to bottom habitat characteristics and understanding of larval movement and settlement preferences will improve this prediction further.

Although there were 21 commercial sea cucumber species off the east and northwest coasts of Sri Lanka, only 11 species were dominant in the commercial catches. But, commercial fishery predominantly relied on two nocturnal species; *Holothuria spinifera* and *Thelenota anax* belonging to the medium-value category and the contribution of high-value species to the total production was negligible. *H. spinifera* had the highest contribution (70%) to the total production in the northwest while it was from *T.anax* (90%) in the east. There were no diurnal fishing operations in the east and the decline of diurnal fishing activities was observed in the northwest. In both regions, there was a high number of dependents on this fishery and a continuation of same fishing pressure was revealed despite the scant catches.

This study indicates that sea cucumber fishery is no longer viable off the east coast of Sri Lanka but there is a potential to expand the fishing on low-value species particularly, *H. atra* and *H. edulis* off the northwest coast of Sri Lanka. Although, *H. edulis* is a commercial species, it is rarely exploited in the coastal waters of Sri Lanka at present. However, this species is mainly exploited in China, Japan, Malaysia, Philippines and Thailand and there is a considerable market demand for this species (Choo, 2008). Hence, it may be timely to promote the exploitation of these two species off the northwestern coastal waters of Sri Lanka to reduce the heavy fishing pressure on the other stocks as well as to add substantial income to the costal livelihoods.

Estimation of natural mortality (M) is one of the most difficult and critical elements in fish stock assessment and tagging and growth studies have commonly been used for this purpose (Hewitt et al. 2007). In the present study, two approaches; simple linear regression and random effects models were used to estimate the average natural mortality of sea cucumbers and the estimated values ($0.5\ yr^{-1}$ and $0.45\ yr^{-1}$, respectively) were close to each other and are consistent with results from other studies. Random effects model predicted lower natural mortality for nocturnal species than for the diurnal species and this could be a result of reduced predation on the former species as they are under sand or rocks during the day time. Possibly these differences in the mortality rates could be associated with some biological and genetic characteristics of larval and juvenile stages of these species but more research studies on larval biology and predation on sea cucumbers are needed to confirm this hypothesis. However, the predicted natural mortality values are very useful when applying stock assessment models, particularly for the tropical multispecies fishery, as natural mortality estimates are often lacking for most of the sea cucumber species.

In order to validate the natural mortality estimates, more data from different temporal and spatial resolution can be incorporated into the models. Separate analyses for nocturnal and diurnal species will be useful to expand the knowledge on the observed differences in natural mortality among the diurnal and nocturnal species. As these models are based on fairly simple data, model applications can be easily extended for fish and other invertebrates.

After identifying the fishing potential on *H. edulis* and *H. atra* off the northwest coast of Sri Lanka, further studies were carried out to identify the habitat preference of these species and reproductive pattern of *H. atra* as this information is important for resource management.

The habitat association of two species was mainly influenced by bottom sediment conditions, depth and bottom habitat types. *H. atra* was more common in seagrass habitat while the dense aggregation of *H. edulis* was reported in reef flats and rocky habitat. Although these two species favoured similar bottom sediment conditions, they have different preferences towards the sediment organic contents making it possible for them to have separate niches. Analysis of biological samples indicated that the size at first sexual maturity of *H. atra* was 16 cm and the population was sexually active throughout the year having peak spawning in April and October. Further, the main spawning event coincided with the highest temperatures.

The findings of this study revealed an urgent need to implement some management measures to avoid further depletion and even a collapse of sea cucumber stocks in the coastal waters of Sri Lanka. The simplest management measure would be the ban or limit of the commercial exploitation of all the species whose stock densities are below some critical level such as 30 ind $ha^{-1}$ defined by Purcell et al. (2009). Re-opening of fishing activities for these species can be considered when populations will overcome the critical level. If a ban is implemented, only three stocks; *H. atra*, *H. edulis* and *H. spinifera* off the northwest coast of Sri Lanka can be exploited by fishers and it would be prudent to make sure that the total catches from these stocks are limited in a manner to ensure long-term sustainability of these resources. Implementation of TAC limit, minimum landing size, routine monitoring and reporting of commercial landings can be considered to achieve this task to some extent. The information presented in this thesis on size at first sexual maturity can be used when setting minimum landing size for *H. atra*. However, detailed studies on reproductive biology are needed to understand the reproductive pattern and the size at first sexual maturity of *H. edulis* and *H. spinifera*.

Marine Protected Areas (MPAs) is seen to have potential to rebuild the highly depleted sea cucumber population off the east coast of Sri Lanka. A Multi-area bulk biomass model was used to design MPAs and simulation results reveal that the rate of biomass recovery mainly depends on larval dispersal rate and the number of closures. As the sea cucumber fishery is multi-species, consideration of multi-species interactions will be useful in future. Localized information on larval biology, larval dispersal rates and oceanographic conditions will further improve the model predictions.

The findings of habitat and ecological requirements of *H. atra* and *H. edulis* will be useful when implementing successful rehabilitation programmes and precise stock assessment surveys. Further, conservation of preferable habitat conditions of *H. atra* and *H. edulis* is important to maintain the high population densities. Aquaculture and mariculture practices are other possible considerations in future to provide alternative source of sea cucumbers to the coastal fishing communities and to reduce the high fishing pressure on wild stocks.

The information gained through this study can provide a basis for the management of the sea cucumber resources in Sri Lanka. Further, this information is important to update the regional and global sea cucumber statistics as well as to contribute for regional management programmes.

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